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Nyckelord: 5-7 st Metanol, fossilfria transporter, effektiva motorer, PPC, rena motorer, elektrobränsle	

Förord

Detta projekt har huvudsakligen finansierats av Energimyndigheten med stöd från AB Volvo, Volvo PV, Scania CV, Wärtsilä AB och Stena Rederi AB. Arbetet har bedrivits vid Lunds Tekniska Högskola av doktoranderna Sam Shamun, Alexios Matamis, Mateusz Pucilowski och Erik Svensson med handledning av Martin Tunér, Xue-Song Bai, Mattias Richter och inledningsvis även av Bengt Johansson.

Referenspersoner har varit Per Stålhammar (Scania), Håkan Persson (Volvo PV), Mats Nilsson (Stena), Jari Hyvönen (Wärtsilä) och Ingemar Magnusson (AB Volvo).

Innehållsförteckning/Contents

Sammanfattning

MOT-2030 projektet har framgångsrikt skapat omfattande ny kunskap om metanol som motorbränsle genom motorexperiment, optikstudier och numeriska studier. Projektet har karakteriserat metanol-PPC förbränning, förklarat emissionsbildningsprocesser och generat nya metoder och modeller som kan användas vid fortsatt forskning och utveckling av högeffektiva och ultrarena motorer. Metanol producerar inte sot vid förbränning och med PPC-förbränning i labmiljö kan övriga reglerade emissioner hållas under EURO VI utan efterbehandling i enskilda stationära driftpunkter. De extremt låga NOx emissionerna för PPC är till skillnad från dieselmotorer frikopplade från en ökad bränsleförbrukning. Kommande hårdare RDE emissionslagstiftning, kan dock innebära att även PPC kräver avgasefterbehandling.

Projektet visar att avancerade partiellt förblandade motorkoncept (PPC) ger de högsta publicerade indikerade verkningsgraderna (53%) av olika typer av metanolmotorer, vilket överstiger även de som nås med dieselmotorer. Metanol är således ett mycket effektivt motorbränsle. Well-To-Wheel analyser visar att metanol generellt har mycket låg energianvändning bland olika förnybara drivmedel och ger reduktioner av koldioxid-utsläpp på mer än 95% jämfört med fossila drivmedel. Livscykelanalyser indikerar att metanolfordon kan ha lägre klimatpåverkan än elfordon på fossilfri el pga batteriproduktionens negativa inverkan.

Metanol-PPC förväntas fungera väl i hybrida fordonsapplikationer för ökad verkningsgrad och temporär körning i noll-emissionszoner. MOT-2030 projektet har också bekräftat andra studier genom att köra en SAAB 9-5, 1000 mil på metanol-, etanol- och bensinblandningar utan problem. Även PPC, med en och samma motor, har visats kunna drivas med bensin, E85, etanol och metanol. Detta förenklar en introduktion till år 2030 eftersom bensin och E85 redan finns på marknaden och att metanol gradvis kan introduceras i takt med att produktionen ökar. Bio-metanol är kostnadseffektivt, enligt Ingvar Landälvs f3-studie från 2017, och kan produceras för ca 10-50% högre pris än oskattad bensin på energibasis. Förnybar metanol kan komplettera existerande biodrivmedel samt förnybar elektricitet från andra källor. Den svenska produktionspotentialen om 40-60 TWh räcker väl till det uppskattade behovet om ca 20 TWh.

Dagens transporter drivs till övervägande del av fossila drivmedel som påverkar klimatet negativt och genererar hälsostörande avgaser. Att ersätta de fossila drivmedlen är en enorm utmaning och kräver alternativ som kan produceras i tillräcklig omfattning men också till rimliga kostnader. För att illustrera utmaningen visar bl a prognosen från EIA, 2017 att världens transporter år 2040, enbart förväntas få 3% av sin energi via elektricitet. Det kommer krävas storskaliga förnybara drivmedel parallellt.

Metanol är en av världens vanligaste råvaror och har fått förnyat intresse som bränsle då den kan tillverkas med låg klimatpåverkan, kostnadseffektivt, i mycket stor skala från ett flertal källor som skogsråvara, avfall, biogas eller som elektrobränsle i samproduktion med förnybar el. Mycket lite metanolmotorforskning har genomförts sedan 80-talet, så målet för projektet har varit att skapa kunskap om hur nya motorkoncept kan användas med metanol för att uppnå miljömässigt och ekonomiskt hållbara transporter som kan implementeras till år 2030.

Summary

The MOT-2030 project has successfully created extensive new knowledge on methanol as an engine fuel through engine experiments, optics diagnostics and numerical studies. The project has characterized methanol-PPC combustion, explained emission formation processes and generated new methods and models that can be used for continued research and development of highly efficient and ultra clean engines. Methanol does not produce soot during combustion, and with PPC combustion in laboratory studies, other regulated emissions can be kept below EURO VI without emissions aftertreatment in some steady-state operating points. The extremely low NOx emissions for PPC are, unlike for diesel engines, disconnected from increased fuel consumption. Future stricter emission regulations might still mean that also PPC would need emissions after treatment.

The project shows that advanced partially premixed engine concepts (PPC) provide the highest published efficiencies for any type of methanol engines ever. 53% gross indicated efficiency has been noted and exceeds that achieved with diesel engines. Methanol is thus an efficient engine fuel. A Well-To-Wheel analysis shows that methanol has very low energy consumption among all renewable fuels and can reduce carbon dioxide emissions by more than 95% compared to fossil fuels. Life cycle analysis indicates that methanol vehicles may have a lower climate impact than electric vehicles on fossil-free electricity due to the negative impact from battery production.

Methanol-PPC will likely work well in hybrid vehicle applications, for further increased efficiency, and to enable driving in zero-emission zones. The MOT-2030 project has also confirmed older studies by running a SAAB 9-5, 10 000 km on methanol, ethanol and gasoline blends without any problems. Also, PPC has been shown to operate effectively on gasoline, E85, ethanol, and methanol with the same engine. This simplifies an introduction by the year 2030 since gasoline and E85 are already on the market and methanol can be gradually introduced, as production increases. Bio-methanol is cost effective, according to Ingvar Landälv’s f3 study from 2017, and can be produced at 10-50% higher price than untaxed gasoline on energy basis. Renewable methanol can complement the existing bio-fuels and renewable electricity that are produced from other feedstocks. The production potential in Sweden is 40-60 TWh and meet the estimated needs of about 20 TWh.

Transportation is largely driven by fossil fuels that lead to exhaust gases that adversely affect health and climate. Replacing the fossil fuels is an enormous challenge and requires alternatives that can be produced to a sufficient extent but also at reasonable costs. To illustrate the challenge, for example, the EIA 2017 forecast shows that world transport in 2040 is expected to only get 3% of its energy through electrification. There is a great need for more renewable fuels in parallel.

Methanol is one of the largest commodities in the world and has gained a renewed interest as a fuel since it can be produced with low climate impact, cost-effectively, on a large scale from a variety of sources such as forest residue, waste, biogas or as an electrofuel in co-production with renewable electricity. Little methanol engine research has been carried out since the 80's, so the goal of the MOT-2030 project has been to provide knowledge about how new engine concepts can be used with methanol to achieve environmentally and economically sustainable transport that can be implemented by 2030.

Introduction and Background

Environmental challenges with transportation

Both Swedish and global transportation is dominantly driven by fossil fuels, such as gasoline and diesel fuel, that lead to exhaust gases that adversely affect health and climate (Energimyndigheten, 2017). The Swedish government has therefore targeted that domestic transportation shall be fossil fuel independent by 2030 (Regeringen, 2012). Considering that climate effects have a global impact, not only Swedish but also international measures are needed and also under implementation.

Replacing the fossil fuels is an enormous challenge and requires alternatives that can be produced to a sufficient extent but also at reasonable costs. Electric drive and electric roads is part of the solution, but to illustrate the challenge, forecasts shows that world transport in 2040 is expected to only get around 3% of its energy from electrification (EIA 2017). There is a great need for sustainable fuels in parallel.

Methanol

A well-to-wheel to study from (Volvo, 2007) showed that methanol, and the methanol-linked gaseous fuel, dimethyl-ether (DME), are the biofuels that provide the combined highest system efficiency, lowest climate impact, most effective land use and the lowest cost. This study was one of the inspirations for the MOT-2030 project. DME, which works as a diesel fuel, has been carefully and successfully investigated recently (Tuner, 2016), but has not reached any wider market penetration, partly since DME is a pressurized gaseous fuel that requires major rebuilds of the infrastructure. Methanol, on the other hand, has received much less research as an engine fuel the last decades.

Methanol is a liquid with the chemical composition CH_3OH (Methanol Institute, 2017). With around 70 million tons produced annually, methanol is one of the largest commodities in the world and is used as a base chemical for several applications. There is vast experience in handling and distribution of methanol. Current production is mainly of fossil origin through gasification of natural gas, or, as in China, from coal. Methanol can be produced sustainably in large quantities from forest residue, waste, straw residue, black liquor or as a so called electro-fuel through electrolysis and metanisation from excess electricity, water and carbon. The carbon source can be captured CO_2, or biomass. The conversion efficiency from biomass to methanol can be very high (above 70%, Bogild-Hansen, 2015) and is typically reported to be higher than for other biofuels (Tunå, 2013). Considering that Sweden, like several other countries in the northern hemisphere, have large assets of forest residues but also large amounts of black liquor (Landalv, 2017), methanol can complement renewable fuels and renewable electricity from other feedstocks such as ethanol from grains and beets, HVO from tallow and cooking oil, bio-diesel from rape-seed and electricity from wind, water and sun. The similarity between methanol, ethanol and gasoline from a combustion perspective (Tuner, 2016) and its large scale availability (currently of fossil origin) may simplify introduction and distribution.

Methanol has significant advantages over fossil diesel or gasoline, not only because of its reduced CO_2 and particulate matter emissions during combustion, but also with significantly reduced long-term environmental effects in emissions and spillages (De Serves et al, 2007). Methanol is not limited as a fuel for combustion engine vehicles. On-going research is working on methanol driven fuel cell vehicles that would simplify on-board storage, fuel handling and distribution compared to hydrogen, that is the more common fuel for fuel cells (Landalv, 2017).

Methanol engines

Methanol has been used since the early 1900s for high power engine applications like fighter aero planes, racing cars, speedway motorcycles and more recently drag racing. The none-sooting, low heat radiating, and with water easily extinguished flame made methanol considered a safer fuel than gasoline in motorsports.

During the oil crisis in the 1970s, methanol was identified as the strongest candidate for replacing gasoline and diesel fuel, and fleet studies were performed in Sweden, as well as in Europe and the USA, during the 1970s to 1990s (Brinkman et al, 1990; STU, 1987, Richards, 1990). The largest fleet study took place in California with more than 15 000 cars sold to the public without restrictions. 10 automotive manufacturers, including Volvo, Mercedes and Toyota, that sold the cars that in the program ran more than 300 million km (Ward et al., 1996). The fleet studies showed that:

- Methanol is an excellent Otto engine fuel with up to 15% higher efficiency than on gasoline operation.
- That methanol work well as a drop-in in gasoline, M15.
- M85 flex-fuel vehicles can operate with either M85 (85% methanol and 15% gasoline) or neat gasoline seamlessly.

- The use of methanol in diesel engines requires either (5-10%) ignition improvers, glow plug assistance, use of ignition systems as in Otto engines or an ignition fuel in the form of a pilot diesel injection.
- Methanol significantly reduces NOx and soot emissions in both Otto and diesel engines, but hydrocarbon and formaldehyde emissions can be problematic at cold starts.
- Experience was built for efficient distribution, manufacturing and material compatibility.

One of the main outcomes of the methanol fleet studies is the M85 technology that was later used for the more than 50 million E85 (ethanol) vehicles that have been sold since.

With falling oil prices from the early 1980s, interest in methanol as a vehicle fuel for energy security reasons largely disappeared. Only in recent years has interest in methanol reappeared, due to low world market prices combined with increased environmental requirements, especially for maritime transportation.

Methanol's low emissions characteristics provides an opportunity to meet more stringent emission regulations in SECA areas (shipping) without the need to resort to expensive emissions aftertreatment devices such as scrubbers or catalysts. The renewed interest resulted, not only in new research programs in parallel with MOT-2030, such as Spireth, Green-pilot, Summeth and Lean-Ships (Marine Methanol, 2017), but also the conversion of Stena Germanica's four main Wärtsilä engines for methanol operation and the production of seven ships with methanol engines from MAN (Haraldson, 2015; MAN, 2016).

Road vehicles driven on methanol are used in China, but still little elsewhere (Chen et al., 2014).

Partially Premixed Combustion (PPC)

PPC is a relatively new concept, researched in Lund, that enables the use of high octane fuels in "diesel" like engines. PPC has been successfully proven to work in lab environment for both passenger cars and truck engines (Manente, 2010). Furthermore, PPC has demonstrated significantly higher efficiencies (about 12% lower fuel consumption) and significantly reduced emissions while operating on gasoline or ethanol than the best conventional passenger car and truck engines (Shen, 2013 and Tuner, 2013). The experience gained, so far, with Ethanol-PPC indicates that PPC can operate on methanol, enabling the most effective and clean engine/fuel combination for sustainable transportation.

Goals

The overall goal of the project is to demonstrate a fossil free engine system for land and sea transportation that is both environmentally and economically sustainable and has a higher well-to-wheel efficiency than any other alternative. The system should be implementable by year 2030.

The system is based on a new type of engine with *partially premixed combustion* (PPC) that realize the use of neat methanol in cars, trucks and ships with significantly reduced emissions and fuel consumption. The research area is thus to understand PPC engine function, efficiency and emissions on methanol / raw methanol.

The project addresses the two major social challenges safe, clean and efficient energy as well as smart, green and integrated transports defined for the research program's activities. The project aims at building excellent skills and create a research environment for methanol with participants from several disciplines at Lund University. The project also aims to strengthen the excellence at Lund University in combustion engines, and especially on PPC engines. In concrete terms, the research project is intended to lead to:

- Research on a sustainable engine/fuel system that is attractive for exporting Swedish vehicle manufacturers.
- 4 licentiate examinations (4 doctoral degrees if funding can be arranged for remainder of time).
- 12 peer reviewed scientific publications
- 6 invited presentations at conferences
- 1 patent application
- A base for new businesses and jobs in the sustainable economy
- Established research group within the Methanol-PPC transport system.
- Continued interdisciplinary research and research schools in the field

The project intends to answer the following questions:

- What is the well-to-wheel efficiency of the system with regard to energy utilization and emissions?
- How does methanol and crude methanol work in PPC combustion with respect to fuel distribution, heat transfer and ignition?
- Is it possible to control / optimize these processes with choice of spray angles and / or combustion chamber shape?
- Can methanol's and especially high methanol's high vaporization heat be used for reduced compression work ("isothermal" compression)?
- Can the greater surface sensitivity of methanol be used with a glow plug? If so, how is combustion with one?
- How high can the engine efficiency be with methanol. We have received 57% indicated efficiency with gasoline. Can we reach 59-60% with "isothermal" compression?
- How much and why does the efficiency differ between light and heavy geometry?
- Which load areas can you drive methanol with and without glow plugs?
- What are the challenges of adjusting methanol-PPC to different engine sizes?
- How much UHC, NOx and CO do you get? We assume that methanol does not form any soot or hence PM.

Funding and project duration

The project has a total budget of 16.4 mSEK and has been funded to 90 % by the Swedish Energy Agency and to the remaining 10% by in-kind contributions from Volvo Cars, Scania CV, AB Volvo, Stena Rederi och Wärtsilä AB. The project started in October 2014 and ended in December 2017.

Implementation

The project has been conducted in cooperation between the division of combustion engines, division of fluid mechanics and the department of combustion physics, all at Lund University. Most of the equipment has been provided by the *Competence Center Combustion Processes* (KCFP) and *Centre for Combustion Science and Technology* (CeCOST). The academic research was divided into four work packages, spanning experimental and theoretical research, while the industrial sponsors from Volvo Cars, Scania CV, AB Volvo, Wärtsilä and Stena have contributed with engine parts, models, in-house tests and experience, and not least reference persons. The project has actively worked for external cooperation and also to spread the results. The project homepage can be found here: http://www.lth.se/mot2030/

MOT-2030 Structure and participants				
	WP1	WP2	WP3	WP4
	Engine Experiments	Optical Diagnostics	Advanced Modeling	System Analysis
Group	Division of Combustion Engines	Department of Combustion Physics	Division of Fluid Mechanics	Division of Combustion Engines
Supervisor	Martin Tunér Bengt Johansson (2015)	Mattias Richter	Xue-Song Bai	Martin Tunér
PhD student	Sam Shamun	Alexios Matamis	Mateusz Pucilowski	Erik Svensson
Other participants	Öivind Andersson Per Tunestål Sebastian Verhelst Marcus Lundgren Sara Lönn Gustav Kristersson Changle Li Can Hasimuglu Sakarya Univ. Ahmet Murcak Sakarya Univ.	Marcus Aldén Zhenkan Wang	Mehdi Jangi Siyuan Hu Cheng Gong	Per Tunestål Sebastian Verhelst
Reference persons	Håkan Persson, Volvo Cars			
	Per Stålhammar, Scania CV			
	Ingemar Magnusson, AB Volvo			
	Mats Nilsson, Stena Rederi AB			
	Jari Hyvönen, Wärtsilä Sweden AB Toni Stojcevski, Wärtsilä Sweden AB			

Working group meetings

MOT-2030 had two working group meetings annually, where new results and plans have been presented and debated. On several occasions were the meetings held at locations of interest for the participants, for instance on-board Stena Germanica to study the implementation of the methanol engines and fueling system and at Perstorp AB to see the production of bio-diesel which depend on methanol.

Cooperations

The strong collaborations with KCFP, CeCOST and industry members was already mentioned, but the project has had valuable collaborations with many other organizations and persons. Below follows a list exemplifying some of them.

Istituto Motori, Italy
Carlo Beatrice, Gabriele Di Blasio, Giacomo Belgiorno
Sam Shamun spend four months at IM in Italy, performing research on a Light-Duty engine fueled with alcohol/diesel blends, exchanging knowledge on research methods. Giacomo Belgiorno spent a similar amount of time in Lund working on PPC light-duty.

Aerosol Technology, Lund University
Joakim Pagels and Ville Malmborg with colleagues

- Detailed measurements of particulates and net working with international groups.

The research efforts together with the Aerosol team has now turned into a long term collaboration in several projects where we together can quantify, characterize and explain important features of engine emissions.

LTU, Luleå Technical University
Rikard Gebart with colleagues

- Methanol know-how and delivery of crude methanol
- Common study with driving a SAAB 9-5, 10 000 km on M56 methanol fuel. No problems where encountered while driving or found when dismantling the engine after the study.

F3, Swedish Knowledge Centre for Renewable Transportation Fuels
Maria Grahn and colleagues
– Discussions on well-to-tank data for different fuels.

Summeth project
The methanol engine research infrastructure and know-how at KCFP and MOT-2030 made Lund's participation in the Summeth project possible.

- HD-DISI methanol engine results were delivered to MOT-2030 for WTW and LCA studies.
- Methanol-PPC results were delivered to Summeth.

Green-Pilot project
Thomas Stenhede and Patrik Molander

- Exchange of know-how
- Lund lent out technical equipment

VTT Technical Research Center of Finland
Rasmus Pettinen spend one week in Lund to learn more about Lund experimental methods and methanol engine research.

Spreading of Results

The project has actively worked to spread results by several activities in parallel.

- Arranged an international methanol workshop to find and share the global knowledge front on methanol and methanol engines as a starting point for the project. The workshop created valuable networking among the around 140 participants.
- Presented results at scientific conferences in Japan, USA, Italy, China and Sweden.
- Produced 16 peer-reviewed scientific publications so far with at least 8 more being prepared.
- Given more than 10 invited lectures to support local Swedish activities and to share information internationally, for instance (Almedalen 2016, Skara, Region Skåne, Making Marine Applications Greener 2015 (Sweden), Methanol Engine Advancement for Sustainable Transport Symposium 2016 (Iceland), Biosystems Engineering 2017 (Estonia). The lecture in Iceland can be viewed here: https://www.youtube.com/watch?list=PLxP_yyrUFwxwVJnvfM6ywBV_w30ry2JkP&time_continue=31&v=ld6DefdfYVo

- More than 10 public lectures at libraries in Skåne or during visits to our lab.
- More than 10 popular science and debate articles in newspapers, Linked-In and other media
- 3 radio interviews
- A final project seminar is under planning for autumn 2018.

Selected Results

WP1 Engine Experiments

Sam Shamun

Introduction

This is a summary of the experimental work that has been conducted, on a metal engine running on methanol, at Lund University. Engine studies is a good way of providing information regarding real time engine performance and emissions measurements as well providing data to engine modelers for model tuning and calibration.

While operating on a high octane fuel, such as methanol, in a compression ignition (IC) engine, ignition delay can be increased to achieve a separation between fuel injection and start of combustion. This improves fuel and air mixing to partially premixed conditions that reduces the risk of soot formation.

In contrast to the conventional diesel combustion (CDC), PPC combusts with higher flame speed, which can be tuned with the aid of, amongst other control parameters; intake temperature and exhaust gas recirculation. The tuning of speed and timing of the combustion increases engine efficiency while simultaneously reducing NO_X emissions.

Substantial amounts of EGR is also used to suppress NOx but may increase soot with certain fuels. The use of neat light alcohols, such as methanol and ethanol, the soot-NO_X trade-off can be reduced significantly. Light alcohols contains oxygen that reduces soot formation. In addition to the decreased emissions, methanol also cools down the combustion to an extent that the heat transfer from the flame to the cylinder walls and exhaust ports is reduced, further increasing efficiency and performance.

One drawback is that the PPC strategy is difficult to control at loads above 10 bar gross indicated mean effective pressure ($IMEP_G$), since the maximum pressure rise rate (PRR_{MAX}) can increases to too high values, which could end up destroying the engine. To overcome this obstacle, a double injection strategy can be utilized to have a larger fraction of diffusion combustion at higher loads, which is easier to control. The efficiency of the methanol engine is still higher than if diesel would be used, due to the cooling effect of methanol.

During the working period, three papers has been published, which of three are published in journals, and two more are submitted and are currently under review, also for journals.

Method

Engine Setup 1

One of the experimental engines is a six cylinder Scania D13, which has been converted to operate only on one cylinder. Specifications of the engine is given in Tab. 1 below. The test rig is displayed below in Fig. 1.

Table 1. Engine specifications for Scania D13 setup.

Displaced volume [cm^3]	2124
Stroke [mm]	**160**
Bore [mm]	**130**
Connecting rod length	**255**
Number of valves [-]	**4**
Swirl ratio [-]	**2.1**
Exhaust valve open [-]	**137° ATDC**
Inlet valve close [-]	-141° ATDC

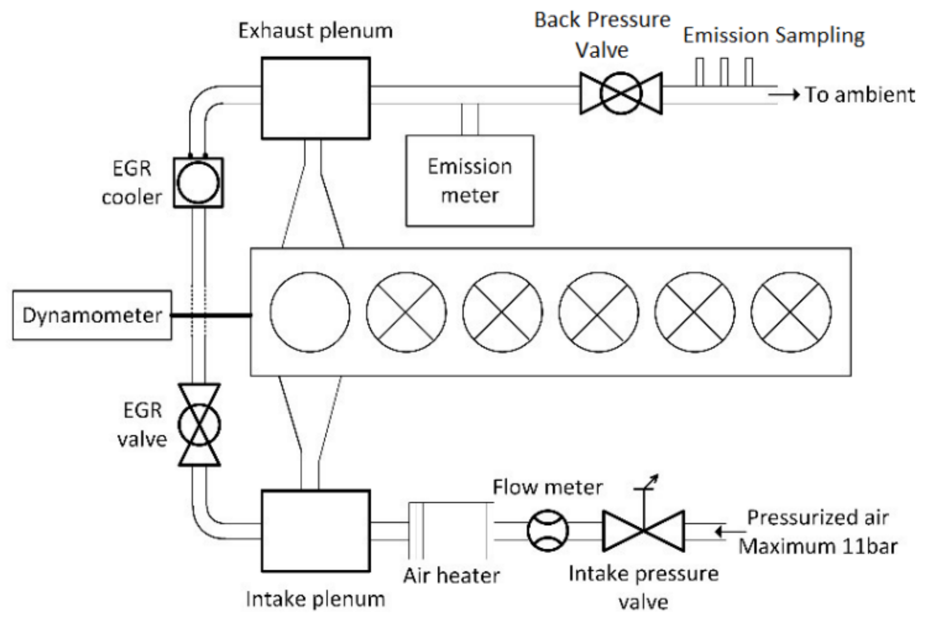


Figure 1. Schematic of the Scania D13 setup.

Since the exhaust flow from a single cylinder is not adequate to run a turbo charger, pressurized air was supplied from an external in house compressor. The O_2 concentration in the inlet was regulated by a back pressure throttle and a EGR throttle. A 7.5 kW air heater was located between the fresh air supply and the intake manifold. The three exhaust sampling probes for the exhaust gas analyzers were located after the back pressure valve with the proper distance between them to avoid measurement inaccuracy due to flow disturbances.

Engine Setup 2

The experimental engine used in this work is a single cylinder, EU5 standard, engine. The geometry is based on the Fiat/GM JTD 1.9 liter engine, however, with custom manufactured block and crank shaft. The cylinder head, originating from the stock engine, is modified to run only one cylinder. The engine specifications and the experimental setup schematic can be observed in Tab. 2 and Fig. 2 respectively.

Table 2. Engine specifications for FIAT/GM JTD setup.

Displaced volume [cm^3]	478
Stroke [mm]	**90.4**
Bore [mm]	**82**
Connecting rod length	**145**
Geometrical	**16.5:1**
Number of valves [-]	4

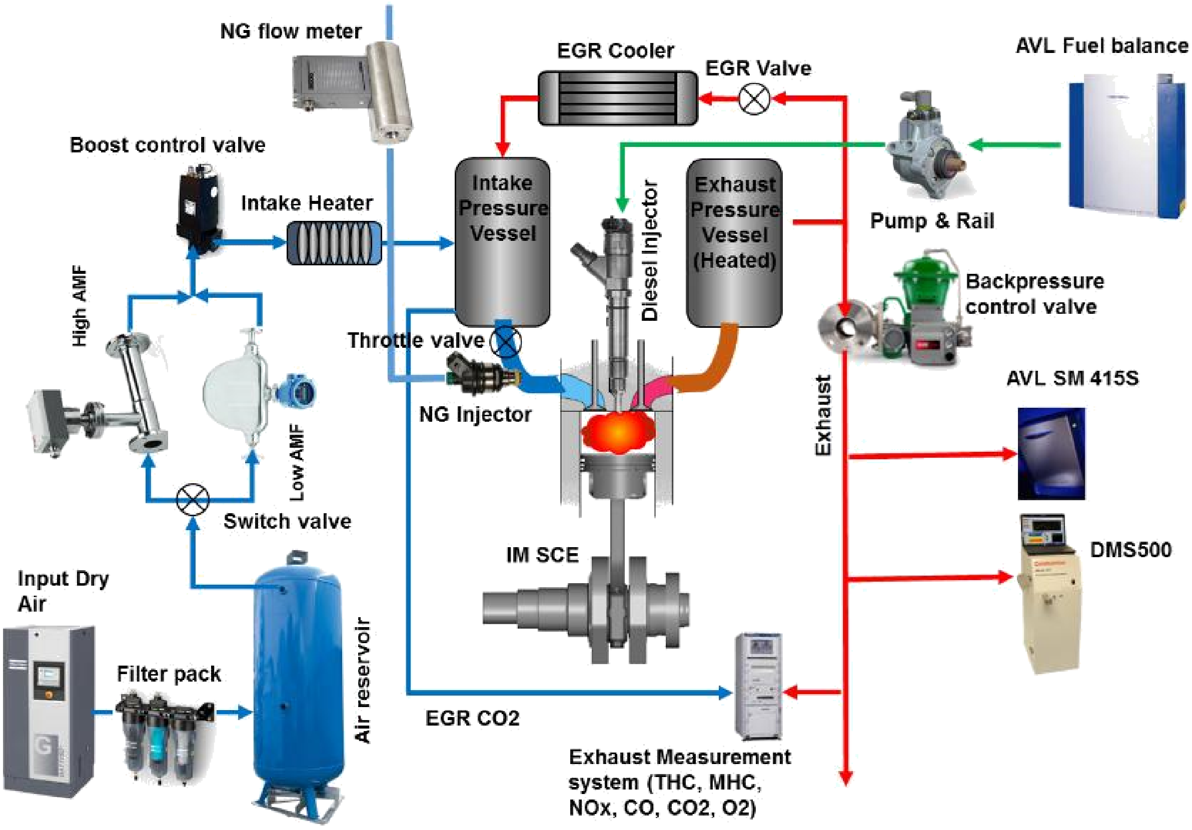


Figure 2. Schematic of the FIAT/GM JTD setup.

To allow full flexibility of the coolant, lubrication and fuel delivery controls, these are decoupled from the auxiliary system. An in-house compressor supplies the engine with air pressure, which was accurately controlled by a throttle. The exhaust back pressure and exhaust gas recycling (EGR) are both regulated using valves and the intake air is heated with a 1.5 kW heat element.

Emission measurement

In both engine setups total hydrocarbons (THC), CO, CO_2, NO_X, O_2 and soot both in terms soot mass concentration and particle size distribution. The gaseous emissions measurement devices used was flame ionization detector (FID), infrared detector, chemiluminescence detector (CLD), paramagnetic detector (PMD). The soot mass concentration was measured using an AVL micro soot measurement (MSS) and an AVL 415s smoke meter, which of both gives the soot in the unit mg/m^3. Particle size distributions were measured by a Cambustion DMS500.

Results

Efficiency

Efficiency has been measured both with methanol in form of a design of experiment (DOE) in the Scania D13 setup. In the other two studies, ethanol was blended in diesel-biodiesel-ethanol blends as well as diesel-gasoline-ethanol blends.

The highest gross indicated efficiency (GIE) for MeOH, in the Scania D13 setup, was measured to ~53 %. The combustion mode in this study was not entirely PPC, but had a slight diffusion tail as for CDC. The main contribution for this high efficiency was, except for the 27:1 compression ratio (r_c), reasoned to be the high level of EGR utilization. The high EGR level, not only reduces NO_X, but also cools down the combustion which results in a heat transfer decrease. Below, in Fig. 3, the effect of EGR on the part efficiencies can be observed.

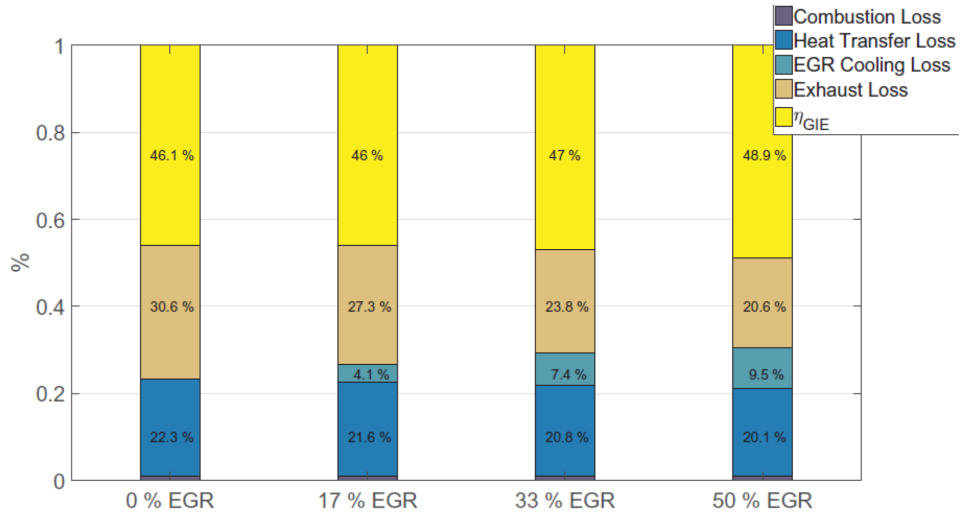


Figure 3. Exhaust enthalpy plotted against EGR.

As it can be seen, adding EGR, while increasing the EGR cooling losses, has a positive effect on overall efficiency. It should be noted, however, that the benefit of EGR on methanol GIE would not be possible without a very high compression ratio to keep the top dead center (TDC) temperature high enough to ignite the methanol charge. On the other hand, there is a trade-off, since a higher compression ratio not only puts heavy restrictions on the geometry of the combustion chamber, but also the freedom of choosing control variables. For example, if the EGR level is set at 50 % and λ=1.5, the load cannot be increased to high levels due to restrictions on the maximum pressure allowed in the cylinder, which is 220 bar.

The LD engine results suggested that blending ethanol with diesel, with the means of an emulsifier, such as biodiesel or gasoline, can increase the efficiency drastically in comparison with regular diesel. In Fig. 4 (a) and (b), seen below, the net indicated efficiency (NIE) can be seen as a function of operation point indicated as SPEEDxBMEP. In Fig. 4 (a) the blends consist of diesel-biodiesel-ethanol, in a ratios of 68:17:15 (DBE15) and 56:14:30 (DBE30) while in Fig. 4 (b), diesel-gasoline-ethanol blends in the same ratios as above can be seen (termed DGE15 and DGE30). These blends where tested at operation conditions close to the original engine map; all burning in CDC mode due to the utilization of a double injection. It is possible to see a notable increase in engine efficiency when increasing the ethanol content of the fuel.

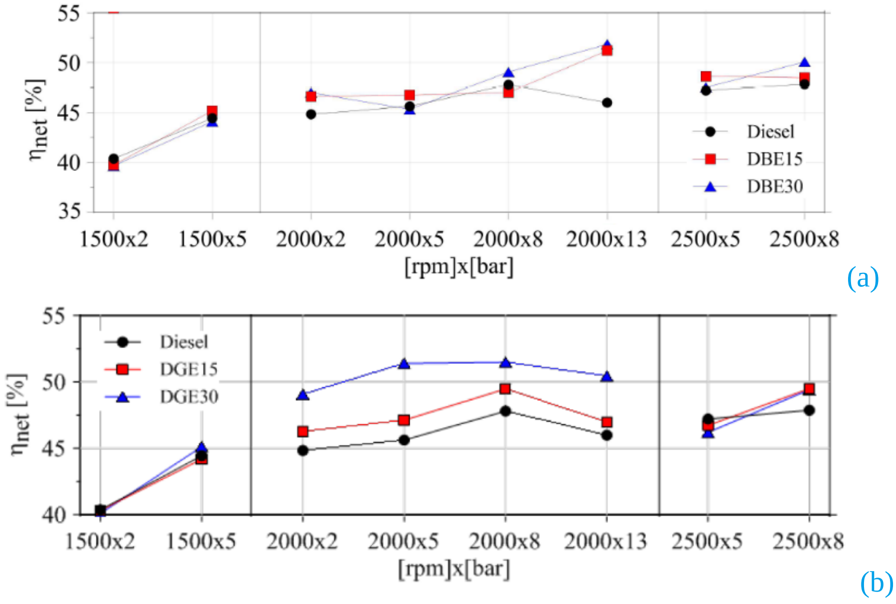


Figure 4. The NIE as a function of operation point in SPEEDxBMEP for (a) diesel-biodiesel-ethanol blends and (b) diesel-gasoline-ethanol blends.

In comparison with diesel, which did not achieve a NIE of higher than ~48 %, both the DBE and DGE fuels achieved approximately 52 % NIE, which is a quite high number for a light duty (LD) engine. As mentioned earlier, the combustion mode in the LD engine was always CDC, so the increase in NIE was mainly a contribution of the cooling effect of ethanol, and only partially due to premixedness.

Emissions

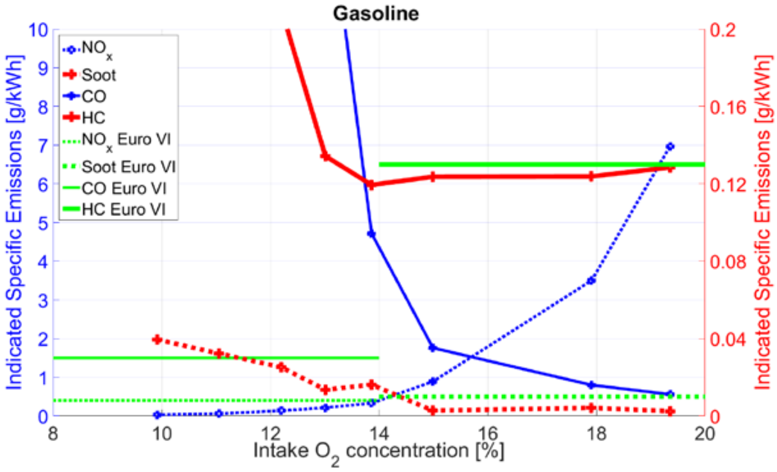
The emissions will be presented both in terms of gaseous and particulate matter (PM) emissions.

Gaseous emissions

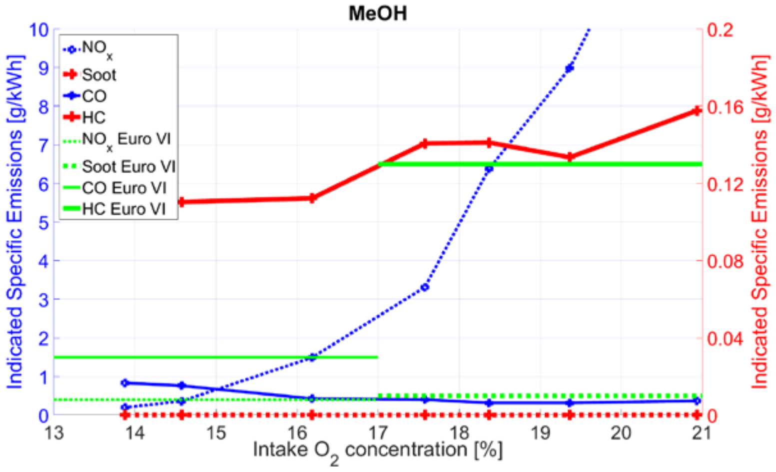
The gaseous emissions as well as the black carbon soot as measured from the AVL MSS for gasoline-PPC and MeOH-PPC are shown in Fig. 5 (a) and (b). In this subsection, only the gaseous emissions will be discussed.

NO_X emissions are reduced for a given intake oxygen concentration for methanol as compared with gasoline PPC. Since NO_X is highly temperature dependent, it can be concluded that the main reason for a lower NO_X emissions is the cooler combustion process, as a result from a high heat of vaporization as well as a low stoichiometric air to fuel ratio for methanol, which leads to a higher fuel amount being injected for a given load. The same principal applies to the NO_X reduction when DBE blends was used in the FIAT/GM LD engine, as observed in Fig. 6.

The THC emissions for methanol-PPC, in comparison to gasoline-PPC, is slightly higher in the Scania D13 engine. This can be explained by the longer ignition delay caused by the charge cooling of methanol. Since the combustion phasing (CA50) was set constant for both fuels at similar operation conditions, the start of injection (SOI) for methanol is set to a more advanced crank angle degree (CAD) in comparison to gasoline. This allows for a longer period of time for the fuel to end up in the crevice volumes of the combustion chamber. This effect can also be observed when running the LD engine on DBE blends; the higher ethanol concentration in the fuel, the higher THC emissions. At higher engine loads however, the difference in THC emissions for diesel and DBE fuels becomes insignificant due to the shortened ignition delay.



(a)



(b)

Figure 5. Gaseous emissions from the PPC combustion as a function of intake oxygen concentration for (a) 69 RON gasoline (b) methanol.

The CO emissions shows two different trends for the alcohols for the HD and LD engines; for the HD engine, alcohols emit a lower concentration of CO in comparison to gasoline and in the LD engine the CO concentration in the exhaust gas is higher. It can be observed in Fig. 5, that when reducing the intake oxygen concentration for gasoline and methanol, CO emission is increased. However, the CO emission for gasoline is increased drastically already at 15 % oxygen concentration, while CO for methanol does not increase above the EURO VI limit even when intake oxygen concentration is lower than 14 %. In this case, the combustion temperature is high enough to burn the methanol properly and oxidize CO into CO_2. This effect is also enhanced by the high oxygen content in the methanol molecule.

In the LD engine, addition of ethanol to diesel actually increases the CO emissions, as seen in Fig. 6, despite the higher oxygen content in the fuel. This can, however, be explained by the low load, being generally unstable in terms of combustion and excessive cooling. A rather cool combustion will emit a higher amount of CO, since this gas requires a certain temperature to be oxidized properly. At higher loads, the combustion temperature needed to oxidize CO to CO_2, is reached and as a result, CO emissions are reduced until no significant difference can be seen between diesel and the DBE fuels.

As for the case of the unregulated CO_2 emission, it come quite naturally that this emission is reduced with a higher concentration of either methanol or ethanol. This is because of the lower carbon content of these fuels in comparison to gasoline or diesel.

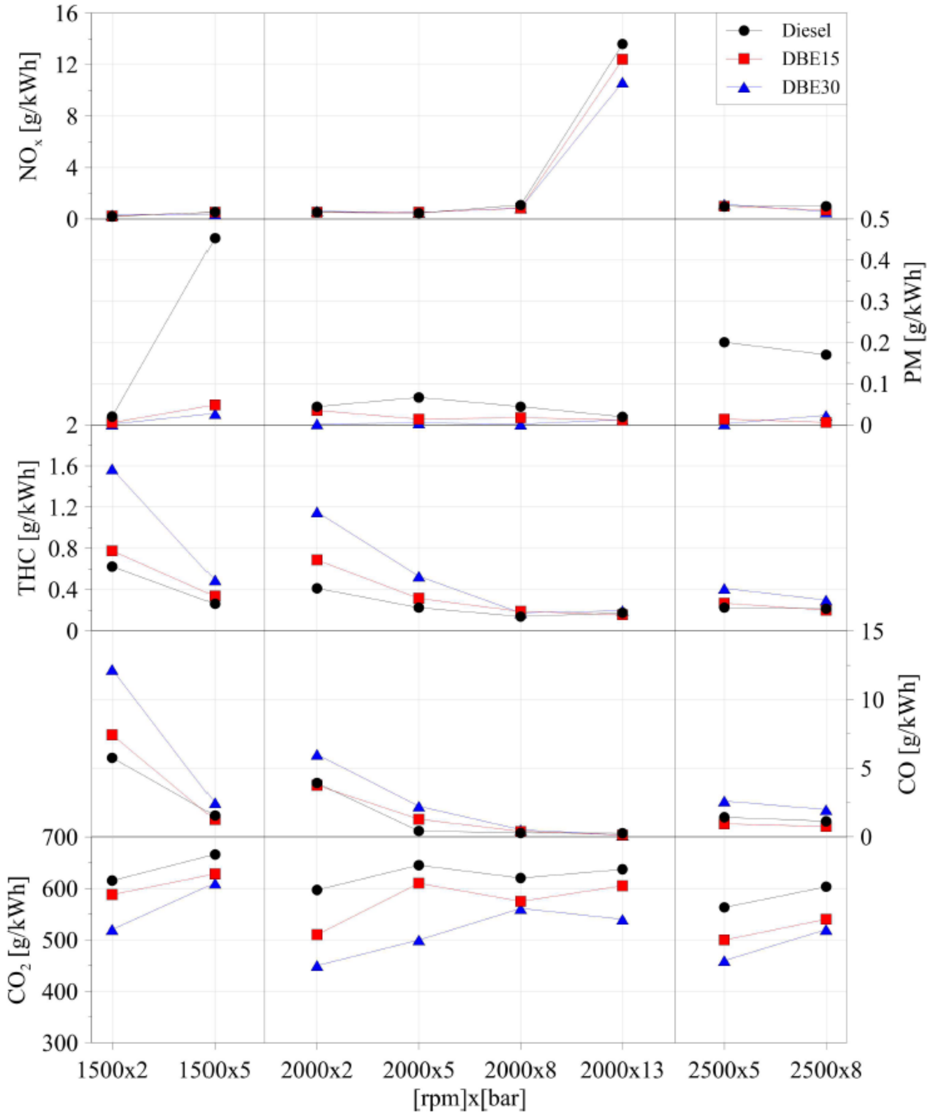
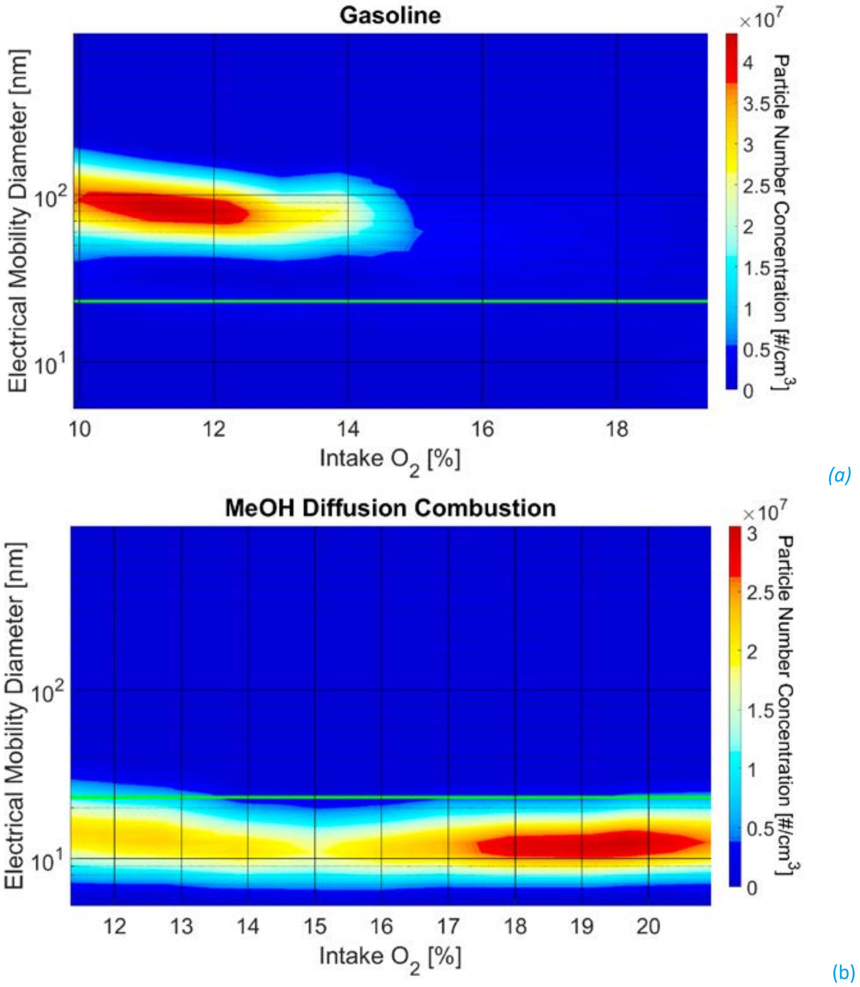


Figure 6. The emissions as a function of operation point in SPEEDxBMEP for (black) diesel (red) DBE15 and (blue) DBE30.

Particulate matter

Two publications were produced regarding the PM emissions from methanol and ethanol combustion in the PPC process as well as the CDC process. The general conclusion from these publications is that, close to neat, methanol and ethanol does not produce more than 0.01 g/kWh (EURO VI legislation) of black carbon soot, in any of the tested operation points. Both of the fuels, when utilized neat, in a CI engine, produce a high amount of particle number (PN). Looking at the particle size distribution of methanol and ethanol, it is possible to observe only a nucleation mode peak. Gasoline and diesel, however, when emitting soot, under the “right” circumstances, a clear accumulation mode peak is generally measured, and in some cases alongside a smaller nucleation mode peak. In Fig. 7, the particle size distribution of gasoline-PPC and methanol-CDC as a function of oxygen intake concentration can be observed. When intake oxygen concentration is decreased for gasoline, a clear increase can be seen in both size and particle count, which is a result of black carbon soot production. This, however, does not apply for methanol-CDC, despite the combustion strategy due to the methanol molecule consisting of only one carbon atom. A molecule consisting of a carbon chain of one, will have difficulties taking the chemical path to form soot, in which polycyclic aromatic hydrocarbons (PAH) is required. Moreover, PN is also regulated by EURO VI, however, the current legislation does not include particles with a diameter below 23 nm, represented by the green line in Fig. 7.



(a)

(b)

Figure 7. The particle size distribution as a function intake oxygen concentration for (a) Gasoline-PPC and (b) MeOH-CDC.

When observing the high amount of nucleation mode particles when running the engine on methanol and ethanol, it was decided that a more detailed analysis is required. In the Scania D13 engine, this time with a r_c=20:1, three fuels were tested: diesel fuel, methanol and ethanol, where the engine was running on PPC when utilizing the oxygenates. In addition to the measurements with the DMS500, particles were collected on transmission electron microscope (TEM) grids for analysis. In Fig. 8 below, the difference between diesel fuel and ethanol grids can be seen.

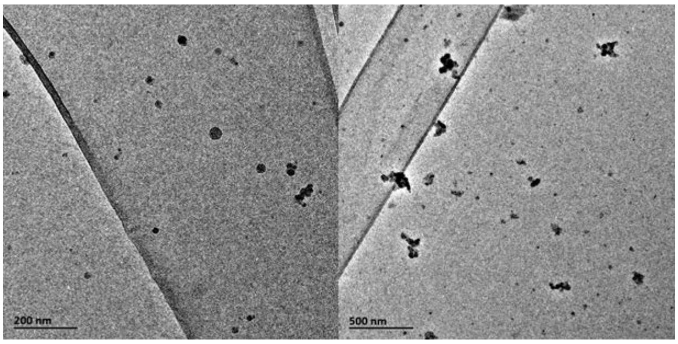


Figure 8. TEM images from (left) ethanol-PPC and (right) diesel fuel and similar operation conditions.

An important notation is that no visible difference could be seen between the methanol and ethanol TEM images, suggesting that the particle type emitted from combustion these fuels in a CI engine are very similar. Moreover, when analyzing the grids with an energy dispersive x-ray (EDX), the peaks showed the following atomic elements: Ca, Zn, S and P. The oil was then send for analysis, and the results showed a clear abundance of Ca, Zn, S and P. This suggests that the particles emitted from methanol and ethanol combustion did not originate from the fuel themselves, but from the combustion of lubrication oil inside the liner. Further research is required to determine if these particles can be avoided with other piston rings or reformulated lubricants.

Load range characteristics

Methanol-PPC is challenging at low loads and cold starting. Idling operation is possible by preheating the incoming air (around 130 °C with 20:1 compression ratio). Using a split injection strategy with a small first injection, the required inlet temperature can be reduced around 15 °C. Glow plugs is an option that will reduce the need of inlet air heating, but our glow plug studies are delayed until 2018. With higher compression ratio the inlet temperature can also be reduced, but our studies show that with 27:1 in compression ratio the maximum load of the engine is reduced due to increased peak cylinder pressure. With pure PPC, with a complete separation between the fuel injection event and the combustion, it is hard to limit the peak pressure rise rate at high load operation. Split injection and a delayed main injection leads to a higher fraction of diffusion combustion and reduced peak pressure rise rate without loss of efficiency or high soot levels thanks to the non-sooting characteristics of methanol.

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WP2 Optical Diagnostics

Alexios Matamis and Mattias Richter

During the 3 years of this project, methanol was studied optically inside a direct injected, heavy-duty engine. By using optical diagnostic techniques, further knowledge of its combustion and injection behavior has been gained. Research was focused mostly on Partially Premixed Combustion (PPC) of methanol and the tools employed were, high-speed video recordings to study the natural flame luminosity, fuel-tracer Laser Induced Fluorescence (LIF) for probing fuel distribution and finally, high-speed imaging of elastic light scattering in order to visualize the liquid part of the sprays during injection.

The optical work within the project was performed along with metal engine experiments and Computational Fluid Dynamic (CFD) simulations. The effects of injection timing and rail pressure on the combustion behavior were studied, as well as the transient behavior of the injection process.

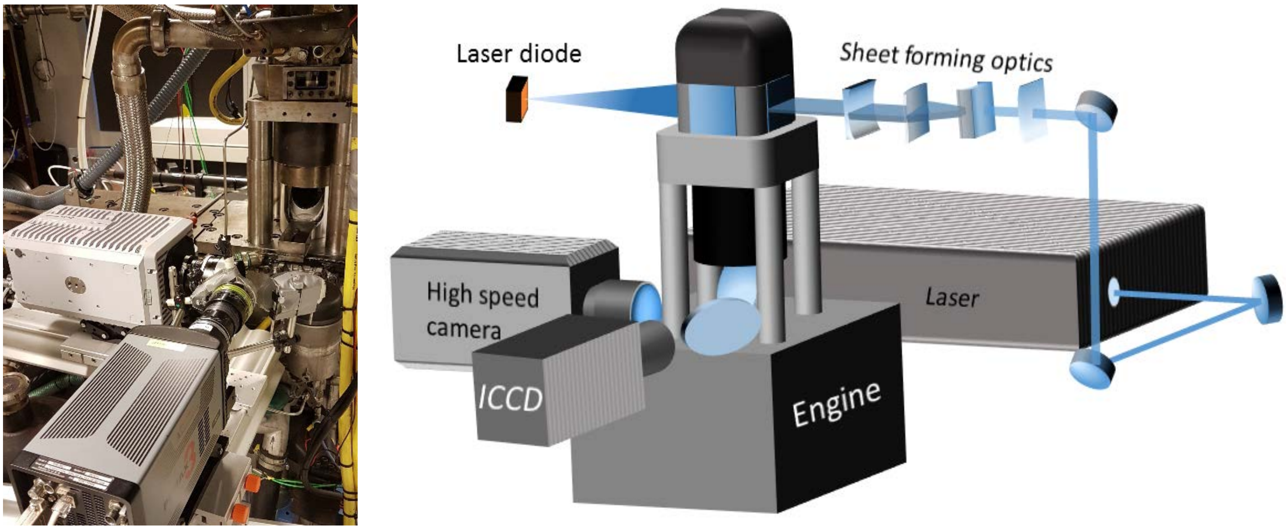

Figure 9: Illustration and actual picture of the optical engine and optical setup. The combustion chamber is lifted and the piston extension is hollow in order to obtain optical access via an angled mirror below. The circular laser beam passes through the sheet-forming optics and transformed into a vertical or horizontal sheet. Two different cameras were used, one high speed camera to capture the combustion and injection process, in addition to an ICCD camera used to capture the fluorescence signal. The laser diode on the other side of the engine is used for global illumination in order to observe the scattering properties of the liquid fuel droplets.

The optical engine in which the experiments took place was a single cylinder, direct injected, heavy-duty Scania D13 engine that was modified to obtain optical access according to the Bowditch design (Fig.9). Initially the engine used a transparent bowl piston with close to stock geometry and a relatively low compression ratio of ~13:1, partly due to increased crevice volumes in the optical engine. With this piston, LIF and MIE-scattering experiments were conducted in order to study the spray and its interaction with the geometry. These studies were conducted under non-reactive conditions since the exact same engine setup was necessary in order to compare the fuel properties of methanol against a previous study that was performed with PRF81 fuel, which is much more reactive. After this first set of experiments, a flat piston top was used. That allows for increased compression ratio and does not introduce optical distortions to the image, which is a common problem that has to be addressed with bowl piston shapes. Thereafter, various injection strategies were studied, including multiple injections and an investigation of combustion modes was conducted by sweeping the SOI timing. Additionally, distortion-free images were obtained allowing for a more accurate study of the injection process and a more precise look in the transient behavior of the sprays with methanol as a fuel.

The optical work performed in the project is at the stage of collecting the final data and soon thereafter, a number of papers, most likely 3-5 (including CFD papers), will be compiled that will thoroughly describe the findings that are briefly described below in this report.

Combustion characterization

By using a high-speed camera (Photron Fastcam SA-X2, 30000fps, corresponding to 4,17frames per CAD, resolution 640x640pixels), the combustion behavior can be investigated via the natural flame luminosity. The flame luminosity either originates from the process of chemiluminescence, where excited radicals emit radiation at certain wavelengths, or by black body radiation emitted by hot soot particles formed during combustion in fuel rich regions. Methanol's flame luminosity consists predominantly of chemiluminescence, apart from the cases where a large amount of fuel is concentrated and burns under very rich conditions, as is the case with injector dribble or wall wetting.

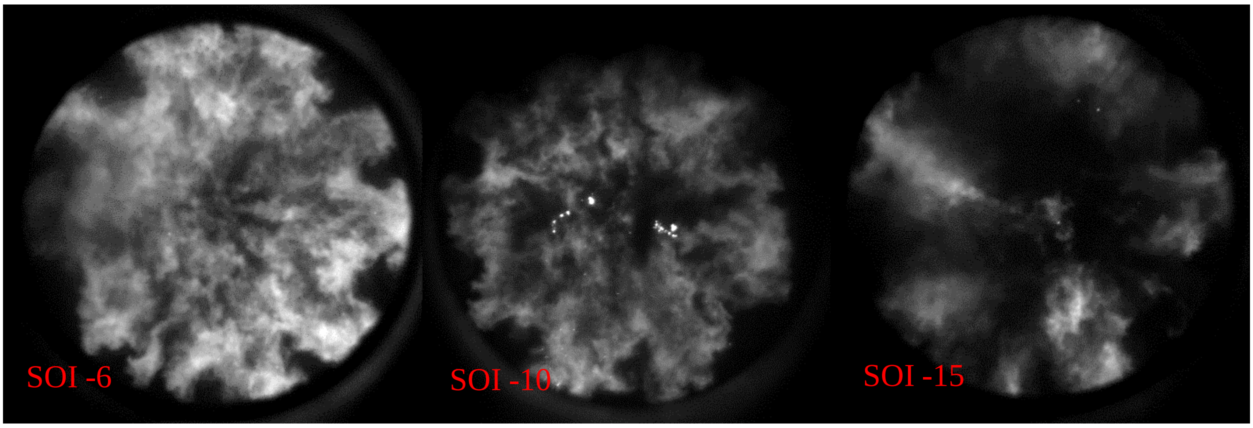

Figure 10: Combustion for different SOI's. As expected, earlier injection timings will have more mixing time and exhibit lower intensity when combusting.

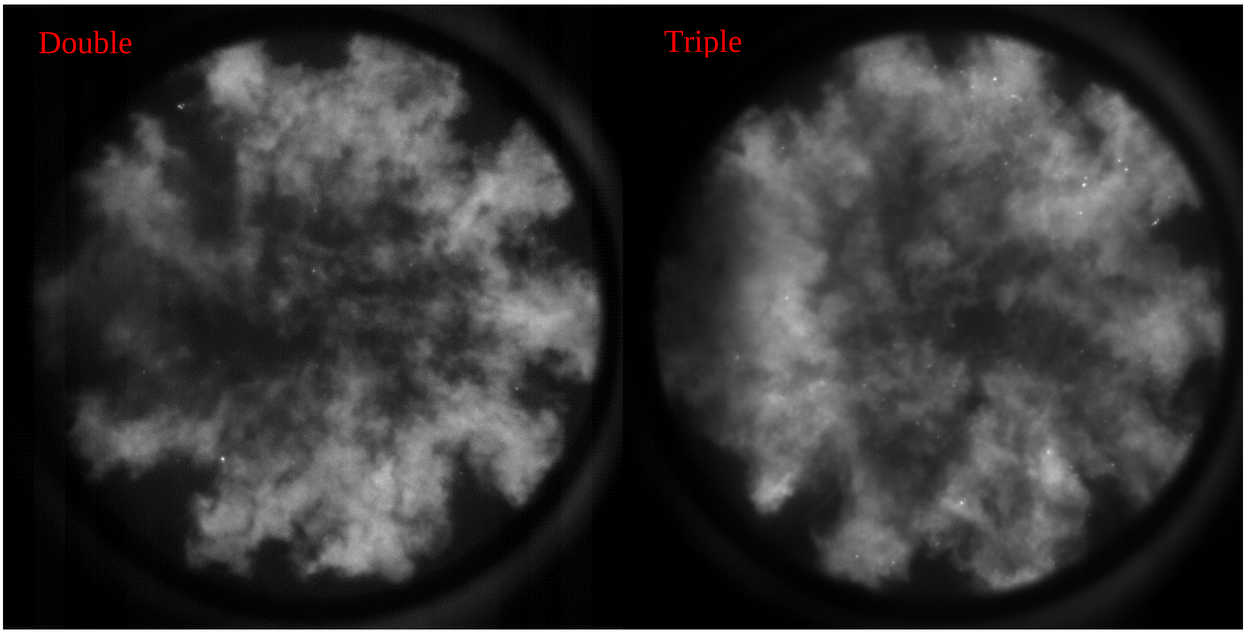

Figure 11: A double and a triple injection are shown above for illustrative purposes. The intensity is indicative of the fuel stratification and from the high-speed sequence, the combustion rate in different spatial locations can be studied. By varying the number of injections and the split of the fuel amount, different combustion properties are achieved and better control of the combustion is possible.

The combustion behavior of methanol was studied for various Start of Injection (SOI) timings measured in Crank Angle Degrees (CAD), ranging from -25CAD to -6CAD Before Top Dead Center (BTDC). Varying the SOI timing leads to significantly different fuel distribution inside the combustion chamber and hence different combustion modes can be observed (Fig.10). For the earlier injection timings, i.e. -25CAD, very homogenous and rapid combustion is observed for methanol, indicating chemically controlled combustion, similar to a combustion type known as Homogenous Charge Compression Ignition (HCCI). This is a result of methanol having low density which enables fast mixing and high evaporative cooling, which prolongs ignition delay, and therefore increases mixing time. As the SOI timing is delayed, methanol starts burning in a PPC type of combustion where individual combustion regions can be observed and the combustion luminosity varies locally. Delayed even further, the combustion will become mixing controlled but with a substantial ignition delay compared to other low-octane gasoline fuels. The latest SOI timing tested was -6CAD, where towards the end of the injection the sprays would drive the combustion. One of the most important results of this study is that all the different combustion types commonly used can be observed within an SOI variation of 20CAD. The same combustion sweep in the case of PRF81 fuel for example, would require more than 100CAD SOI variation to achieve a similar mode transition. In addition to the SOI sweep, multiple injection strategies were studied, where double and triple injections were employed and the fuel amount was varied between the first, second and third injections (Fig.11). The finding from this study was that multiple injections can substantially lower the required inlet temperature for maintaining a specific combustion phasing. The engine operating load and the CA50 index (crank angle at which 50% of the fuel energy has been released) were kept constant in this set of experiments and it was observed that adding extra injections could lower the required inlet temperature by 30°C in some cases (from 117 to 87°C). This can be attributed to the increased control of the charge stratification level and the mitigation of the high evaporative cooling due to the splitting of the fuel amount, which cannot be avoided in single injection strategies.

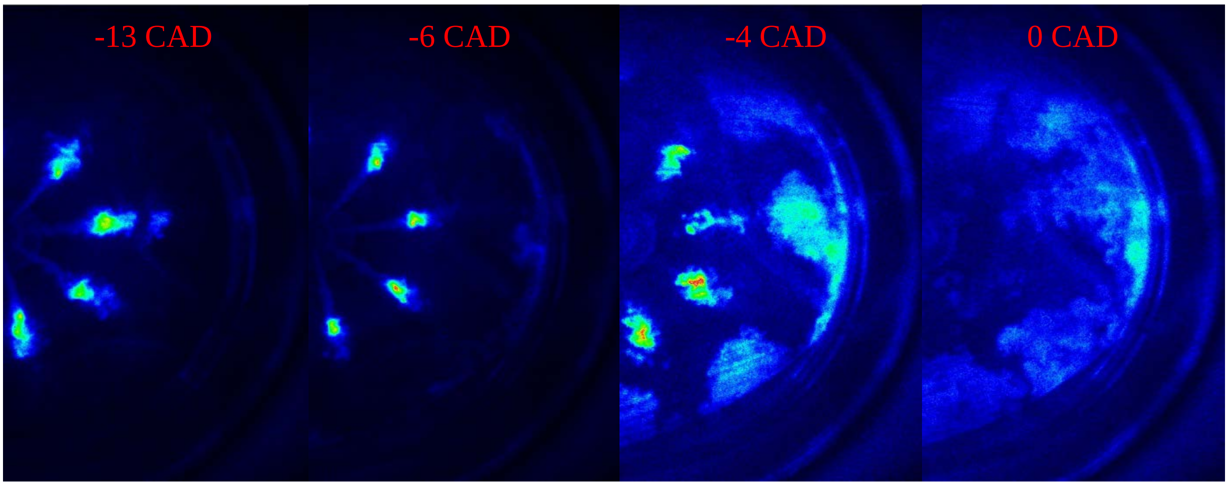

Figure 12: Horizontal plane-LIF for SOI -17CAD, at different timings throughout the cycle. Initially, the laser sheet is dissecting the spray plumes until -6 CAD. Later on, the fuel reaches the bowl wall and continues mixing, aided also by the swirling charge motion.

Fuel-tracer Laser Induced Fluorescence

In the fuel-tracer LIF process, a tracer substance is added to the fuel, that when excited with a certain wavelength will fluoresce in a certain manner. The tracer that was chosen was acetone that is readily available, has good fluorescence yield, it is not toxic or hazardous compared to other tracers commonly used and most importantly, the boiling point is closely matched to methanol. This is important since what is monitored is the tracer that is mixed in the fuel. Therefore, if the tracer evaporates differently it would provide inaccurate fuel distributions.

Initially, LIF images were taken with the bowl-piston at various SOI's, at different timings of the compression stroke and in both planes of the piston, vertical and horizontal. This provided information about where the fuel is delivered and how the stratification levels vary throughout the cycle (Fig.12). This data can also be compared with a previous study which was performed on the same engine with PRF81 as fuel. Fuel stratification plays a major role in PPC combustion and methanol mixes rapidly, therefore a good understanding of the fuel distribution is necessary. The camera used was a 10Hz, 16-bit, Princeton Instruments Pi-Max 3 Intensified camera (ICCD).

With the flat piston in place, experiments resumed with the purpose of probing the fuel distribution right before the onset of combustion. By having the high-speed camera recording the same field of view as the ICCD, the combustion location can be found and positioned on the fuel tracer image, which is recorded just before combustion begins. This way the fuel distribution (Fig.13) remains unaffected by the combustion, which would otherwise consume the tracer. In this case, it was not feasible to look at the vertical plane since the squish height is too small to obtain any useful information.

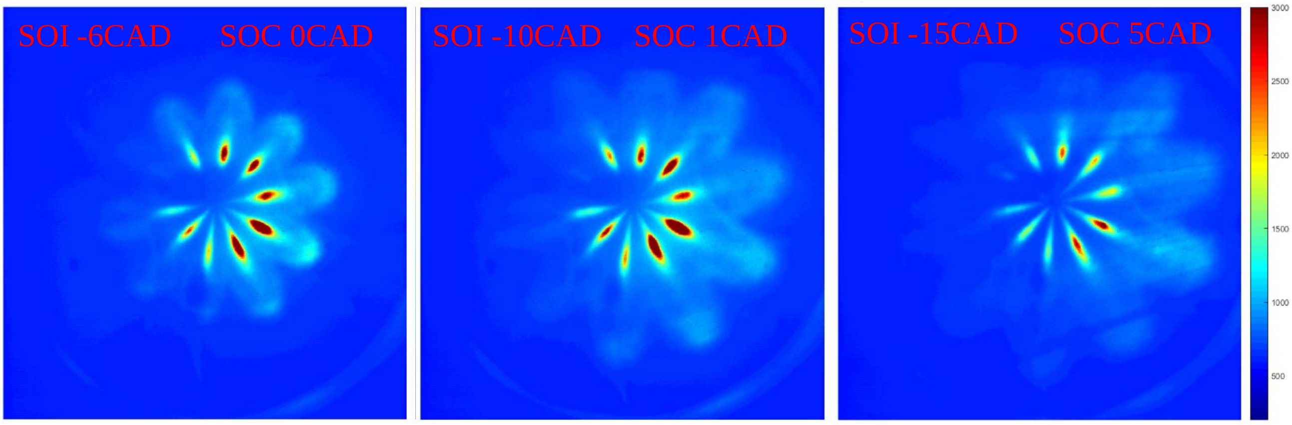

Figure 13: Fuel tracer LIF images with the pancake piston, right before the onset of combustion, for three different SOI's where CA50 was held constant at 7CAD ATDC, averaged over 50 cycles. The high intensity values are from the liquid part, which has not mixed fully due to the limited time before the start of combustion (SOC). Significant differences in fuel distribution can be observed for the three different timings, which can be explained by the difference in mixing time (6, 9 and 10CAD respectively)

Currently, more operating conditions are being investigated that allow for longer mixing time, like SOI -17, -25 and -35CAD. These earlier SOI timings aim to demonstrate if methanol preferably ignites in leaner regions, as is indicated in CFD simulations.

Elastic light scattering

Most particles scatter light in an elastic manner, where monochromatic light is only redirected to certain directions, based on the polarization and wavelength of the incident light and the size of the particles. The elastic scattering regime is composed of Rayleigh scattering and Mie scattering, with the distinction being the relation between particle size and incident light wavelength.

A single 2 Watt laser diode with a wavelength of 452nm was used as a light source in these experiments and provided enough monochromatic light to visualize the liquid part of the spray jets. Similar to the LIF experiments, geometric effects were studied in the bowl shaped piston by observing the liquid penetration length and thereafter the flat piston was used to capture the sprays and the combustion simultaneously.

An SOI sweep was performed in non-reacting conditions in the bowl shaped piston, only with the air density adjusted so that the air entrainment in the sprays would remain the same as in previously performed metal-engine experiments within the MOT-2030 project. Effects like wall wetting or charge motion due to geometric factors will be evaluated and compared with the PRF81 results. However, the bowl shaped piston introduces optical distortions and therefore, all images need to be corrected before measuring any properties. Moving on to the flat piston, another non-reacting SOI sweep was performed in order to provide evaluation data for CFD simulations. In order to calibrate the injection model used for the simulations, three SOI timings were used (-8,-25,-46CAD) and for one of them two inlet temperatures (70°C and 90°C) (Fig.15). Additionally, three different injection pressures were tested (800, 1200, 1600bar) at a constant inlet temperature of 70°C (Fig.6). The reacting SOI sweep was then performed with CA50 kept constant by adjusting the inlet temperature and ranged from -6 to -35CAD, as described in the LIF and combustion sections as well.

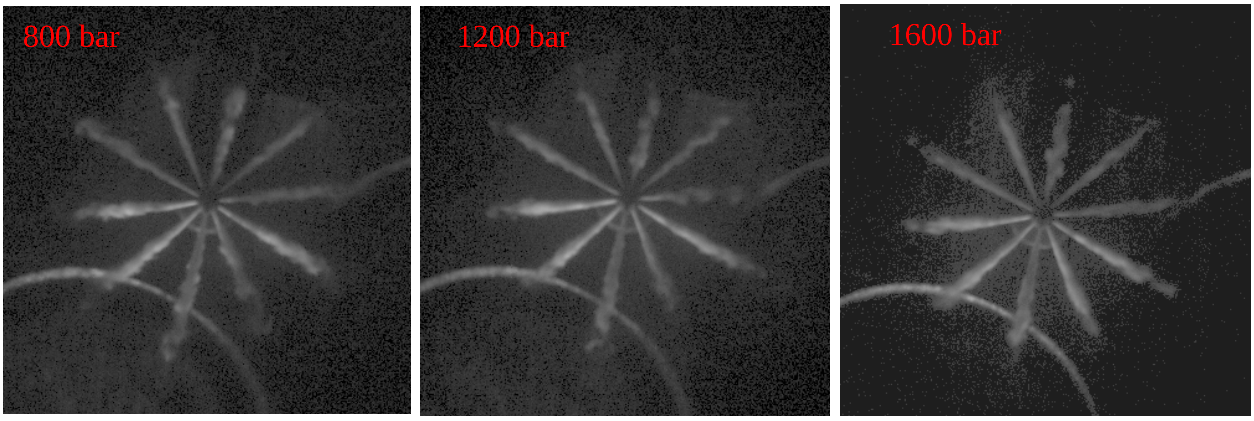

Figure 14: No great effect is observed in liquid length when the rail pressure is varied. Further analysis of this data will be conducted and the fuel distribution is going to be investigated in order to see if the fuel reaches further away due to higher momentum flux from the higher injection pressure.

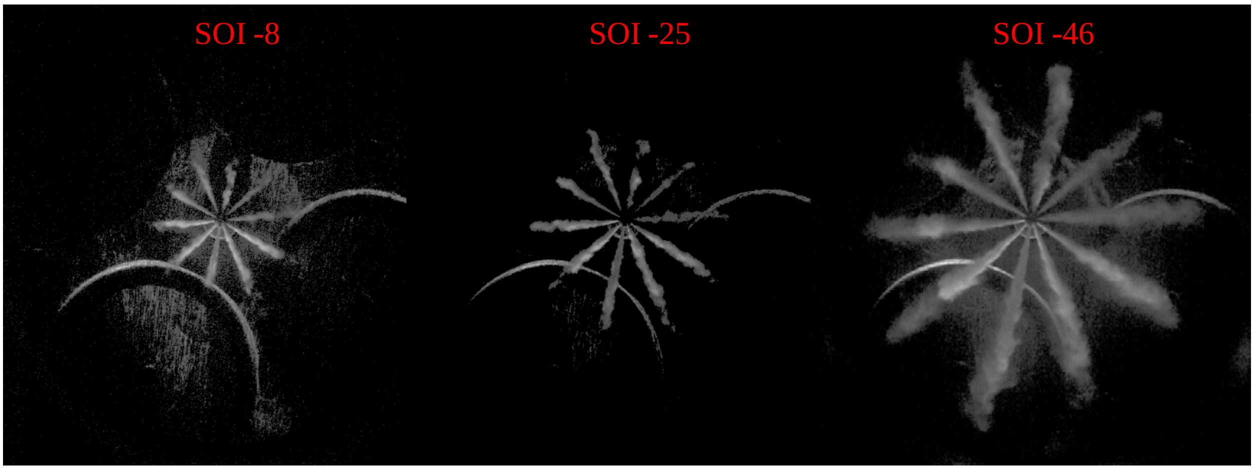

Figure 15: A great effect on ambient pressure and temperature on the liquid length can be observed.

WP3 Advanced Modeling

Mateusz Pucilowski

Introduction

CFD tools were employed to get deeper insight for the mixing and combustion process for Partially Premixed Combustion (PPC) of methanol in a heavy-duty engine. As PPC should include both lean and rich local conditions during the combustion process, fuel properties will determine SOI timings that are required to fulfill such conditions. The performed numerical simulations reveled more detailed information in terms of fuel distribution, homogeneity level and emissions trends to find appropriate range of SOIs suitable for methanol PPC.

CFD tools and development

The solver code used in calculations is based on openFoam technology, which is an open source CFD code. Based on its basic engine solver, additionally a chemistry speed-up algorithm CCM and combustion model WSR/ESF were implemented [1,2]. Furthermore, activities for generating grid and debugging: injector setup for Lagrangian Particle Tracking method (LPT), field mapping, initial conditions, decomposition strategy, post processing and simulation stability were carried on continuously.

Work load

During MOT2030, CFD work has produced two SAE papers, and one conference paper. Work progress has been also presented at two KCFP meetings and the MOT-2030 project meetings. Optical benchmarking and geometry studies are ongoing.

Research questions

CFD analysis were performed to answer following research questions.

1.How is methanol mixing process and ignition process depending on SOI? What is an optimal SOI range for PPC methanol combustion?

Fuel	Stoichiometry mass ratio (A/F)s	Heat of vaporization (kJ/kg)
Methanol	6.47	1103
Ethanol	9	840
Gasoline	14.6	350

Table 1 - Fuel properties

There are two important methanol properties that govern methanol/air mixing. First one is that, methanol as an alcohol, carries an oxygen atom so that stoichiometric fuel/air mass ratio is low compared to other common fuels, meaning that less oxygen is required to mix methanol for local lean conditions, Table 1. The second one is the high cooling effect during the injection phase, which depends on the high latent heat of vaporization. As a result, the ignition delay time is relatively longer than for conventional fuels such as diesel or gasoline, giving rise to additional time for fuel and air to mix.

Such properties are beneficial in terms of soot and NOx emissions, but it is critical to maintain in-cylinder temperature to reach the autoignition event. Additionally, methanol fuel is more prone to wall-wetting issues, especially when injected at early SOIs. Based on these factors, the challenge is to find an appropriate balance between positive and negative mixing effects by controlling the SOI.

Typical injection timings for PPC with PRF or gasoline fuels, are placed around middle range SOIs from -70 to -40 ATDC, so that the homogeneity level to achieve PPC is fulfilled. In the case of methanol this SOI range should be shifted towards TDC, meaning that for the same stratification level, between local lean and local rich zones, one should inject no earlier than around SOI -20 ATDC. In the other case, the methanol air mixture tends to easily become locally lean, resulting in a very rapid HCCI type of combustion, regardless of the stratification.

Methanol injections at SOIs closer to TDC i.e. SOI -20 ATDC, results in a stratification level increment going towards PPC conditions. At the same time, the local equivalence ratio increases, resulting in an increasingly richer partially premixed mixture. However, due to the methanol properties, it is difficult to achieve local rich conditions and for that SOIs must be set even closer to TDC.

Figure 16 shows the correlation between MPRR and SOI for single and double injections. While keeping CA50 constant, MPRR increases until SOIs are set very close to TDC. The break point in MPPR happens when diffusion mode is achieved. The MPRR trend would be more acceptable for engine performance using gasoline fuel, since gasoline would burn in diffusion mode at earlier SOIs. This difference makes methanol a unique fuel for PPC.

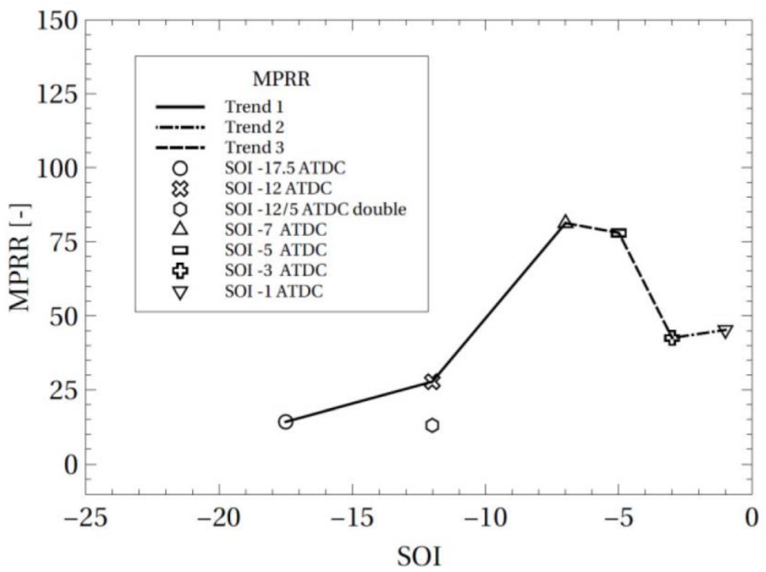

Figure 16 - MPPR as a function of SOI with single injection and double injection.

Single injection

Figure 17 shows the T-Phi distribution in a D13 engine piston bowl, which suggests that maximal local equivalence ratio at the onset of ignition is around 0.75, even at such late SOI as SOI -12 ATDC.

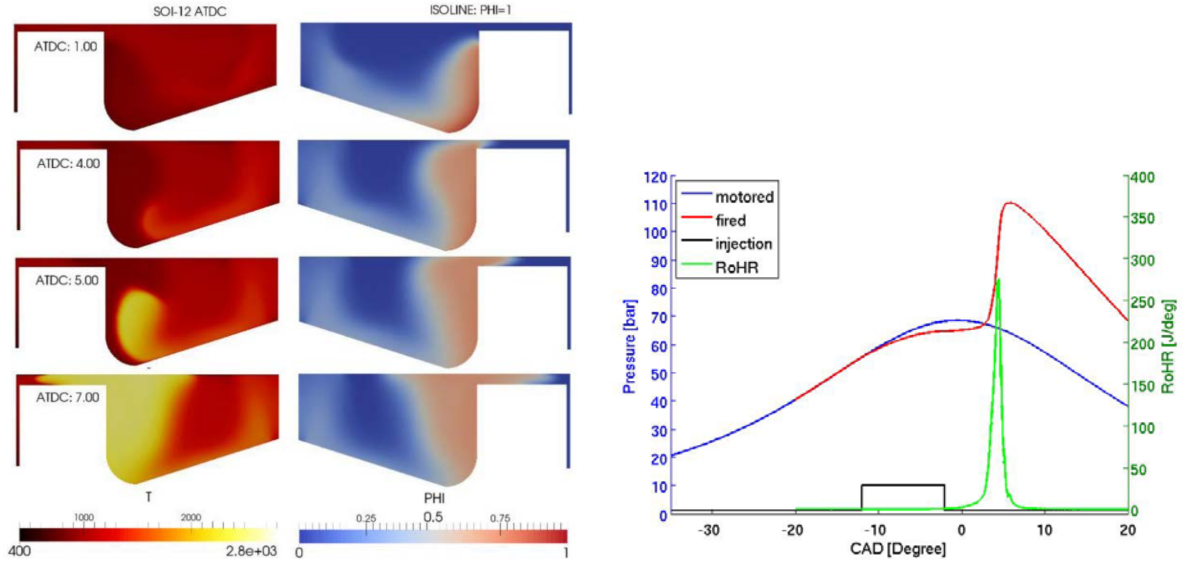

Figure 17 - T-Phi distribution for SOI-12 ATDC in a time sequence (left), pressure and RoHR trace (right).

Figure 18 shows the case of SOI -3 ATDC, where the ignition event starts to remind about that of conventional diesel combustion (CDC). However, due to the methanol properties, most of the injected fuel is auto-ignited at already premixed conditions, so that the duration of the diffusion flame is very short. The auto-ignition also takes place at conditions close to stoichiometry, leading to a high dp/dcad.

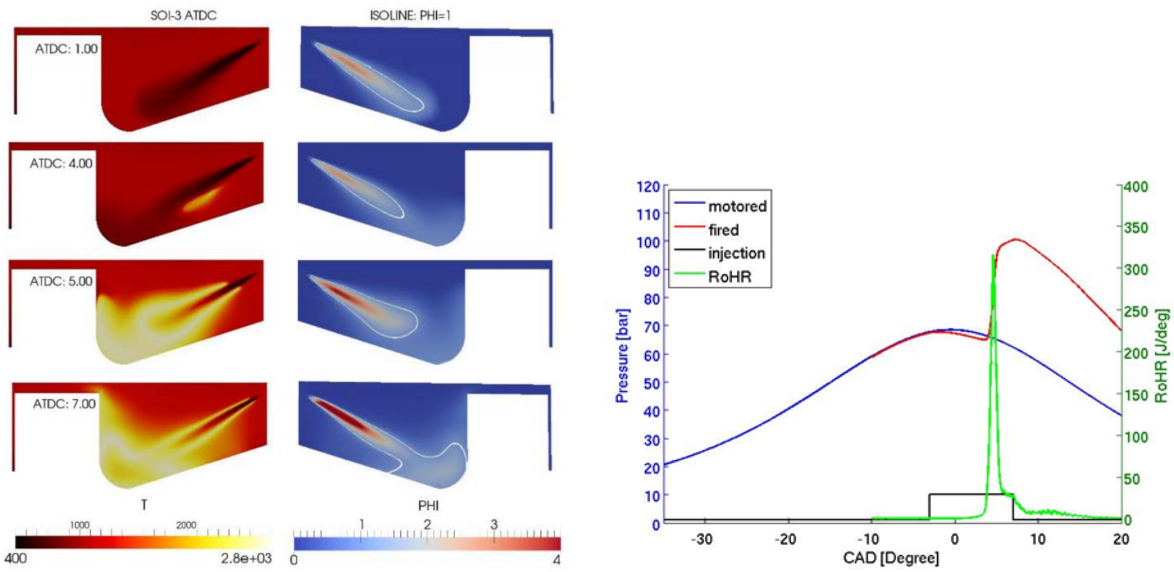

Figure 18 - T-Phi distribution for SOI-3 in a time sequence (left), pressure and RoHR trace (right) [3].

The most important finding is that methanol in a PPC engine is rather difficult to operate with a single injection. The auto-ignition of the partially premixed part of the charge is dominating and give rise to very aggressive combustion as the SOI is delayed. Additionally, the intake temperature must be sufficiently high to work against the cooling effect.

Double injection

Figure 19 shows an example of a double injection strategy at SOI -12 ATDC and SOI 5 ATDC with an equal fuel distribution. The fuel coming from the pilot injection is ignited as a premixed charge giving much smaller PRR compared to the single injection strategy. The first reason is that the local equivalence ratio is leaner, and the second reason is that only half of the fuel load is injected at once. The smaller pilot injection also reduces the cooling effect problem, giving more flexibility to intake temperature. The main injection is ignited as a typical CDC, with a small fraction of premixed charge and a longer duration of the diffusion combustion while injection is ongoing. With the presented double injection strategy one can lower MPRR and introduce typical CDC combustion mode. This is positive in terms of MPRR, cooling effect, and wall-wetting but negative in terms of NOx emissions. The ideal injection strategy would be to have only a short post injection diffusion flame and more premixed combustion with acceptable MPRR by splitting pilot injections.

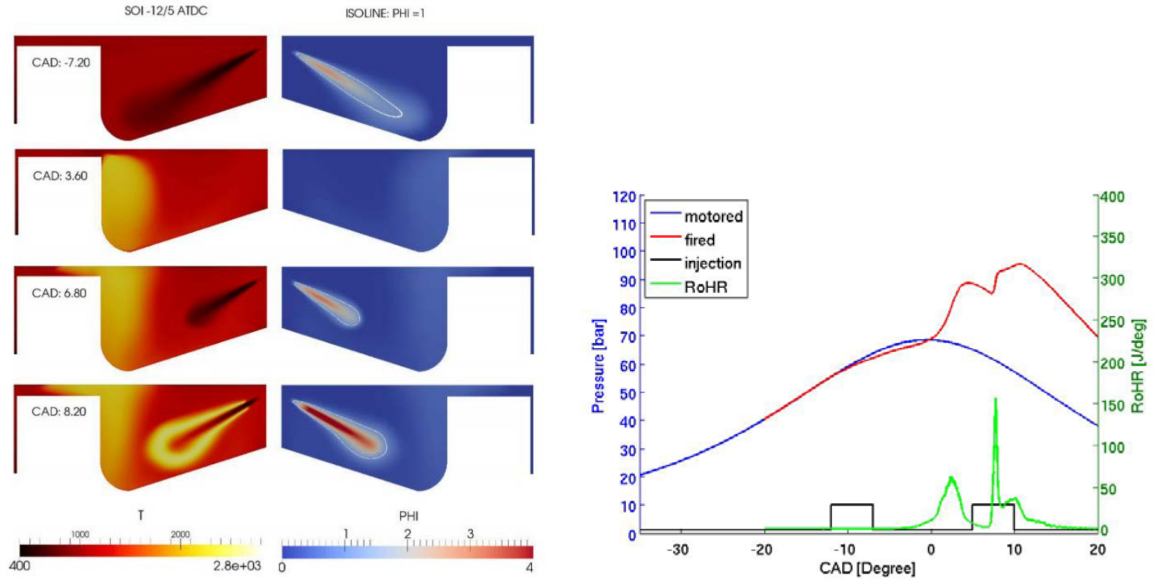

Figure 19 - T-Phi distribution of double injection strategy SOI-12 ATDC and SOI5 ATDC with duration 540um and 540um respectively and equal fuel split.

Triple injection

By applying a triple injection strategy, as in Figure 20, one should be able to significantly reduce the duration of diffusion combustion during the main injection, and at the same time reduce the amount of premixed fuel combustion close to stoichiometry. The triple injection case showed that the fuel from the first and second pilot injection burns at very low local equivalence ratios, around 0.2, resulting in a small heat release that pre-heats the charge and has an impact on the ignition delay of the main injection. The main injection, as the overlap of EOI and SOC is minimal, results only in a post injection diffusion combustion. Such strategy seems to fulfill PPC conditions of local lean and local rich conditions giving acceptable MPRR and reducing drawbacks of CDC.

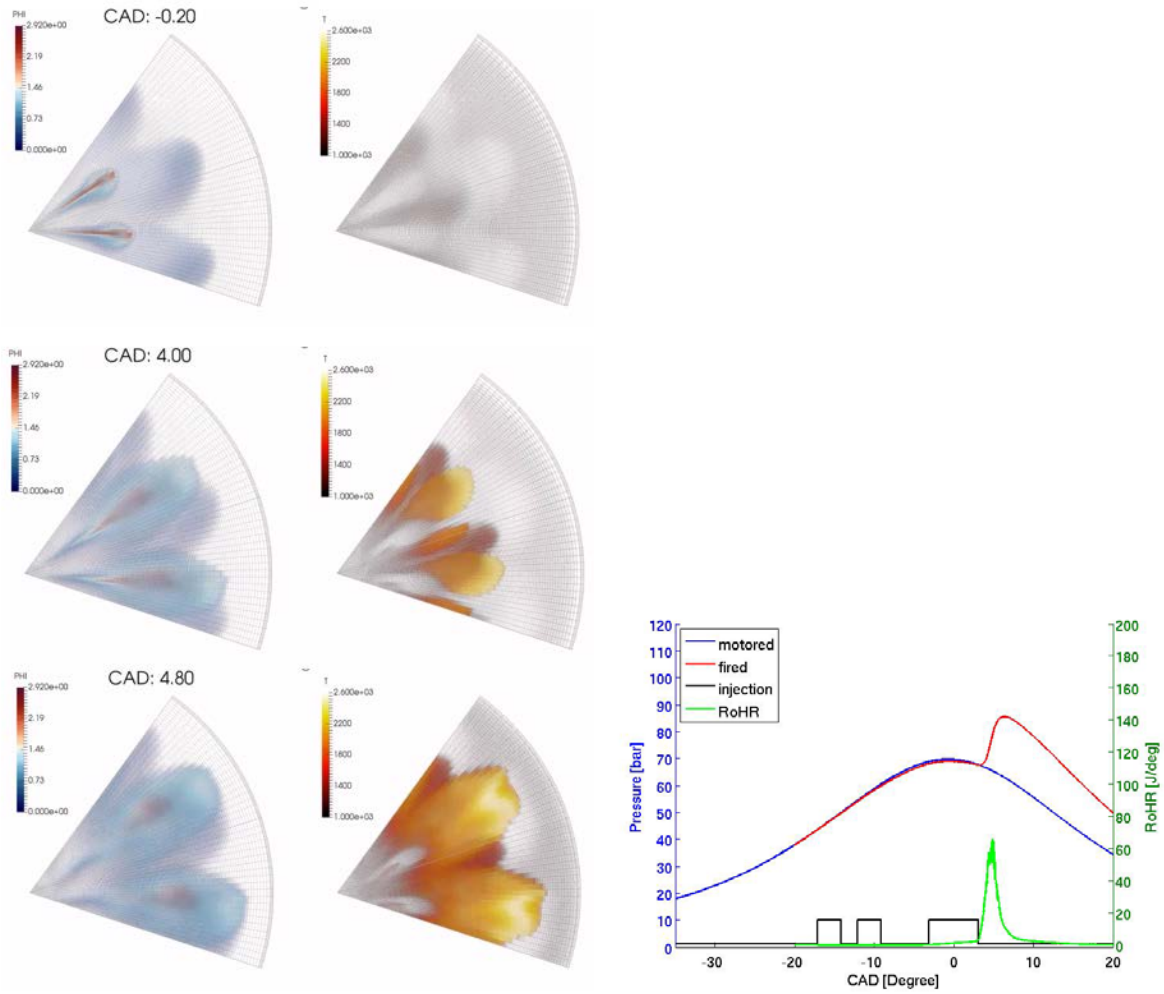

Figure 20 - Triple injection strategy SOI -17 ATDC, SOI -12 ATDC and SOI -3 ATDC with duration of 430um, 430um and 850um respectively. First and second pilot injection give rise to lean mixture pre-heating the charge. Main injection results in post-injection diffusion flame.

To summarize, SOIs should be adopted by introducing double or triple injection strategies so that as little fuel as possible is auto-ignited as a partially premixed mixture at close to stoichiometry conditions, which otherwise leads to a high MPRR. At the same time, one must reduce the duration of diffusion combustion mode in order to achieve acceptable NOx levels.

2.How injection pressure affects final emissions? Is methanol any different from other fuels?

It has been shown that at higher injection pressures, spray turbulence energy is increased and thus the mixing process is stronger. As a result, fuel-air mixture is more premixed at the onset of ignition. Another consequence of high injection pressure is that the same amount of fuel is injected during a shorter period of time. For example, in the case of diesel combustion, CDC, combustion speed becomes faster first due to the better mixing and second due to the larger amount of fuel present in the domain at the same time. In the methanol case, it is similar except that due to the cooling effect, the ratio between fuel burned in the premixed mode and fuel burned in the diffusion mode is largely affected. It means that with higher injection pressure methanol mixing is further improved, which results in a domination of the premixed combustion mode.

A CFD study based on the experimental work with a single fuel injection at high compression ratio 27:1, replicated the NOx increment with higher injection pressures.

It was concluded that the spray plume volume and its stoichiometric boundary area is larger at the onset of ignition for higher injection pressure cases. As a result, more mass could burn at peak temperatures, giving rise to a high rate of NOx formation.

Figure 21 shows the direct comparison for spray propagation and fuel distribution at the onset of ignition between low and high injection pressure cases. Due to the higher injection pressure, larger part of the injected fuel is present and ready to ignite at once. Although the NOx formation duration is shorter for higher injection pressure case, its formation rate is significantly larger resulting in more total NOx emissions, Figure 22.

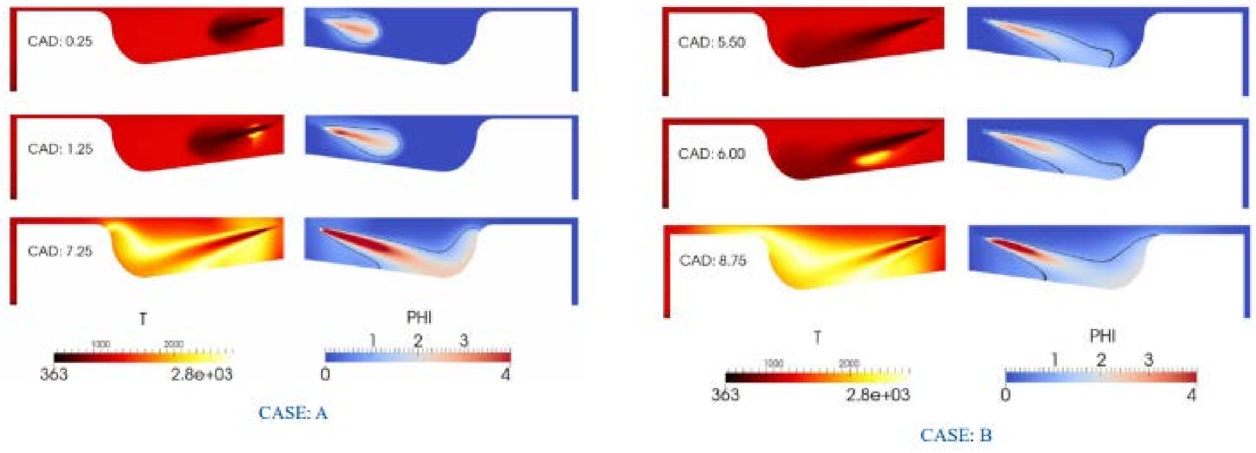

Figure 21 - Temperature and fuel distribution for CASE A 800 bar and CASE B 1600 bar injection pressure.

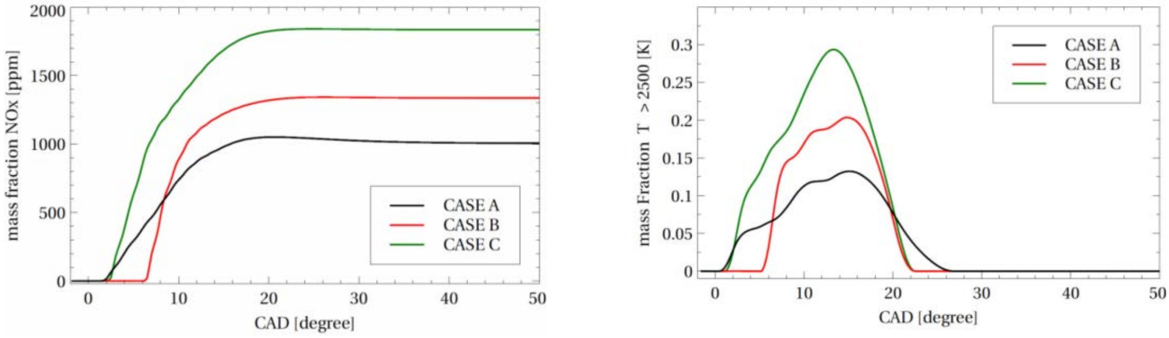

Figure 22 - Mass Fraction of NOx and high temperature mass in-cylinder domain versus time. CASE A 800 bar, CASE B 1600 bar.

3.Is modeling tool accurate enough against optical data and emission data?

The CFD tool at the current stage can predict pressure and heat release traces with a satisfactory match. However, that involves a certain calibration of boundary conditions. Since ignition delay in PPC mode is still kinetically driven, the key parameter in simulations is the inlet temperature at IVC. Additionally, modeling of the temperature field is important to capture the correct ignition event in space, which is dependent on wall temperatures. However, the temperature stratification becomes less important as the SOI is delayed.

The injection flow profile has shown to be a very important factor at SOIs close to TDC, where the combustion mode is divided between partially premixed and diffusion. By controlling the injection flow, the ratio of the fuel that auto-ignites and the fuel burned in diffusion mode is changed, largely affecting the pressure and HRR traces.

The liquid phase modeling is based on the partial results from the optical engine. Common methods for grid generation and grid moving methods was tested to validate sensitivity for the spray behavior both for the liquid and vapor penetration lengths. The influence of grid size and model constants was investigated.

In terms of emissions, the NOx study showed that the CFD tool can capture the same trends as in the experiments. However, to compare quantitative data, more experimental operation points are required.

4. What is piston geometry effect on the heat losses?

A geometry study includes variations of the Scania D13 piston geometry at a constant compression ratio. The depth and length of the piston bowl were modified so that the distance from the injector nozzle to the piston wall is varied. That will change the mixing rate and the local fuel distribution. The validation case is based on the metal engine experiment for a single injection strategy at SOI -3 ATDC.

The heat transfer losses are governed by the temperature gradient at the piston walls, the wall area and the heat transfer coefficient. It means that even if the piston wall area is reduced, as for pistons C and D, the distribution of a temperature gradient or heat transfer coefficient can still cause high heat losses.

Figure 23 shows the temperature distribution at about CA1 for each piston design. It can be observed that the adiabatic temperature surface has a different spatial distribution in each case. This distribution is an effect of the spray mixing process influenced by the distance to the piston wall, and will change the heat flux.

The performed simulations in Figure 24 shows, that piston C has the highest heat losses, although its area is lower than for the piston A and B. However, the longest distance between the injector nozzle and the piston wall, allows to accumulate stoichiometric fuel mixture within a small volume, enhancing the heat flux. Piston D has least heat losses, because of a better stoichiometric fuel distribution.

The conclusion may be that the peak temperature gradient has a greater impact on the heat losses than the area of the piston walls. The presented study is undergoing, validating more cases, and focusing on the fuel distribution at the onset of ignition.

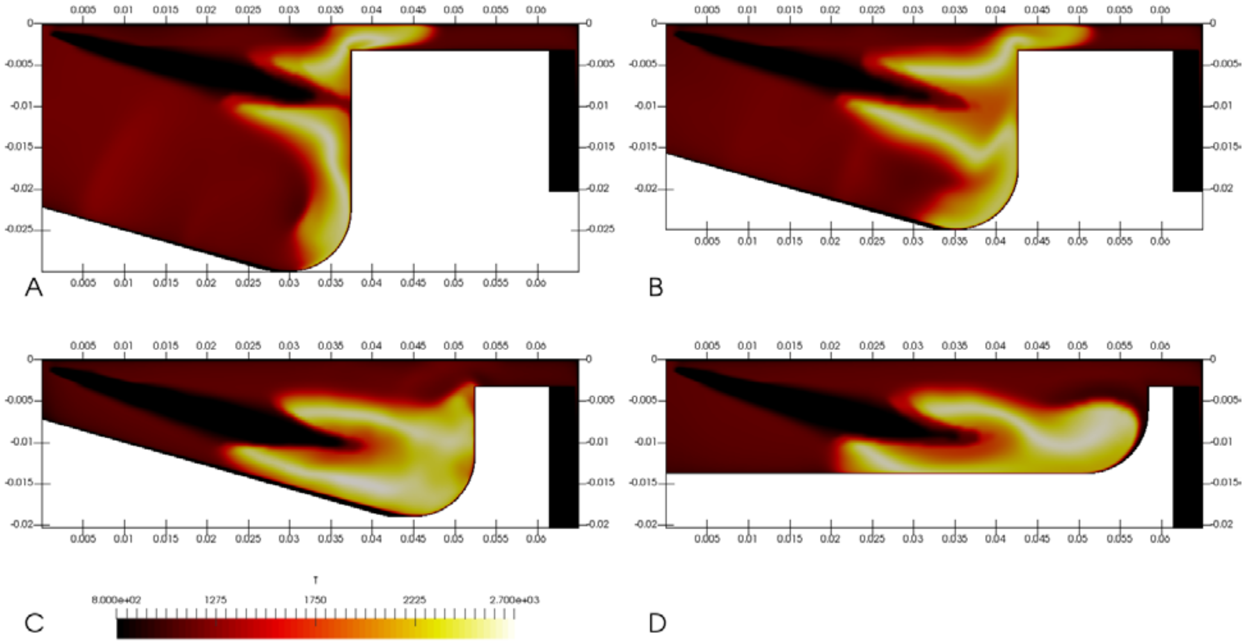

Figure 23 - Temperature distribution at early combustion phase for varied piston designs. Normalized area to volume ratio is following: A) 0.99, B) 1, C) 0.94, D) 0.87. Piston B is original piston design used in the experiment

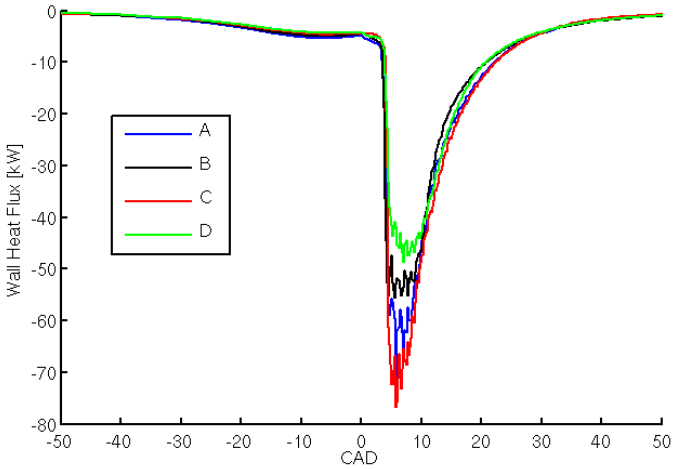

Figure 24 – Average wall heat flux for each piston design vs CAD.

Contributions

- Working and validated CFD code based on the openFOAM technology
- Characterization of local mixing and ignition process for methanol
- Impact of SOI and injection strategies on the performance of methanol PPC engine
- Impact of injection pressure on NOx emissions
- Spray benchmarking in optical engine
- Effect of geometry on the heat losses

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WP4 System Analysis

Erik Svensson

Background

System simulations have been used in this project to study the effects on the gas exchange system of an internal combustion engine as well as looking into the potential levels of emissions from methanol. Single cylinder experiments are ideal for analyzing and developing new combustion concepts. However, with such experiments it is only possible to investigate the in-cylinder conditions. In order to see if the combustion concepts can be viable on a production viable multi-cylinder engine, system simulations can be helpful. Both to reduce the time needed for experiments but also the associated cost. A combination of single-cylinder experiments and system simulation have proven to be a fruitful approach. There is also the possibility of using combustion models, and thereby be able to simulate a full engine cycle. In this way, experimental campaigns can be guided to limit the amount of tests needed.

Potential Levels of Soot, NO_x, HC and CO for Methanol Combustion

In the first part of the project we directed our focus towards the local emissions that arises when using methanol in an internal combustion engine. To put the results into context a comparison with a diesel surrogate fuel was also done. This was summarized in an SAE article (E. Svensson et al., 2016). The work was divided into two parts. In the first part the concept of $T - \phi$ maps was used. Simulations using a homogenous combustion reactor were conducted and the resulting emissions were collected and presented as a function of temperature and equivalence ratio. Such a map can be used to get a fundamental understanding of the mechanisms driving certain emissions to form when using different fuels. However, it is not possible to entirely quantify this when the combustion occurs inside an engine cylinder. Therefore, in the second part, simulations with a stochastic reactor model (SRM), to predict the combustion, were conducted. The simulation model was validated against two experiments.

A selection of the results from the first part can be seen in figures 1-3. Figure 1 shows formation of soot and NO_x for diesel and methanol combustion. The region of highest soot concentration is located in the same area for both fuels, however, the magnitude is significantly lower with methanol. When it comes to NO_x emissions it can be seen that the potential of forming NO_x is as great with methanol as it is with diesel fuel.

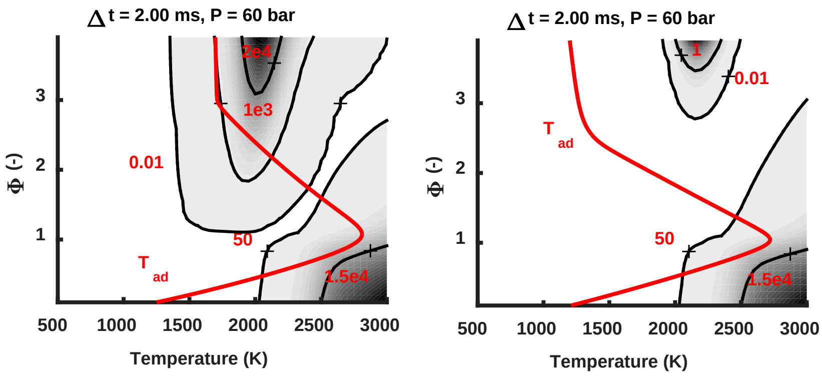

Figure 22. The formation of soot and nitrous oxides (NO_x) from combustion of diesel fuel (left) and methanol (right).

Figure 2 shows the formation of methane (CH_4) which is a potent greenhouse gas. It can be concluded that the likelihood of forming methane with methanol is less than with diesel fuel. The formation of formaldehyde (CH_2O) is presented in figure 3.

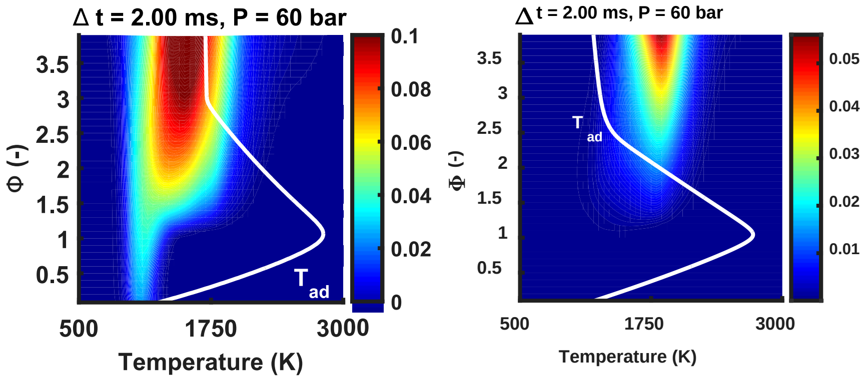

Figure 23. The formation of methane (CH4) from combustion of diesel fuel (left) and methanol (right).

Formaldehyde is mainly formed in the low temperature region of the $T - \phi$ map. If the fuel is port injected as it is in spark ignition engines, it will decompose into formaldehyde and formic acid during the compression stroke and part of it will accumulate in the various crevice volumes. This will lead to a relatively high amount of formaldehyde in the exhausts. In conventional diesel combustion or partially premixed combustion (PPC), the fuel is direct injected close to top dead center (TDC), hence the crevice volume issue is not major. This means that formaldehyde and formic acid emissions from direct injected engine in most cases will be low.

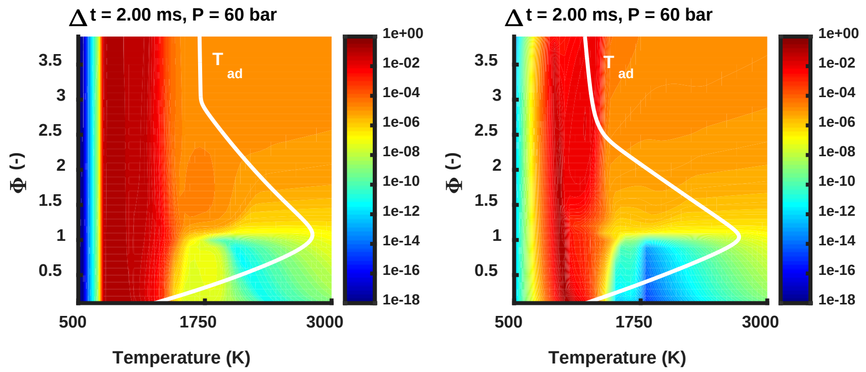

Figure 24. The formation of formaldehyde (CH2O) from combustion of diesel fuel (left) and methanol (right)

The $T - \phi$ diagrams were then linked to in-cylinder conditions using engine simulations. Figure 4 shows particle trajectories from one of the simulations at four different crank angle degree positions. The particles are superimposed on the $T - \phi$ diagram showing soot and nitrious oxides. Also shown in the figure are the adiabatic flame temperatures as a function of equivalence ratio and initial temperature (T_{soi} and T_{soc}). It can be seen that the ignition occurs in a relatively lean fuel-air region leading to low soot emissions. This stands in contrast to diesel combustion, where the fuel is ignited almost immediately after it is injected. This in turn means that particles containing more fuel is ignited before they can be mixed with the air. There are two reasons for this behavior. First, the ignition delay is much longer for methanol, hence the fuel and air have more time for mixing. Second, the higher heat of vaporization of methanol makes the particles containing more fuel decrease more in temperature, i.e. they will ignite later.

Evaluation of Different Turbocharger Configurations for a Heavy-Duty Partially Premixed Combustion Engine

In the final phase of the project all focus has been directed towards 1D system simulations. A detailed virtual engine model of a multi-cylinder heavy-duty truck was built and validated against experimental data taken from our laboratory.

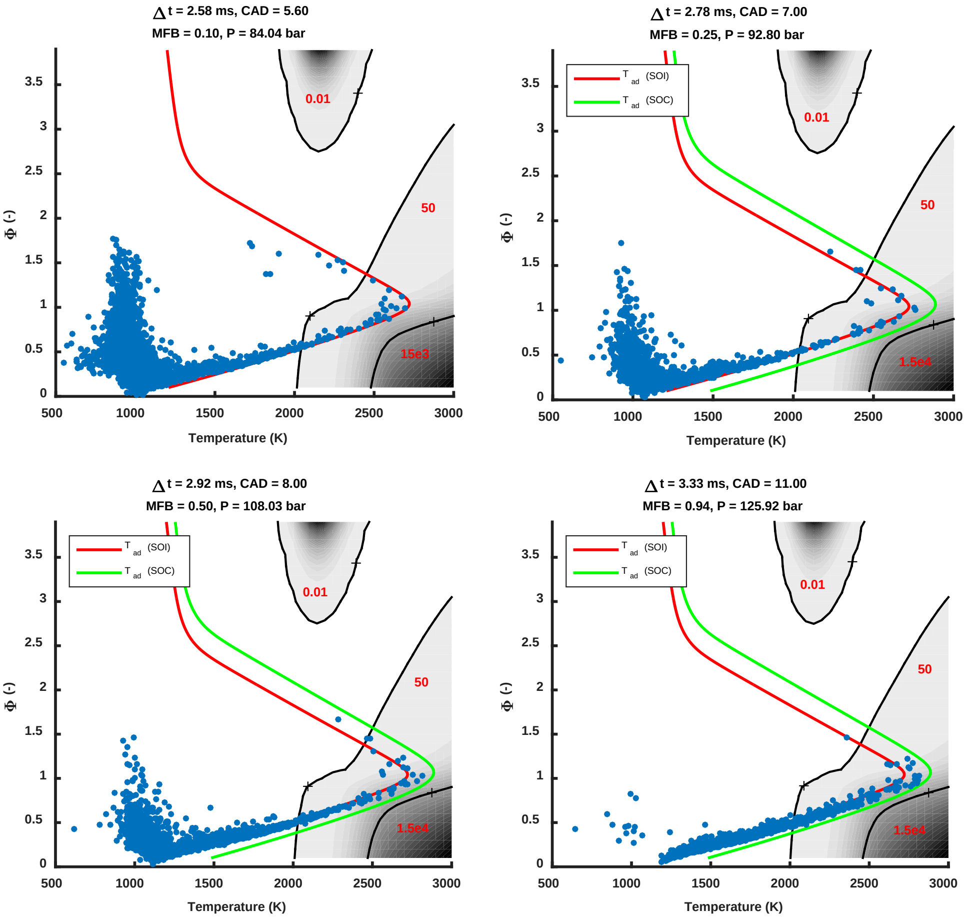

Figure 25. Particle trajectories from an engine simulation, taken as snap shots at four different crank angle positions.

Two different studies were then undertaken, (Erik Svensson, Yin, Tunestål, Thern, & Tunér, 2017) and (Erik Svensson, Yin, Tunestal, & Tuner, 2017). In the first one, different turbocharger configurations were compared when the engine was operated with a PPC strategy. Although the fuel was not methanol most of the results and conclusions would apply to methanol operation as well. A schematic layout of the engine is shown in Figure 5. Four different turbocharger configurations were compared, see Table 2. One fictive with constant isentropic efficiency served as the reference case. Then two single-stage turbochargers with somewhat different geometrical properties and finally a two-stage turbocharger where the stages were operated in series.

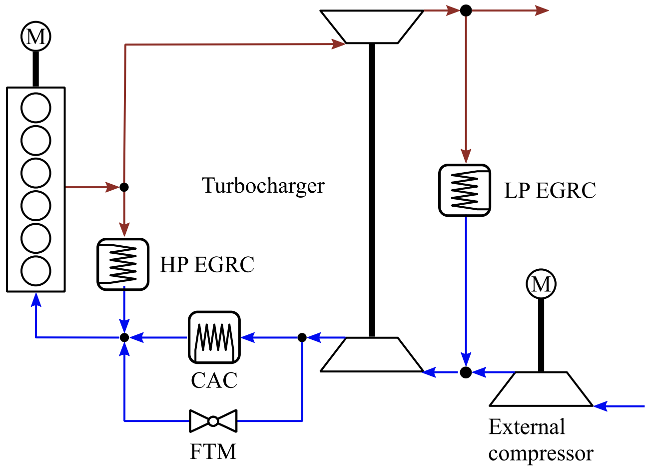

Figure 26. Schematic layout of the multi-cylinder, heavy-duty compression ignition test engine used in the work.

Table 2. The specifications of the four different turbochargers used in the modelling work. The diameters of the turbine and compressor impellers are normalized with respect to turbocharger (TC) TC1's turbine diameter.

	HP turbine	HP compressor	LP turbine	LP compressor
TC0	η_{is} = 78 %, varying diameter	η_{is} = 78 %	(-)	(-)
TC1	VGT, diameter = 1.00 (-)	diameter =	(-)	(-)
TC2	VGT, diameter = 1.05 (-)	diameter =	(-)	(-)
TC3	VGT + WG, diameter = 1.05	diameter =	WG, diameter=	diameter = 1.91

The resulting brake efficiencies are shown in Figure 6. The complete speed-load range was simulated and TC3 showed the best performance, however, it was not as good as the reference TC0. An average brake efficiency for the four configurations were 42.1, 39.3, 39.7 and 40.2 percent respectively. An attempt was also made to estimate the effect that the inlet temperature has on the brake performance. The results are presented in Figure 7 where it can be seen that the brake efficiencies decreased significantly with higher inlet temperature.

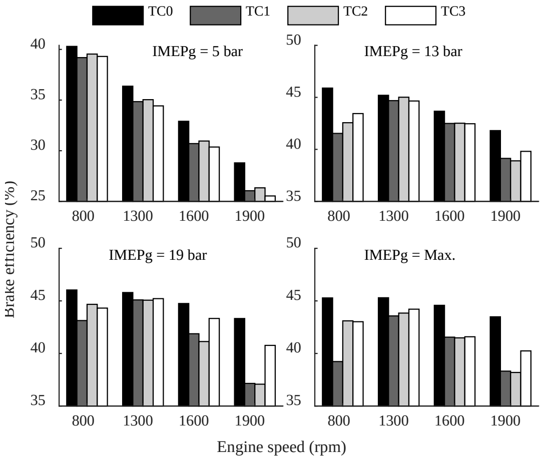

Figure 27. Engine brake efficiency of the complete speed-load range and comparing TC0, TC1, TC2 and TC3. Notice the different scale on the y-axis.

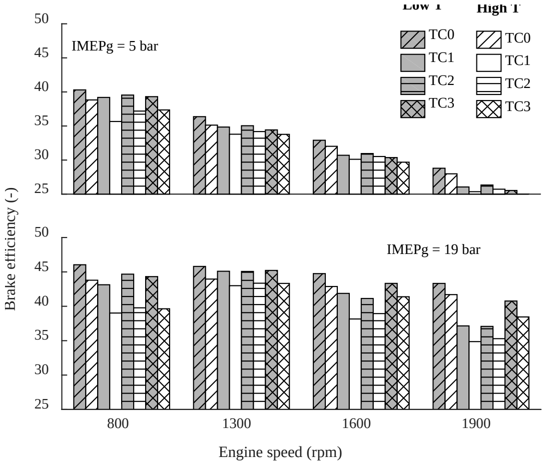

Figure 28. Simulated brake efficiency comparing low and high inlet temperatures.

Finally, a theoretical approach was taken to see what isentropic efficiency of the turbocharger is needed to achieve different boost pressures. The results are presented in Figure 8. The required turbocharger isentropic efficiency increases with boost pressure and decreasing exhaust temperature.

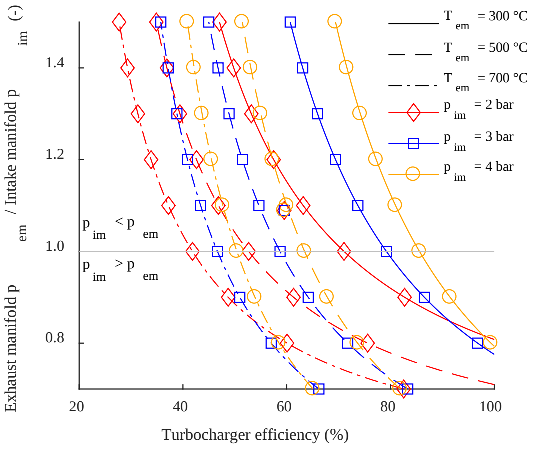

Figure 29. Ratio of exhaust manifold pressure, p_{em}, to exhaust manifold pressure, p_{im}, as a function of turbocharger efficiency.

Combined Low and High Pressure EGR for Higher Brake Efficiency with Partially Premixed Combustion

The second study dealt with configuring the EGR system. Three different configurations were compared. High pressure (HP) EGR, low pressure (LP) EGR and dual loop (DL) EGR. In Figure 9 the brake efficiency of the engine is presented. It can be seen the DL EGR configuration performs best. The average brake efficiency was 39.9, 39.5 and 41.6 % for HP EGR, LP EGR and DL EGR respectively. Especially at higher and lower engine speeds and loads the DL EGR concept was proven to useful. The reason was that it was possible to adjust the amount of mass flow going through the HP EGR route (Figure 12) and hence optimize the turbocharger setting. This can be seen by comparing Figure 10 with Figure 11.

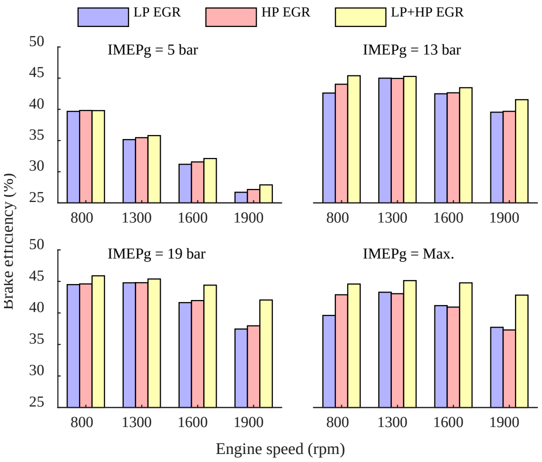

Figure 30. Engine brake efficiency of the complete speed-load range and comparing LP EGR, HP EGR and DL EGR.

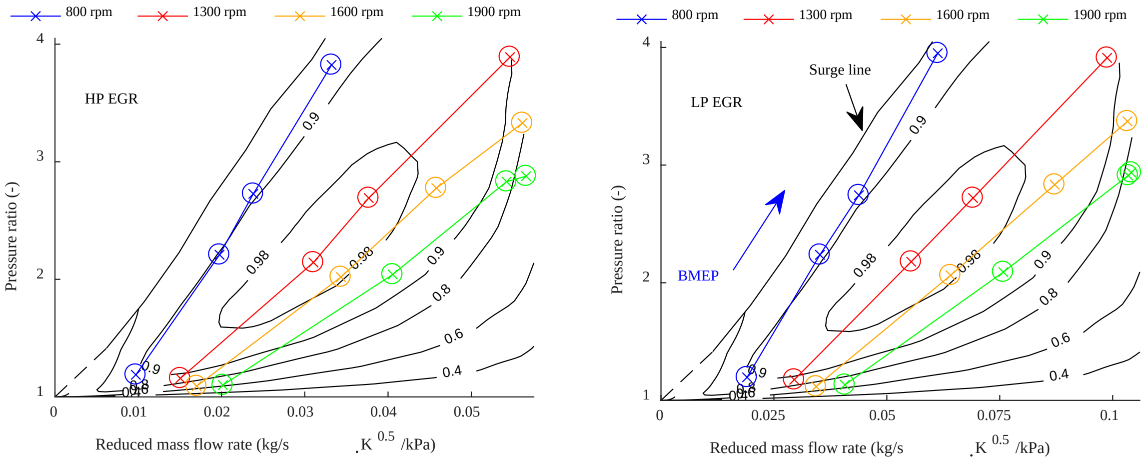

Figure 31. Compressor characteristics of HP EGR (left) and LP EGR (right).

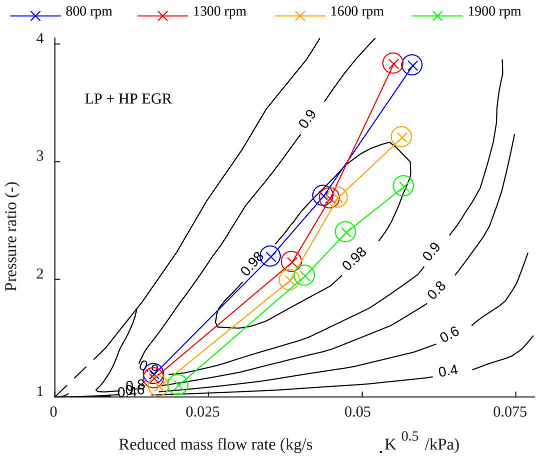

Figure 32. Compressor characteristics of DL EGR.

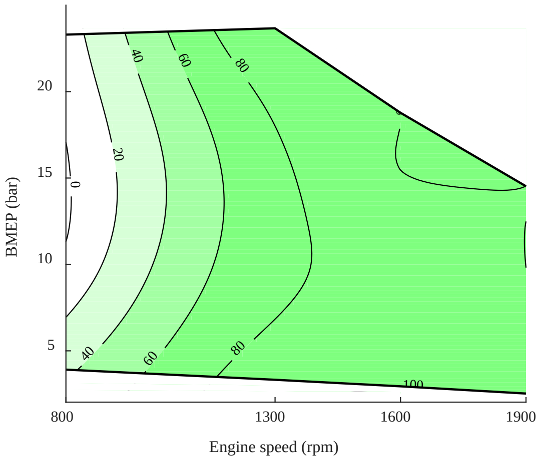

Figure 33. HP EGR fraction in the case with DL EGR.

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Methanol-PPC – a comparison to other potentially sustainable propulsion systems

To be able to compare methanol-PPC with other methanol engine concepts the MOT-2030 has gathered data from the project partners and other projects (figure 34). Detailed descriptions of the various engine concepts can be found in (Tuner, 2016).

- Methanol-PPC works by compressing air and EGR and then inject the low reactivity methanol fuel 40-20 degrees before combustion to achieve partial premixing. The data was all created at Lund University within the MOT-2030 project with a Scania D13 engine.
- MD95 works very similar to a conventional diesel engine. The methanol fuel is blended with an ignition improver to give a high reactivity fuel that ignites almost immediately when injected. Data for MD95 operation was provided by Scania and also by VTT through the Summeth project
- Conventional SI with port fuel injection (PFI) is the most traditional way of operating a methanol engine. Fuel and air is mixed before entering the cylinder and the homogenous charge is ignited after compression by a spark. Data was provided by the Green Pilot project for a Weichai, 12-liter engine and for a converted Scania D13 engine.
- Dual-Fuel (DF) works similar to the PFI-SI engine above, but with the spark plug replaced with a pilot injection of high reactivity diesel fuel that ignites the charge. No data was available for methanol/diesel DF. Instead was data for E85/diesel DF included.
- Direct injected Dual-Fuel (DIDF) works similar to DF but here both fuels are direct injected. The benefits are lower emissions and higher efficiency and is the concept adapted by Wärtsilä for Stena Germanica. Data was provided by Wärtsilä.
- Direct injected SI (DISI) is similar to SI but with late direct injection of the methanol fuel. This concept is common for modern gasoline cars, but little researched for heavy-duty engines. The results were created in Lund as part of the Summeth project with a Scania D13 engine.

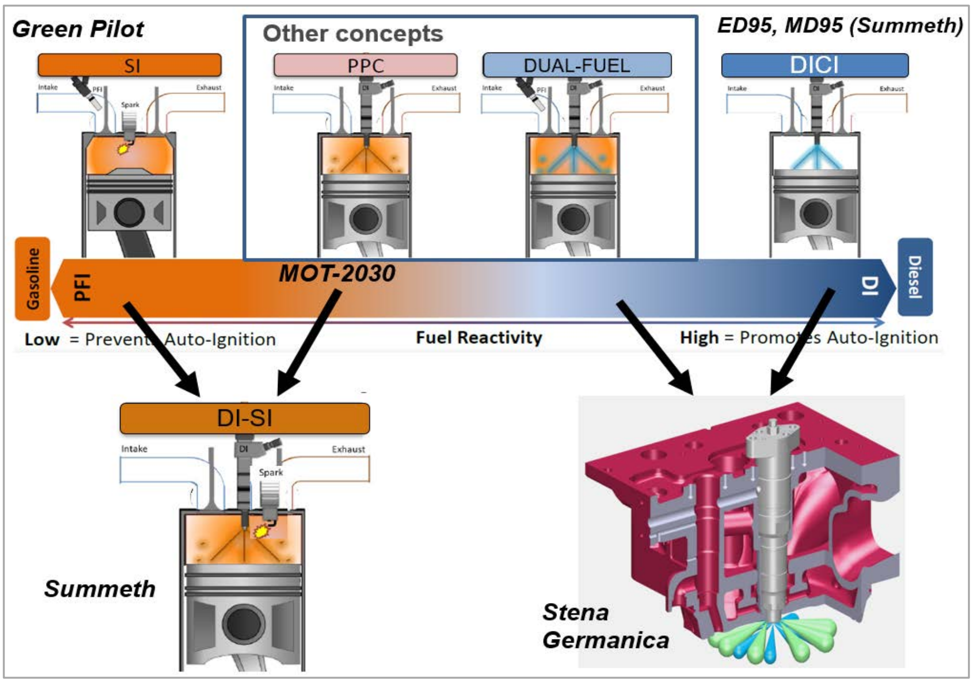

Figure 34. Overview of different methanol engine concepts and related projects

Comparison with other engine types and fuels

Figures 35 and 36 compares peak gross indicated efficiency and related engine out emissions for a number of engine concepts and fuels. The reader should be aware of that both efficiency and emissions vary substantially with operating conditions. Those presented are best cases found in the literature (see details in Tuner 2016).

Some conclusions can be drawn, however. PPC shows consistently higher indicated efficiency than other engine concepts. Methanol-PPC has not been optimized and so far not reached as high indicated efficiency as Ethanol/PPC or Naphtha/PPC. The research indicate that Methanol/PPC likely can reach the same efficiencies as Ethanol/PPC with further work.

Methanol/PPC is also the fuel/engine concept with the absolute lowest regulated emissions. EURO VI can be achieved without emissions-aftertreatment in some steady-state operating conditions.

Other renewable fuels such as biogas (CNG), HVO and RME show less performance compared to Ethanol-PPC and Methanol-PPC in terms of efficiency and emissions except for HC and CO emissions.

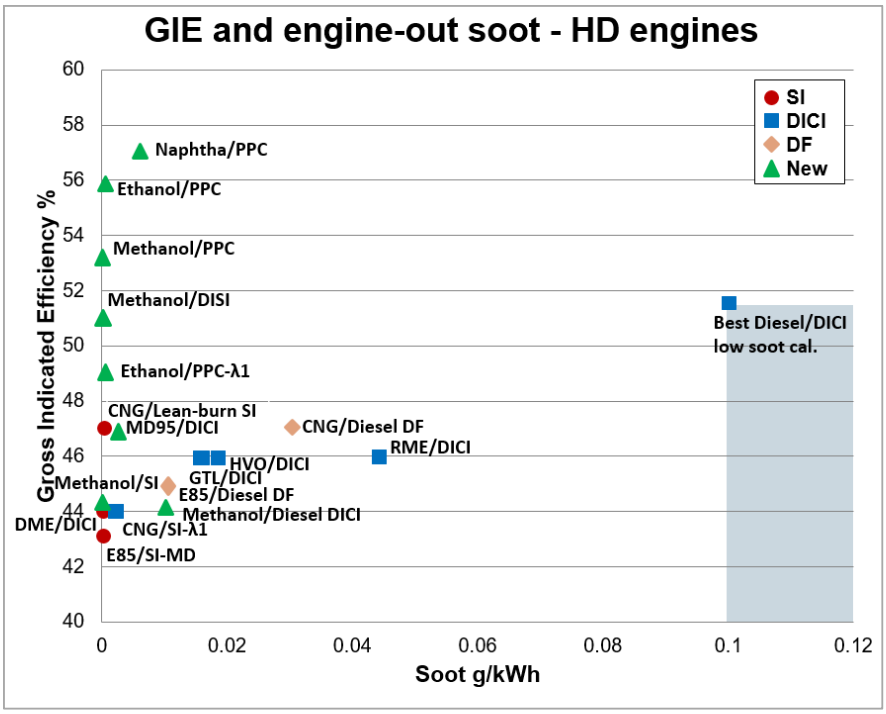

Figure 35. Gross indicated efficiency (GIE) and engine out emissions of soot for selected heavy-duty engine/fuel combinations. See also (Tuner, 2016).

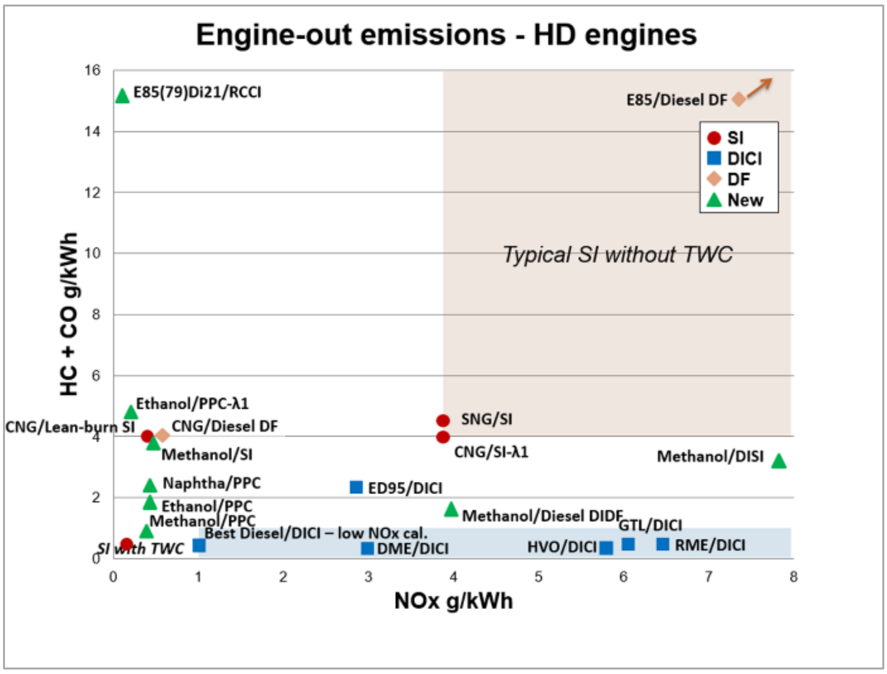

Figure 36. Engine out emissions of hydro carbons (HC) + carbon monoxide (CO) and nitric oxides (NOx) for selected heavy-duty engine/fuel combinations. See also (Tuner, 2016).

An attempt has been made to compile the relative merits and weaknesses for different methanol engine concepts (Table 4). First of all, it can be concluded that all methanol engine concepts can give lower engine out soot and NOx emissions than diesel engines. PFI-SI with a Three-Way-Catalyst (TWC) can be extremely clean and is a comparably simple concept to implement. The efficiency might be too low to be interesting. Scania has already the ED95 concept on the market since 20 years and an adoption to MD95 will likely not be too complicated. Wärtsilä and MAN both market and produce the DI-Dual-Fuel concept for ships, but an adoption to road vehicles will require further development. PPC currently offers the highest efficiency (around 20% lower fuel consumption than PFI-SI) but also the lowest maturity. Low load operation stability is yet limited. DISI shows promise but requires exhaust-aftertreatment for road applications. A combination with mode-shifting PPC and DISI could be the best overall concept but requires further research and development.

Table 4. Estimation of potential benefits and weak points of various methanol engine concepts compared to a conventional diesel engine. The table reflects primarily heavy-duty marine applications.

Engine type	Robustness	Efficiency	Operation cost	Power	Noice	HC	CO	NOx	soot
DICI Diesel	0	0	NA	0	0	0	0	0	0
DICI Diesel with particulate filter / SCR	0	-	NA	0	0	0	0	++	++
MD95 with oxidation catalyst	-	0	-	-	0	0	0	+	+
MD95 with particulate filter / SCR	-	-	-	-	0	0	0	++	++
PFI-SI Lean burn	-	0	-	-	++	-	-	++	++
PFI-SI TWC	-	-	-	0	++	++	++	++	++
DI-SI Lean burn	-	+	+	-	+	-	-	+	++
DI-SI TWC	-	0	0	0	+	++	++	++	++
Dual-Fuel	(-)	--	-	-	+	--	--	0	+
DI-Dual-Fuel	0	0	+	0	0	-	-	+	+
PPC	--	++	++	0	-	0	0	++	++

Challenges with methanol-PPC

PPC is not a concept that is commercialized yet, although Mazda and also Hyundai have announced that they plan to introduce PPC-like concepts on the market 2019. “Pure” PPC has only seen laboratory work and not yet real implementation on-board vehicles. Commercial applications need substantially more development work to perform well and also to meet all regulations under all operating conditions.

One of the challenge is to transform the indicated efficiency from a laboratory engine into break efficiency in a commercial engine application. Our multi-cylinder PPC engine work and system simulations reveal that with correct matching of the gas exchange system it is possible to carry over the high indicated efficiency into high break efficiency if EGR levels are kept below 35%. Gasoline-PPC cannot meet this requirement without increased NOx emissions while Methanol-PPC seem to be able to do that.

Another challenge is to fulfill emission regulations during all operating conditions. For shipping, the use of methanol-PPC, even without emission aftertreatment, would lead to strong reductions of soot and NOx. Emission regulations for road transportation is much stricter than for shipping, and even though methanol-PPC can meet EURO VI in certain steady state operation conditions in the laboratory, this is probably not good enough to fulfill the requirements at all operating conditions for road vehicles. Our studies indicate that an oxidizing catalyst could be sufficient to meet current emissions regulations for methanol-PPC since soot cannot be formed and NOx possibly can be controlled by combustion strategies, with no penalty in fuel consumption (unlike diesel engines, hence diesel-gate). Future stricter real driving emissions regulations might still mean that also PPC would need emission aftertreatment devices, but possibly simpler and cheaper than for diesel vehicles.

The robustness of PPC is, as already mentioned, a challenge that requires further research. The low load control requires high inlet temperatures for methanol-PPC and possibly a combination with DISI can be a good solution where cold starting and low load operation is handled by spark assistance while mid to higher loads are operated with PPC, for maximized efficiency where it matters. PPC is also a noisy engine concept due to the fast combustion. The MOT-2030 project has, however, demonstrated that methanol can be operated with multiple injections to slow down the combustion rate without any penalty in soot production. The research also revealed that high numbers of very small particulates (<23 nm) where released for PPC with methanol, ethanol or gasoline. These small particulates consist of metal oxides originating from the engine lubricating oil. Since all measurements were performed on the same diesel engine there is growing suspicion that the original diesel engine piston rings are not suitable for PPC operation. Further research is needed to confirm this suspicion or to verify other means to reduce the particle number count.

The MOT-2030 project does not answer any questions related to long term testing of engine components sustainability during methanol operation. It was, however, observed that the seals of diesel fuel injectors only lasted hours with methanol fuel and that one fuel rail had cavitation wear. After changing to ethanol specified injectors and pumps no problems were encountered. The cavitation wear has not been investigated further.

Well-To-Wheel

Data from (JEC,2014) but also official fuel consumption figures from Volvo, Toyota, VW and BMW, were compiled to create an WTW assessment for various fuels and powertrain configurations in the NEDC drive cycle (figure 37). Several fuels from various feedstocks are not visible in the chart since they have too high overall energy use. The Volvo V70 running on diesel fuel is a relevant representative of current generation fossil fuel driven cars. Fuel-cell vehicles (FCEV) and battery electric vehicles (BEV) give little or no improvement in terms of CO_2 emissions since both hydrogen and electricity is currently dominantly produced from fossil energy. Both these vehicle types can have excellent GHG performance once their propulsion energy is produced from renewable sources.

Methanol from black-liquor is one of the most energy effective renewable fuels and can also give a reduction of CO_2 of about 97% compared to diesel fuel. HVO from cooking oil does also give a very strong reduction of CO_2 and has the benefit that it is accepted by several car manufacturers to be used in their diesel cars without modifications. But just like biogas, another low CO_2 emitting fuel, the amounts that can be produced are comparably limited in comparison to renewable methanol. Gasification data for methanol production in the JEC-2014 is based on old data with only 50% biomass conversion efficiency, which penalize concepts using fuels or electricity from gasification (see figure 37). More recent research show potential between 73-82% for gasification, which would place performance close to that of black liquor (Morandin et al., 2015; Bogild-Hansen, 2015).

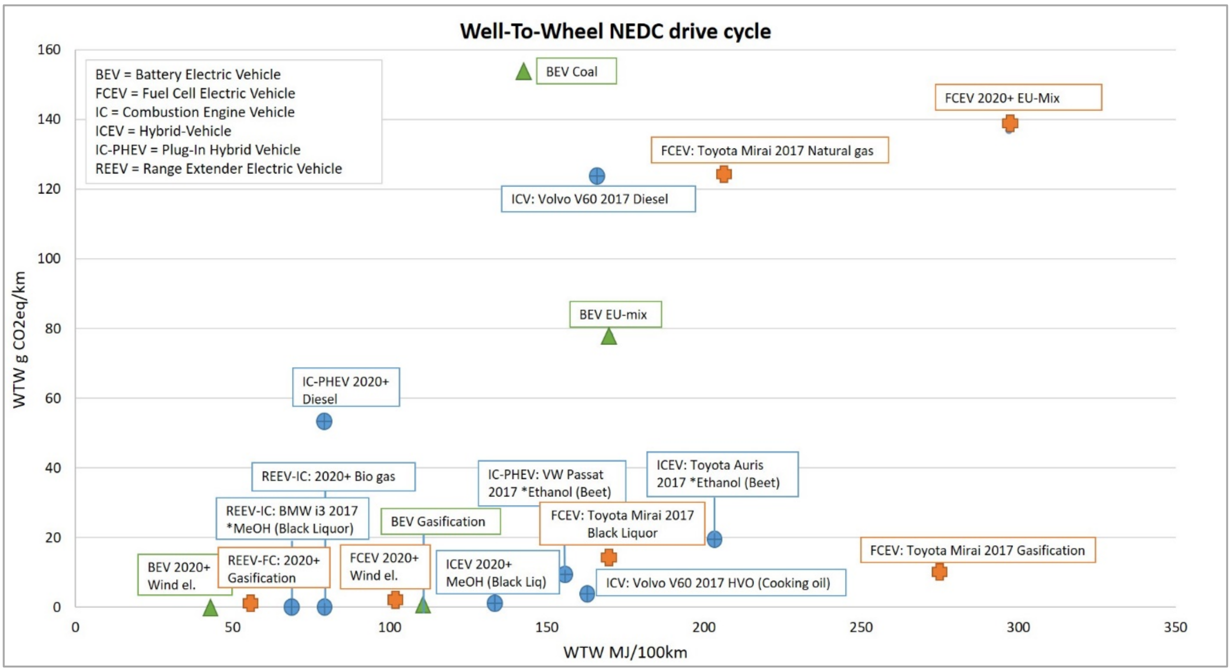

Figure 37. Well-To-Wheel estimation of energy use and equivalent CO_2 emissions for several vehicle/fuel combinations in the NEDC. Data from JEC-2014 and vehicle manufacturers.

Another important observation is the value of combining combustion engines with electric drive. Such hybrid applications can reduce energy use further while also providing extended driving range and also enables driving in zero-emission zones. In principle all needed knowledge and hardware is available to create highly effective and clean methanol range extenders, as represented by the BMW i3 in the figure. It should be observed that BMW has not certified the i3 for methanol, but since methanol engines is more effective than gasoline or diesel engines the example is valid. It is interesting to notice that the existing range extender vehicles, such as BMW i3, are already much more efficient than predicted for REEV 2020+ by JEC-2014.

Life Cycle Assessment

Well-To-Wheel does not provide a complete picture of a vehicle's overall environmental performance. Life Cycle Assessment (LCA) is needed to also account for the manufacturing of the vehicle, the production of the fuels and also the recycling. LCA is complex and results will vary depending on the level of detail in the assessment, the available information and also on what type of resources that were exploited. Never the less; LCA is the approach that must be used for any meaningful assessment of any systems environmental performance, to guide governments and other policy makers. By compiling the IAV-2016 LCA study with methanol data from JEC-2014, figure 38 was created.

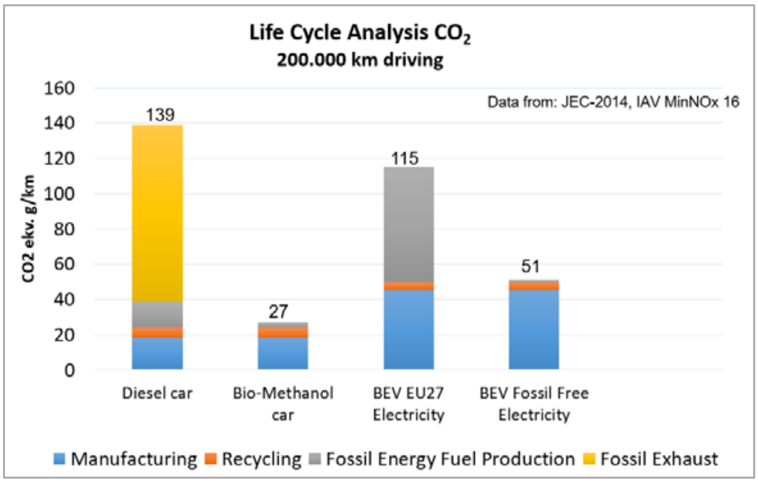

Figure 38. Estimated average equivalent CO_2 emissions during the life time of selected vehicle/fuel combinations. Data comes from (JEC, 2014; IAV, 2016).

By shifting from diesel fuel and EU27 electricity mix to bio-methanol and fossil-free electricity, large reductions of CO_2 equivalent emissions can be realized. As can be noted, the methanol car performs even better than the electric car. The reason for this is the high CO_2 equivalent contribution for the battery production for the electric car. With increased fractions of renewable energy in society the production and recycling of the vehicle will have lower impact. Similar behavior is reported by (Bicer et al., 2017) although with methanol from fossil origin. As mentioned before; the overall environmental performance and efficiency can be improved further by combining electric drive with methanol operation.

Other experiences of methanol fuel in MOT-2030

While performing the experimental work in the Lund laboratory, the staff experienced handling of methanol as normal to that of gasoline, diesel or ethanol. The only reported difference was that methanol does not smell much or bad as diesel or gasoline and the single small spillage was easy to handle. No other incidents were reported.

Stena has been running with methanol as a main fuel and diesel fuel as a pilot fuel since 2013. All four main engines are today converted into methanol operation. The engine operation has worked largely and contributed to significantly reduced emissions of soot and NOx, but mistakes with programming of control systems have contributed to damage to individual cylinders due to excessive injected fuel energy. A positive side effect of the transition to methanol is that the engine and fuel compartments are much easier to keep clean compared with the sticky heavy fuel oil used previously. Due to the fact that the heating requirement of heavy fuel oil has disappeared, the temperature is much more comfortable in engine and fuel compartments, and the working environment on board is considerably better for these reasons. SP has conducted fire studies on behalf of Stena to provide knowledge of suitable methods for detecting and combating leakage and fire. Methanol burns with an invisible flame which increases the risk and makes conventional smoke detectors unreliable. At the same time, heat radiation from a methanol fire is much lower, which facilitates firefighting and reduces damage.

MOT-2030 ran a SAAB 9-5 (figure 39), over 10 000 km on the bio-methanol-M56 in collaboration with Luleå Technical University, LTU. M56 consists of 56% methanol and 44% gasoline and is identical from the engine's perspective to E85 and also miscible with the same. No problems occurred during driving and after the 10 000 km, the engine was dismantled to determine if any engine damage had occurred. Abnormal wear or damage was not found and was not expected for this relatively short driving distance.

Figure 39. Participants from MOT-2030, Summeth, Green Pilot and others lined up next to the SAAB 9-5 car, a speedway motorcycle, Pilot boat and the ship Stena Germanica. All vehicles are running successfully on methanol fuel.

Discussion

Scientific contributions

The MOT-2030 project has substantially extended the international knowledge front about methanol engines. The world class combined research efforts with engine experiments, optical diagnostics and numerical simulations has created a number of unique results that can be used to guide the industrial development of efficient and ultra-clean methanol engines. The MOT-2030 project has:

- Proved that PPC can be operated with methanol and also raw-methanol. The measurements indicate, to our knowledge, the highest ever recorded efficiencies (53%) for a methanol engine concept in the world.
- Demonstrated that methanol PPC can be operated with extremely low emissions (below EURO VI) without emissions aftertreatment devices in some operating conditions.
- Concluded that methanol offers 95% reduction of green-house-gases and overall better LCA performance than battery electric vehicles on fossil-free electricity.
- Proved that there is no soot from methanol-PPC but also discovered that PPC may produce very small amounts but high numbers of small particulates originating from the engine lubricating oil.
- Showed that a PPC engine can be operated on methanol, ethanol or gasoline by only changing control parameters.
- Proved that direct injection is a key to avoid emissions of formaldehyde and formic acid that historically could be a problem with carbureted or port fuel injected methanol engines.
- Characterized a number of key features of methanol combustion in engines. Examples include the lean auto-ignition process and also the mixed mode flame front propagation.
- Demonstrated that methanol compression ignition can be achieved at low compression ratios by injecting a smaller amount of fuel that combusts and provide enough heat to burn the diffusion combustion bulk fuel injection. There is no soot penalty thanks to the none-sooting properties of methanol while peak pressure rise rate can be easily controlled.
- Explained the relation between methanol's chemical and physical fuel properties and their link to emission formation depending on combustion strategies. Examples include that methanol cannot form soot due to methanol's high content of oxygen and that compression work losses can be reduced due to the extremely high heat of vaporization of methanol.
- Explained the relation between EGR levels and gas exchange system configuration for engine efficiency. These results are valid for all types of PPC engines and not limited to methanol.
- Demonstrated how two EGR loops can be used to improve engine efficiency throughout the operating range.
- Created engine and optical hardware, as well as strategies for engine control and measurements. These are available for further research and also "lead the way" for industrial development of methanol engines.

- Developed a number of numerical models and modeling approaches, from detailed combustion studies to system analysis, that can be employed for further research or by industry for engine development.
- Showed that adapted piston geometry can reduce heat transfer losses for methanol PPC operation.
- Confirmed that methanol in blends with ethanol and gasoline can be used in a regular E85 car (SAAB 9-5) without any modifications.
- Created a team and environment at Lund University with excellence in methanol engine research with strong links to other research groups and also industry.

The relevance of Methanol and PPC for sustainable transportation

The above mentioned results were evaluated in a larger context to verify the main goal of the project *"to demonstrate a fossil-free road and sea engine system that is environmentally and economically sustainable and has a higher system efficiency well-to-wheel than other known alternatives. The system should be practically implementable in society until 2030"*.

From a technical and sustainability perspective, little disproves that methanol-PPC has the potential to meet this goal. The results show that methanol-PPC can provide simultaneously the highest efficiency and lowest emissions of all known methanol engine concepts. Fuel energy consumption is for instance indicated to be up to 20% lower than for gasoline engines and also lower than for diesel engines. Further research but also use of optimization would likely reveal even further improvements in efficiency. The results also indicate that renewable methanol fuel can provide excellent Well-To-Wheel and also Life-Cycle-Assessment performance.

We can thus conclude that methanol-PPC can offer:

- Very low fuel energy consumption
- Extremely low emissions and no soot at all
- Among the best in terms of well-to-wheel efficiency and CO_2 equivalent emissions (97% reduction)
- Excellent Life Cycle Assessment performance
- A relevant complement to other renewable fuels and electric drive from other renewable feedstocks.

To phase out the fossil fuels in Sweden, there is a need to replace about one-third of the currently used gasoline and diesel fuel with renewable fuels, since the remaining part of fossil fuels will be replaced by improved transportation, efficiency improvements and electrification, according to the report on "fossil-free vehicle traffic" (Johansson, 2013). This is exemplified by figure 40 which accounts for the road transportation energy of around 80 TWh.

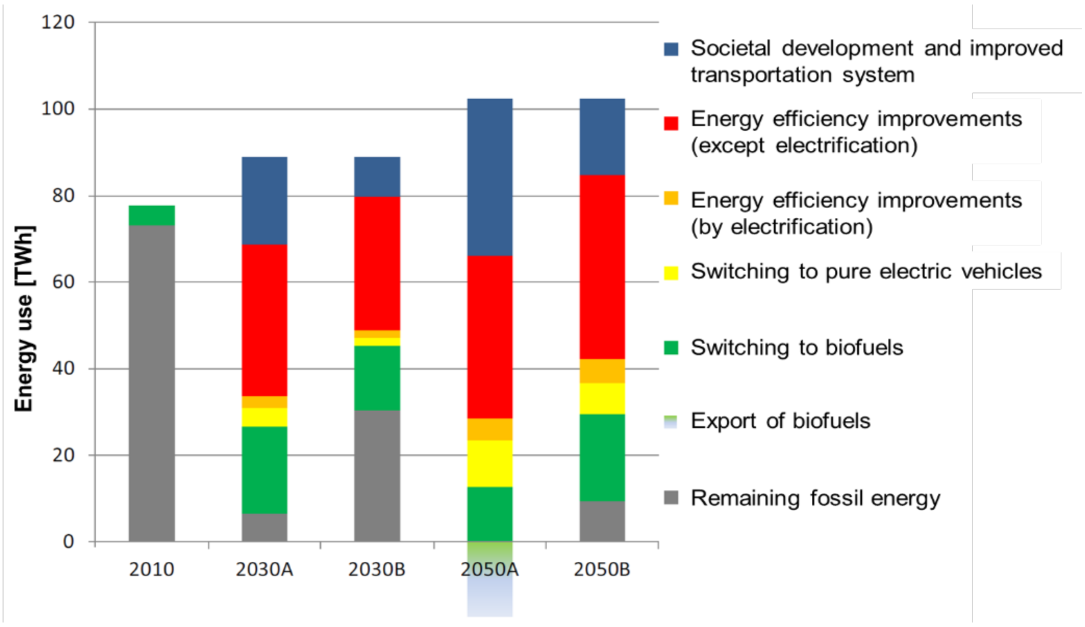

Figure 40. Best (A) and worst case (B) scenarios for Sweden 2030 and 2050 (Johansson, 2013)

If agriculture and work machinery is included there might be a need for around 25-40 TWh sustainable fuels. Considering the existing renewable fuels and the quickly growing use of HVO, around 20 TWh renewable methanol might be needed for the Swedish market (Energimyndigheten, 2016). According to (Landalv, 2017) the potential production of renewable methanol in Sweden is in the order of 40-60 TWh, which could meet the Swedish demands and possibly open up for export of renewable fuels and sustainable electricity to other markets, rather than importing fossil and renewable fuels as today.

Landälv estimate that Swedish renewable methanol would cost 40-50% more than untaxed gasoline, which is competitive compared to other renewable fuels. On markets where biomass is available at lower cost, for instance USA, the price might be as low as 10-15% higher than untaxed gasoline. But, considering that actors that invested in methanol propulsion, when fossil methanol price was low, now are investing in conventional fossil fuel technology and exhaust aftertreatment devices, indicates that economic realities leave little room for price bonus for sustainable fuels. It is hard to see that the market will choose more expensive sustainable fuels than fossil gasoline and diesel fuel. A carbon-dioxide tax, incentives for vehicle producers or other political instruments will probably be required to create a market equal to all participants to drive the change towards sustainable transportation.

Implementation paths for methanol vehicles is a complex question. The discussion in (Landälv, 2017) is well worth reading, but to summarize shortly, there is little consensus among vehicle manufacturers, and while some vehicles are accepted for use with methanol fuels in China the same vehicles are not approved for methanol use on other markets.

PPC has been shown, just as E85 cars, to operate effectively on gasoline, E85, ethanol, and methanol with the same engine. This simplifies an introduction by the year 2030 since gasoline and E85 are already on the market and methanol can be gradually introduced as production increases. The drop-in of methanol in gasoline is another option. For neat methanol it will probably be sensible to start any introduction in Sweden with applications that involve few vehicles that consumes larger amounts of fuel from few filling points. This could be shipping, agricultural machinery or possibly long-haulage trucks. If those control fleets are successful a more widespread implementation can be considered.

The created know-how on Methanol-PPC engines can provide an opportunity to introduce cost effective methanol transportation that complement existing renewable fuels and electrification. If that can help Sweden (and other contries) to produce its own sustainable fuels, this will lead to improved energy security, create work opportunities and help Sweden and the world towards sustainable transportation.

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Appendix

Slutrapport MOT-2030 Admin