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Untersuchungen zur kombinierten Anwendung von Abgasrückführung und Wasserbrennstoffemulsion für mittelschnelllaufende Dieselmotoren

Investigation on the combined application of EGR and water fuel emulsion for medium speed diesel engines

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Zusammenfassung

Die gleichzeitige Reduktion der Stickoxid- sowie Russemissionen mittels Anwendung der Technologien Abgasrückführung (AGR) sowie Wasserbrennstoffemulsion wird am W6L20CR Motor der Large Engine Research Facility (LERF) am PSI untersucht. Im Rahmen der Projekte CCEM "Low-NOx" und Hercules-2 (Horizon 2020 Projekt) wurde der Versuchsmotor modifiziert um Betrieb mit „semi-short route" AGR zu ermöglichen.
Basierend auf Erfahrungen aus früheren Versuchsreihen wurden weiterführende Untersuchungen durchgeführt. Dabei wurden z.B. die Versuchsparameter Wassergehalt, Raildruck und Einspritzstart variiert. Die Messresultate wurden anschliessend hinsichtlich „engine performance" unter anderem mit Hilfe eines 0-D Simulationsmodel (GT-Power) ausgewertet. Des Weiteren wurden die gasförmigen Emissionen sowie Russ charakterisiert.
Durch die Beimischung von Wasser wurde eine Reduktion der Russemissionen von bis zu 85% erzielt bei einer leicht gesteigerten Effizienz von bis zu 0.85%. Zusätzlich wurde NO_x bei WFE-Betrieb zusätzlich leicht reduziert. Einzig nachteilig war die relative rasche Materialbeschädigung in den Injektoren und diesbezüglich wären konstruktive und Materialänderungen erforderlich für den längerfristigen Betrieb.
Die Resultate ergeben ein erweitertes Verständnis und generieren Referenzdaten hinsichtlich innermotorischer Massnahmen zur Einhaltung der gesetzlichen Abgasvorschriften für Stickoxide (IMO TIER) in Kombination mit Reduktion der Feststoffemissionen.

Summary

In this project, an investigation on the combined application of water-in-fuel emulsion (WFE) and exhaust gas recirculation (EGR) in a medium speed common rail, 4-stroke diesel engine at the Large Engine Research Facility (LERF) at PSI has been performed in order to achieve low NO_x and soot emissions.
Within the projects CCEM "Low-NOx" and Hercules-2 (Horizon 2020), the test engine has been modified to operate with a semi-short route EGR configuration and the TC-system has been re-matched in order to operate over the entire load range. An advanced fuel consumption measurement and WFE equipment was successfully applied.
In the framework of this project, a measurement campaign has been conducted, which includes parameter variation such as water content (up to 10 wt%), rail pressure and start of injection timing. The measurement campaign is accompanied the analysis of engine performance data via a 0-D simulation tool (GT-Power) to analyse the heat release behaviour. Furthermore, the gaseous emissions and soot have been characterized.
Applying low content water-in-fuel emulsion (up to 10wt%) reduce the soot emission up to 85% with the according injection pressure and start of injection time tuning. The engine efficiency has been observed to slightly increase up to 0.85%. Furthermore, the NO_x emission was slightly reduced with WFE operation. Only the rather quick damage of injector components show a drawback and additional measures regarding material and design would be needed.
The results of the combined application of EGR and WFE in a medium speed diesel engine give a more detailed insight into the applicability of these two technologies to meet the emission legislations for NO_x (IMO TIER) and the simultaneous abatement of soot.

Astratto

In questo progetto e stata effettuata una campagna sperimentale al fine di raggiungere basse emissioni di NO_x e fuliggine nel motore diesel 4-stroke alla Large Engine Research Facility (LERF) del PSI. Il progetto si focalizza sul combinare water-in-fuel emulsione (WFE) e exhaust gas recirculation (EGR).
Nel progetto CCEM “Low-NOx” and Hercules-2 (Horizon 2020 project), il motore è stato modificato per operare con una configurazione semi-short route EGR e il TC-sistema stato ricalibrato per operare nell’intero range di carico. Una misurazione avanzata del consumo di carburante e dell’equipaggiamento WFE è stata applicata con successo.
Una campagna sperimentale è stata condotta variando parametri come il tenore d'acqua, (fina a 10 wt%), pressione common rail e l'inizio dell'iniezione. Uno 0-D simulation tool (GT-Power) è stato utilizzato come complemento all’analisi dei dati per analizzare il rilascio di calore. Le emissioni di gas e fuliggine sono state caratterizzate.
Applicando un basso contenuto di acqua nel carburante (fino al 10wt%) le emissioni di particolato sono state ridotte dell’85% con la rispettiva pressione d’iniezione e lo start dell’injection time tuning. L’efficienza è crescuta dello 0.85%. Inoltre, le emissioni id NO_x sono state marginalmente ridotte con la WFE operazione. Solo il precoce danneggiamento dei componenti dell’iniettore richiedono misure addizionali per I materiali impiegati e il design dei componenti stessi.
I risultati della combinazione di EGR and WFE in un medium speed diesel engine forniscono dettagli sull’applicabilità delle due tecnologie al fine dell’osservanza delle leggi sui NO_x (IMO TIER) e sul simultaneo abbassamento della fuliggine.

Contents

List of abbreviations

BSFC	Brake Specific Fuel Consumption
CA	Crank Angle
EGR	Exhaust Gas Recirculation
LERF	Large Engine Research Facility
SOI	Start of Injection
WFE	Water-in-Fuel Emulsion
wt%	weight percentage

1. Executive summary

1.1. Project Goals

Medium speed diesel engines are utilized as prime movers or auxiliary generators in the maritime transportation sector as well as for stationary power generation. To regulate the environmental footprint, strict emission legislations are effective and further regulations are under evaluation. Therefore, continuous overall improvement of engine performance and R&D on low emission technologies, with respect to NO_x as well as PM emission reduction, are of high importance. Within this project, a further understanding of the simultaneous abatement of NO_x and soot by the combined application of exhaust gas recirculation and water-in-fuel emulsion on medium-speed diesel engines shall be generated. The effects on the performance parameters and emission characteristics (including particle size) give a further insight in the underlying phenomena as well as applicability of these emission reduction technologies.

1.2. Simultaneous NO_x and Soot Abatement Project Accomplishments

During the scope of the project, the combined application of exhaust gas recirculation (semi-short route setup) and water-in-fuel emulsion technology on the medium speed marine diesel engine at the Large Engine Research Facility was successfully investigated. For a comprehensive study on engine performance and emission characteristics the engine has been instrumented with advanced measurement technology.
The measurement campaign included the variation of water-in-fuel emulsion (up to 10wt%) and performance tuning via injection pressure variation and adjusting the timing for the start of injection.
The influence of the WFE, while operating the engine with 23% exhaust gas recirculation, show promising results with regard to the simultaneous abatement of NO_x and soot. The NO_x emission has been reduced below the IMO TIER III regulation levels (2.2 g/kWh at 1000 rpm) [1]. The increase of the water in the fuel decreased the soot emission up to 85% in combination with the adjusting of the injection pressure and start of injection timing.
Furthermore, the engine efficiency has been slightly increased and hence, no penalty on the fuel consumption has been measured.
The application of a particle analyser gave a more detailed insight into the characteristics of the soot emission with regard to the influence of these low water contents on the particle size distribution.
Overall, a comprehensive database has been elaborated in order to see the potential of the simultaneous application of the two emission abatement technologies. Moreover, the data of the measurements will be further used to evaluate the phenomena with regard to the soot characteristics.

2. Introduction

During the project work the combined application of EGR and WFE for the simultaneous abatement of NO_x and soot is investigated on a medium speed diesel engine. Such engines are widely spread for marine propulsion and stationary power applications due to their unrivalled efficiency and low maintenance operation. The study assesses the applicability and technology potential in order to fulfil the upcoming stricter emission legislations [1].
The aim of the engine operation with the combined application of exhaust gas recirculation and water-in-fuel emulsion is the simultaneous abatement of the NO_x and particulate emission. The recirculation of cooled exhaust gases is a well-established method to reduce the NO_x in diesel engines [2,3]. With EGR the flame temperature during the combustion process is lowered which results in a reduced NO_x formation. Due to the known trade-off regarding the NO_x and soot emission [5,6], the lower NO_x emission by using EGR yields to an increase in soot emission. The lower flame temperature and the reduced availability of oxygen causing a reduction of soot oxidation [2,4-6]. To overcome the disadvantage of the increase emission of particulate matter when operating the diesel engine with EGR, the application of water-in-fuel emulsion has shown promising results to simultaneously reduce soot and NO_x, while potentially improving, or at least not significantly increasing, the fuel consumption and thus, reducing engine efficiency, respectively.
Diesel and water emulsion consist of water droplets homogenously distributed in the fuel. Most applications need a stabilization of the emulsion over a longer time period (e.g. storage purpose) and therefore, surface-active agents, so-called surfactants, are added to the water/fuel mixture as they reduce the surface tension of the water [7,8]. Past research has shown that the operation with WFE can reduce soot emission [4,5,7]. Investigations on WFE revealed that soot reduction is mainly caused by the leaning-out of the fuel/air mixture as a larger share of the fuel and charge is pre-mixed. The ignition delay is prolonged when adding water to the fuel since the latent heat of evaporation and dilution of the fuel [7,9,10] which is deferring the physical and chemical ignition delay. Furthermore, the results of some experiments found in literature suggest when the WFE is evaporating phenomena like “micro-explosions” and “puffing” can occur due to the superheating of the water in the fuel (lower evaporation temperature of water compared to the fuel) [7,9,11-13]. This processes could result in an improved atomization and subsequent mixture formation before start of combustion.
All these effects lead to a lean mixtures and in combination with the lower flame temperatures to a reduction of soot precursors and hence, particulate emission. Moreover, some results in the literature show an engine efficiency increase attributed by the improved mixing behaviour and the “faster” combustion [4,7,14]. But this conclusion is still under discussion as the measurements are not concrete and sound through the available studies.
A more common agreement can be found on a favourable influence of WFE operation on NO_x reduction. The lowering to the flame temperature, due to the increase in the mixture specific heat (higher latent heat of water) [3,4,9,15] and the dilution effect from the addition of water, yields to a decrease of NO_x formation even though the premixed share of the combustion process is increased when operation on WFE.
The doctoral thesis of D. Wuethrich, which was mainly elaborated in the framework of the CCEM “Low-NOx” at PSI, is investigating the WFE injection and spray combustion with low water content with optical diagnostics at a generic constant volume cell setup in order to further extend the fundamental knowledge regarding WFE combustion. The findings give a better insight into the involved processes and underline the observed characteristics with more detailed explanations.

3. Measurement Setup and Methodology

3.1. Experimental Facility

The Large Engine Research Facility (LERF), located at the Paul Scherrer Institute (PSI) in Villigen, Switzerland, was designed and built for research into low emission technologies as well as new turbo-charging and combustion concepts on marine diesel engines. The test engine used for the investigations is a Wärtsilä 6L20CR, 4-stroke, medium speed marine Diesel engine with a common rail fuel injection system from L'Orange GmbH. The main engine specifications are listed in Table 1.

Table 1 Test engine specification

Bore	*mm*	200
Stroke	*mm*	280
Number of Cylinders		6
Displacement Volume	*l*	8.8 (52.8)
Compression Ratio		16
Nominal Speed	*rpm*	1000
Rated Power	*kW*	1080 (1278 kVA)

The existing control and measurement equipment allows steady-state and transient exhaust gas measurements, as well as fast in-cylinder and manifold pressure indication. The engine has been modified to allow variable inlet closure and the valve timing was changed to earlier closing (Miller cycle) above 50% load. Furthermore, the original turbo charger system has been changed to a prototype two-stage turbocharger system (from ABB Turbo Systems Ltd), to be able to achieve higher boost pressures in order to compensate the power output reduction caused by the earlier inlet valve closure.
Figure 1 shows an overview of test engine and plant facilities. More information about the engine setup and past experiments can be found in [16-22].

Figure 1 View of the LERF test engine

3.2. Exhaust Gas and Particulate Analysis

The exhaust gases are sampled directly in the exhaust pipe and analyzed with an FTIR spectrometer (AVL SESAM). The device allows simultaneous and time-resolved measurement of multiple species via a broad band spectrum analysis of the exhaust gas (spectral resolution of 0.5 cm-1) and a sampling rate of 1 Hz.
The particulate mass information was obtained by using an AVL Smoke Meter. This filter-based measurement device estimates the soot mass concentration by measuring the paper blackening with a reflectometer (detection limit 0.02 mg/m^3, accuracy 3% of measured value).

Figure 2 Exhaust gas analytics and soot measurement setup

The particle number measurements have been performed using a Cambustion DMS500 MkII rapid response engine particulate analyser. The DMS500 uses a high voltage discharge to charge each soot particle proportional to its surface area. Charged particles are introduced into a classification section with a strong radial electrical field. This causes the particle to drift through a sheath flow toward the electrometer detectors. Particles are detected at different distances down the column, depending upon their aerodynamic drag/charge ratio. Outputs from the 22 electrometers are processed in real-time at 10 Hz to provide spectral data and other metrics. The device provides particle size measurement from 5 nm to 1 µm.

3.3. Exhaust Gas Recirculation – Semi-Short Route Setup

Medium speed diesel engines with high turbocharging efficiencies have positive scavenge pressure, which does not allow high pressure EGR to be directed from the exhaust manifold to the intake without the use of a pumping device. The two-stage turbocharger system installed, facilitates the application of the so-called semi-short route (SSR) EGR setup [23,24], which is a promising concept to allow EGR in positively scavenged engines.
With the SSR setup the exhaust gas recirculation is made available by directing part of the exhaust gas from the high pressure exhaust manifold to the intermediate pressure manifold. The exhaust gases are introduced between the intermediate charge air cooler (ICAC) and the high pressure compressor, and are controlled via a pneumatically driven throttle valve. The recirculated exhaust gases along with the charge air are then compressed in the high pressure compressor (HPC) of the second turbocharger stage. The setup is completed by the installation of an EGR cooler (EGRC) in the recirculation stream between exhaust and inlet manifold.
The EGR rate is calculated using the measurement of CO2 concentration in the intake, exhaust and ambient:

$$EGR[\%] = \frac{CO_{2,intake} - CO_{2,ambient}}{CO_{2,exhaust}}$$

The ambient and intake measurements are obtained with a non-dispersive infrared sensor (NDIR) and the exhaust concentration is measured via the FTIR device. Figure 2 shows a schematic of the engine air-path including the installed semi-short route EGR system.

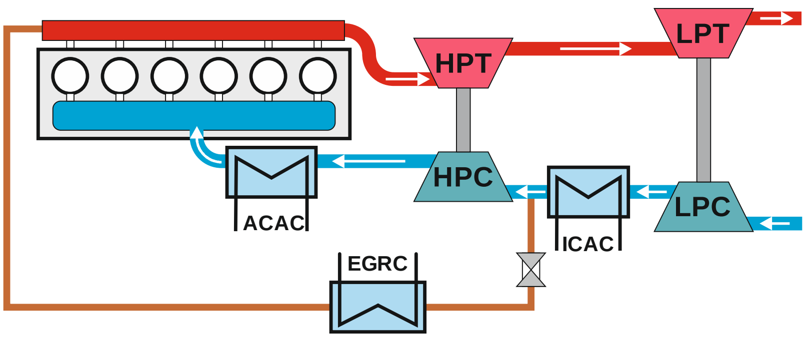

Figure 3 Schematic of the engine air-path setup, showing the semi-short route EGR system

3.4. Water-in-Fuel Emulsion System

The WFE is introduced into the fuel system via a prototype system, which is able to mix the water online in the fuel supply line just before the high pressure pump. This application has been designed in-house and built to provide a high degree of homogenization between water and fuel.
In Figure 4, the schematic of the prototype WFE system installed on the engine. The installation consists of a water supply tank, water pump and water injection nozzles connected to the emulsifier. In addition, the fuel and water mass flow measurement system is depicted, which determines the fuel flow rate upstream of the emulsifier to ensure an accurate acquisition of the engine fuel consumption.

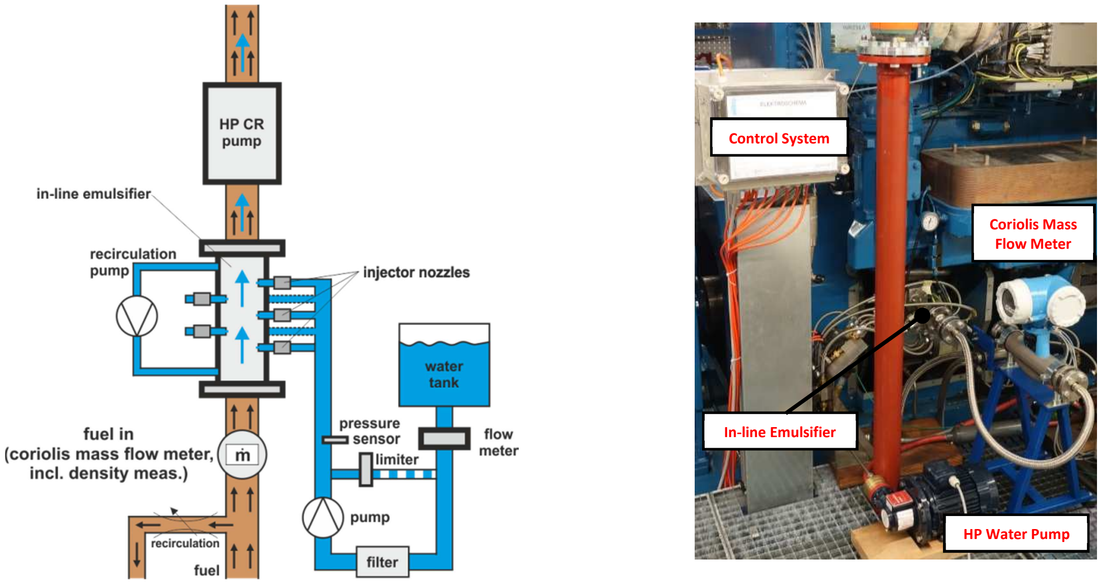

Figure 4 Schematic of the prototype WFE system, showing the water supply, the emulsifier and the fuel lines

Water is injected at high pressure (12-14 bar, compared to the fuel line pressure of 6 bar) to ensure high water injection velocities. The injected water is directed onto strain plates opposing the injection nozzles. This impingement further reduces the water droplet size and secondly helps to initially distribute the water droplets over the fuel line cross-section, by having a small angle between the strain plate normal and the injection axis. The WFE setup incorporates several advantages as it allows a very precise and fast control of the water mass fraction as well as a quick variation of the water mass fraction according to demand. The system allows quick switch-off in order to protect the fuel system components (e.g. injectors) from corrosion. Furthermore, such an on-line preparation has the additional benefit of avoiding the utilization of additional additives (surfactants) for stabilizing the water-in-fuel emulsion. Investigation of the emulsion composition showed that droplet sizes below 10 µm can be achieved. More detailed information on the layout and design of the WFE setup can be found in [22].

3.5. Fuel Consumption Measurement

Fuel consumption measurement is intricate, especially when using fuel-water emulsions. This is not at least because of the utilization of various measurement devices that sums-up inaccuracies for the final result. Direct fuel measurement was performed using two flow meters. Coriolis flow meters were chosen due to their very high accuracy (error <0.15% over the nominal measurement range) and their ability to measure mass flow rate directly, independent of density (the density of the fuel changes with temperature and with the addition of water). For the analysis of the engine inlet fuel flow, a flow meter is located in the engine fuel supply, after the fuel recirculation valve and before the emulsifier. This allowed the direct measurement of the total neat fuel supply to the engine without the addition of water, with an error of <0.15%. The engine-out fuel flow is determined by using a mass flow meter measuring in the return leak fuel stream after the injectors, with an error of <0.1 %. After the device, the leak fuel line was directed to a waste tank, in order to ensure the emulsion did not mix with the neat fuel. In order to ensure normal engine and injector operation when using WFE, a fuel line pressurization system, which uses air pressure and a pressure regulation valve to pressurize the return line, was used.

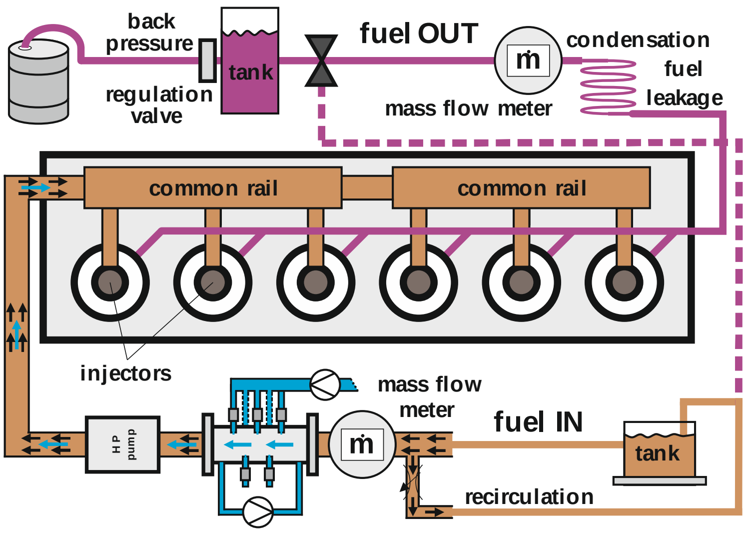

Figure 5 Schematic of the fuel systems, showing supply (neat) fuel (in brown) and control leak fuel (neat fuel or emulsion, in purple)

Using the neat fuel flow rate measurement from the primary flow meter, in combination with the water flow rate measurement from the emulsifier system, it was possible to estimate the water percentage in the leak fuel, and thus, subtract it from the total flow measured in the second flow meter to deduce the neat fuel flow out of the engine.

4. Results and Discussion

The measurements obtained from the engine tests at the LERF test bed are presented in the following sections. The influences of the main engine performance tuning settings, rail pressure and shift of start of injection (SOI) on the exhaust gas emissions as well as engine performance will be discussed. Furthermore, the particulate emission is analysed in detail and the corresponding particle number distribution will be shown.

In order to comply with the future TIER III regulation on exhaust gas NO_x emission, the engine has been operated with 23% exhaust gas recirculation to achieve the demanded 2.2 g/kWh NO_x emission at the nominal speed of 1000 rpm. The EGR intercooler cooling flow has been adjusted to match the temperature before the high pressure turbine to a similar level as without exhaust gas recirculation.

All investigations have been measured at 50% engine load, where the intake valve timing has been adjusted to earlier closing (Miller cycle). At the moment the soot emission is not regulated but first overall emission levels are under discussion.

From the comprehensive measurement campaign, the focus of the results in the report lays on the influence of the water content in the fuel for 5 and 10wt% and the effects of the main engine tuning parameters rail pressure, 1000 bar (reference) and 1500 bar, as well as start of injection, 10±3°CA bTDC.

4.1. Exhaust Gas Emissions and Engine Performance

The exhaust gas emissions have been corrected according to the ISO 8178 international standard to account for the temperature as well as humidity of the intake air.

The analysis of the heat release characteristics have been performed with the 0D-Simulatioin software GT-Power. Due to several collaborations among PSI and FHNW a profound knowledge basis with the

application of this tool to the LERF engine could yield to consistent and sound results. For the heat release study the three pressure analysis burn rate calculation (TPA) has been used. Herein, the apparent heat release rates (including burn rate etc.) is calculated with the input of the in-cylinder cylinder pressure measurement as well as exhaust and intake pressure traces. Furthermore, the injected mass and rate is an input parameter for the TPA. To achieve the best possible accuracy and significance on the results, actual injection rates measurement of the injection valves have been interpolated to the desired rail pressure levels used in the measurement campaign.
For the evaluation of the engine performance data, the operation of the engine with WFE has been taken into account in the mass flows and lower heating values for the fuel consumption/efficiency calculation as well as heat release analysis.

4.1.1. NO_x – Soot Trade-off

The influence of water addition to the neat diesel fuel on the emission characteristics under EGR operation at 50% load is shown in Figure 6 as a NO_x – Soot trade-off plot. Besides the operation on the reference rail pressure of 1000 bar, the injection pressure level has been elevated to 1500 bar. The rail pressure affects the mixture formation as it improves the mixing of fuel and air during the injection. Furthermore the start of injection has been varied by ±3°CA from a reference timing of 10°CA bTDC.

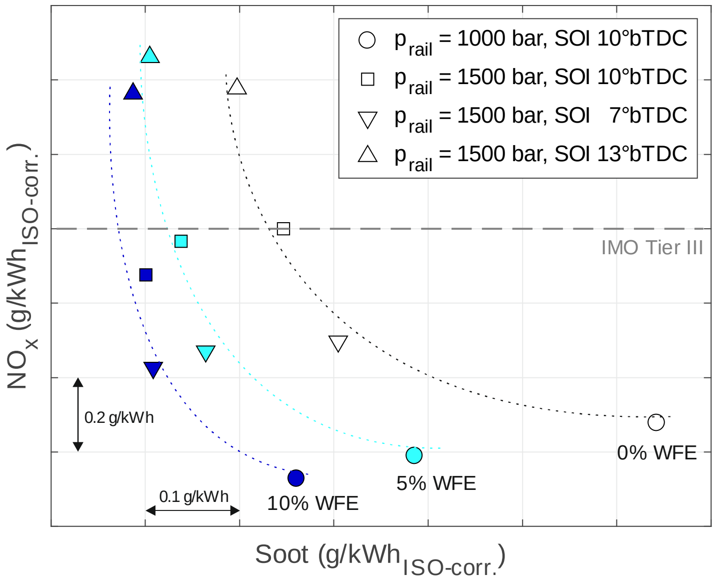

Figure 6 NO_x and soot emission with WFE variation for 1000 and 1500 bar rail pressure including SOI variation 10° ± 3°CA bTDC at 50% load and 23% EGR operation

The experiments of NO_x and soot emissions with neat fuel show the well-known behaviour of an increased NO_x emission when the injection pressure is elevated. On the other hand, the soot emissions are decreasing with higher injection pressures. The adjustment of the SOI to earlier (+3°CA bTDC) further follows the trade-off behaviour of NO_x and soot whereas a shifting of the injection time has an opposed effect, see e.g. [25]. The addition of water to the fuel is lowering both the NO_x as well as soot emissions for the two investigated rail pressures. The effect of the WFE is mainly on the reduction of soot and for the NO_x in a less pronounced manner recognizable. This influence is also observable for the variation of the start of injection time. Only the NO_x reduction for the 1500 bar and (13°CA bTDC) injection time is not consistent, meaning also slightly higher NO_x emission were observed. Overall, the EGR operation in combination with the 10% WFE fuel and the increase of the rail pressure is able to reduce the soot emission for roughly 0.5 g/kWh (-85%) while not exceeding the IMO TIER III NO_x emission limitation of 2.2 g/kWh.

4.1.2. Fuel Consumption and Efficiency

Figure 7 presents the brake specific fuel consumption (BSFC) and the corresponding efficiency data with regard to the rail pressure variation and the WFE operation for a constant SOI of 10°CA bTDC and 23% EGR engine operation at 50% load. As mentioned in the previous section, the BSFC and engine efficiency were measured directly by the difference of the engine fuel in- and out-flows.

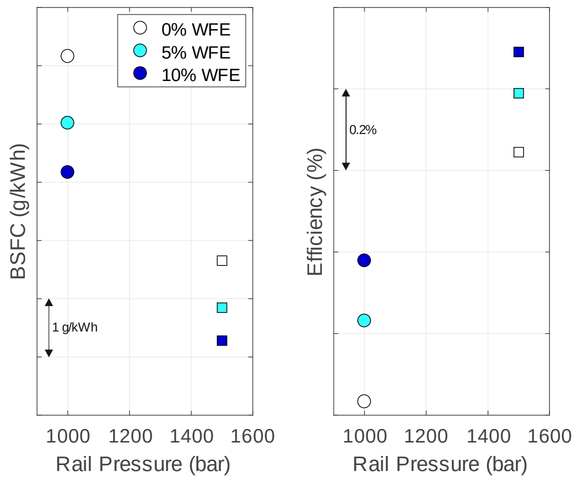

Figure 7 BSFC and efficiency variation for 1000 and 1500 bar rail pressure including at SOI variation 10°CA bTDC 50% load and 23% EGR operation

It can be recognized that the rail pressure elevation is beneficial for the BSFC and hence, also for the engine efficiency. The operation with WFE shows an additional reduction of the BSFC for both of the investigated rail pressure levels. Therefore, also the engine efficiency is affected in a positive manner. The addition of water into the inlet fuel stream can decrease the fuel consumption of up to 2 g/kWh and in combination with the rail pressure increase a benefit of roughly 5 g/kWh can be observed. The corresponding efficiency increase is about 0.85% when the engine is operated with 10% WFE and 1500 bar rail pressure. With this engine configuration (EGR and 2-stage turbocharging) the consumption at full load (100%) is roughly 208 g/kWh.
The engine is equipped with various sensors (flow, temperature) in order to allow studies on the energy balance (heat losses) of the engine. Earlier investigations [26] (but only with 5% WFE), where the engine energy losses have been characterized, suggest that the increase of the rail pressure leads to a reduction of all heat losses at the engine apart from the high temperature cooling losses. When the fuel has been changed to WFE, a slight decrease of all heat losses was observable. Especially, the losses to the exhaust gas and the EGR cooling system were reduced. It is assumed that the reduced air flow (brake specific air consumption) [22] and hence, the decrease of the turbocharger boost pressure is beneficial. Furthermore, the WFE change the ratio of the specific heat capacities of the charge air.

4.1.3. Heat Release Analysis

The heat release analysis is discussed by presenting the burn rates as well as injection rates, both normalized by the total amount of the injection fuel, in Figure 8. On the left hand side, the data for the

1000 bar injection pressure is show and on the right, the results for the elevated rail pressure experiments can be seen. The engine has been operated with a constant SOI of 10°CA bTDC and 23% exhaust gas recirculation at 50% load.

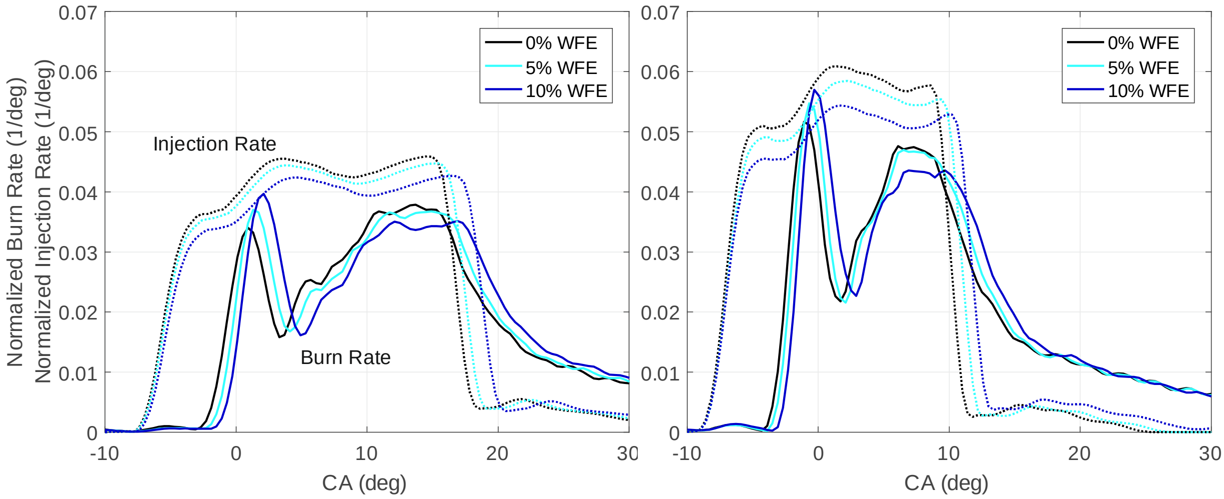

Figure 8 Burn and injection rate (normalized by total fuel) emission with WFE variation for 1000 bar (left) and 1500 bar (right) rail pressure at 50% load, 23% EGR and constant SOI (10°CA bTDC)

The influence of the increasing water mass fraction in the diesel fuel is prolonged the injection duration as the decreasing energy content introduced per time has to be compensated in order to achieve the needed power output at the corresponding load point.

Comparing the neat diesel burn rates for the two injection pressure, it can be seen that the increase of the pressure is affecting the premixed mode of the combustion process to be enhanced. Even though there is a slight decrease in the ignition delay. This results due to the improved spray atomization and its better dispersion, which promotes a quicker mixture formation prior to the onset of combustion. As a consequence, the main combustion duration (mixing-controlled mode of combustion) is decreased according to the shortened injection duration for 1500 bar rail pressure operation.

The addition of water to the fuel is influencing the burn rate to be prolonged due to the injection duration. Furthermore, the ignition delay is increased with WFE as the latent heat of vaporization and the dilution effect is deferring the physical and chemical ignition process. This leads to a better mixing of the fuel prior to the ignition, which is increasing the proportion of premixed combustion. For both of the rail pressure levels, this effect is adding to the according burn rate with neat fuel. The subsequent combustion behaviour during the diffusion mode of combustion is influenced by the WFE to be reduced.

It is understood that the slight NO_x emission reduction by WFE can partially attributed form the combustion phasing (delayed combustion) [22] and the local flame cooling. The soot reduction is suggested to be due to a lower soot formation as the addition of water to the fuel is favourable for the mixing of fuel and air as well as its effect on the spray atomization and flame lift-off length. Furthermore, the water in the flame is dissociated to OH radials which may improve the soot oxidation process.

4.2. Soot Characterization

Additional to the conventional soot mass concentration measurement by a filter-based smoke meter, a particle analyser has been applied at the exhaust. As not only the mass concentration is of importance also the particle number concentration as it gives additional information on the soot characteristics and its health effects.

The diesel particle sizes distribution and its classification are defined in Figure 9. A bimodal character is well established according to the involved particulate nucleation as well as agglomeration mechanisms. The ultrafine and nanoparticle size range is to be considered as most harmful with regard to health aspects.

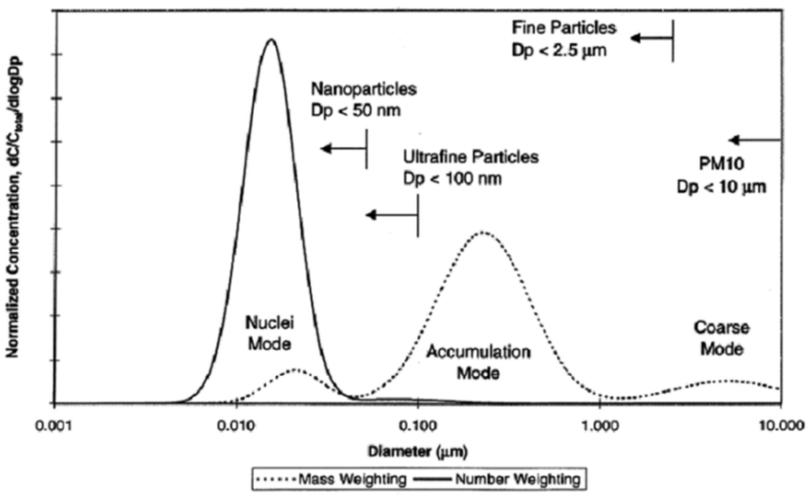

Figure 9 Mass and number weighted particle size distribution and classification [27]

In Figure 10, the particle number size distribution with WFE variation for both investigated injection pressures can be seen. The engine has been operated at 50% load and 23% EGR with a constant SOI of 10°CA bTDC.

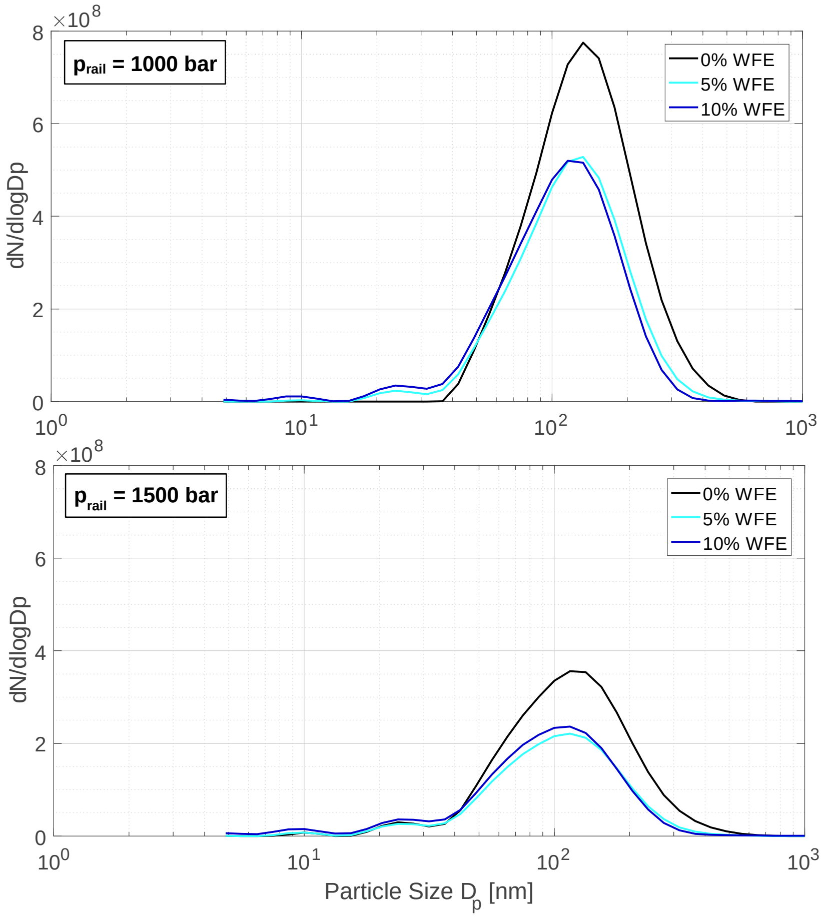

Figure 10 Particle number size distribution with WFE variation for 1000 bar (top) and 1500 bar (below) rail pressure at 50% load, 23% EGR and constant SOI (10°CA bTDC)

Overall, the largest share of the soot particles is detected in the accumulation mode due to the operation with exhaust gas recirculation. When comparing two injection pressures, the amount of emitted particles is clearly reduced when the injection pressure is increased from 1000 bar to 1500 bar. But the modal characteristic is preserved.

The addition of the water to the fuel is reflected in the particle size distribution as it decreases the peak of the accumulation mode. Furthermore for the WFE 10% case, a slight shift to this peak to a smaller particle size can be recognized. With regard to the ultrafine and nanoparticle size range, a marginal increase is measured when the exhaust gas of WFE operation has been analysed.

Interestingly, the WFE 5% measurements show a similar distribution as for WFE 10%. For the 1500 bar measurements, the peak of the accumulation mode is even slightly below. On the other hand, it can be observed that the WFE 5% distribution for both of the rail pressures show an increased amount of the largest particles compared to the WFE10%.

The explanation of this effect is still under investigation and additional measurement and evaluations have to be considered.

4.3. Effect on Injection System Components

During the experiments, certain issues occurred with regard to the injection system when operating with WFE. Note that the injection system has not been designed and was not approved for WFE operation by the manufacturer (L'Orange).
After inspection of the injectors, overall no corrosion was observed but certain parts were found with severe erosion. On the contrary, the high pressure pump did not show any signs of erosion, corrosion or wear.
Despite the very high promise shown from the combination of EGR and WFE, the addition of water in the fuel created significant problems for the engine Common Rail fuel injection system. It has to be noted that the applied system has not been specifically designed for operation with water-in-fuel emulsions. The injection valves have not been "officially" approved by the supplier for such an application. During the engine operation with WFE, the control leak fuel rate has been observed to gradually increase. After the measurement campaign, the injectors had roughly 30 hours of operation with WFE (some injectors have more WFE operation hours and some less), with water contents ranging from 5 to 10 wt%. For inspection, the injectors were removed and sent to the L'Orange.
A similar outcome of the inspection as for earlier investigation has been found. There were no significant damages from corrosion or other sources to the main needle and main valve sealing surfaces. In contrast, significant damage was observed on the pilot (control) valve pin and seat. Figure 11 shows the injector pilot (control) valve and pilot valve seat for one of the injectors after operation with WFE for an earlier measurement campaign with about 50h or WFE operation [22].

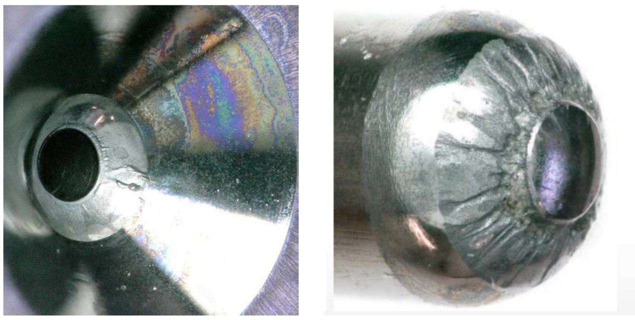

Figure 11 State of injector pilot valve pin (left) and seat (right) after roughly 50h operation with 5-15 wt% WFE, showing heavy erosion and blow hole marks due to cavitation [22]

In the pictures, heavy erosion and blow-hole marks are clearly visible both on the pin and seat, probably caused by very heavy cavitation in this part. Cavitation is understood to be caused by the very high pressure drop over the pilot valve, which in combination with the increased temperature (due to the heating for the combustion chamber) leads to the formation of cavitation bubbles from the water in the WFE. This points to a design of the valve which is not optimal for operation with water. The result of the cavitation was the observed excessive leakage of fuel during operation, which is expected to eventually lead to severe changes in the injector performance, and ultimately to uncontrollable opening of the injector main valve [22].
Apart from the damages mentioned above, no other problems were observed during and following the operation with water.

In all, it is clear that significant adjustments to the injection system need to be performed to allow long-term operation of the engine with WFE. In particular, a redesign of the pilot/control valve and seat area should be undertaken, to minimize cavitation when running with WFE. This could be aided by a reduction in temperature of the whole system, since this would reduce the vapor pressure of the water. Naturally the cooling method is only applicable to non-HFO applications.

5. Publications and Information Dissemination

Following the successful completion of project the scientific highlights will be published in a peer-reviewed journal. The results and understanding of the underlying effects elaborated during the CCEM “Low-NOx” project and dissertation of D. Wuethrich, where the WFE characteristic have been investigated by laser diagnostics, a detail understanding of the fundamental phenomena as well as knowledge transfer to real engine application is given.

6. National and International Collaboration

The Large Engine Research Facility has a good relationship to industry partners regarding the large engines technologies (e.g. ABB Turbocharging Systems) and its accompanying fields such as exhaust aftertreatment (e.g. Hug Engineering) and measurement technologies. A close and fruitful collaboration with the Aerothermochemistry and Combustion Systems Laboratory (LAV) of Prof. Boulouchos at ETHZ as well as with the Northwestern School of Applied Sciences (FHNW) and its group of Prof. Herrmann and Prof. Gossweiler has been established. The latter is a preferred partner for example with regard to the data evaluation in the framework of GT-Power modelling (besides other various collaboration activities).

This project is based on work which has been elaborated in the HERCULES-C as well as HERCULES-2 project [9]. These are large-scale international R&D projects in the frame work of the Horizon 2020 program. The main partner with regard to the research work is Wärtsilä Finland Oy.

7. Conclusions and Outlook

During the project the investigation of the combined application of exhaust gas recirculation and water-in-fuel emulsion in regard to medium speed diesel engines could be successfully completed. A simultaneous abatement of NO_x and soot while even slightly increasing the engine efficiency has been documented. Operating the engine with 23% EGR reduced the NO_x emission below the IMO TIER III regulation levels and applying low content water-in-fuel emulsion (up to 10wt%) reduce the soot emission up to 85% with the according injection pressure and start of injection time tuning.
Moreover, the particulate emission has been characterized not only with regard to mass concentration but also particle number size distribution. Hence, a further insight in to the characteristics of the soot emission with WFE could be reported.
Besides the multiple benefits seen by the combined application of EGR and WFE, the injection system has been affected by (mainly) cavitation effects occurring due to the water in the fuel.
Based on the results and findings and the comprehensive data set further evaluations will be performed in order to understand the effects on engine efficiency and emissions. Especially, the influence of the low water content to the soot emission will be further elaborated to understand the effects of the water in the fuel on the particulate matter formation and oxidation.

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