KCFP – Competence Center for Combustion processes

ANNUAL REPORT | 2020

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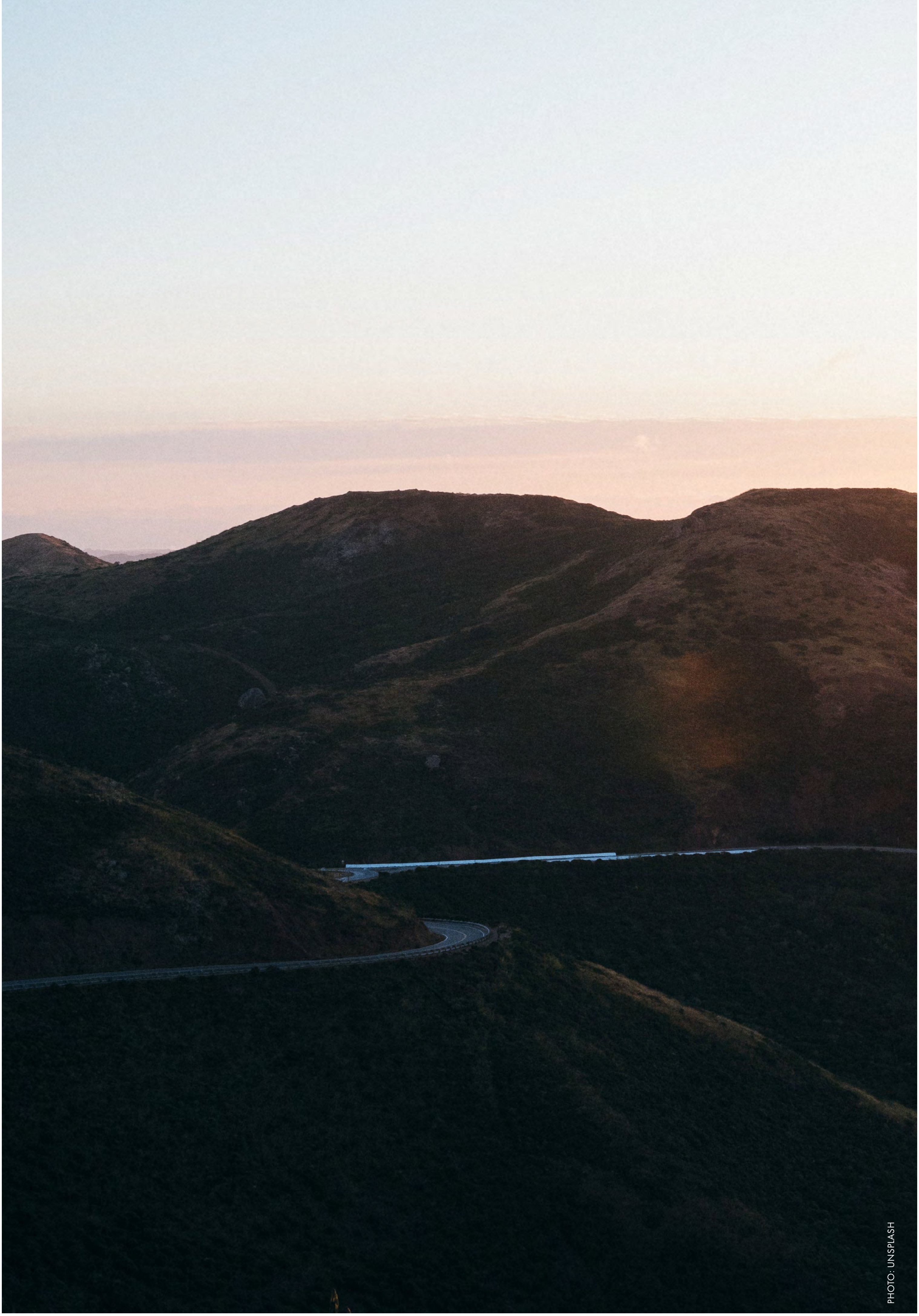
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THE COMPETENCE CENTER FOR COMBUSTION PROCESSES (KCFP)

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.

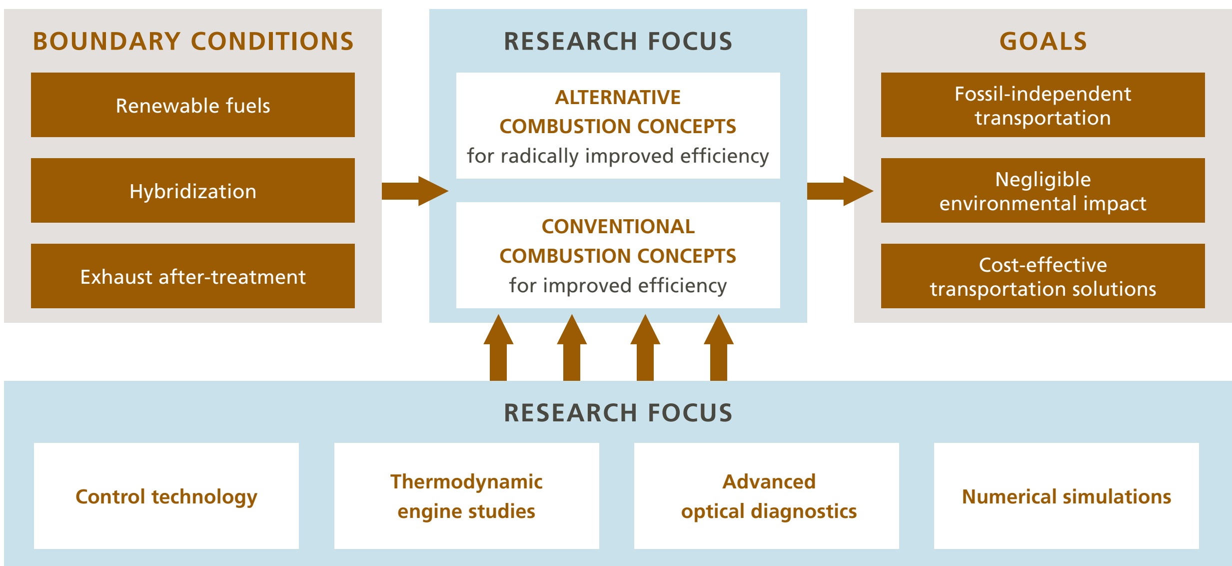
KCFP should conduct research to facilitate a transition to more knowledge- and research-based methods in order to reduce development times for more efficient, cleaner and, if applicable, hybrid drive trains powered to a substantial extent by renewable fuels.

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.



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Important events during 2020

Two "KCFP Days" events were conducted during 2020, one in May and one in November. Both featured one full day of research seminars as well as open discussions about the activities in the center. Due to the pandemic, both events were conducted entirely online. The successful keynote presentations that were introduced for the 2019 KCFP Days were continued during the 2020 events with one novelty added. In addition to the synthesis presentations of KCFP research by senior researchers within KCFP there was also a keynote presentation by Dr. Jari Hyvönen from Wärtsilä who presented Wärtsilä's view on the need for combustion engine research. We will most likely repeat something similar during the 2021 events with representatives of other KCFP member companies.

As mentioned in the 2019 report 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, Metatron and Convergent Science joined 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. Convergent Science provides CFD tools for combustion engine simulation.

One new project on diluted SI combustion with alcohol fuels in heavy-duty engines was initiated during 2020 which will also generate some additional in-kind contributions from industry. Alcohol fuels have been recognized as important contributors for increasing the fraction of renewable fuels and also for their low soot production even with direct-injection systems.

During 2020 the following PhD students were awarded their doctoral degrees:

- Nikolaos Dimitrakopoulos based on the thesis "Evaluation of Gasoline PPC in a Multi-cylinder Engine : Capabilities & Challenges"
- Xinda Zhu based on the thesis "A Study of Injector Aging Effects on the Spray and Combustion in a Diesel Engine"
- Vikram Singh (associated Waste Heat Recovery project) based on the thesis "Low Temperature Waste Heat Recovery in Internal Combustion Engines"
- Miao Zhang based on the thesis "Optical Diagnostics for Engine Efficiency in Gasoline Compression Ignition"
- Amir bin Aziz based on the thesis "High Octane Number Fuels in Advanced Combustion Modes for Sustainable Transportation"
- Ahmad Hadadpour (separate project but within KCFP subject domain) based on the thesis "Spray combustion with multiple-injection in modern engine conditions"

Consequences of COVID-19

COVID-19 arrived as an unpleasant surprise towards the end of 2019 but developed into a full-fledged pandemic in the beginning of 2020 with severe consequences for people's health, lives and the world economy. Not surprisingly, the pandemic has had severe implications also for KCFP with cancelled and interrupted research stays, both incoming and outgoing. Work in the engine laboratory has been restricted to a bare minimum and the normal hallway and coffee break discussions that are so important for creativity have been reduced to scheduled discussions in Teams and Zoom meetings. As mentioned above, the KCFP Days have also been limited to online events instead of the normal on-site events. The contacts with our research partners have also been severely hampered by different levels and durations of shutdowns. We can only hope that a world-wide vaccination will bring things back to normal before 2021 is over.

Organization

BOARD

Sören Udd, Chairman, Johan Engström, Malin Ehleskog, AB Volvo, Carolin Wang-Hansen, Håkan Persson, Volvo Car Corporation AB, Per Stålhammar, Hualu Karlsson, Scania CV AB, Erik Swietlicki, Maja Novakovic, Lund University, Sofia Andersson, Anders Johansson, Swedish Energy Agency

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, fuels

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., Loge, Wärtsilä Finland Oy, SEM AB, Convergent Science Inc., Metatron

KCFP RESEARCH STAFF

The following PhD students and postdocs have had a substantial part of their research activity within KCFP during 2020. Ted Lind (postdoc), Saeed Derafshzan, Alexios Matamis, Amir bin Aziz, Xinda Zhu, Xiufei Li, Nikolaos Dimitrakopoulos, Menno Merts, Ola Björnsson, Mike Treacy, Leilei Xu.

Research

There are obviously many logical ways to split the research activities within KCFP. Based on the frequencies of certain keywords we found it logical to split the content into "Alternative and renewable fuels", "LTC combustion", "CI combustion" and "SI combustion". Needless to say, all contributions under "Alternative and renewable fuels" apply one of the listed combustion concepts just like many of the contributions included under the various combustion concepts use alternative and/or renewable fuels. The inclusion of a contribution in a specific section hence reflects the mutual relevance/importance of the contribution with respect to the subject of the section.

Alternative and renewable fuels

One of the major pathways to reduce our net carbon emissions, is to use lower carbon intensity fuels, and move away from fossil fuels by increasing the share of renewable fuels. In the short term, there is room left for an increased use of 1st generation biofuels. 2nd generation biofuels can be used on top of 1st generation fuels to further displace fossil fuels, produced from non-food biomass as well as waste. In the longer run, e-fuels will become available as the production of renewables is scaled up further, offering a way for large scale energy storage, building blocks for the chemical industry, and energy density for heavy duty transportation. Methanol is one of the focus e-fuels as it is the simplest hydrogen carrier that is liquid at atmospheric conditions.

In the following contributions an overview is given on: the work done on dual fuel combustion, enabling the use of alternative fuels in CI engines; the use of isobutanol (which can be produced from waste streams); how to characterize the behaviour of fuel blends; and studies of methanol combustion in both metal as optical engine configurations.

A. Professor
Sebastian Verhelst

Researchers:
Menno Merts
Saeed Derafshzan

Supervisors:
Sebastian Verhelst
Mattias Richter

AN OPTICAL INVESTIGATION ON PILOT IGNITION IN A MEDIUM SPEED DUAL FUEL ENGINE

Objectives

After an optical measurement campaign on the Wärtsilä W20DF medium speed dual fuel engine, an analysis has been performed on the measurement results. The objective is to create insight into the ignition of the pilot diesel injection, and the subsequent combustion of the (premixed) natural gas.

Introduction

The dual fuel concept allows the usage of methane as a fuel in a diesel engine. Only a small amount of the energy supply is still delivered by the pilot diesel injection, which acts as an ignition source for the premixed methane. Although NO_x emissions for dual fuel engines are generally lower than for diesel engine, NO_x can still be formed in significant amounts. This mainly takes place during intense combustion after the ignition phase of the diesel pilot fuel. An investigation has been performed to see how different injection conditions affect the ignition phase of combustion and subsequently the heat release profile.

Methods

The work is based on high speed recordings of natural luminosity inside the cylinder. Optical access to the 200mm bore combustion chamber of the medium speed engine is created using a Bowditch design. Images were recorded at a frame rate of 15kHz, with an effective resolution of 533x533 pixels. Cylinder pressure data were recorded, together with all common engine sensor signals. To limit the temperature of the glass piston-top, the engine was operated in skip-fire mode. As a consequence, no emission measurements were performed. The test program contained 10 different combinations of injection-pressure and injection-length, tested both with early injection timing (RCCI-mode) and late injection timing (Conventional Dual Fuel)

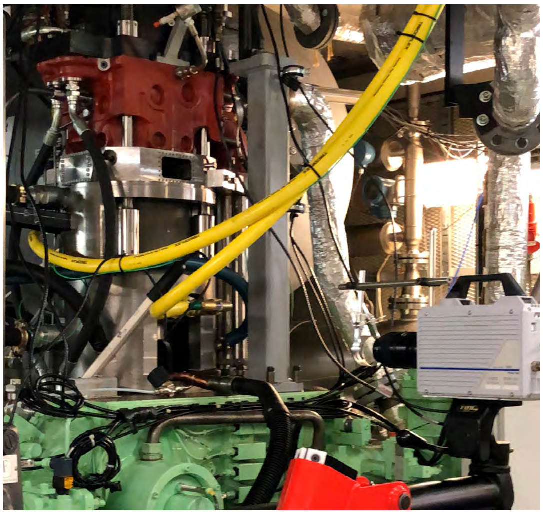


Figure 1 Wärtsilä 20DF optical engine

Results

An acceptable combustion phasing has been achieved with both combustion modes. This resulted in a significantly longer ignition delay for the cases with early injection, as concluded from injector control and heat release analysis. The optical results show that in such cases, the long ignition delay leads to a strong premixing of the diesel fuel. Combustion takes place further outwards in the combustion chamber, under more diluted conditions. As a result a gradually increasing heat release rate is seen. On the contrary the cases with late injection show a start of combustion where clearly the diesel jet shape can be recognized in the images, as shown in the right image of Figure 2.

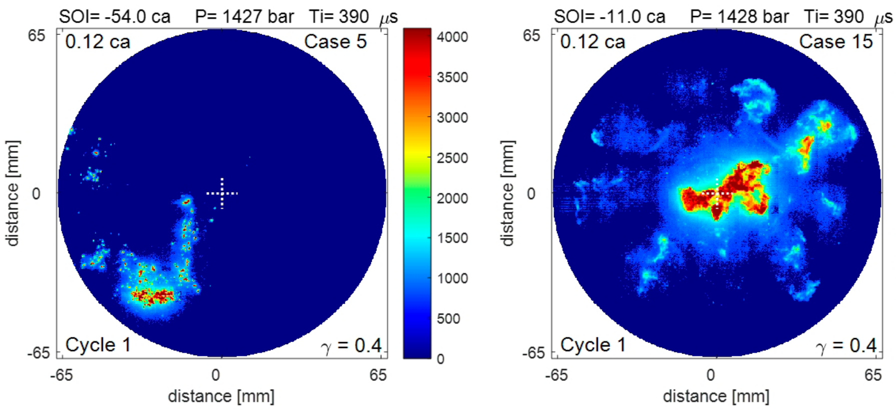


Figure 2
Optical comparison of RCCI and CDF at initial combustion stage

The combustion starts around lift off length, under rich conditions. This leads to high intensity of the emitted light, and a sharp rise in heat release rate. It is this typical premixed diesel heat release peak, as shown for CDF in Figure 3, that is related to NO_x emissions.

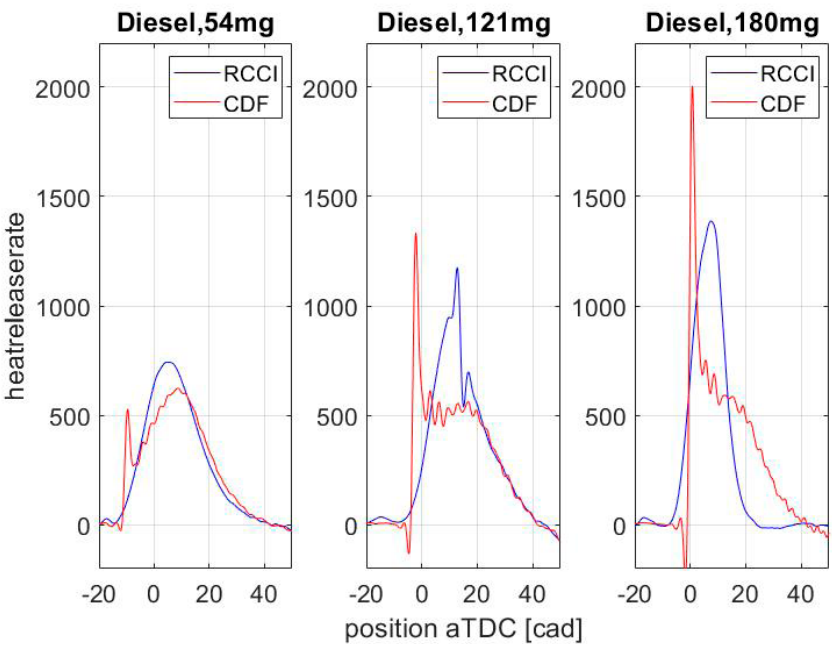


Figure 3
Comparison of heat release profiles for RCCI and CDF combustion

Conclusions

High speed images, combined with cylinder pressure analysis, have shown that the heat release rate at the start of the dual fuel combustion can be limited by allowing strong dilution through applying very early pilot-injection. By preventing the strong initial peak in heat release, which is accompanied by high intensity combustion light, the formation of NO_x is expected to be significantly reduced. A planned future campaign in metal configuration, including emission-measurements, has to confirm this relation.

Researcher:
André Olson

Supervisor:
Sebastian Verhelst

ISOBUTANOL AS A GASOLINE OXYGENATE AND AS NEAT FUEL FOR DIRECT-INJECTION SPARK-IGNITION ENGINES: EFFECT ON ENGINE PERFORMANCE AND EMISSIONS

Introduction

Due to concerns regarding climate change, global energy security, and the depletion of world oil resources, the utilization of renewable fuels for transportation has been on the rise for many years. To ensure that transportation fuels contain a minimum amount of renewables, several countries have implemented government mandates, such as the European Union's Renewable Energy Directive (RED) and the United States' Renewable Fuels Standard (RFS2).

Ethanol, the foremost biofuel in terms of consumption, is widely used around the world as a gasoline oxygenate, typically in low-level blends that do not not require engine modifications, such as 5 vol% (E5) and 10 vol% (E10). However, in spite of its widespread adoption, ethanol exhibits a number of drawbacks – like materials compatibility and corrosiveness – that hinder the approval of higher-level blends with gasoline to be used in unmodified engines, effectively limiting the overall amount of renewable energy that can be used – i.e. a "blend wall" is created. Because of that, the introduction of gasoline-ethanol blends beyond E10 has been problematic in the U.S.

Isobutanol (also known as isobutyl alcohol or 2-methyl-1-propanol) is a branched four-carbon alcohol that is extensively used as a solvent in the chemical industry, but it also has properties that make it an attractive fuel for spark-ignition engines, as an alternative to ethanol. Even though it is synthetically produced via carbonylation of propylene, isobutanol can – similarly to ethanol – be biologically produced via fermentation of sugars. Moreover, advances in genetic engineering have made it possible to genetically modify the isobutanol producing microorganisms (yeasts and bacteria) so they are able to ferment the sugars present in abundant, low-cost lignocellulosic biomass which does not compete with food crops. The present investigation is related to "BioRen", an EU-funded Horizon 2020 project that aims to convert municipal solid waste (MSW) into transportation fuels – isobutanol being one of them – via fermentation, utilizing genetically modified yeast strains to increase the efficiency and productivity of the process.

As a fuel, when compared to ethanol, isobutanol has the following advantages:

- Higher heating value (25% higher than ethanol on a volumetric basis)
- Lower blend Reid Vapor Pressure (which simplifies the blending with gasoline and decreases evaporative emissions)
- Limited water solubility (which prevents phase separation and allows it – unlike ethanol – to use the existing pipeline infrastructure)
- It is less corrosive and has better materials compatibility
- Isobutanol still has a high octane rating (RON around 100)

Additionally, isobutanol, due to its lower oxygen content and better compatibility, can be blended into gasoline in larger amounts, thus overcoming the blend wall limitations, allowing renewable energy targets to be met.

Objectives

The goal of the present study is to investigate the potential of isobutanol as a gasoline oxygenate, (i.e. blended with gasoline), and also as a neat fuel, using a state-of-the-art light-duty direct-injection spark-ignition (DISI) engine. The focus will be on engine performance and exhaust emissions, with an emphasis on particulate emissions.

Methods

In the first phase of the investigation, low-level gasoline-isobutanol blends will be prepared and tested together with gasoline-ethanol blends, with both blends having the same oxygen content. Therefore, a blend consisting of 16 vol% isobutanol in gasoline (iBu16) will be tested against a blend of 10 vol% anhydrous ethanol in gasoline (E10), as both contain the same amount of oxygen. Additionally, both blends are going to be tested and compared to neat (100% fossil) gasoline.

In the second phase, the performance of medium-level blends will be investigated. A blend of 40 vol% isobutanol in gasoline (iBu40) is going to be tested and compared to a blend of 25 vol% ethanol in gasoline (E25) – both containing the same amount of oxygen – as well as to neat gasoline.

Finally, in the third phase, the performance of neat isobutanol as a fuel will be tested and compared to neat gasoline.

An experimental test matrix will be designed, consisting of engine speed and load points that are representative of real driving conditions. Combustion analysis will be carried out by calculating the in-cylinder heat release rates at every test point. Because engine knock is a significant limiting factor in SI engine performance, in each phase of the experiments described above, the knock sensitivity for each fuel will be measured by varying parameters such as spark timing, boost pressure, and EGR levels. Additionally, the potential for lean engine operation is going to be investigated for all fuels by diluting the fuel-air mixture beyond stoichiometric.

For all fuels tested and for all engine operating points, the typical regulated gaseous pollutant emissions (that is, THC, CO, NO_x) are going to be measured engine-out.

A special emphasis will be put on the sampling and measurement of exhaust particles. In addition to measuring soot emissions, special care will be taken to characterize the size distributions of the exhaust particles, as particulate emissions can be especially problematic for DISI engines. Further, to be in line with standard European type-approval procedures for particle number (PN) measurements, only *solid* particles are going to be measured. To that end, the particle sampling and measurement system will be fitted with a dedicated volatile particle remover that eliminates undesirable volatile material that could produce volatile particles. This is specifically important when sampling particles in the nanoparticle size range (< 50 nm) and also when using oxygenated fuels (such as isobutanol), as the lower soot formation may lead to an increase in the concentration of tiny volatile particles.

Conclusions

Isobutanol has some intriguing fuel properties, especially when compared to the currently dominant biofuel – ethanol. It is generally more compatible with gasoline than ethanol. Unlike ethanol, it has the advantage of being able to use the existing pipeline distribution infrastructure, facilitating the logistics and decreasing transportation costs. All these advantages are promising enough to warrant carrying out a comprehensive engine test campaign. It will be interesting to investigate how isobutanol performs as a fuel in a modern DISI engine. It will be interesting to see how it affects the exhaust particulate emissions at a wide range of engine operating conditions. Therefore, the tests described herein should provide a valuable picture of the advantages and limitations of the use of isobutanol fuel in modern DISI engines.

Researcher:
Magnus Svensson

Supervisor:
Sebastian Verhelst

INVESTIGATION OF THE POTENTIAL OF METHANOL IN HEAVY DUTY CI ENGINES

Objectives

The objective of the project is to investigate the potential and limitations of methanol as a fuel in heavy duty CI engines, as well as to study techniques to tackle the limitations.

Introduction

The Paris and IMO agreements target a 50% reduction of CO2 emissions from maritime transport by 2050. The EU Horizon2020 project FASTWATER, which this project is part of, aims to meet this target by moving shipping towards the clean and renewable fuel methanol. Methanol is a non-sooting fuel burning at low temperatures, which enables it to, in the short term, immediately reduce the pollutant emissions. With the possibility to create climate neutral synthetic methanol using renewables it can be effective also in the long term. Methanol can thus make an immediate impact and is a future-safe fuel. Being already available in large quantities in most ports today and being a liquid fuel, it simplifies ship design, and enables relatively simple retrofitting of current diesel engines. Furthermore, methanol has compelling environmental properties with regards to marine life, with rapid dispersing and biodegrading of spills at sea in case of leakage. Methanol also enables high energy efficiency in internal combustion engines, gas turbines as well as fuel cells, providing a long term value chain for current but also future technologies that few other fuels can offer.

This PhD project´s part of FASTWATER is focused on developing the MD95 concept, using direct injection of a fuel consisting of 95% methanol and 5% ignition enhancer, to the MD100 concept in a heavy duty CI engine. The reason for doing this on a CI engine is that marine engines used today are predominantly CI, so being able to use the same engine with only minor modifications is appealing. The challenges with this are the high heat of vaporization together with the low volumetric energy density. This leads to a drop in the in-cylinder temperature at injection, making it harder to ignite.

Method

The research is going to be carried out on a single cylinder Scania D13 engine, with focus on research into concepts and techniques that can improve the combustion of methanol. Examples are injection strategies to minimize the temperature drop at injection, and glow plug assistance to help start the combustion.

Results

Together with research on SI methanol combustion carried out at Ghent University, also within FASTWATER, the goal is to produce a recommendation on which methanol engine concept to continue with (depending on application). i.e. if either SI or CI gives the best trade-off between achievable power density, efficiency and emissions.

Conclusions

The first testing is planned to happen this spring, and will focus on getting a diesel reference and on expanding previous work using a single injection strategy on methanol.

FUTURE ALTERNATIVE FUEL FOR TRANSPORTATION

Objectives
The main objective of this study is the development of a standard test method to quantify the ϕ-sensitivity for different fuels.

Introduction
Low temperature combustion (LTC) is a modern combustion concept which shows great advantages in terms of fuel efficiency and emissions compared to conventional combustion concepts. The main characteristic of LTC is the high dependency of combustion controllability to the fuel/air mixture chemistry. Therefore, a better understanding of fuel/air mixture combustion properties is needed to increase LTC controllability. Experimental research is mainly limited by the experimental setup safety (pressure gradients, maximum pressure, etc.). Detailed chemical kinetics study can evaluate the fuel response to the engine conditions and results in precise solutions of chemical kinetics mechanisms at specific state conditions.

Methods
Experimental apparatus for this study is a CFR F-1 engine which has been modified for Homogeneous Charge Compression Ignition (HCCI) combustion. The data is collected from combustion of 12 different toluene, ethanol reference fuels (TERFs) blends, in an equivalence ratio (ϕ) range of 0.31– 0.37. Three intake temperatures (323, 373, and 423 K) and the engine speed of 900 rpm are investigated. Among 12 tested blends, experimental results of those which were auto ignited at Tin= 323K and compression ratio (CR) below 18 (CFR F-1 engine limit) are selected for the method development.

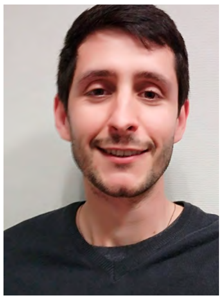
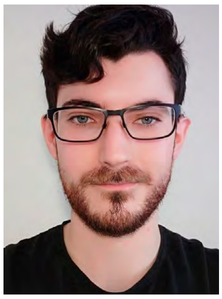
The CFR F-1 engine was modelled using GT-Power aiming at predicting mixture composition and the pressure-temperature trajectory prior combustion under different ϕ levels at HCCI combustion. The results provided by GT-Power were used as boundary conditions for the detailed chemical kinetics solver (Cantera). In this solver, each engine-state was modelled by means of a constant volume reactor. The individual states were correlated by applying the Livengood and Wu method. Two contrasting fuels (ethanol and PRF 63) were selected from the experimental data to provide a database for the model development. Finally, correlations and tabulated chemistry were proposed as an alternative to speed up the calculation process.

Results
Experimental results shows that some of the in-cylinder parameters depend on CR variations and some remain unchanged. The effect of ϕ variation on the ignition delay variation and the required compression ratio to keep the CA50 constant where the main factors for the method definition. This study shows that the ϕ-sensitivity of each fuel is partially independent of RON, MON and S (RON-MON) of the fuel.

Figure 1 shows the distribution of coefficient of variation of indicated mean effective pressure (CoV_{IMEP}) for different blends in respect to the content of toluene and ethanol (V/V%, volumetric percentage) in the blend. The low CoV_{IMEP} is an indicator of combustion stability for this data set. Figure 2 shows the maximum pressure rise rate (PRR_{max}) as a function of ethanol and toluene content. Figure 3 shows a detailed comparison between two different chemical reaction mechanism in terms of their ability in predicting the occurrence of low (LT), intermediate (IT), and high temperature (HT) heat release according to representative species of each zone. As it can be observed, significant differences are obtained depending on the mechanism. Andrae's mechanism tends to predict earlier IT ignition delays compared to SNL. This is even more pronounced in the case of HT ignition delay.

The results for the LT ignition delay with PRF 63 are depicted in Figure 4. It can be concluded that the proposed framework enables the determination of the ignition delay values with reasonable accuracy.

Conclusions
The results show that Fuel composition, independent of fuel RON has a strong effect on the fuel ϕ-sensitivity. This study proves that tailoring fuels with a similar RON and different ϕ-sensitivity is applicable. Different fuel components have both individual and combined effect on combustion behavior and therefore the fuel ϕ-sensitivity. The use of the numerical routine has demonstrated to be a feasible option to quantify the auto-ignition behavior of both fuels with single and two stage heat release. The

Researchers:
Nika Alemahdi
Rafael Lago Sari
Álvaro Fogué Robles

Supervisors:
Martin Tunér
Antonia García
Javier Monsalve

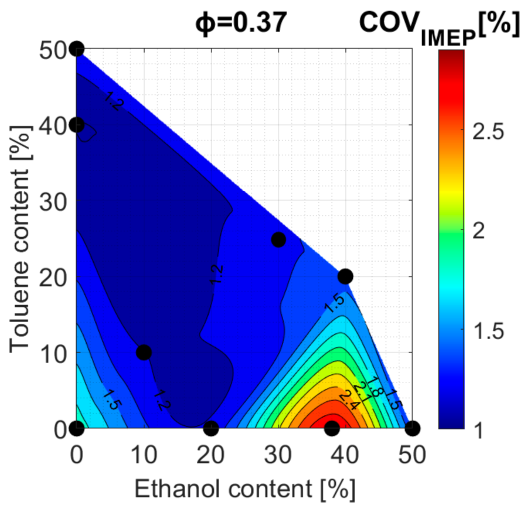


Figure 1
COVIMEP as a function of ethanol and toluene content.

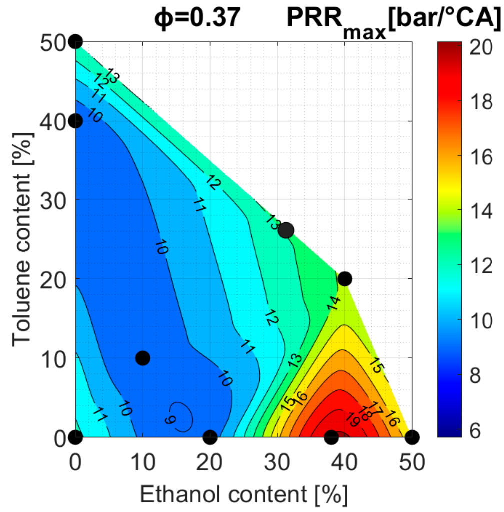


Figure 2
Maximum pressure rise rate as a function of ethanol and toluene content.

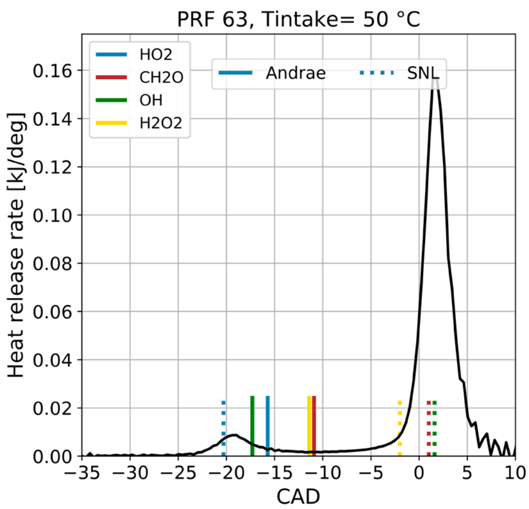


Figure 3
Onset of low, intermediate and high temperature ignition delay, Andrae VS SNL.

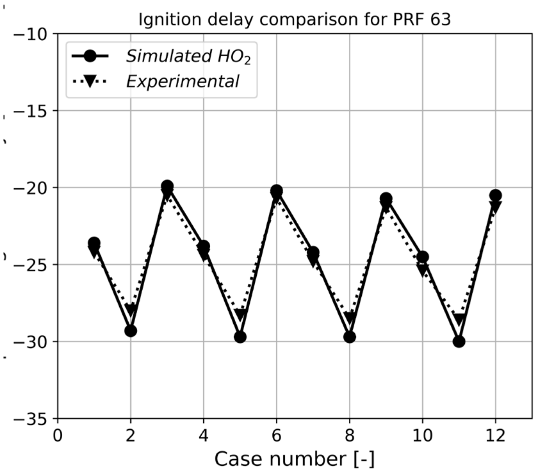


Figure 4
Low temperature ignition delay, simulation VS experiment.

use of experimental boundary conditions allows to quantify the dominant reactions that leads to the fuel ignition. On the other hand, the use of non-reactive conditions from GT-Power provides an alternative to explore limiting conditions.

These two papers are under the final evaluations for journal publication:

1. Development of an empirical test method to quantify the ϕ-sensitivity of TERFs in a wide range of Octane number
2. Development of a fast-virtual CFR engine model and its use on auto ignition studies

Publication:

Alemahdi N, Tuner M. The effect of 2-ethyl-hexyl nitrate on HCCI combustion properties to compensate ethanol addition to gasoline. Fuel 2020;270. **https://doi.org/10.1016/j.fuel.2020.117569.**

EFFECT OF INJECTION TIMING AND AIR DILUTION ON METHANOL COMBUSTION

Researcher:
Amir bin Aziz

Supervisor:
Martin Tunér

Objectives

The objective of this study was to enhance our understanding on the effect of injection timing and air dilution on methanol combustion.

Introduction

With the aim of extending the partially premixed combustion (PPC) operation towards higher loads, gasoline-like fuels with high octane number were explored. However, the use of fossil high-octane fuel contributes to high well-to-wheel carbon dioxide (WTW CO2) emissions. As an option for sustainable engine operation, methanol as a high-octane renewable fuel has been chosen. Although there has been research on methanol combustion, few studies have been conducted to explore the influence of injection timing on the combustion characteristics, emission and engine performance. Moreover, much of the current literature pays particular attention only to single intake pressure, with no studies conducted to compare and explain the impact of different intake pressures, while sweeping the injection timing for methanol fuel from homogeneous charge compression ignition (HCCI) to partially premixed combustion (PPC) strategies.

Methods

This experimental study was performed using a fully instrumented Scania D13 engine modified for single cylinder operation. The engine setup included an alcohol complaint fuelling system derived from the Scania ED95 engine. The compression ratio was 17.3 and no exhaust gas recirculation (EGR) was used. A comparison was performed between methanol and isooctane (primary reference fuel, PRF100) under injection timing sweep from HCCI to PPC. Methanol was then compared at two intake pressures.

Results

The NO_x emissions from methanol is lower than those from PRF100 at later injection timing, because of methanol´s lower combustion rate. In general, methanol shows higher UHC but lower CO emissions than does PRF100. Moreover, there is no trade-off between soot and NO_x emissions present for methanol because soot is always low and insensitive to injection

Conclusions

The results revealed that the soot emission was always low for methanol and insensitive to injection timing, compared to PRF100. When the intake pressure was increased, the mixture became globally leaner, resulting in a lower NO_x and unburned hydrocarbon (UHC) but at a minor penalty on carbon monoxide (CO) emission. The gross indicated efficiency of methanol was improved at the later injection timing for the boosted case.

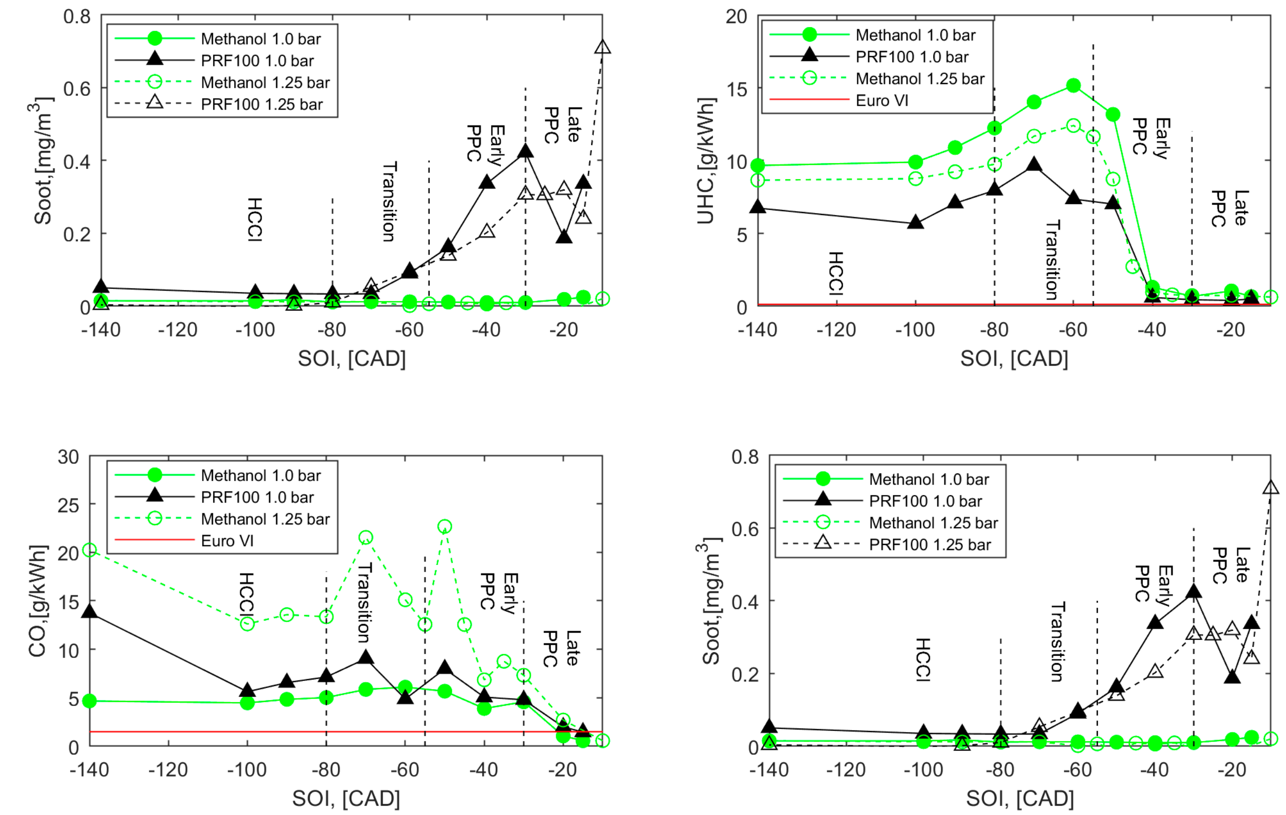


Figure 1
Emissions of methanol and PRF100 at different air intake pressures

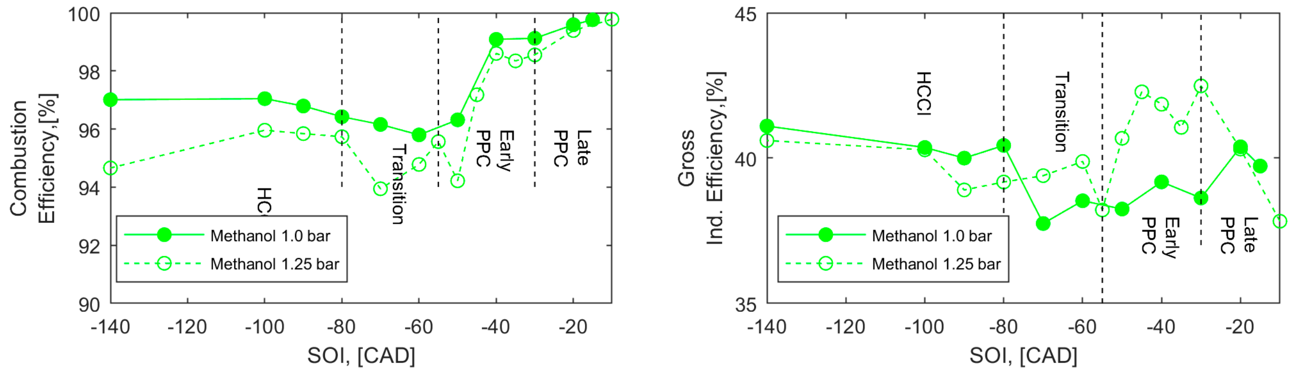
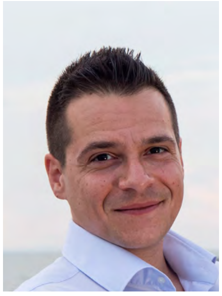


Figure 2
Efficiency of methanol at different air intake pressures

OPTICAL CHARACTERIZATION OF METHANOL COMPRESSION IGNITION



Researcher:
Alexios Matamis

Supervisor:
Mattias Richter

Objectives

The aim of this study is to optically characterize methanol injection and combustion in compression-ignition processes. A literature survey reveals a surprising lack of knowledge on methanol behavior in spray driven and Partially Premixed Combustion (PPC). Historically, this has been due to methanol's auto-ignition resistance and high heat of vaporization making it difficult to ignite and control the combustion process. Within this project, we have demonstrated that high auto-ignition resistance and high combustion rate can be mitigated by using advanced injection and combustion strategies. By analyzing the injection and combustion processes of methanol in a compression-ignition optical engine, we understand the in-cylinder processes and demonstrate its potential as an alternative fuel that can combine low emissions and high engine efficiency.

Introduction

Previously we have mostly focused on characterizing methanol combustion behavior under PPC and spray driven combustion. The results can be found in [1] and for 2020, the focus remained on processing additional experimental data acquired during that same experimental campaign with the Scania D13 optical engine (Figure 1). This time the data analysis was focused on characterizing the injection process of methanol over a range of start-of-injection (SOI) points, injection pressures and a comparison to an established low octane fuel suitable for PPC combustion, in this case PRF81. The tools used to characterize the injection process included laser light scattering of the liquid fuel droplets to visualize the liquid spray length and fuel-tracer Laser Induced Fluorescence (LIF) to view the fuel distribution within the cylinder over various operating conditions.

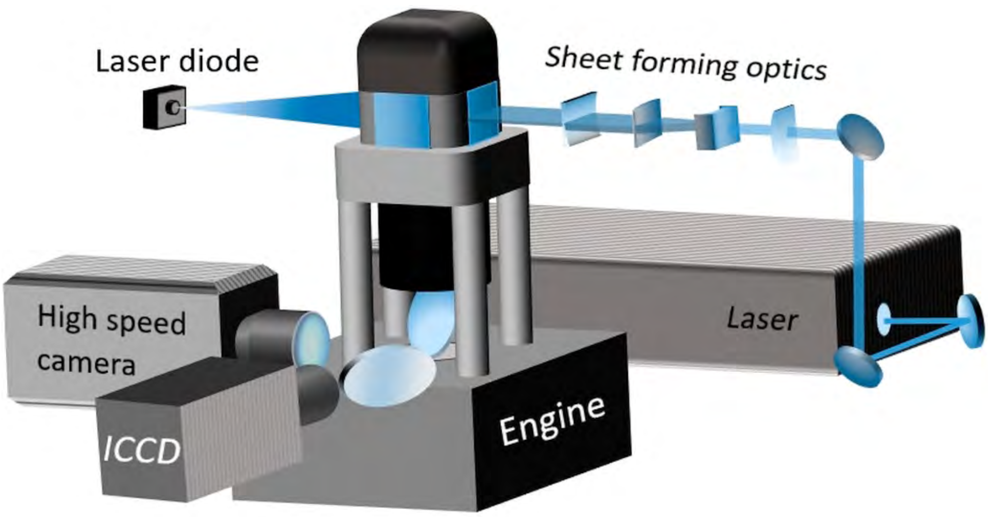


Figure 1
Sketch of the optical engine and measurement setup.

Methods

A 10Hz, 266 nm wavelength laser system is used to visualize the fuel distribution by exciting acetone which is mixed in the fuel (10% v/v). The laser beam is formed to a sheet and enters the combustion chamber via one of the lateral liner windows, providing a cross-section view of the pancake-shaped combustion chamber (Figure 2). The fluorescence signal is captured by an ICCD camera that views straight into the Bowditch mirror.

For liquid spray length measurements, a 452 nm wavelength continuous wave laser diode is used to provide global illumination in the combustion chamber and light is scattered by the liquid fuel droplets. A high-speed camera is mounted perpendicular to the ICCD camera and views the Bowditch mirror through an additional 45° angled mirror. In order to obtain the liquid penetration length, a smoothing filter is applied on the image to reduce noise and improve edge detection. Each spray plume is processed individually and the furthest point from the injector tip is detected, thus obtaining the liquid penetration length (Figure 3). Only the spray plumes on the entry side of the laser light are evaluated as they inherently yield a higher signal-to-noise ratio.

Figure 2
An example average image of 50 cycles is shown where all the cylinder bore is visible. (Right) A region of interest is selected for analysis on the entry side of the laser where attenuation is minimal and laser fluence is high.

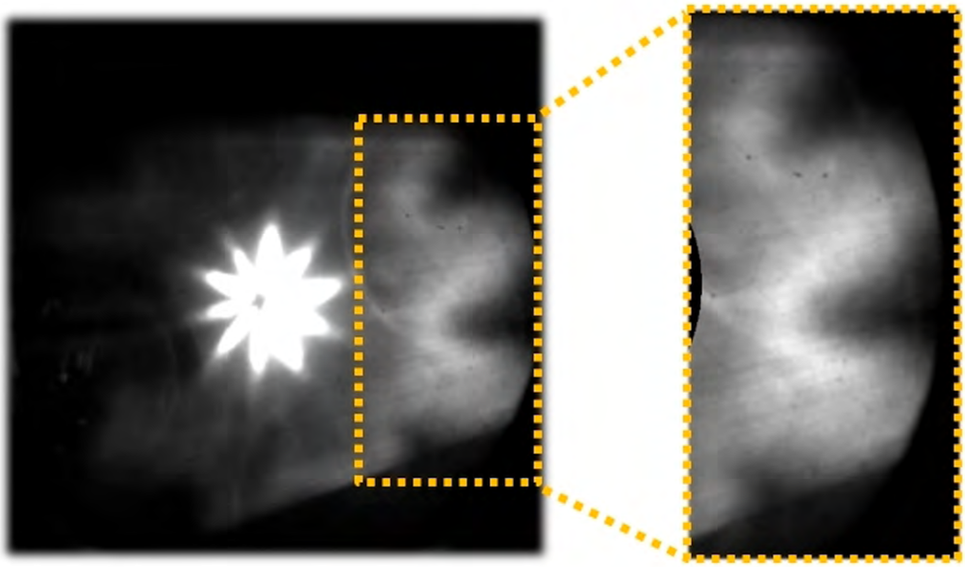


Figure 3
Illustration of the data processing to extract liquid spray length. The spray plumes processed are the ones on the entry side.

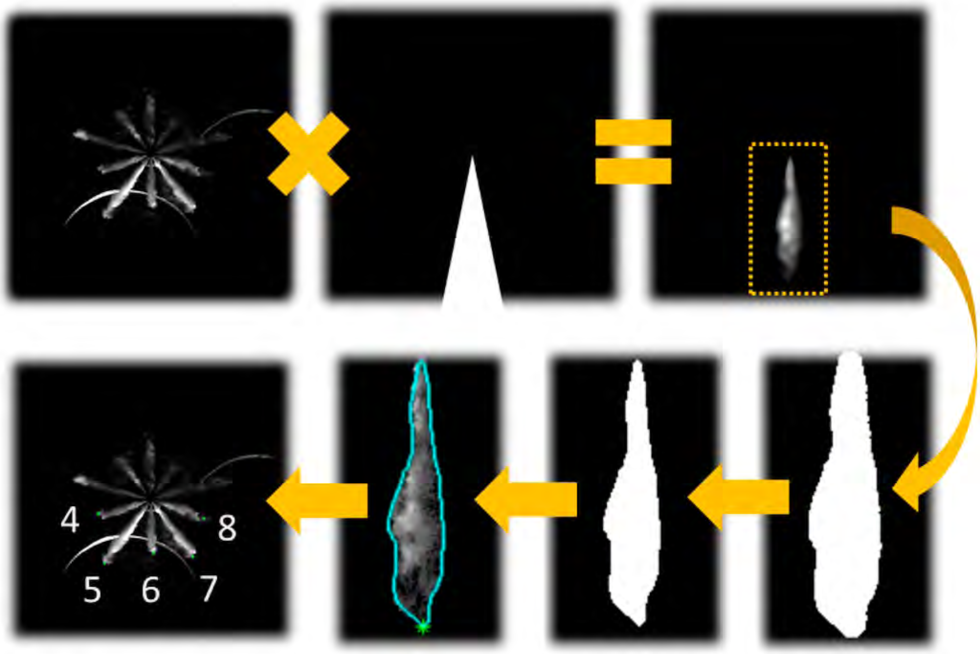
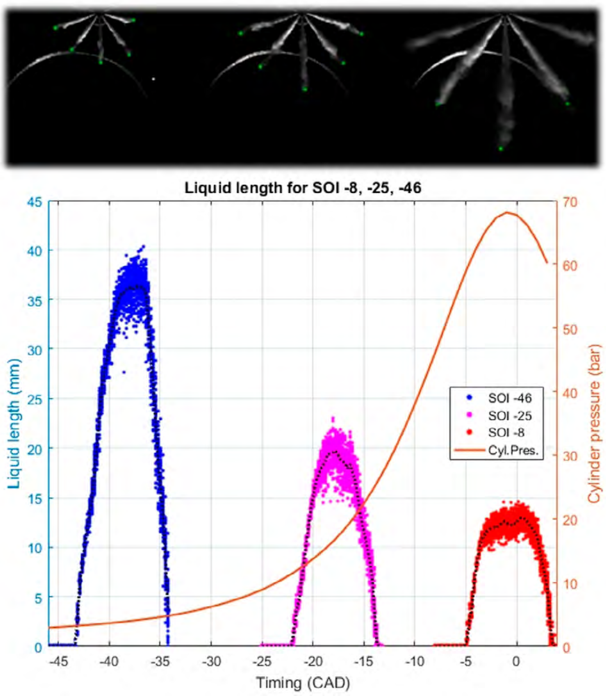


Figure 4
Above, actual images of the three SOI timings are shown along with the selected tip for each of the sprays. Below, the transient liquid length is shown for all cycles, for the three SOI timings tested, along with a curve of the in-cylinder pressure.



Results

The analysis of laser scattering data demonstrates the dependence of liquid penetration length on various engine operating conditions. The tested parameters in this set of experiments are cylinder pressure and temperature, injection pressure, along with a comparison between methanol and PRF-81 in identical conditions.

Three different SOI timings were tested of 8, 25 and 46 CAD BTDC. For each SOI timing, in-cylinder conditions are different as the piston is at a different phase of the compression stroke and liquid penetration length is found to vary greatly depending on ambient air density and temperature (Figure 4).

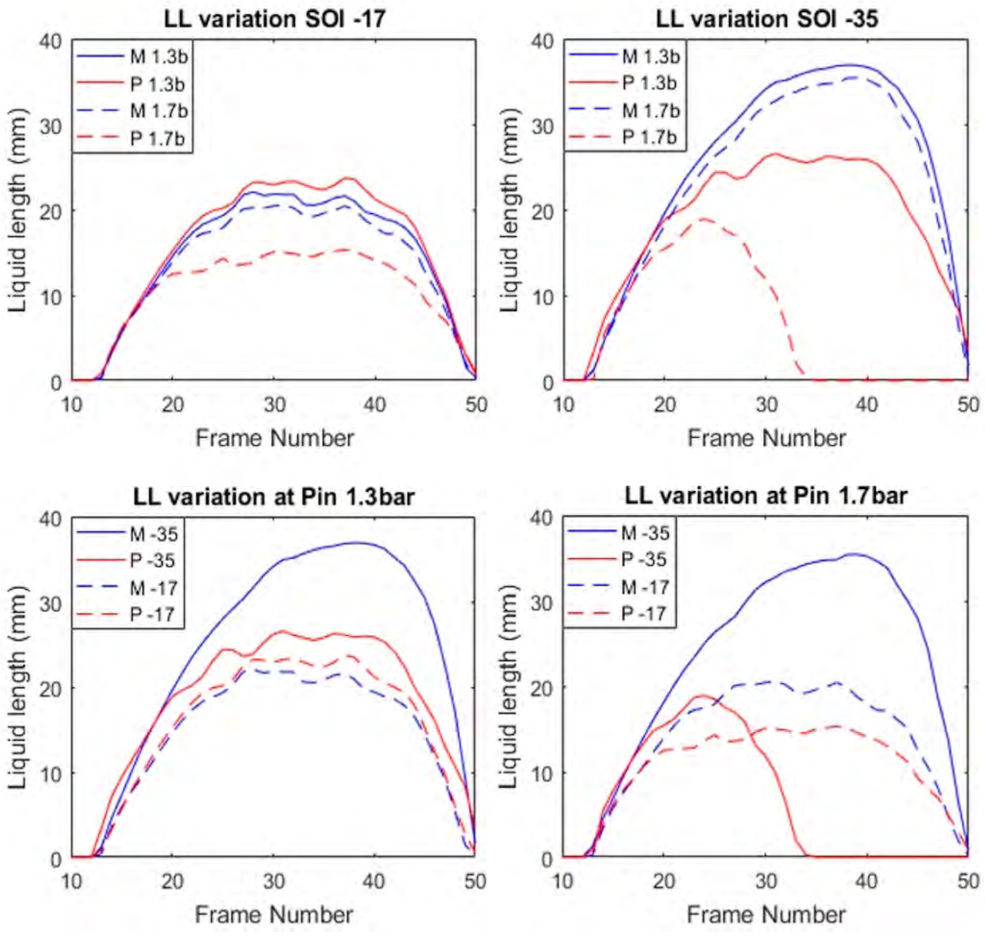


Figure 5
Top two graphs demonstrate the dependence of each fuel to ambient pressure, while the bottom graphs show the variation in liquid length with SOI timing.

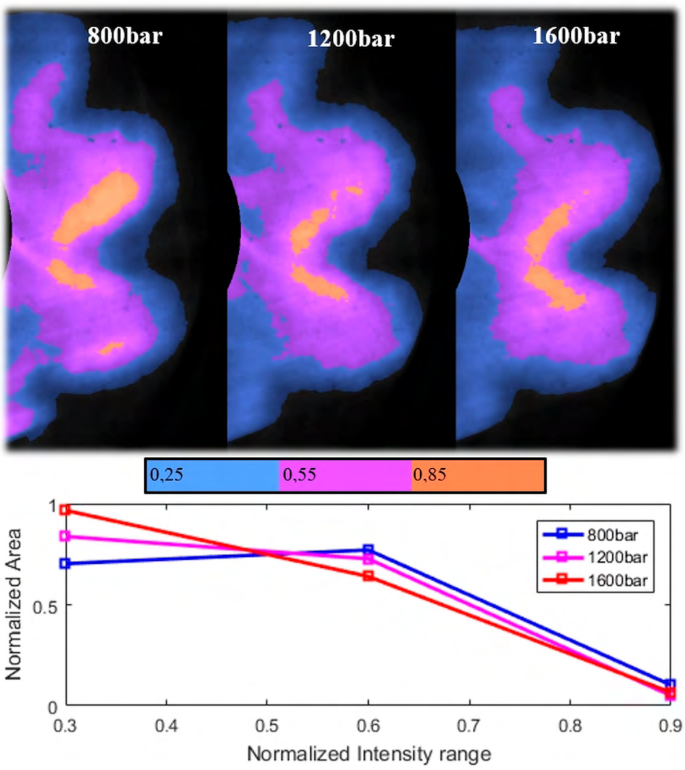


Figure 6
Average fuel distribution images for the three different injection pressures. Higher rail pressure leads to a more homogeneous mixture despite the lower mixing time available. The intensity colorscale represents arbitrary intensity bins and not measured stoichiometry.

Cylinder pressure is measured as the engine is equipped with a pressure sensor and the in-cylinder temperature can be derived. Thus, methanol's spray characteristics can be analyzed in these realistic engine operating conditions providing valuable real-world data for calibrating CFD injection models.

In comparison to PRF81 fuel, which is typically used for PPC combustion, methanol shows much greater variation in liquid length depending on in-cylinder temperature while PRF81 show a much greater dependence predominantly on in-cylinder pressure. This can be observed as two SOI timings and two intake pressures are tested for both fuels. Methanol is greatly affected by the variation of SOI from -17 to -35 CAD, where the liquid length approximately doubles at the much cooler and less dense case of -35 (bottom of Figure 5). When the intake pressure in increased from 1.3 bar to 1.7 bar, liquid length is only marginally affected thus showing a small dependence on density. Meanwhile, the opposite applies for PRF81 where liquid penetration length is greatly affected by the change in intake pressure and minor dependence on SOI is observed (top of Figure 5). Despite temperature and pressure being co-dependent for SOI timing changes, the resulting data indicate a higher sensitivity of methanol to ambient temperature and a higher dependence of PRF81 to ambient pressure for the tested operating conditions.

For the three injection pressures tested, the increased fuel mass injection rate due to higher injection pressure is compensated by a reduction in injection duration, thus corresponding to the same final amount of fuel injected. These injection strategies were first implemented in single-cylinder metal engine experiments, simulated in CFD software and finally were tested in the optical engine. Only marginal reduction of liquid spray length with increasing injection pressure was found and are thus not presented here. However, the fuel distribution images obtained by fuel tracer LIF, show that progressively higher injection pressures result in a less stratified charge with overall leaner mixtures before onset of combustion (Figure 6). Low injection pressure leads to greater fuel rich regions which progressively reduce in size as the injection pressure is increased. More findings from this study can be found published and detailed in much greater length in [2]. The optical technique used here cannot provide quantitative information regarding the stoichiometry of the mixtures present. Nevertheless, this qualitative assessment is in perfect agreement with previously conducted CFD studies [3], which showed higher injection pressures to have more homogeneous mixtures and a greater amount of the fuel mixture close to stoichiometric. Since a greater amount of fuel burns at close to stoichiometric, the resulting NO_x emissions are higher due to higher flame temperatures under such fuel mixtures. In addition, greater effort is required to pump the fuel to higher pressures resulting in greater losses, thus we can conclude that high injection pressures are best avoided in direct-injection compression-ignition applications of methanol.

Conclusions

In this study we have showcased the characteristics of methanol injection and mixing processes. The dependence of in-cylinder conditions is demonstrated and compared to a more conventional fuel used in PPC combustion. The injection pressure effect regarding liquid penetration length and the resulting fuel mixing is highlighted and can be linked to tailpipe emission characteristics from other studies. The data and knowledge accumulated within this project is available and can be used to better simulate injection and combustion processes for various engine relevant conditions.

The results presented here conclude the activities related to optical engine work with methanol compression ignition, however more research is necessary in order to better understand the combustion and injection behavior. Since methanol is a non-sooting fuel, lower injection pressures than the ones presented here could be tested and would further reduce parasitic losses. Additionally, in order to reduce cyclic variations and achieve better engine control, particularly in low load operation, spark or glow-plug assisted compression-ignition combustion would be a promising direction to follow for methanol in order to maintain good emission characteristics and high engine efficiency.

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3. M. Pucilowski, M. Jangi, S. Shamun, M. Tuner, and X.-S. Bai, "The Effect of Injection Pressure on the NO_x Emission Rates in a Heavy-Duty DICI Engine Running on Methanol," 2017.

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). Three LTC related studies are included in the report. The first one deals with the development of gas system mean value models to simplify combustion control of flex-fuel CI engines. The second study looks into the use of glow plugs to improve low load operation of a LD PPC engine, while the third study uses 3D numerics to investigate how injection timing and combustion chamber geometry affects PPC combustion of a primary reference fuel resembling low-octane gasoline.


Professor
Martin Tunér

Researcher:
Xiufei Li

Supervisors:
Per Tunestål
Rolf Johansson

GAS SYSTEM AND IGNITION DELAY MODELING

Objectives

The objective of the gas system and ignition delay modeling is to build control-oriented models for flex-fuel CI engine control. The combustion process of the flex-fuel engine is sensitive to inlet conditions and varying with changing fuels. The ignition delay, defined as the time between the start of injection and the start of combustion, is one key indicator of the changing fuel properties.

Introduction

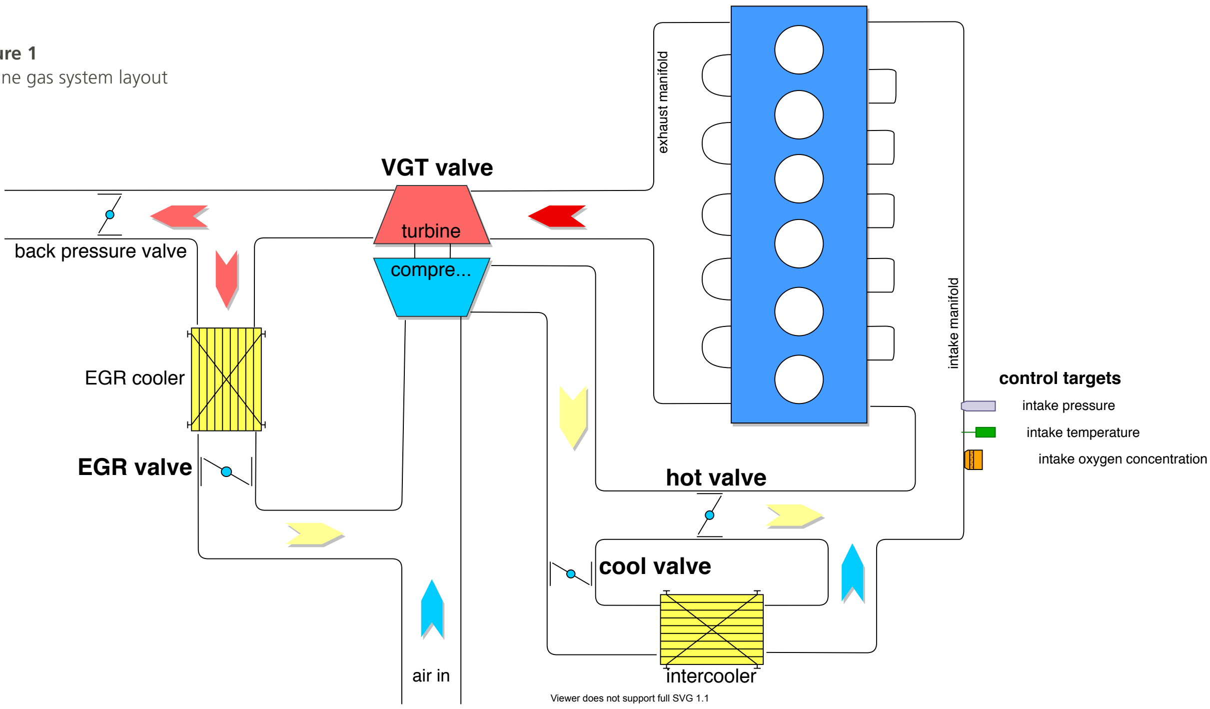
The control-oriented modeling of the gas system in a heavy-duty CI engine is developed and validated. The intake pressure, temperature, oxygen concentration, and their interplay are modeled. The actuators are EGR, VGT, and thermal management valves. The gas system is described based on physical relationships and parametric models. The physical-based model and data-based model for ignition delay are established and compared. The data-based models adopted are the Gaussian processes (GP) and neural networks (NN) with different structures. The intended model applications are system analysis, simulation, and development of model-based control systems for flex-fuel CI engines.

Methods

The gas system layout used in the experiment is shown in Figure 1. The intake oxygen concentration is measured by one wideband zirconia sensor. The measured oxygen concentration value is a function of oxygen partial pressure which depends on intake pressure and the actual oxygen concentration. The EGR and VGT mass flows are modeled as a compressible flow through the changing area. The intake pressure is modeled using the ideal gas law. The intake temperature is a mix of air temperature from the direct path and the path with an intercooler.

The physical ignition delay model is the widely adopted Arrhenius-like expression. It gives the dependence of the chemical reaction rate on temperature, pressure, etc. A Gaussian process is a collection of random variables, any finite number of variables that have joint Gaussian distribution. The Gaussian process then can calculate the conditional probability by conditioning on collected training data. With this posterior, the Gaussian process is able to give a measure of uncertainty of the prediction when predicting. The neural network is a connectionism system inspired by biological neural networks in the animal brain, normally constituted by input layer, hidden layers, and output layer.

Figure 1
Engine gas system layout



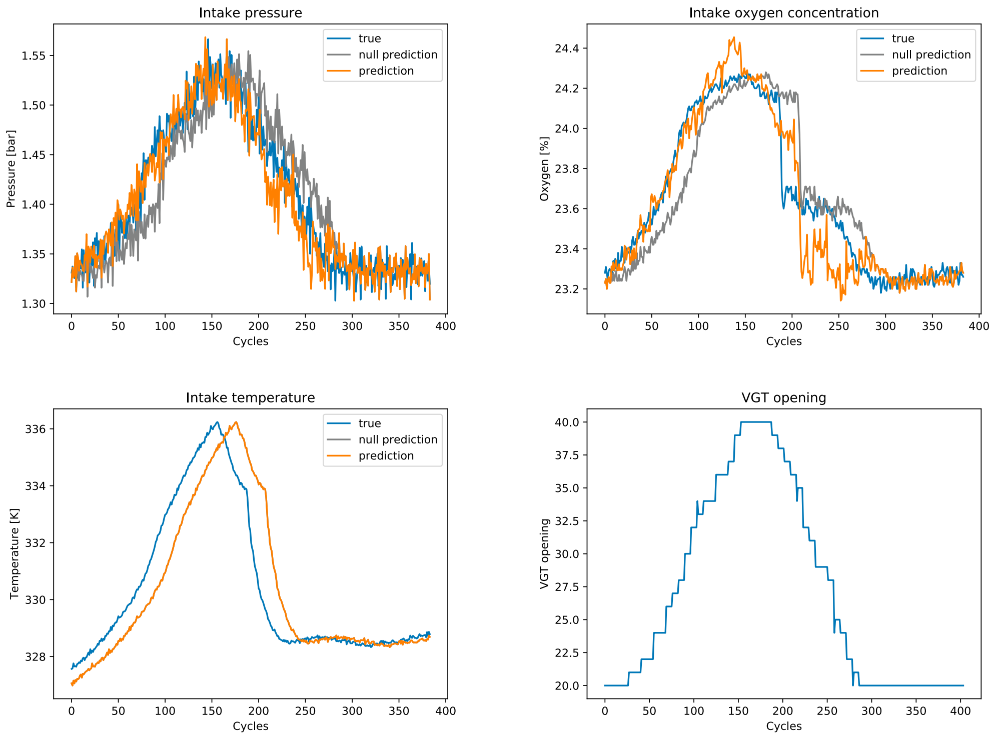


Figure 2
Model performance in VGT opening transient

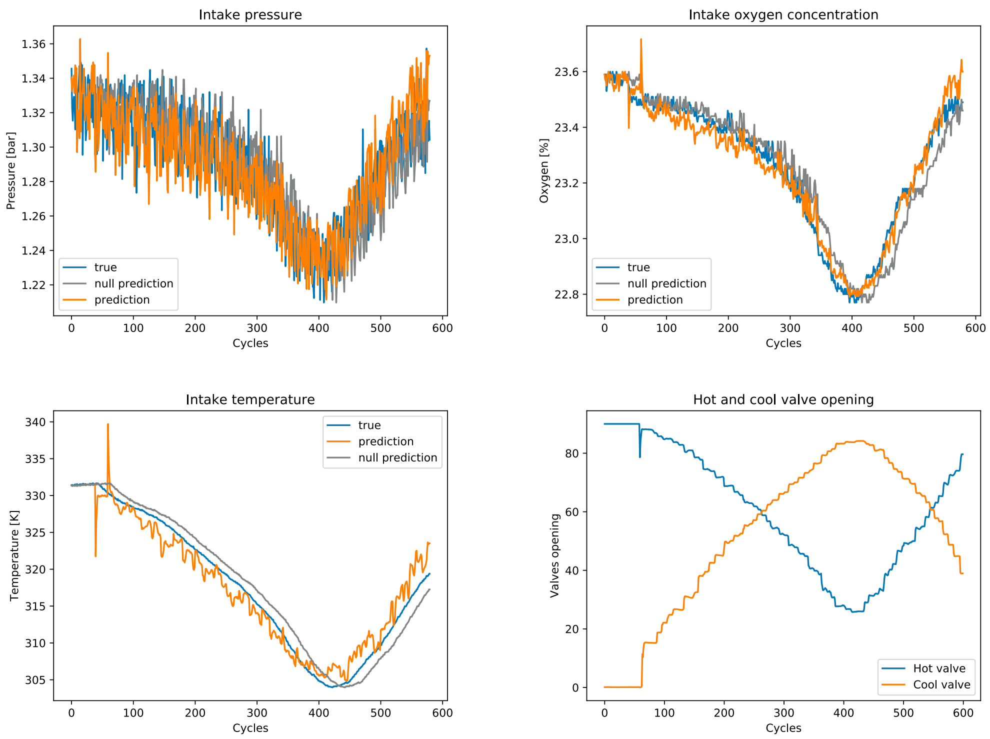


Figure 3
Model performance in hot and cool valve transient

Results

The proposed models are validated with the engine operation data.

Figure 2 shows the model prediction performance in the VGT valve changing scenario, where the EGR, hot, and cool valve are kept constant. From which we can see that increasing VGT opening will increase not only the intake pressure but also the measured oxygen concentration. The 20 steps ahead prediction of the model shows an agreement with the true value and outperforms the null prediction, which simply uses current value as a prediction of future value. Figure 3 shows the 20 steps ahead prediction when the hot valve and cool valve are changing while EGR and VGT valves are set constant. Figure 4 is the 10 steps ahead prediction with the EGR valve and VGT valve changing at the same time. The model shows good consistency to the true value.

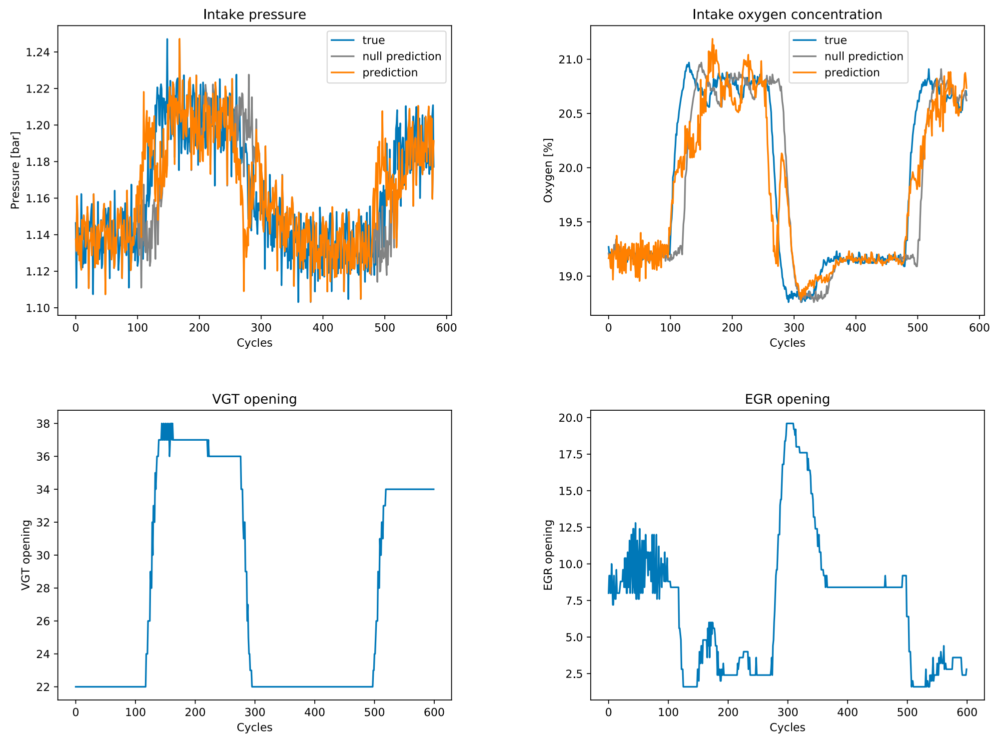


Figure 4
Model performance in VGT and EGR opening transient

The ignition delay model performance comparison is shown in Table 1. The data contains fuel choices ranging from diesel, gasoline/n-heptane mixture to ethanol/n-heptane mixture and various RPM and IMEP. The physical model has the worst performance due to its limited parameters. For GP models, adding more features will increase the performance effectively. The same improvement can be seen in NN by increasing the network structure complexity. The data-based models achieve a similar best accuracy.

Conclusions

The gas systems are modeled by mean value models with suitable simplification for control purposes. The ignition delay, one key indicator for mutative fuel properties, is modeled by empirical chemical-reaction expressions and data-based models. Those models are validated and compared in the engine running data. The established gas system models are able to capture the intake temperature, pressure, and oxygen concentration dynamics, and the data-based machine learning models have higher accuracy than the Arrhenius-type model for ignition delay.

Table 1
Model performance comparison

Model	Specifications	Inputs (Features)	RMSE (Error)
Physical	None	$p_{in}, T_{in}, O_{2\,in}$	0.429 (24.44%)
GP	Matérn 5/2	$p_{in}, T_{in}, O_{2\,in}$	0.192 (10.95%)
	Matérn 5/2	$p_{in}, T_{in}, O_{2\,in}, p_{IMEPg}, N_{speed}$	0.027 (9.31%)
	Matérn 5/2	$p_{in}, T_{in}, O_{2\,in}, p_{IMEPg}, N_{speed}, \theta_{SOI}$	0.089 (5.06%)
NN	(3, 10, 1)	$p_{in}, T_{in}, O_{2\,in}$	0.343 (19.58%)
	(3, 10, 20, 10, 1)	$p_{in}, T_{in}, O_{2\,in}$	0.227 (12.92%)
	(3, 64, 256, 64, 1)	$p_{in}, T_{in}, O_{2\,in}$	0.178 (10.17%)
	(5, 64, 256, 64, 1)	$p_{in}, T_{in}, O_{2\,in}, p_{IMEPg}, N_{speed}$	0.144 (8.19%)
	(6, 64, 256, 64, 1)	$p_{in}, T_{in}, O_{2\,in}, p_{IMEPg}, N_{speed}, \theta_{SOI}$	0.093 (5.28%)

PPC PERFORMANCE USING LIGHT-DUTY DIESEL ENGINE HARDWARE

Researcher:
Nikolaos Dimitrakopoulos

Supervisor:
Martin Tunér

Introduction

The PPC-LD (Partially Premixed Combustion – Light Duty) project focuses on the application of the PPC concept on a commercially available engine. PPC is an advancement over the older HCCI concept and 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 NO_x 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. A positive aspect of this combustion concept, is that it can operate with different kind of gasoline-like fuels of high and medium octane rating, renewable fuels as well as alcohols.

Background

One of the questions in the PPC-LD project is to explore means to extend the low load range with improved brake efficiency and while respecting operation quality thresholds such as operation stability and combustion noise.

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 and water cooled intercooler for faster intake temperature control, an in-house control system and various measurement sensors.

Results

Low load operation is challenging with the current engine setup while using regular gasoline fuel of RON 95. Previous results show that it is difficult to have stable combustion at loads lower than 5 bar imep. To improve on that, glow plugs can be used to increase the in-cylinder temperature and reduce the combustion instability (Figure 1) as well as improving efficiency at lower loads (Figure 2). The peak brake thermal efficiency of this engine setup is above 40% and with the use of glow plugs, low load and low speed operation can operate at strongly improved brake thermal efficiencies at around 30%. The use of glow plugs extends the low load operation range down to around 2 bar IMEP gross Figure 3.

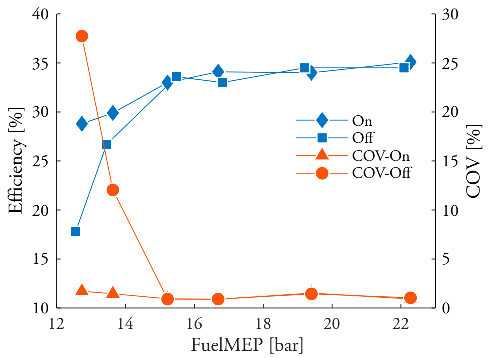


Figure 1
Effect of glow plug operation on combustion stability

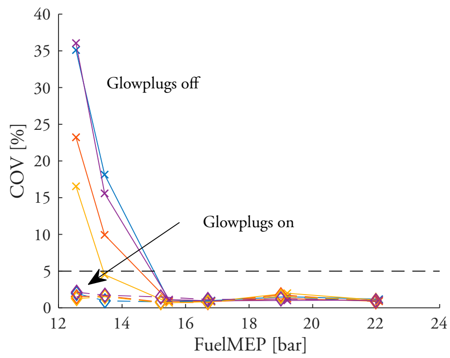


Figure 2
Improvement of engine efficiency at low loads at 1200 rpm with glow plugs

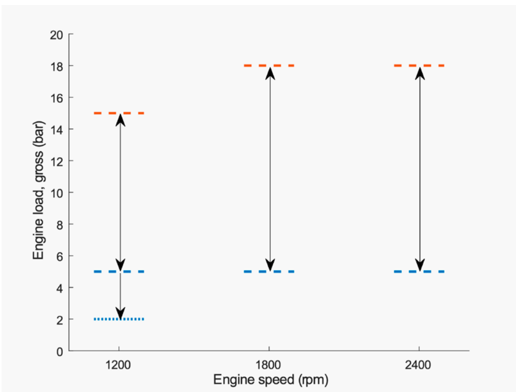


Figure 3
Achievable load range with PPC with gasoline fuel for three different engine speeds. The extended arrow for the lowest speed shows the extended low load range due to the use of glow-plugs.

Researchers:
Leilei Xu
Mark Treacy

Supervisor:
Xue-Song Bai

CFD MODELLING OF PPC ENGINE COMBUSTION

Objectives

CFD simulations were conducted in a heavy-duty gasoline DICI engine with different piston geometrical profile, compression ratio, and injection timing. The main objective of this sub-project is to gain a comprehensive understanding of how the charge composition and temperature distribution are affected by the injection timing and engine geometry in the gasoline fueled DICI engines under low temperature combustion (LTC) conditions, and subsequently, how the combustion and emissions are affected.

Introduction

Low temperature combustion (LTC) of high-octane number fuels in compression ignition engines offers an opportunity to simultaneously achieve high engine thermal efficiency and low emissions of NOx and particulate matter without using expensive after-treatment technologies. LTC engines are known to be sensitive to the operation conditions and piston geometry. In our previous studies [1,2], the fuel stratification, emission characteristics and engine performance during the transition from HCCI to PPC in a gasoline direct-injection compression-ignition (DICI) engine with a toroidal chamber were investigated. According to the spray-wall impingement locations and fuel–air mixture stratification, the whole injection timing range was divided into four zones that involve three combustion regimes: HCCI, PPC, and transition between HCCI and PPC. It was found that the performance of gasoline DICI engines is sensitive to the injection timing, compression ratio (CR) and engine bowl geometry. Systematic investigation of the effects of these parameters on the in-cylinder combustion process is important for the development of injection strategies. In the current sub-project, a joint numerical and experimental investigation was conducted in a heavy-duty engine fueled with PRF81 fuel (81% iso-octane, 19% n-heptane) to investigate the effects of piston geometry, CR, and injection timing on the fuel/air formation and combustion process during combustion regime transition in DICI engines. The SOI was swept from −100 to −20 °CA ATDC to achieve different levels of charge stratification in the cylinder while the intake air temperature was adjusted to keep the CA50 at 3 °CA ATDC. Two piston bowl shapes, a standard production piston with the stepped-lip profile and a piston from the Scania D13 engine with straight-wall profiles were compared. By analyzing the simulation results of the straight-wall piston, the impacts of CR are also discussed in detail.

Methods

The computational fluid dynamics (CFD) code, KIVA3V coupled with CHEMKIN was used for the simulation of the engine combustion process. The numerical simulations are based on the Reynolds-Averaged Navier–Stokes (RANS) framework together with Lagrangian Particle Tracking (LPT) method for the discrete spray droplets. Several updated sub-models were used to improve the prediction accuracy of the mixing and combustion process in the engine. A modified generalized renormalization Group (gRNG) κ-ϵ turbulence model with adjusted model coefficients for variable-density flows was used to model the turbulence in the engine, which can predict the turbulent kinetic energy and flow length scale more accurately with compressing/expanding flows. A new injection rate model for the common rail fuel injection systems was employed to evaluate the actual injection duration, injection rate-shape, and liquid droplet initial velocity [3]. The Kelvin–Helmholtz (KH) instability model was used to predict the primary breakup and the Rayleigh–Taylor (RT) accelerative instability model was used to predict the secondary breakup. A new spray/wall interaction model and an enhanced liquid film model developed for particular emphasis on the premixed charge engine-relevant conditions were introduced to reproduce the liquid film dynamics, wall/spray interaction, wall/film heat flux, and liquid film vaporization characteristics. A multi-component quasi-dimensional vaporization model was employed to model the multi-component fuel vaporization process of liquid droplets of PRF81 fuel. A skeletal PRF mechanism [4] made up of 136 species and 617 reactions including NOx formation (thermal N2O and NO2 pathways) is employed to model the combustion process and emission formation. The chemistry is coupled with the flow through a well-stirred reactor model that was shown to be suitable for LTC engines. Further details about the model and the CFD code, and validation of the model can be found in Ref. [5].

Results

The engine experiment was conducted on a four-stroke, six-cylinder Scania D13 heavy-duty direct injection engine. After modification, only one cylinder was activated with the independently controlled intake/exhaust and injection systems. The bore/stroke length is 130/160 mm, and the connecting rod is 255 mm. An external compressor supplies the intake air with a maximum output pressure of 11 bar. The concentrations of NO_x, CO, UHC, intake and exhaust CO2, and O2 were analyzed with the AVL i60 emission measurement system.

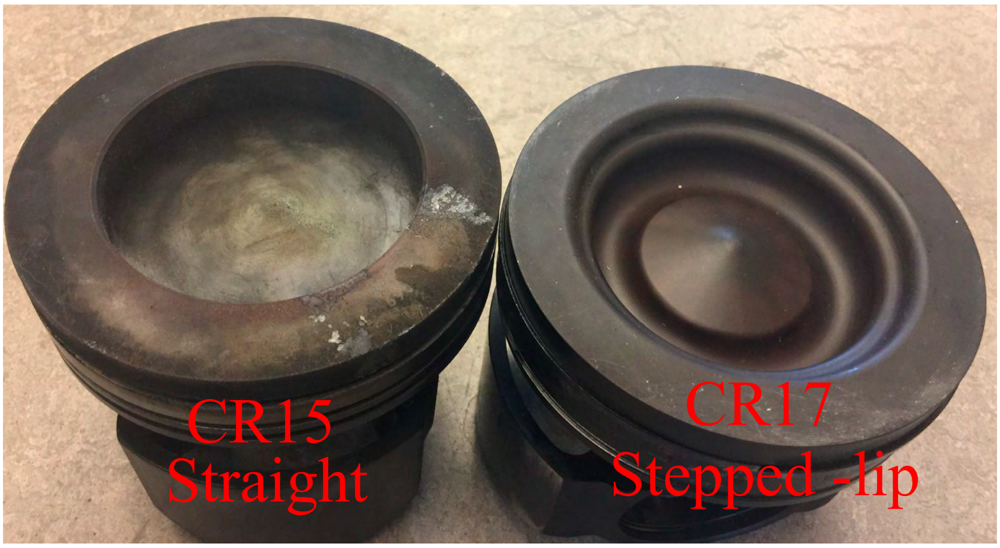


Figure 1
Two piston geometries used in the experiments and CFD simulation.

Two combustion chamber types were compared in the experiments and simulations: a straight-wall combustion chamber and a stepped-lip wall chamber, as shown in Fig. 1. The stepped-lip chamber with a modified transition to the squish region can enhance the turbulent flow within one zone or between two adjacent zones. During the experimental testing, the straight-wall chamber has a geometry CR of 15.0 (hereafter referred to as CR15), and the stepped-lip with a CR of 17.3 (hereafter referred to as CR17). In order to evaluate the CR effect, in the CFD simulations the CR15 bowl is modified to have a CR of 17 by reducing the piston bowl profile by 1.45 mm. The modified piston (hereafter referred to as CR17(15)) has the same CR as the piston CR17 and the same piston bowl profile as the piston CR15.

The required intake/IVC air temperatures to maintain CA50 of 3 °CA at different SOI in the experimental and numerical simulations for the CR17 piston are compared in Fig. 2(a). It can be seen that the overall trend of initial temperature at IVC in the numerical simulations agrees very well with that of the required intake temperature in the experiments. The variations of both intake temperature and initial temperature under different SOI show a "spoon" shape. The required IVC temperatures for three pistons to maintain the CA50 of 3 °CA at different SOI are shown in Fig. 2(b). The compression process can be regarded as isentropic when both wall heat transfer and the low-temperature reaction of fuel are ignored. Thus, the required initial temperature can be estimated under different CR. It is calculated that when the CR is increased from 15 to 17, the initial temperature is reduced by 3.74% to achieve the same temperature at TDC (here κ = 1.388 and CR from IVC to TDC is 13.8 and 15.22 respectively). The difference in the required IVC temperature at the same SOI is consistent with the theoretical estimation when comparing the required IVC temperature for the CR15 and CR17(15) pistons with the same bowl shape. Thus, the differences in IVC temperature between CR17 and CR17(15) piston are attributed to different fuel–air distributions affected by the piston geometry.

As shown in Fig. 3(a), the numerical simulation can accurately reproduce the trend from the experiments of NO_x emissions at different SOI. When the SOI is earlier than –39 °CA, the NO_x emission is lower than 50 ppm, corresponding to the 0.4 g/kWh, meeting the EURO VI standard (the IMEP is around 4 bar and the fuel mass is 44 mg/cyc). At SOI of –65 °CA, a small peak of NO_x can be found which is from the combustion of the fuel-rich mixture in the squish region. When the SOI is retarded to –40 ~ –28 °CA, the NO_x emission increases rapidly due to the more fuel distributed around the stoichiometric mixture. Further retarding SOI causes a substantial reduction of NO_x emission due to the higher heat transfer losses. The

NOx emission characteristics for the three piston cases are compared in Fig. 3(b). Compared with CR15 and CR17(15) pistons, it can be found that increasing CR significantly reduces NOx emission. Compared with CR15 and CR17(15) pistons, CR17 piston allows a more retarded SOI without violating NOx regulation, i.e., the latest acceptable SOI with low NOx emission is postponed from −48 to −39 °CA.

Fig. 4(a) shows the UHC emissions for the CR17 piston at different SOIs from the experiment and numerical simulations. For an SOI earlier than −50 °CA, a large amount of fuel trapped in the crevice region leads to the higher UHC emission. For an SOI later than −46 °CA, all the fuel is directly injected into the piston bowl and the UHC emissions are much lower. The numerical simulation can accurately predict the UHC emissions trend of the CR17 piston at different SOI. From Fig. 4(b), it can be seen that the emission of UHC becomes sensitive to the piston geometry and the CR after the combustion transitions to the PPC regime with the SOI later than −50 °CA. The UHC emission of the CR15 piston is higher than that of the CR17 at the SOI of −48 ~ −35 °CA, while the UHC emission of the CR17 is much higher in the SOI of −35 ~ −20 °CA. Comparing the UHC emission characteristics of CR15 and CR17(15) pistons, it can be found that the UHC emissions increase with the increasing CR in the PPC regime.

More detailed description of the CFD simulations and analysis of the results can be found in the publication [5].

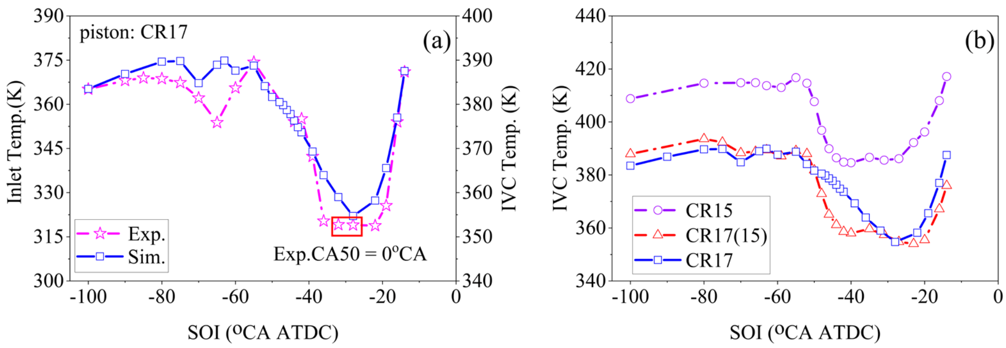


Figure 2
(a) Comparison of required inlet temperature to maintain the same CA50 for the CR17 piston at different SOI in the experiment and simulation;
(b) Comparison of required inlet temperature for the three pistons.

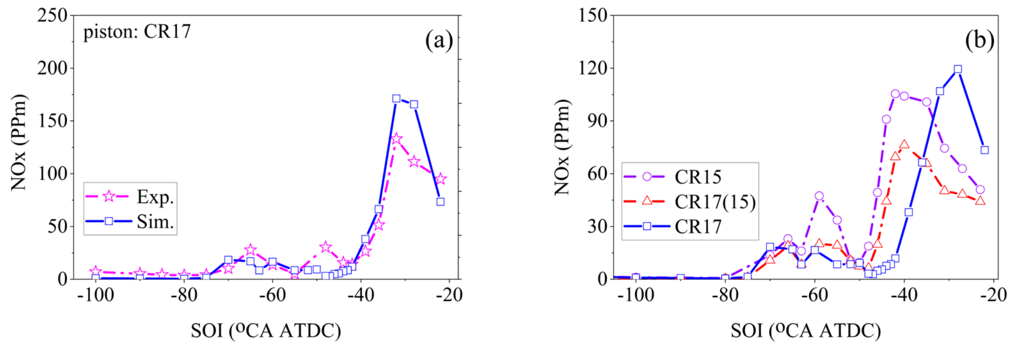


Figure 3
(a) Comparison of NOx emission with the CR17 piston at different SOI in the experiment and simulation;
(b) Comparison of NOx emission for different piston.

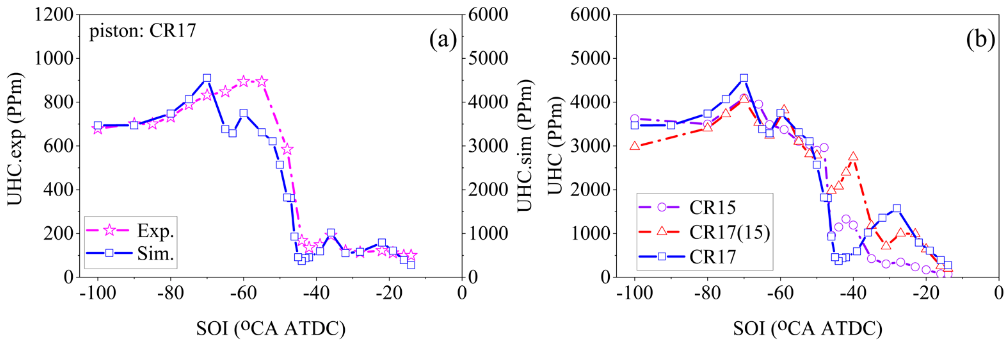


Figure 4
(a) Comparison of UHC emission with the CR17 piston at different SOI in the experiment and simulation;
(b) Comparison of UHC emission for different piston.

Conclusions

A joint numerical and experimental investigation was conducted in a heavy-duty compression ignition engine using a primary reference fuel with an octane number of 81 to investigate the effects of injection timing, piston geometry, and compression ratio (CR) on the fuel/air mixing and combustion covering different regimes of LTC engines, homogeneous charge compression ignition (HCCI), partially premixed combustion (PPC), and the transition regime from HCCI to PPC. The results show that with the same combustion timing, a higher CR leads to a lower NO_x, but a higher emission of UHC and CO. The piston geometry shows a significant impact on the combustion and emission process in the transition regime while it has minor influence in the HCCI and PPC regimes. It is found that high engine efficiency and low emissions of NO_x, CO and UHC can be achieved in the earlier PPC regime and later transition regime. The fundamental reason behind this is the stratification of the mixture in composition, temperature and reactivity, which is dictated by the interaction between the spray and the cylinder/piston walls.

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CI combustion

Professor
Öivind Andersson

Though alternative powertrain technologies are slowly emerging, CI engines are still the dominating power sources for road transport. In this report, three studies are presented under this heading. One describes how an annular cavity connected to the piston bowl affects the soot emissions from a diesel engine. Another study investigates how a novel combustion chamber geometry affects the flow pattern in a diesel engine. This has been demonstrated to produce more energetic flow, improving the efficiency and reducing the soot emissions. The study presented here compares two diagnostics for in-cylinder flow measurements; one based on tracking the movements of seeded particles and one based on tracking the movevement of the flame luminosity. The third study investigates how injector ageing and fuel additives affect the combustion and in-cylinder soot oxidation in 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.

SOOT REDUCTION THROUGH THE USE OF AN ANNULAR CAVITY

Researcher:
Ted Lind

Supervisor:
Öivind Andersson

Objectives
The effect of an annular, piston bowl-rim cavity on soot emissions is studied in a single-cylinder diesel engine using in-cylinder soot diagnostics and exhaust smoke emission measurements.

Introduction
Reduction of soot emission from internal combustion engines is still of high importance and today most compression ignition engines rely on relatively costly diesel particle filters (DPF) to meet the legislation levels. Increasing the soot oxidation rate inside the cylinder might allow manufacturers to decrease the size or even omit the DPF.

Methods
By introducing an annular cavity along the piston bowl wall, according to the drawing in Figure 1, we could investigate its effect on the soot emission.

Introducing the cavity reduces the compression ratio to 10.91 compared to the nominal configuration of 11.22 and it's established that a decreased compression ratio leads to lowered soot emissions. To better isolate the mixing effect of the cavity we compare the soot emissions from the cavity piston to two other piston configurations with even lower compression ratio (10.75 and 10.32).

Results
Several injection durations were studied for the four different piston configurations but all other engine conditions were kept constant around the time of injection and the results are presented in Figure 2.

By studying the apparent heat release rate, it is possible to detect a small increase in the late cycle heat release with the cavity configuration. This is shown in Figure 3 and while the figure only depicts a single injection duration, or rather duration of solenoid energizing (DSE), this effect was consistent for all DSEs studied within this experiment.

Conclusions
A novel piston design with a cavity has been tested and we show that the design consistently reduces the soot emissions, sometimes by as much as 70 %. This effect is attributed to an increase in late cycle soot oxidation. This hypothesis is also supported by the fact that the cavity configuration has a higher apparent heat release rate for 20-30 CAD starting at the time of global pressure reversal (~375 CAD).

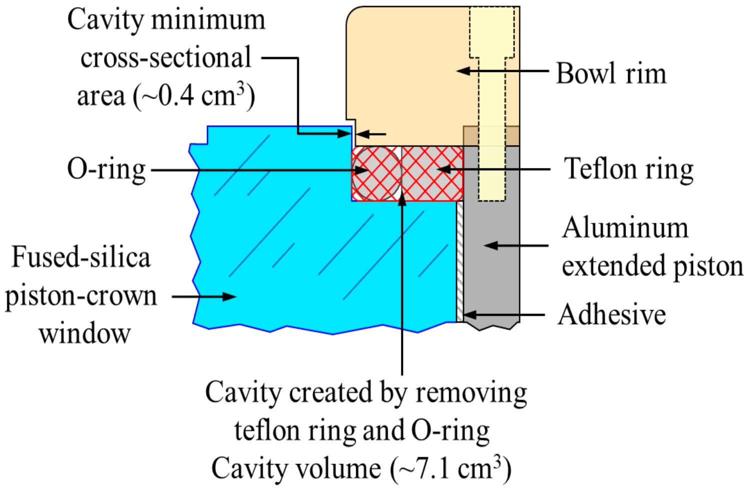


Figure 1
Cross section of the piston bowl, the checkered region corresponds to the region where the cavity was present

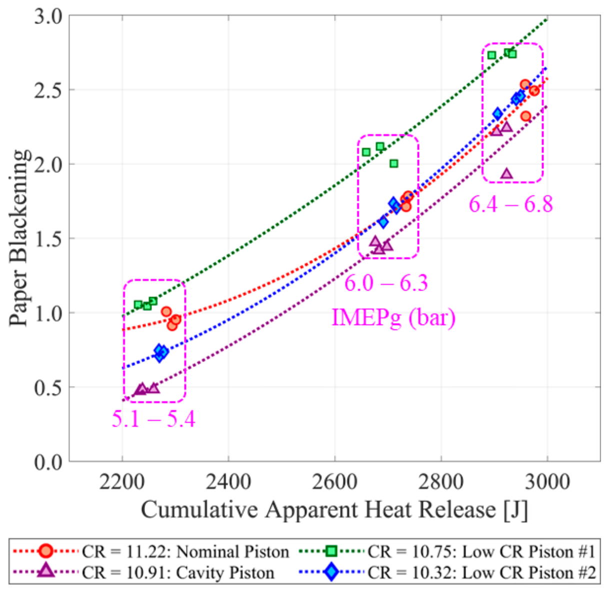


Figure 2
Plot of the soot emissions measured as paper blackening and the cumulative heat release of each piston configuration

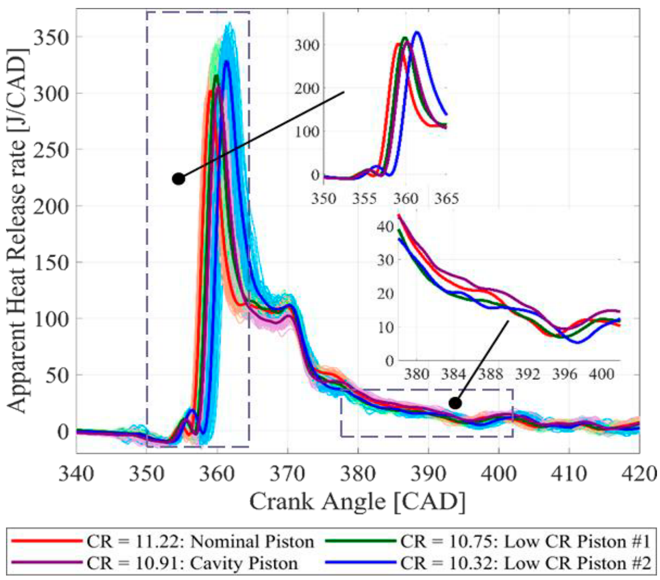


Figure 3
Apparent heat release rate of the various piston configurations with a 2550 μs DSE.

INFLUENCE OF INJECTOR AGING AND TPGME FUEL ADDITIVE ON SPRAY FORMATION, COMBUSTION AND SOOT OXIDATION STUDIED IN AN OPTICAL DIESEL ENGINE

Researchers:
Manu Mannazhi
Xinda Zhu

Supervisors:
Per-Erik Bengtsson
Öivind Andersson

Objectives

The main objective is to study the effects of injector ageing and TPGME additive on spray formation, combustion, and soot oxidation, using optical diagnostic techniques. 3D X-ray tomography was used to characterize the nozzle geometries of the aged and new injector. High speed imaging of Mie scattering was used to study the spray formation in new and aged injectors. High speed imaging of natural luminosity was used to visualize the combustion processes. Investigation of soot oxidation was performed using laser-induced incandescence (LII) and laser extinction.

Introduction

Previous studies have shown that aging of injectors affect the spray patterns and combustion process which results in reduced efficiency, power loss, high emissions, etc. While injector aging results in elevated soot emissions, fuel additives such as tripropylene glycol monomether ether (TPGME) can be used to reduce soot emissions. However, to comply with the emission regulations throughout the lifetime of the engine, it is essential to understand the effects of ageing on spray formation and combustion processes. Spray formation can be effectively visualized using Mie scattering measurements. Combustion processes can be visualized using line-of sight averaged natural luminosity measurements. In addition to these, laser-induced incandescence in combination with extinction can be used to semi-quantitatively determine soot concentrations and soot oxidation rates.

Methods

Measurements were performed in a single-cylinder light-duty Volvo diesel engine. The optical engine has four optical windows on the cylinder liner giving optical access from sides to the top volume of the cylinder. Additionally, it was equipped with a transparent quartz piston mounted on a piston extension, which is optically accessible using a 45° mirror. Measurements were performed at two load conditions, called low-load (IMEPg ~ 4 bar) and mid-load (IMEPg ~ 9 bar) conditions.

Various optical diagnostic techniques were employed for this study. Firstly, 3D X-ray tomography was used to visualize the internal geometry of the nozzles of the aged and new injectors. High speed imaging of Mie scattering was used to study the spray formation in a non-reactive environment, where the elastic light scattering from the spray and droplets are used to characterize the spray. A continuous wave (CW) diode laser operated at 452 nm was used to illuminate the combustion chamber, where the light entered from one of the windows. A Photron FASTCAM SA5 camera operated at a speed of 25,000 fps was used to capture the scattering from sprays. The spray was imaged through the quartz piston using the 45° mirror. High speed imaging of natural luminosity from the flame was the second diagnostic technique used. For the natural luminosity measurements, there was no laser-illumination involved. The same camera used for Mie scattering measurements was used for imaging natural luminosity as well. Two-dimensional laser-induced LII incandescence was one of the techniques used for studying soot oxidation. An Nd:YAG laser (Brilliant b, 10 Hz) operated at 1064 nm was used for LII measurements. LII signals imaged onto an ICCD camera (PIMAX 4) were calibrated into soot volume fractions using extinction. Extinction measurements were performed using a continuous wave laser operated at a wavelength of 690 nm. Extinction was also used as a stand-alone technique to study late-cycle soot oxidation. LII measurements were performed between 25° crank angle after top dead center (CA aTDC) to 70° CA aTDC in steps of 5° CA. Meanwhile, extinction measurements were crank angle resolved and was reported from 25° CA aTDC onwards.

The 2D signal images of Mie scattering, natural luminosity and LII were spatially distorted due to the shape of the piston and the optical windows. Procedures were developed for the correction of these distortions in MATLAB and applied for all the images.

Results

Figure 1 shows the overlapped cross-section view for both the aged and new injectors at two different positions in the nozzles. The images show no significant differences in the geometry between the aged and new injectors. Thus, the hypothesis of deposits or nozzle wear can be eliminated. Some of the results from Mie scattering measurements are given in Fig. 2. Figure 2a shows the Mie scattering signal from the whole imaging region and one spray is selected for detailed analysis, which is shown in Figs. 2a and 2b. Figure 2c shows the Mie scattering signal for the aged and new injector at mid-load conditions. The aged injector shows a prolonged signal for the main injection while producing significantly higher signal for the two pilot injections. This would result in a higher load for the aged injector compared to the new injector for the same needle actuation signals. It was also seen that the aged injector produced more dribbles at the end of the fuel injection events.

Natural luminosity imaging of the combustion processes reveals differences in the in-cylinder soot processes. As Fig. 3 shows, at low load, the difference in fuel quantity dominates the total luminosity signal between the new and aged injector. More soot is formed with more fuel and the oxidation also lasts longer, with a longer high temperature window. No significant difference is observed between the two fuels. The stronger soot luminosity from the TPGME fuel might be caused by elevated temperatures, due to the oxygen content.

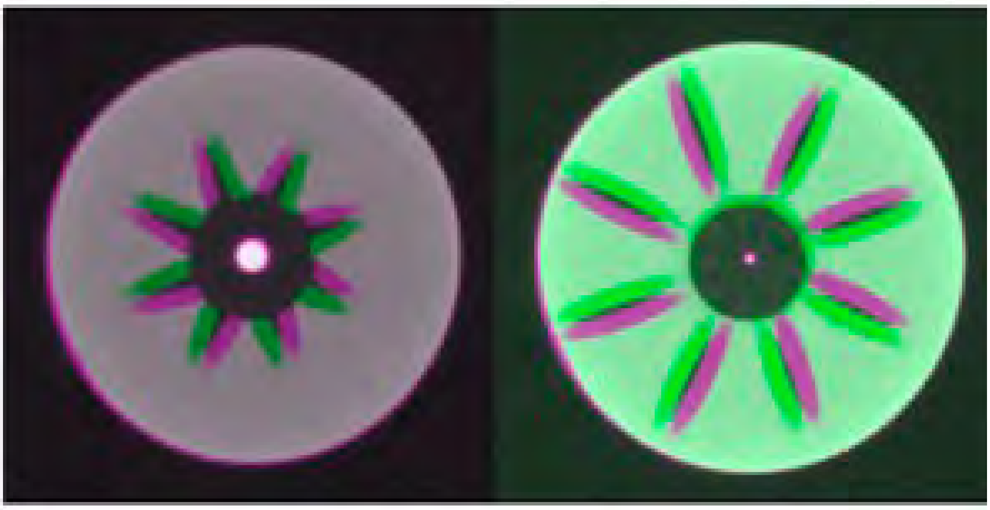


Figure 1
Overlapped cross section views of the nozzle area from the new and the aged injectors at different distances from nozzle tip. Purple: new injector. Green: aged injector.

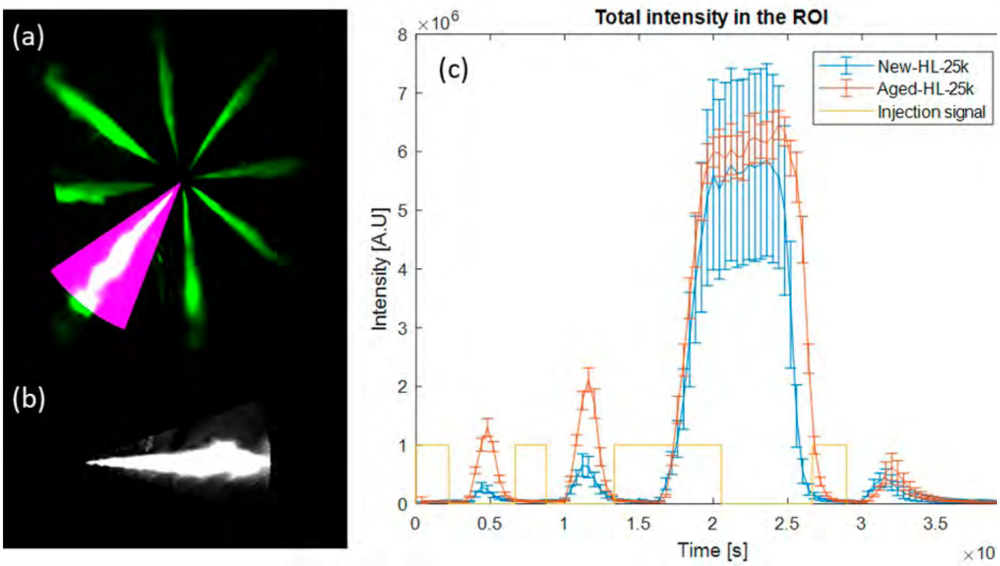


Figure 2
(a) Mie scattering signal of all the sprays with the spray selected for analysis marked.
(b) Isolated spray.
(c) Mie scattering signal at the mid-load condition for both new and aged injectors.

Figure 4 shows the behaviour of soot late in the cycle characterized using extinction and 2D LII. The parameter $K_{ext}\,L$ in Fig. 4a represents line-integrated soot volume fraction (f_v) along the beam path of the extinction laser. Figure 4b represents 2D (f_v) distributions (color-bars represent f_v in ppm) obtained after calibrating the 2D LII signal using extinction for various crank angle degrees after top dead centre (CAD aTDC). Aged injector produced higher soot concentration compared to the new injector for both the loads, which might be due to its longer injection durations. Aged injector also showed faster soot oxidation rates at low load conditions. The fuel blend with TPGME produced lower soot concentrations compared to the baseline fuel for both loads. The soot oxidation rate was higher for the TPGME case at the mid load condition, while at low load both the baseline and TPGME cases displayed rather similar oxidation rates.

Conclusions

Optical diagnostic techniques such as 3D X-ray tomography, high speed imaging of Mie scattering and flame luminosity, extinction and 2D LII were successfully performed in the optical diesel engine to study the influence of aging of injectors and TPGME fuel additive. Aged and new injectors showed no significant differences in the geometry of the nozzles and symmetry of sprays. However, aged injector showed a longer injection duration compared to the new injector which results in a higher load. It also showed higher soot formation at both loads, and faster soot oxidation rates at low load conditions. The fuel with TPGME additive produced lesser soot compared to the baseline diesel at both load conditions while resulted in faster soot oxidation rates at mid-load conditions.

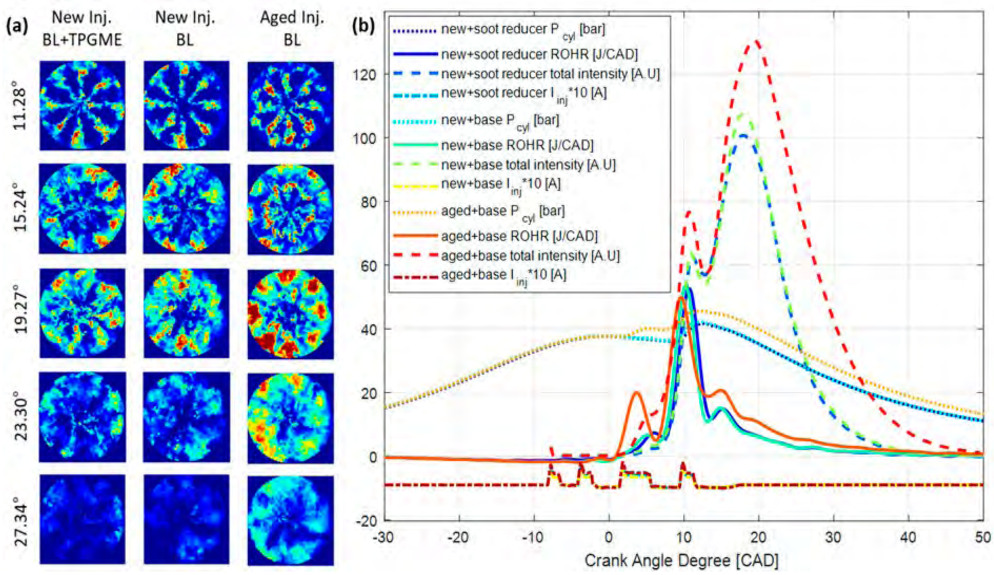


Figure 3
Low-load conditions. (a) Natural luminosity images at various CADs for the new injector with TPGME additive, with baseline diesel (BL) and the aged injector with BL fuel.
(b) Pressure, heat release rate and spatial integration of natural luminosity signal during combustion.

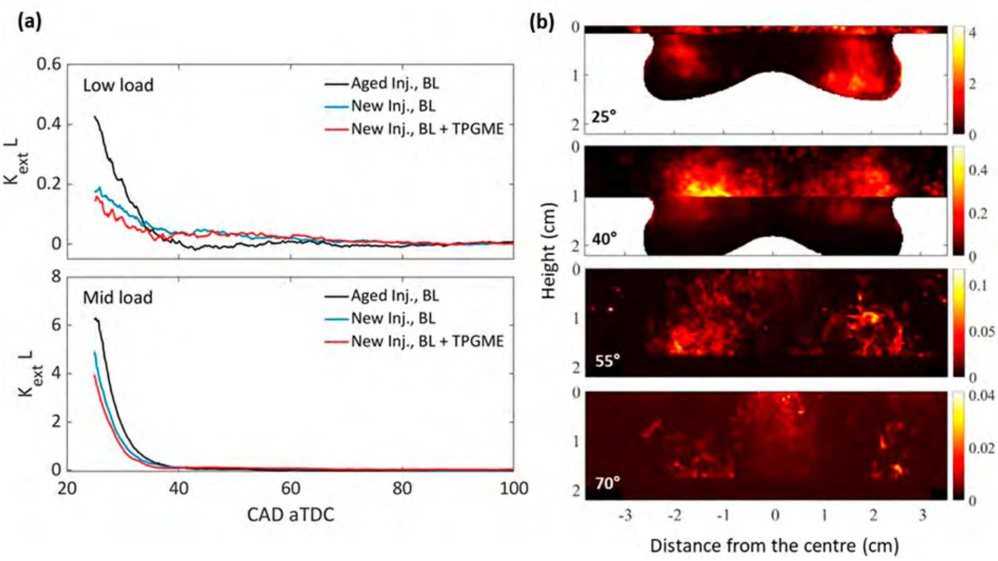


Figure 4
(a) $K_{ext}\,L$ values representing f_v obtained from extinction measurements for both low load and mid load conditions for all the cases.
(b) 2D f_v distributions obtained from LII measurements after extinction calibration. Color-bars represent f_v in ppm.

Researchers:
Saeed Derafshzan
Ted Lind
Miaoxin Gong

Supervisors:
Mattias Richter
Öivind Andersson
Marcus Lundgren

OPTICAL DIAGNOSTICS ON WAVE PISTON, PIV AND CIV STUDIES

Objectives

An optical wave piston, designed based on the novel Volvo wave piston, is mounted in Volvo MD-13 heavy-duty optical engine, and different aspects of the flow field and the combustion are investigated. These studies cover a wide range of phenomena during the combustion cycle, from the flow field inside the cylinder during compression stroke, to fuel injection, and combustion. By injecting TiO_2 seeding particles into the air manifold, the flow field inside the combustion chamber during different stages of the cycle are derived with particle image velocimetry technique (PIV). Furthermore, a simultaneous recording of combustion natural luminosity (NL) provides additional information of the effects of this wave design. Finally, a comparison between flow field derived from PIV and NL will be made.

Introduction

Increasing the efficiency of combustion and reducing the engine emissions are increasingly important and one area to help achieving these goals is optimizing the geometry of the piston bowl shape and design. The increase in efficiency and reduction of soot emissions associated with the wave piston is believed to be attributed to better mixing of fuel and air. In this study an optical wave piston with similar design is investigated to yield more insight on the effects that this design has on flow field and combustion.

Methods

Inside the combustion chamber the flow field is derived by using particle image velocimetry technique (PIV), during later stages of the compression stroke and the injection of the fuel and further on to the interaction of fuel jets with the piston wall and each other and ultimately during the combustion. A dual-cavity Nd:YLF laser creates double-pulsed laser light sheets, and the scattered light from the TiO_2 particles that are seeded into the intake manifold, is recorded with a high-speed CMOS camera. Simultaneously, combustion natural luminosity (NL) is recorded with another high-speed camera and provides a detailed insight on the combustion and the effect of the wave design. Additionally, a flow field during combustion phase can be derived from NL and a comparison between this flow to the one derived from PIV is of importance from diagnostics point of view. Figure 1 shows the optical setup of this research campaign.

A wide range of engine parameters were investigated, including injection timing and duration to better understand the effects that this wave design creates. Additionally, some cases were operated with high EGR to avoid the combustion and only focus on recording the Mie scattered light from the fuel jets to visualize their interactions with piston walls.

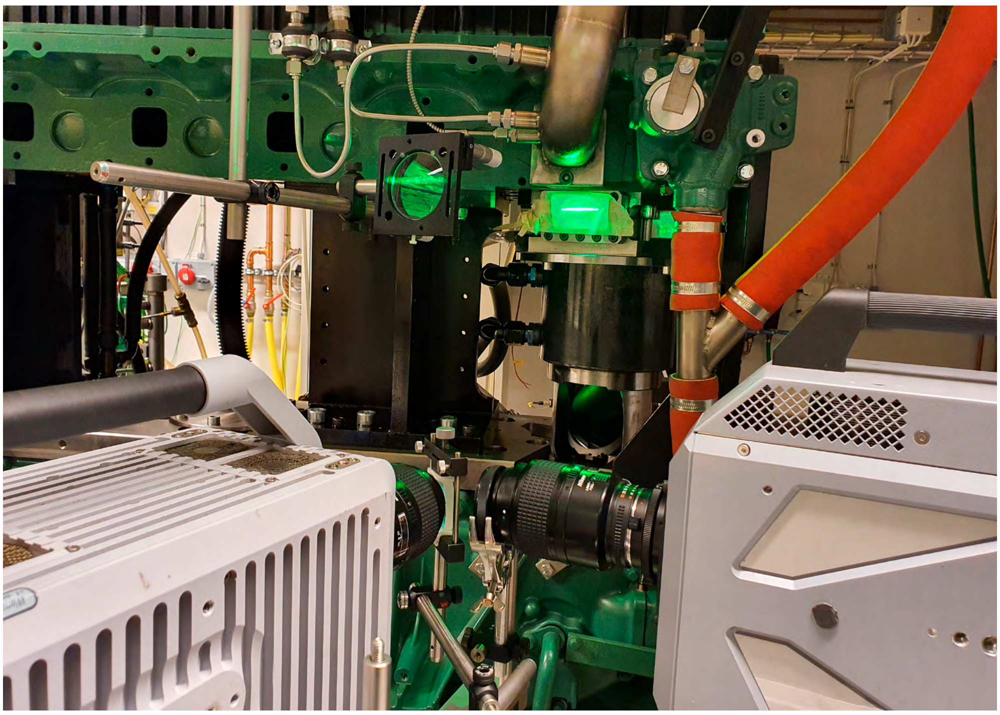


Figure 1
Optical Setup, including optical engine, PIV and NL camera and laser shaping optics

Results

Current study enables us to gain knowledge of several important aspects of the engine cycle, including the flow field, fuel injection and mixing processes all the way to combustion and heat release, and it is even more valuable considering the effects and differences that we can observe due to the waves in the piston. In Figure 2 example of these stages are presented.

Results show obvious differences between the fuel sprays and the combustion in the side of the piston with three waves (upper half in Fig. 2) and the other side which has a conventional flat bowl-shape design (lower half of the images in Fig. 2). The reason for using a flat bowl piston design is to have an undistorted optical access to the combustion chamber, and it is practically even more beneficial as we can compare the effects of the wave directly within one image. The waves affect the fuel jet interactions with each other and the wall, thus resulting in different mixing and combustion characteristics. The wave design effects on mixing and combustion depends highly, amongst other factors, on the timing and duration of the injection, and can help increasing the mixing, and avoiding fuel-rich areas, as it is greatly affected by the piston geometry.

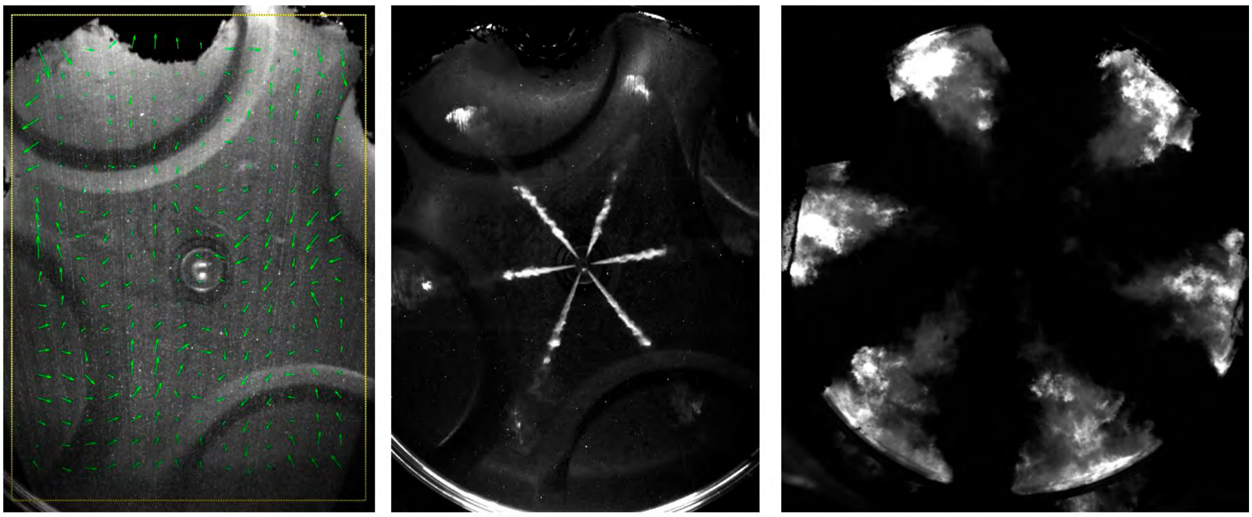
Furthermore, using a technique called combustion image velocimetry (CIV) it is possible to obtain the flow fields of the combustion without the use of seeding. A comparison between the CIV data and the PIV data is currently being conducted in addition to the coupling and comparing of the optical data together with the engine parameters.

Conclusions

The measurements are concluded in this research campaign, and currently the post-processing of the data is ongoing, and the achieved or ongoing goals and conclusions are as follows:

- Flow field visualization in the wave piston
- Visualization of the fuel sprays and the jet-jet and jet-wall interaction of the fuel, in which the effects of the wave are investigated
- Capturing combustion natural luminosity in a wide range of engine conditions
- A comparison of two different optical techniques in flow field visualization, CIV and PIV

Figure 2
From left to right: flow field prior to injection, fuel sprays (Mie scattering), and combustion natural luminosity



SI combustion

A. Professor
Marcus Lundgren

Spark ignition (SI) is commonly referred to as a combustion system for light duty applications. However, with the transition to renewable fuels such as, hydrogen, biogas (methane) and alcohol fuels the interest of using SI in heavy duty applications has increased.

Within KCFP we have a number of ongoing activities to tackle common challenges of: flame speed, knock mitigation, ignitability etc. All to facilitate combustion of renewable fuels and increase the system efficiency of the engine.

The ongoing projects are:

- Gas engine control through ion current
- Direct Injected Spark Ignited alcohol fuel study
- Ignitability Study on natural gas

DIRECT INJECTION SPARK IGNITION WITH ALCOHOL FUELS – SINGLE CYLINDER STUDY

Researcher:
Marcus Lundgren

The following study is ongoing and we are in the process of perform experiments within a single cylinder metal configuration. These results will be a baseline for both simulations and optical studies during 2021.

Introduction

Alcohol fuels are promising in the transition to more CO2 neutral combustion systems. With a high octane rating, these fuels are well suited for SI combustion. However, SI combustion suffers from poor efficiency due to throttling and unburned hydrocarbon in crevice volumes, compared to traditional CI combustion with diesel. These issues can to some extent be overcome with the use of EGR, lean operation and direct injection. To improve the understanding of the SI with alcohol fuels in heavy duty engines more research is needed.

Methods

The current experiments will start by using stoichiometric condition and use EGR as mean to increase efficiency at low and mid load. Both early and late injections will be utilized, but with the current setup is limited with an injector with an umbrella angle of 120 degrees which narrows the start of injection window. The spark plug is located at a radius ~1/2 of the bore radius and well inside the piston bowl, as seen in Figure 1.

The piston bowl design is based on other heavy duty SI combustion systems, and with the use of methanol as fuel we aimed at a compression ratio of 14:1 to facilitate high load.

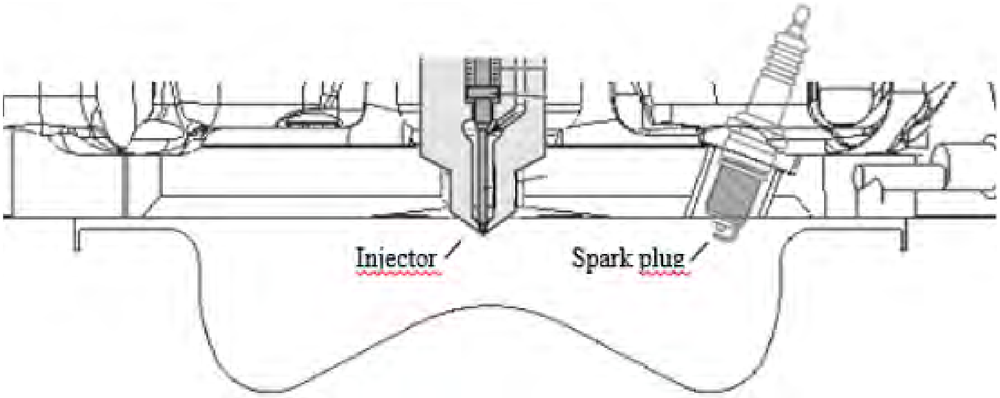
The same cylinder head and piston geometry will be used in both the simulation work and the optical studies. The optical engine is currently under construction, but is expected to be up and running in the end of this spring 2021, see Figure 2.

Expected results

Using methanol, we expect to be able to present a data answering:

- Heat transfer behaviour due to stratified and homogenous fuel mixtures and combustion?
- Combustion effects due to locally rich fuel mixtures – stratified?
- Efficiency potential using EGR or lean operation?

Figure 1
Combustion chamber
and spark plug location



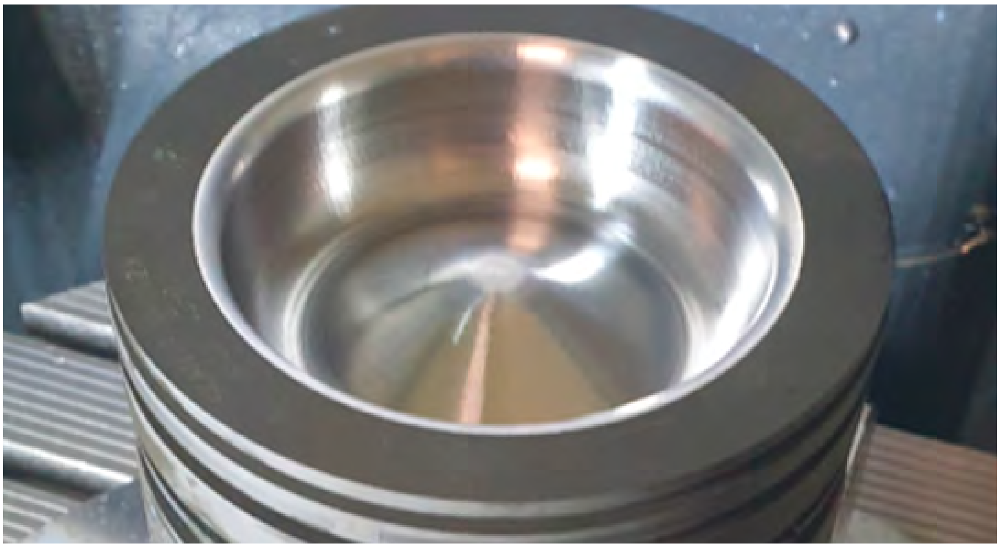
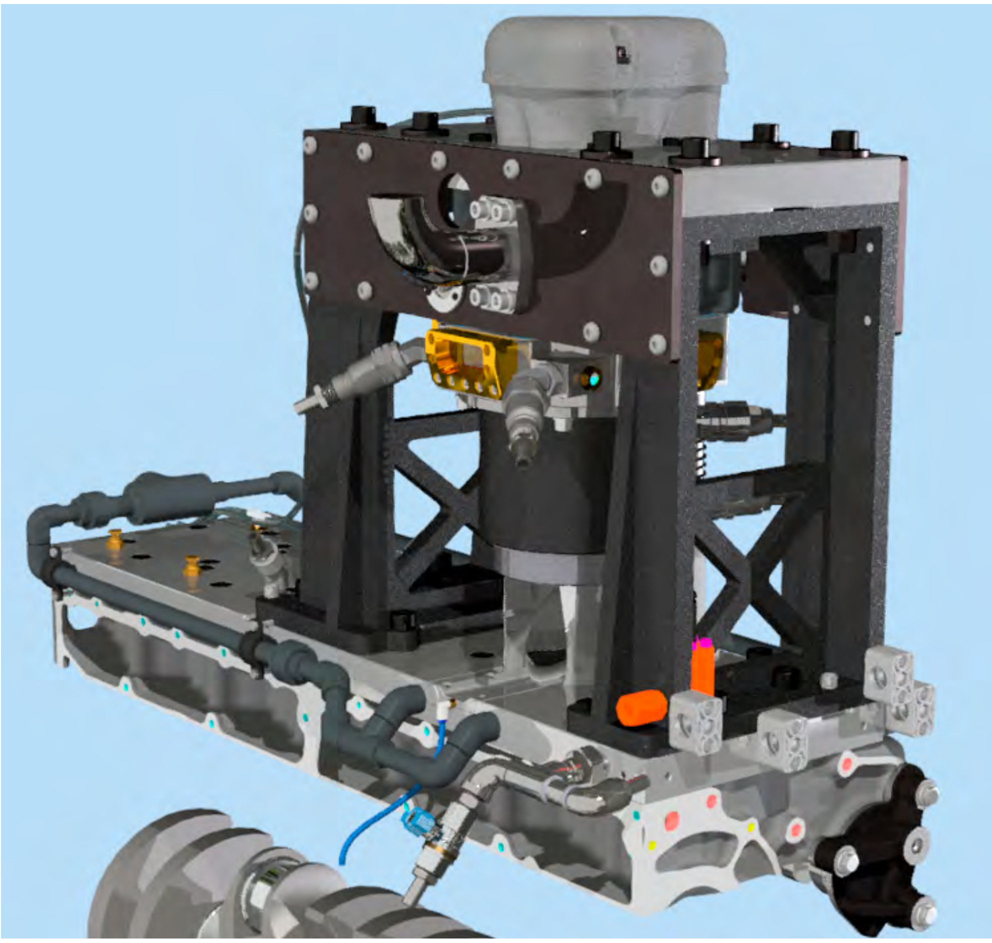


Figure 2
CAD-model of the new
optical engine. Lead research
engineer: Patrik Johansson



COMBUSTION PHASE ESTIMATION USING ION CURRENT MEASUREMENTS

Researcher:
Ola Björnsson

Supervisor:
Per Tunestål

Objectives

The aim is to verify and improve existing ion current based peak pressure location algorithms and develop a statistical framework to estimate the combustion phase based on the ion current measurements.

Introduction

Since the second half of 2020 the work has revolved around getting the engine and data acquisition system fully operational. In parallel, a detailed research plan has been laid out. The engine will soon be ready, and as the first phase is coming to an end, we are looking forward to exploring the first research topic, estimating peak pressure location/combustion phasing.

Spark timing plays a vital role in the performance of a spark-ignited engine. Traditionally the timing is controlled in open-loop, based on lookup tables set during calibration. However, with fuels such as natural gas/biogas certain parameters, e.g. heat release rate and proneness to knock, may vary. This leads to efficiency losses when the fuel deviates from nominal due to incorrect combustion phasing. By developing robust algorithms to estimate the combustion phase and to detect knock we want to implement closed-loop control of the spark timing, thereby being able to account for varying fuel properties.

Methods

The ion current is measured in each cylinder, using the spark plug as a sensor. The peak pressure location is then estimated and validated using the in-cylinder pressure trace.

Results

During the second half of 2020 the first fire-up took place. Since then, additional mechanical installations, sensors, and calibrations have been made. In the coming weeks, the engine is expected to be fully operational.

Preliminary tests of the existing peak pressure location estimation have shown that the estimated peak pressure location strongly correlate with the peak pressure location calculated from the in-cylinder pressure trace, see Figure 1. Furthermore, the estimation error, see Figure 2, has a standard deviation and bias around 1 crank angle degree, cycle by cycle. By averaging, the standard deviation can be further reduced. The bias can be compensated for through tabulation.

Conclusions

A lot of progress has been made on the engine which will soon be fully operational. Furthermore, a detailed research plan has been made, and an initial study on the peak pressure location estimation has been made

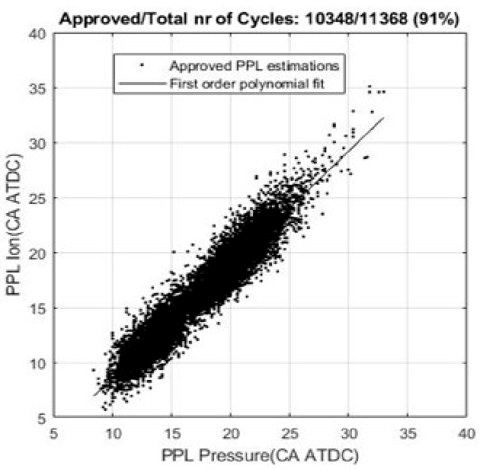


Figure 1
Comparison of peak pressure location estimation based on Ion current (y-axis) and the "true" peak pressure location calculated from the in-cylinder pressure trace (x-axis).

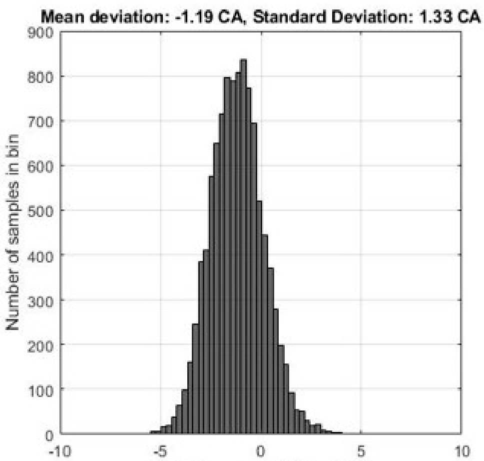


Figure 2
Distribution of the error between the ion current based estimation and true peak pressure location

Researchers:
Mark Treacy
Leilei Xu

Supervisor:
Xue-Song Bai

CFD MODELLING OF ALCOHOL SI ENGINE COMBUSTION

Objectives

The main objective of this sub-project is to study the effects of injection pressure, injector umbrella angle and injection timing on the engine performance, CO, NO_x and UHC emissions of alcohol-fueled direct injection spark-ignition (DISI) engines, using CFD modeling. Additional goals of this sub-project include evaluation of an extended coherent flamelet model (ECFM) for numerical simulation of alcohol fueled DISI engines and providing support to design of experiments of alcohol DISI engines by supporting validated numerical results about in-cylinder flows, fuel/air mixing, and engine performance.

Introduction

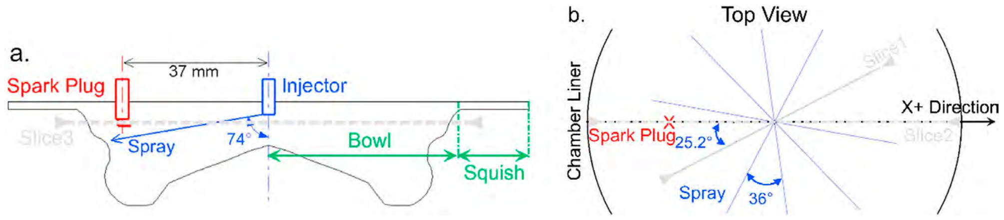
Alcohols, including methanol and ethanol, are promising low-emission and renewable fuels that can be used in both compression ignition (CI) and spark-ignition (SI) engines. In a previous STEM funded project "MOT2030" studies of methanol CI engines using CFD model and experiments have been carried out. Detailed CFD simulations of engine combustion and emission processes under different engine operating conditions including injection timing, single/multiple injection strategies, injector pressure and EGR have been studied [1]. In the present project, methanol and ethanol fuels the SI engines are considered. The focus is on direct-injection spark-ignition (DISI) strategies in order to benefit from enhanced engine efficiency due to direct injection and make use of the advantage of low soot emission from alcohol fuels. In DISI the fuel/air mixture is stratified, which gives rise to variation of the ignition and combustion characteristics since the local equivalence ratio and temperature at the spark location may change in the turbulent environment, and under different engine geometry and operation conditions. Thus, CFD simulations are needed to gain insight to the combustion process including local composition and temperature at the SI location, initial flame development, and emissions of CO, unburned hydrocarbons (UHC) and NO_x, under different engine conditions.

Methods

The three-dimensional computational fluid dynamics (CFD) simulation software, CONVERGE [2] with enhanced sub-models, is adopted in this study to explore the spray and combustion processes in methanol DISI engines. The re-normalization group (RNG) k-ε turbulence model is used, which is particularly suited for the simulation of internal combustion engines. The hybrid Kelvin Helmholtz-Rayleigh Taylor (KH-RT) model is employed to simulate the spray droplet breakup process. Within the characteristic breakup distance (L_b), only KH instabilities are responsible for the droplet breakup. Beyond the breakup length, both KH and RT instabilities are considered to model the second breakup. Developing from the basic probability model for stochastic collision, the no-time-counter (NTC) numerical scheme is used to predict the spray collision. The change of droplet radius over time is described using the Frossling evaporation model, and the thermal transfer to a droplet is calculated by assuming the droplet temperature uniform. The spray-wall interaction is modeled by considering four different situations, including stick, rebound, spread, and splash. The imposed stretch spark ignition model (ISSIM) based on an Eulerian approach is used to simulate the spark ignition process. The flame kernel propagation is described using a flame surface density (FSD) function. After determining the radius and FSD of the initial flame kernel, the subsequent flame propagation process is modeled using the extended coherent flamelet model (ECFM), based on the resolution of a transport equation for the FSD. Further details about the model and the CFD code, and validation of the model in a CFD simulation of methanol fueled DISI engine can be found in Ref. [3].

Results

The experiment is conducted on a modified six-cylinder Scania D13 heavy-duty engine, with only one cylinder fired and the rest in motored run. In consideration of the high knock resistance of methanol, a high geometry compression ratio of 17.3 is adopted to improve the fuel efficiency. The piston geometry at top dead center (TDC) can be seen in Fig. 1a. An XPI common rail injector is mounted in the center of the cylinder, which can provide the injection pressure up to 2200 bar and at most triple injections in one cycle. In order to compensate for the small lower heating value (LHV) of methanol, ten nozzle holes are drilled in the injector to provide an umbrella-shaped fuel sprays with an included angle of 148°, cf. Fig. 1a for half of the spray-included angle. The cylinder head is modified to install an off-center spark plug. The distance from the spark plug to the cylinder axis (also the injector axis) is 37mm along X-axis. The relative location of spark plug and injected spray can be seen in Fig. 1. In the experiment, Infinium R655 lubricity additive was blended with methanol at a ratio of 4 mg to 20 L to protect the fueling equipment.



(b) locations of spark plug and injector (b) locations of spark plug and injector

Figure 1
Piston geometry, locations of spark plug, injector, and three characteristic cross-section slices.

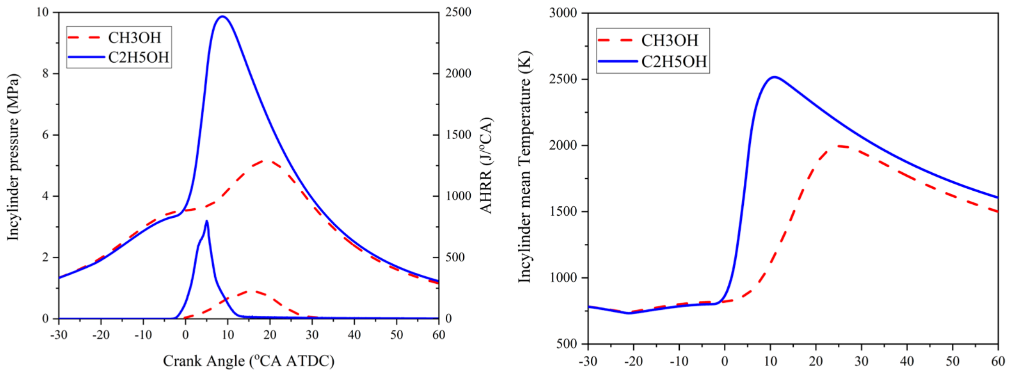


Figure 2
Comparison of in-cylinder pressure and in-cylinder mean temperature of methanol- and ethanol-fueled DISI engine.

Comparison of methanol- and ethanol-fueled DISI engine

First, the combustion process of the Scania D13 engine operation with two different alcohol fuels, methanol and ethanol, in DISI mode is carried out. The engine geometry, injector and all operation conditions are set the same for the two fuels. Detailed description of the operating conditions can be found in Ref. [3]. It is clear that, although the spark timing (2 CA before TDC) is the same, the flame propagation is significantly faster and the combustion duration is shorter in ethanol engine than in methanol engine, Fig. 2.

NAME	CH3OH	C2H5OH
LHV (MJ/kg)	19.93	26.7
IMEP (bar)	7.393	9.571
Efficiency (%)	44.862	43.343
MPRR (bar)	1.516	13.468
CO (g/kWh)	0.282	0.492
NO_x (g/kWh)	3.126	34.205
UHC (g/kWh)	7.679	0.029

Table 1
Performance of methanol- and ethanol-fueled DISI engine. The start of injection is at 33 CAD before TDC; the injection pressure is 200 MPa.

With the same amount of fuel injected, due to the high low heating value of ethanol than methanol, the in-cylinder temperature and peak pressure, as well as peak heat release rate are significantly higher in ethanol engines, see Fig.2. As seen in Table 1, the IMEP of the ethanol engine is higher, the combustion is more complete resulting in a lower UHC emission, but much higher NO_x emission in the ethanol engine. The engine efficiency in the ethanol engine is slightly lower than that in the methanol engine, due to the higher heat loss in the ethanol engine.

Effects of injection pressure, umbrella angle, and SOI on ethanol-fueled DISI engine

It is expected that one can use a lower injection pressure in DISI engines than in diesel engines. Table 2 shows the CFD predicted engine performance data for ethanol-fueled DISI engine. In the simulation the start of injection is kept at 33 CAD before TDC and the spark-timing is 2 CAD before TDC. It can be found that the value of IMEP and engine thermal efficiency is not sensitive to the injection pressure. Except at 120 MPa pressure, the maximum pressure rise rate (MPRR) increases with injection pressure, Table 2. The UHC emissions decrease with injection pressure. The CO emission has a non-monotonic variation with injection pressure, with higher CO emission at intermediate injection pressure. The NO_x emission is not sensitive to the injection pressure, although it has a general trend of increasing with injection pressure. CFD data suggests that, with increasing pressure (and thus shorter injection duration to maintain the same amount of fuel injected), the mixing of the fuel and air is faster, giving rise to better combustion efficiency and lower UHC emissions. The emission of CO is mainly from the fuel-lean mixtures, which less sensitive to the injection pressure.

CFD simulations of ethanol-fueled DISI engines are carried out with different umbrella angle and start-of-injection (SOI). Table 3 shows the performance data of the engine. It is seen that CO/UHC/NO_x emissions are very sensitive to the umbrella angle, with the 120° U-angle injector having much higher CO emissions, along with lower NO_x emissions and higher UHC emissions. This is due to the poorer mixing in the 120° U-angle case than in the larger U-angle (148°) case. The effect of umbrella angle on engine efficiency and IMEP is less significant, and the trend is not monotonic, depending on the SOI. At earlier injection (SOI earlier than 35 CAD before TDC) the low umbrella angle injector gives rise to high IMEP and engine efficiency than those with the higher umbrella angle injector. The results would certainly be different if the piston geometry is different. It is expected that optimization of the engine performance should be done by considering simultaneous multiple variables, e.g., piston geometry, injector umbrella angle, SOI, injection pressure, etc.

Table 2
Performance of ethanol-fueled DISI engine at different injection pressure. The start of injection is at 33 CAD before TDC.

Inj_P MPa	CO	NO_x g/kWh	UHC	MPRR Bar/CA	Efficiency %	IMEP bar
80	0.384	31.245	1.148	8.902	43.432	9.591
100	2.111	28.206	1.665	10.077	43.064	9.509
120	0.975	36.091	0.023	13.797	43.565	9.62
150	1.812	31.065	0.272	11.500	43.135	9.525
180	1.419	33.218	0.103	13.381	43.466	9.598
200	0.492	34.205	0.029	13.468	43.343	9.571

Table 3
Performance of ethanol-fueled DISI engine at different umbrella angle (U-angle of 120° and 148°) and SOI. The injection pressure is 200 MPa.

SOI CAD	CO		NO_x g/kWh		UHC		Efficiency %		IMEP bar	
-20	7.3	*0.03*	21.3	39	16.1	8.8	43.6	44.5	9.6	9.8
-25	7.8	*0.03*	22.6	39.4	17.1	8.9	40.9	44.1	9	9.7
-30	7.02	*0.028*	20.5	37.2	15.5	8.4	45.2	46.7	10	10.3
-35	6.87	*0.029*	20.05	39.3	15.2	8.7	46.2	45.3	10.2	10
-40	6.58	*0.034*	19.22	44.3	14.5	10	48.2	39.2	10.7	8.7
U-angle	120°	148°	120°	148°	120°	148°	120°	148°	120°	148°

Conclusions

CFD simulation of methanol- and ethanol-fueled DISI engines are simulated. The engine is based on the Scania D13 geometry. Several observations are made:

- With the same engine geometry, injector and operating condition, and the same mass of injected fuel, the engine thermal efficiency is rather similar, although the in-cylinder pressure, in-cylinder mean temperature, and NO_x emissions are much higher in the ethanol engine. Due to the high LHV of ethanol the IMEP is higher, and combustion efficiency is also higher.
- The injection pressure has rather low impact pm the engine efficiency, IMEP, and CO emissions of ethanol-fuel engines. The combustion efficiency increases and UHC emissions decrease with injection pressure, while NO_x emissions increase slightly with injection pressure.
- The effect of injector umbrella angle has a significant effect on CO, UHC and NO_x emissions. For Scania D13 piston geometry, a lower umbrella angle (120°) gives higher CO and UHC emissions but lower NO_x emissions than the higher umbrella angle injector (148°).

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Tryckt av Media-Tryck, Lund 2021 Svanenmärkt trycksak, 3041 0903

LUND UNIVERSITY

Box 117
SE-221 00 Lund

Tel 046-222 00 00
www.lunduniversity.lu.se