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Lowest GHG emissions on medium-speed engines by higher Epsilon and H2 admission to the fuel gas

Dual Fuel / Gas / Diesel

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DOI: https://doi.org/10.5281/zenodo.15191332

ABSTRACT

The LP dual-fuel combustion process, in which the combustion of a premixed air-fuel gas mixture is initiated by a diesel pilot injection, offers great potential for low emission operation of medium-speed marine engines. This combustion process will play a very important role in achieving the long-term climate targets for shipping. Although currently still derived from fossil sources, today, only LNG combines the properties of already having a well established land-based infrastructure, of enabling 100% climate-neutral supply via electrolysis and methanization, and of the ability to use any high proportion of climate-neutral LNG as a drop-in fuel during the transformation process in the next decades. The 1/34DF single-cylinder research engine with a common-rail pilot injection system installed at the University of Rostock offers excellent conditions for investigating this combustion process in detail and developing emission-reducing and efficiency-enhancing measures.

In the ongoing research project TEME2030+, the focus is on reducing greenhouse gas emissions through various individual measures. This paper will take a closer look at two of these individual measures for the LPDF combustion process: Increased compression ratio and admixing hydrogen into the fuel gas.

In previous investigations, a control concept for the use of different gas qualities was developed. An optimized pilot injection strategy allowed fuel gases with widely varying fuel gas compositions to be used with moderate knock levels and high efficiencies without power losses. In the ongoing research project TEME2030+, the control concept was transferred to a different pilot injector concept with a slightly decentralized injector optimized for small pilot injections. The optimized pilot injection strategy enables an increase in the compression ratio in order to increase the thermodynamic efficiency and fundamentally reduce the GHG emissions of LPDF engines. As part of this project, investigations were carried out with increased compression ratio in order to prove the basic applicability and evaluate the GHG reduction potential. The results are presented in this paper.

In addition to the experimental investigations with modified gas compositions using propane and carbon dioxide admixture, the addition of up to 30 vol.-% hydrogen to the fuel gas was also investigated. With increasing hydrogen admixture rates in the natural gas system in the future, the influence on the combustion process of DF engines, for example in stationary power generation, is very important. On the one hand, the hydrogen admixture already leads to reduced CO2 emissions due to the substitution of methane; on the other hand, the hydrogen improves the combustion process behavior of natural gas, so that CH4 emissions are also reduced, which further improves the overall GHG balance. In this paper, the effects of hydrogen on the combustion process will be discussed in detail.

The combination of different technology concepts has to make a significant contribution to reducing GHG emissions. In general, it should be possible to use different fuels or fuel gas compositions in engine applications without having to compromise on efficiency and emissions due to the high degree of fuel flexibility. Alternative concepts, such as the pre-engine separation of carbon through cracker processes, could also be used. This leads to further increasing significance of the effects of hydrogen components in the fuel gas.

1 INTRODUCTION

The low pressure dual-fuel (LPDF) combustion process, in which the combustion of a premixed air-fuel gas mixture is initiated by a diesel pilot injection, offers great potential for low emission operation of medium-speed marine engines. This combustion process will play a very important role in achieving the long-term climate targets for shipping and decentralized power supply. Although currently still derived from fossil sources, today, only LNG combines the properties of already having a well established land-based infrastructure, of enabling 100 % climate-neutral supply via electrolysis and methanization, and of the ability to use any high proportion of climate-neutral LNG as a drop-in fuel during the transformation process in the next decades. DF engines can theoretically reduce CO_2 emissions by around 25 % in comparison to diesel engines due to the high H/C ratio. One problem that can negate the CO_2 advantage is methane slip with its high GWP factor of 28 over a 100-year horizon [1,2].

Medium-speed dual-fuel engines face additional challenges related to efficiency in diesel or dual-fuel part-load operation. One major factor is the relatively low compression ratio (CR) of DF engines compared to conventional diesel engines, which is limited by the risk of knocking combustion. Current designs often compromise CR based on the expected LNG composition, leading to efficiency losses in diesel and dual-fuel part-load operation. Advanced technologies like variable compression ratio (VCR) systems, already implemented in large two-stroke engines by manufacturers such as WinGD, offer promising solutions to improve efficiency and reduce GHG emissions and operating costs [3-6].

The 1/34DF single cylinder research engine with a common rail pilot injection system installed at the University of Rostock offers excellent conditions for investigating this combustion process in detail and developing emission-reducing and efficiency-enhancing measures. In the ongoing research project TEME2030+, the focus is on reducing greenhouse gas (GHG) emissions through various individual measures. This paper will take a closer look at two of these individual measures for the LPDF combustion process: Increased compression ratio and admixing hydrogen into the fuel gas.

While such a VCR system is not available for the single cylinder at the present time, it can be simulated via hardware modifications. Within the research project, investigations with varying compression ratios were carried out to quantify the potential benefit in efficiency and GHG emissions and get a detailed understanding of the effective mechanisms in the combustion process. The aim is to obtain a reliable data basis based on measured experimental values in order to better evaluate the benefits of such a VCR system.

Another option to reduce GHG emissions is to substitute a share of the LNG with hydrogen. This is a promising approach especially for stationary engines. There have been several studies on the effect of hydrogen admixture in different engine types like spark ignited gas engines or high-speed dual-fuel engines. Hydrogen has a high reactivity and therefore leads to shorter combustion durations, therefore higher efficiencies, reduced unburned fuel emissions, higher peak pressures and gradients and knocking [7,8]. The goal within the current research project was to analyze and quantify the effects on a medium-speed dual-fuel engine based on experimental investigations performed on the SCE.

In previous research, investigations with regard to different gas qualities were carried out and a control concept was developed to operate a DF engine with differing gas qualities without derating or excessive efficiency losses. The gained knowledge about the general dual-fuel combustion process and abnormal combustion phenomena like knocking and ringing combustion can be transferred to the investigations within this paper. The effects were investigated separately to evaluate each technology concept individually. In principle, the different measures investigated on the single cylinder engine in various measurement campaigns can also be combined to maximise the benefit and get a holistic view of the potential of LPDF engines [3,9].

By addressing these two measures individually, this research aims to establish a comprehensive understanding of their potential for enhancing LPDF engine performance and advancing sustainable energy solutions.

2 EXPERIMENTAL INFRASTRUCTURE

The Department of Piston Machines and Internal Combustion Engines (LKV) has the opportunity to use one of the largest single cylinder research engines at a European university for the investigation of dual-fuel combustion processes (Bore 340 mm, see Figure 1). The test bed was built up in several phases from 2014 onwards and offers the following key features:

- Pilot fuel system up to 2,200 bar
- Gas mixing unit: natural gas, CO_2, H_2, C_3H_8
- NGC (Natural Gas Chromatograph) for gas quality assessment
- HP (High Pressure) gas supply up to 600 bar
- Methanol & LPG supply possible
- Charge air supply up to 8.5 bar_{abs}
- Charge air heating & humidification
- Open ECU platform
- FTIR for exhaust gas analysis
- Bypass for exhaust gas aftertreatment components
- EGR System, up to 30 % EGR rate at full load

The gas mixing unit was set up in a previous research project and already described in CIMAC paper 018 from 2023 with the focus on propane and carbon dioxide admixture to simulate different gas qualities from around the globe [9]. In the current research project, TEME2030+, the capability of hydrogen admixture was added to the gas mixing unit. The hydrogen can be taken from a 200 or 300 bar storage trailer or bundle. The gas mixing unit is suitable for around 30 vol.-% share of hydrogen at full engine load. At lower engine load higher fractions are possible. During the engine operation, the mass fraction of the admixing components is controlled and the volumetric share is measured via the NGC. The measured composition is then used to calculate gas properties like calorific value and minimum air requirement and further results like air fuel ratio and efficiency.

While there are different approaches for variable compression ratios with the most promising being an eccentrically adjustable piston pin, the compression ratio of the research engine used for this paper cannot be adjusted during engine operation [4,5]. Such a system can be simulated on the test bed by using different intermediate plates on the marine connecting rod or different piston crowns. The standard compression ratio of the research engine is 12.75.

The engine's gas injection system uses a low pressure gas admitting valve, which injects the fuel gas into the intake port directly upstream of the inlet valves (PFI = port fuel injection). This technology is currently the most common system for dual-fuel engines. To ignite the fuel gas, a common rail injector, which is only capable of the micro pilot injections required for DF mode and located slightly off-axis and tilted, is used.

The engine is equipped with a freely programmable research ECU based on the PXI platform by National Instruments. It is able to perform online pressure indication and the necessary thermodynamic analysis for next cycle control strategies. The SCE is typically operated with a constant speed of 720 min^{-1} on the generator curve in stationary operation at different load points from 25 % part load to full load. To approach an operation point, the charge air pressure and pilot injection quantity are usually set to a constant value depending on the engine load or respective values depending on the current focus of investigation. The duration of the gas injection, and therefore the injected mass, is controlled by a pm_i controller (mean indicated pressure) implemented in the ECU. The air fuel ratio (lambda) therefore results from the fuel composition and the current efficiency. Deviations in efficiency during one measurement series therefore lead to slight changes in lambda. In addition to the pm_i controller, a CoC controller is typically used to adjust the center of combustion by an adapted pilot injection timing.

Measurement points are recorded at 1 Hz for a duration of 140 s for arithmetic averaging. Higher frequency measurement channels like the in-cylinder pressure are recorded in sync with the crank angle at a resolution of 0.1 °CA (crank angle degrees) for 250 cycles. Characteristic results from the thermodynamic analysis within the pressure trace analysis system are sent to the ECU (e.g. for the pm_i and CoC controller) and the low frequency measurement recording system via CAN bus. Exhaust emissions are recorded with a SESAM i60 FTIR (Fourier Transform Infra-Red), which is able to measure all essential exhaust gas components (e.g. NO_X, CO_2, CH_4, …) simultaneously.

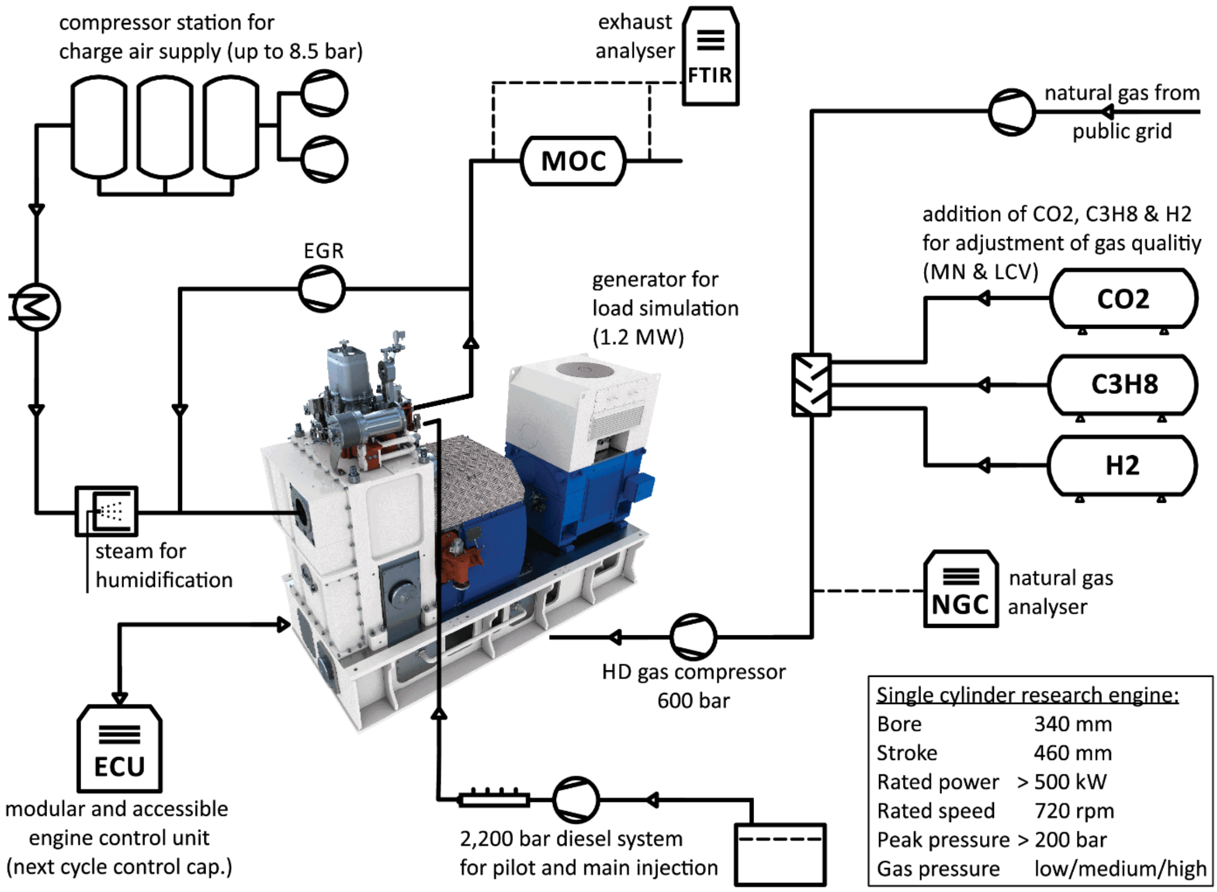

Figure 1. Schematic overview of the experimental infrastructure.

3 EXPERIMENTAL INVESTIGATIONS ON THE SCE

The main goal of the current research project TEME2030+ is to reduce GHG emissions through various different technologies available for the single cylinder engine and relevant in future development of marine or stationary applications. For this paper, two of the technologies mentioned in chapter 2 are selected for a more detailed analysis. On the one hand, hydrogen can be mixed into to the natural gas to substitute hydrocarbons and optimize the combustion process. This measure is described in chapter 3.1. On the other hand, the compression ratio can be increased to improve part load efficiency. The effectiveness of this measure is analyzed in chapter 3.2.

Other measures to reduce GHG emissions in medium-speed dual-fuel engines that are under investigation within the current research project TEME2030+ using the described research engine are subjected to detailed examinations in further contributions:

- Paper No. 178: Experimental Long-Term Study on the Methane Reduction Potential of a Methane Oxidation Catalyst with Palladium Coating on a Medium-Speed Dual-Fuel Research Engine
- Paper No. 156: Numerical and Experimental Analysis of Gas DI Operation on a Medium Speed Dual Fuel Marine Engine
- Paper No. 174: Experimental characterization of a MPDI gas injector for 4-stroke applications

3.1 Hydrogen Admixture into Natural Gas

Hydrogen blending with natural gas is a promising approach that is becoming increasingly important in making the energy supply more sustainable and reducing CO_2 emissions. The combination of hydrogen and natural gas has the potential to offer a flexible solution to accelerate the transition to a greener energy future. Hydrogen can be admixed into the natural gas grid as a potential zero emission energy carrier, making use of the infrastructure and increasing the share of renewable energy at the same time. Currently, up to 10 vol.-% hydrogen can be added to the natural gas grid in Germany with pilot projects and future developments considering 20 vol.-% or higher hydrogen fractions [10].

Therefore, the application of a medium-speed dual-fuel engine is to be investigated regarding the technical requirements and to quantify the potential of hydrogen admixture with the focus on combustion process development. Therefore, a detailed understanding of the processes and mechanisms during the usage of hydrogen-blended natural gas is needed.

Hydrogen stands out with an extremely high reactivity, characterized for example by the minimum ignition energy, the wide flammability limits and the high laminar burning velocity. Table 1 shows some basic fuel properties of hydrogen compared to methane, being the main component of natural gas. On the one hand, this is advantageous for the usage in internal combustion engines, but on the other hand also creates risks with regard to combustion anomalies like knocking combustion.

Table 1. Fuel properties of hydrogen compared to methane [11].

Property	Unit	H_2	CH_4
Lower heating value	MJ/kg	120	50
Energy density[1,2]	MJ/m³	10,8	35,9
Air-fuel-ratio (stoich.)	kg_{fuel}/kg_{air}	34.3	17.2
Min. Ignition energy	mJ	0.02	0.29
Autoignition Temperature[1,4]	°C	585	595
Flammability limits[1,2,4]	vol.-%	4-75	5-15
	λ-range	0.13-10	0.6-2
Laminar burning velocity[1,2,3,4]	cm/s	230	42
Methane number	-	0	100

[1]at 1.013 bar
[2]at 25 °C
[3]at λ=1
[4]in air

The mass fraction of hydrogen is the directly adjustable parameter within the gas mixing unit of the research engine. The correlations with the volumetric and energetic fractions, which are typically used parameters in the consideration of natural gas systems or the overall view of energy demand, are shown in figure 2, based on measurements with the natural gas chromatograph at the test bench.

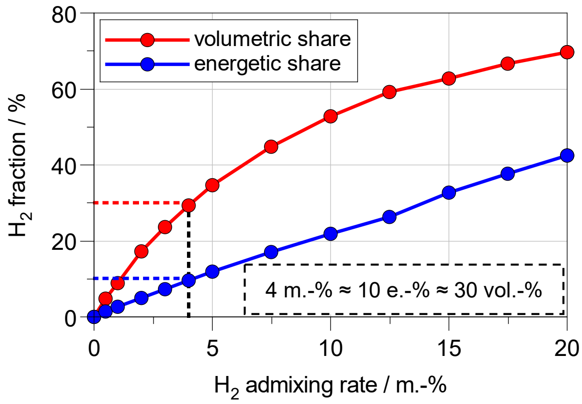

Figure 2. Volumetric and energetic fraction of hydrogen over mass fraction.

To achieve the required understanding of the effects of hydrogen admixture, a measurement series with a variation of hydrogen mass fraction was carried out at different load points with constant operating conditions. After that, a more detailed measurement series regarding the impact of hydrogen admixture on the effect of different operating parameters available to adjust the combustion process was performed.

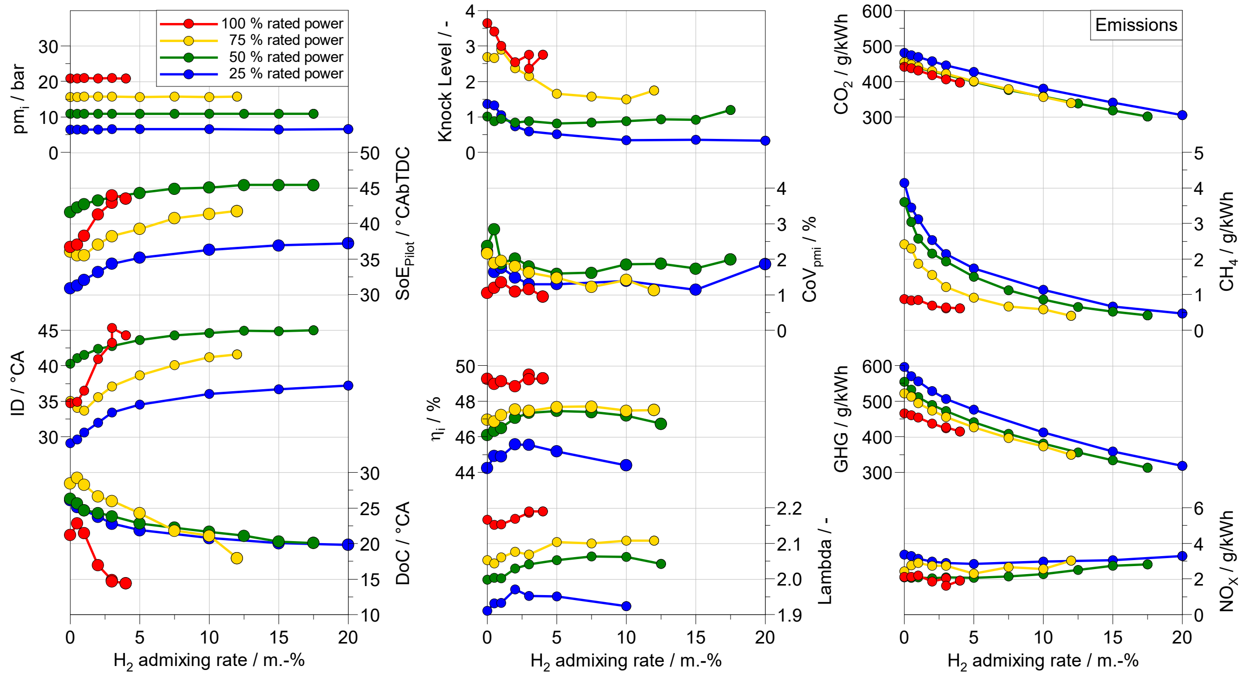

Figure 3. Investigation of the effects of varying hydrogen admixing rates on engine operation at different load points with a constant center of combustion and other operating parameters held constant according to table 2.

Figure 3 shows a measurement campaign with a variation of the hydrogen admixture rate at different engine load points. At full load, the hydrogen fraction was increased to 4 m.-%, which corresponds to ca. 30 vol.-% or 10 % energy content. As the mass flow in the gas mixing unit is the limiting factor, higher admixing rates were possible at lower load, with a maximum of 20 m.-% which equals 70 vol.-% or 42 e.-% respectively. The valve timing was adjusted during the measurement campaign with light miller in the two lower load points and strong miller for 75 % and 100 % engine load.

The other operating parameters like pilot fuel quantity (PQ) and rail pressure (p_{Rail}), charge air pressure (p_{CA}) and temperature (T_{CA}) and the center of combustion were kept constant throughout each load point and can be taken from table 2.

The lower volumetric energy density with higher hydrogen fractions leads to more air displacement, as a greater volume of fuel gas must be admitted via the intake port. The air mass flow through the intake valves therefore is reduced as the air pressure is held constant. Due to the higher calorific value and hydrogen's lower density the fuel gas mass flow is however also reduced. These effects approximately cancel each other out, so that the air fuel ratio only increases slightly.

Table 2. Operation parameters for the measurement series from figure 3.

Load	%	25	50	75	100
pm_i	bar	6.4	10.8	15.6	20.8
CoC	°CAaTDC	8	8	8	8
p_{CA}	bar_{abs}	1.25	2.05	3.00	4.03
T_{CA}	°C	45	45	45	45
PQ	mg/shot	60	70	70	70
	e.-%	≈4.5	≈3.3	≈2.2	≈1.7
p_{Rail}	bar	1200	1200	1200	1200
CR	-	12.75	12.75	12.75	12.75

The following effects can be observed for increasing hydrogen shares in figure 3:

- Duration of combustion decreases due to the high flame speed of hydrogen. Steeper gradients can be observed at higher engine load.
- Ignition delay was extended by an advanced pilot timing to keep the CoC constant.
- Engine knock is reduced - contrary to expectations - probably due to the shorter DoC.
- The coefficient of variation of the mean indicated pressure (CoV_{pmi}) decreases slightly with lower substitution rates but seems to increase at higher admixing rates. The value stays below 3 %, so the engine could be operated stably throughout the whole measurement series.

- Small amounts of hydrogen lead to higher efficiency at lower load.
- Lambda increases slightly at lower admixture rates due to the increased efficiency while keeping pm_i and charge air pressure constant and the described correlation between volumetric and gravimetric energy density.
- The results for efficiency and lambda for operation points with 15 m.-% hydrogen or more are not shown due to the gas chromatograph being unavailable, which affects the calculated values for calorific value and minimum air requirement.
- CO_2 emissions decrease linearly due to the substitution of hydrogen for natural gas. The reduction approximately corresponds to the energy share of hydrogen (Figure 2).
- Methane slip is reduced especially at low substitution rates. This effect is stronger at lower loads.
- The total GHG emissions (Methane considered with a factor of 28) can therefore be reduced overproportionally.
- NO_X emissions were nearly constant over each measurement series being near the IMO Tier III limit. The limit can be reached by optimization of other operation parameters but was not in the focus of the current measurement campaign.

To summarize, the high flame speed of hydrogen makes adaptions of the pilot strategy necessary. On the research engine, the CoC controller of the programmable ECU was used to achieve this. If the pilot injection were not advanced, the faster combustion would lead to earlier CoC and an increase in knock. Hydrogen admixture to the natural gas can be used to reduce the CO_2 and methane emissions. On the one hand, the CO_2 emissions are reduced through the substitution of natural gas and therefore higher H/C ratio of the fuel itself. On the other hand, hydrogen supports the combustion and improves the burn-through especially at part load, so even small amounts of hydrogen can reduce the methane slip significantly.

Table 3 shows the reduction of CO_2, CH_4 and GHG emissions due to the admixture of 5 m.-% hydrogen during part load operation points and 4 m.-% at full load. The reduction of CO_2 approximately equals the energetic fraction of hydrogen according to figure 2. Methane slip is reduced by around 60 % at part load and 30 % at full load. Due to the high GWP factor of methane, the total GHG emissions can therefore be reduced by ca. 20 % at part load and 11 % at full load. The difference between partial and full load can be traced back to the shorter DoC and therefore relatively low methane slip at full load in general. The better burn through is also reflected in an efficiency benefit of around 1 to 1.5 % at part load and a higher operation stability due to the beneficial combustion properties of hydrogen, while knocking poses no problem when the combustion controller is accordingly fitted.

Table 3. Emission reduction due to the usage of 5 m.-% hydrogen (4 m-% at full load) corresponding to figure 3.

Load	%	25	50	75	100
CO_2	%	-11	-12	-12	-10
CH_4	%	-58	-58	-62	-30
GHG_{F28}	%	-20	-20	-18	-11

While these measurement points were recorded with a basic set of engine parameters, detailed investigations on the parameters CoC and lambda were also performed to improve the understanding of the combustion process and possibly maximise the potential benefit of hydrogen admixture for this type of dual-fuel medium-speed large engines. Figure 4 shows a variation of the CoC with hydrogen admixing rates up to 10 m.-% at 50 % engine load.

Table 4. Operation parameters for investigations of the effects of CoC and lambda in figures 4 to 6.

Variation Figure	- -	CoC 4	CoC 5	Lambda 6
Load	%	50	100	50
pm_i	bar	10.8	20.8	10.8
CoC	°CAaTDC	varied	varied	8
H_2 fraction	m.-%	0-10	0-4.5	0-10
p_{CA}	bar_{abs}	2.05	4.00	varied
T_{CA}	°C	45	45	45
PQ	mg/shot	70	70	60
	e.-%	≈3.3	≈1.7	≈2.6
p_{Rail}	bar	1200	1200	1200
CR	-	12.75	12.75	12.75

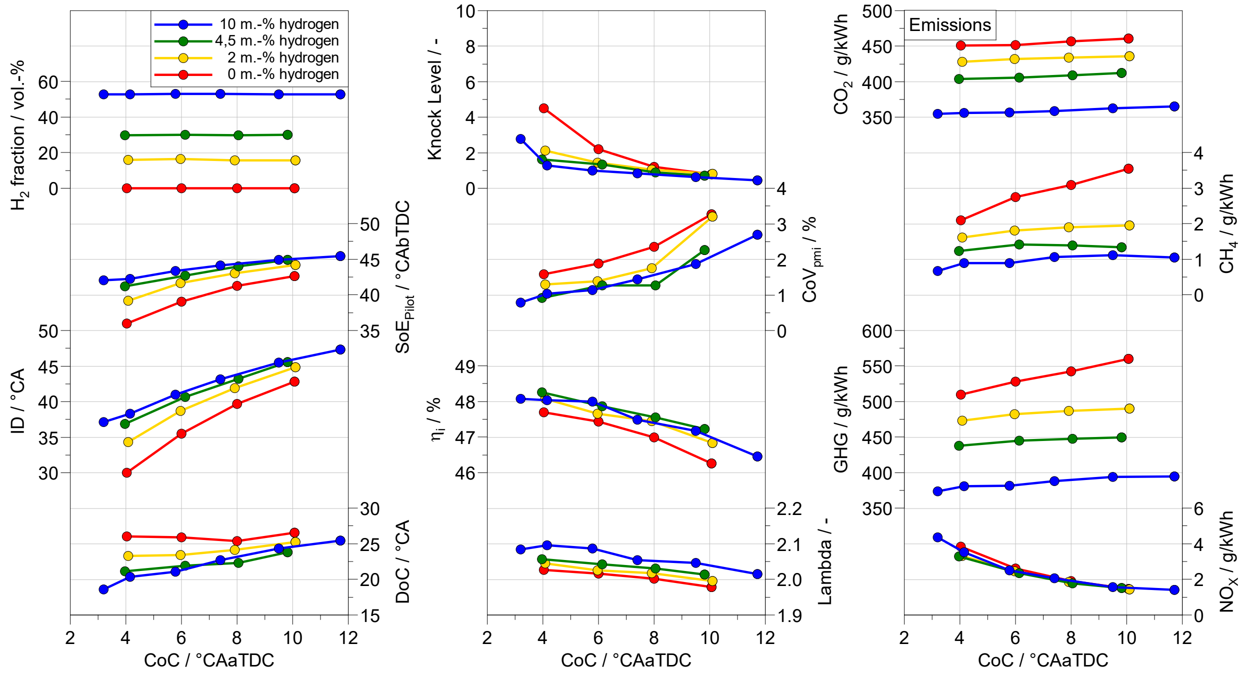

Figure 4. Effects of center of combustion at different hydrogen admixing rates at 50 % engine load with operating parameters according to table 4.

During this measurement series, pilot quantity, rail pressure and charge air pressure were kept constant. The center of combustion was varied using the timing of the pilot injection. The respective operation parameters are shown in table 4.

Without hydrogen admixing, the CoC shows the typical effects for DF engines [3,12]: A late pilot injection leads to short ignition delays, high values for efficiency, knock and NO_X emissions at early CoC's. Late CoC's typically produce more instable engine operation (high CoV_{pmi}), more methane slip and lower efficiency. To keep CoC constant at increasing hydrogen admixture, the pilot injection had to be advanced, leading to longer ignition delays, as already observed before.

Noticeable deviations occur in the course of the DoC. Without hydrogen admixture, the DoC stays nearly constant over the variation of CoC, so the whole combustion process gets shifted to later timings. With higher admixing rates, the CoC shows a clear impact on the DoC, with a shortening of over 5 °CA from the latest to the earliest CoC at 10 m.-% hydrogen. Meanwhile, at the latest CoC, the DoC is still nearly on the same level as in the measurement series without hydrogen admixture. The high flame speed of hydrogen therefore comes into play particularly at earlier CoC's and therefore higher combustion temperatures due to an increase of the maximum fuel conversion rate.

The earlier observed effects of hydrogen leading to lower knock levels, lower CoV_{pmi} and higher efficiency are reflected over the whole range of CoC.

Another difference appears in the observation of the emissions. While the typical NO_X-CH_4-tradeoff occurs in the measurements without hydrogen, this conflict gets reduced with higher admission rates. The already lower methane slip at early CoC's nearly stays at the same level with later CoC's. Meanwhile, the NO_X emissions are lowered during later combustions and are not clearly affected by the hydrogen admixture. Therefore, the overall GHG emissions do not increase that much if the combustion has to be retarded to consider IMO Tier III limit for NO_X emissions or knock limit. At full load, where knocking is more relevant, similar effects could be observed (Figure 5).

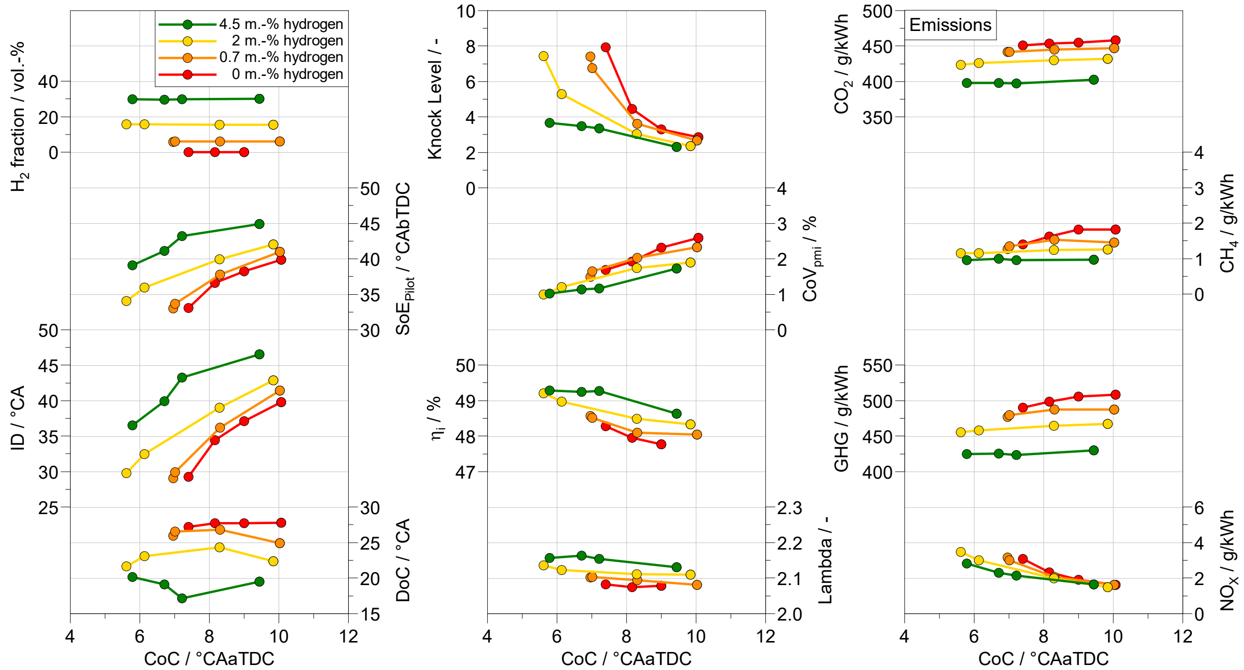

Figure 5. Effect of varying center of combustion at different hydrogen admixing rates at 100 % engine load with operating parameters according to table 4.

At full load, no clear impact of the CoC on the DoC could be observed. Otherwise, the correlations between injection timing, ignition delay and hydrogen fraction correspond to the observations made previously. During the measurement without hydrogen at a CoC of 10 °CAaTDC, an unavailable NGC analysis led to incorrect values for lambda and efficiency, which are therefore not shown.

The effect of the decreased knock level at higher hydrogen fractions becomes very clear at full engine load. With higher hydrogen fractions, the knock level was decreased over the whole range of CoC. Moreover, the effect of increasing knock levels towards early CoC is weakened. This goes along with the trend of the NO_X emissions, that drift apart at early CoC. Therefore, an advanced CoC would be possible to operate the engine with highest efficiency while maintaining similar knock levels and NO_X emissions. However, a cross-influence that must be taken into account here, is the slightly increased lambda with hydrogen admixture.

The effect of lambda on the combustion process at different hydrogen admixing rates is shown in Figure 6. During these measurements at 50 % engine load, the variation of the air fuel ratio was realized by adjusting the charge air pressure. The exhaust back pressure was also adjusted according to a turbocharger characteristic curve. The center of combustion was kept constant by adjusting the pilot injection timing. Other parameters like the pilot fuel quantity or the charge air temperature were kept constant. The respective operation parameters are shown in table 4. During these lambda variations, the engine is typically operated between the knock limit at low values and the misfiring limit at high values, characterized by a CoV_{pmi} of 3 %. During these experiments at 50 % load, the knock limit wasn't reached due to the relatively late CoC at 8 °CAaTDC, therefore the limit was defined by high exhaust gas temperatures and NO_X emissions.

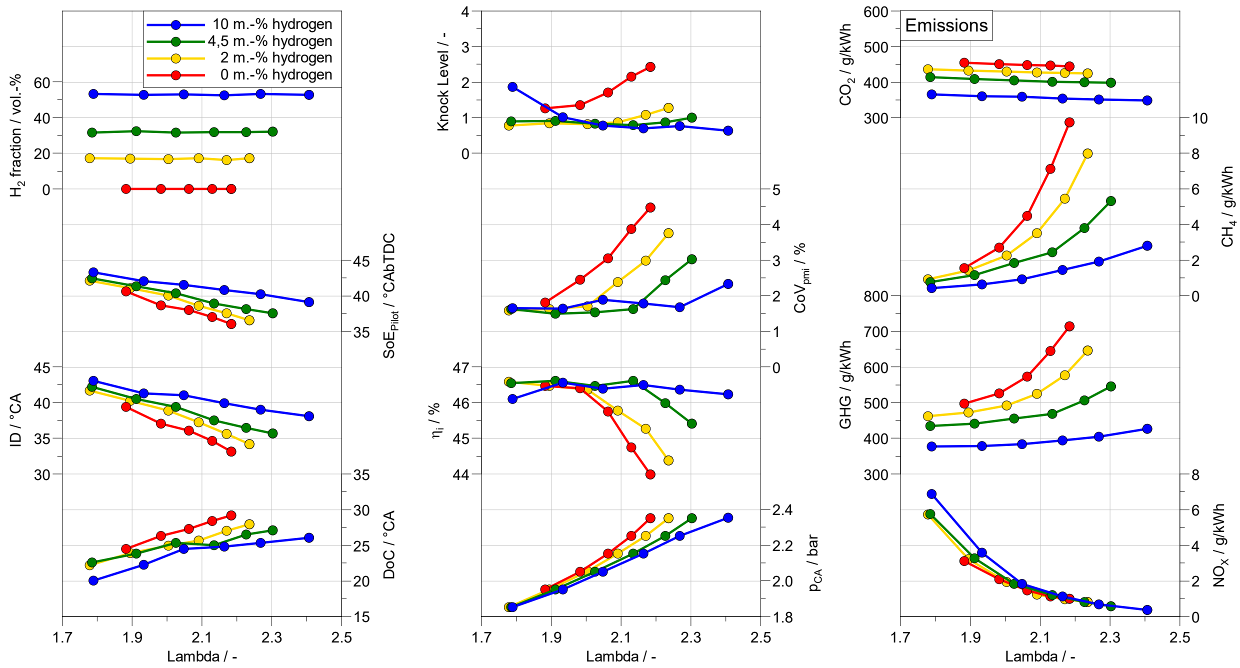

Figure 6. Effects of lambda at different hydrogen admixing rates at 50 % engine load with a constant center of combustion and other operating parameters held constant according to table 4.

With rising air fuel ratios, the pilot timing was retarded to shorten the ignition delay and counteract the slower flame speeds resulting from the lean mixture. The high flame speed of hydrogen reduces this effect, recognizable by the flatter gradients in pilot timing and ignition delay. As previously observed, the pilot injection timing had to be advanced with higher hydrogen fractions.

Against all expectations, the knock level increased with higher air fuel ratios. That effect has been previously observed and was already described in several publications, for example CIMAC paper 018 from 2023 [3,9,13]. These slightly higher knock levels are the result of pressure oscillations caused by the pilot ignition (ringing combustion) that are misinterpreted as knocking. At 2 or 4.5 m.-% admixing rate the knock level was very low over the whole range of lambda, only at the highest admixing rate and lowest air fuel ratio, a knock level of almost 2 was reached, which is still considered to be very light knocking.

The wide ignition limits of hydrogen are reflected in the significantly higher misfire limit. With 10 m.-% hydrogen fraction, even at lambda 2.4, the CoV_{pmi} was below 3 %. Hydrogen again supports the burn-through of the natural gas and reduces methane slip significantly up to very high air fuel ratios, which can also be seen in the indicated efficiency. Without hydrogen, the efficiency drops rapidly at air fuel ratios above 2. With the highest admixing rate, no significant efficiency losses could be observed in the examined range. The NO_X emissions show very similar trends with slightly higher values at high hydrogen fractions and low air fuel ratios. As there is no significant increase of knock or NO_X emissions, methane slip and therefore the total GHG emissions can be reduced significantly by adding hydrogen to the fuel gas.

To summarize, hydrogen admixture doesn't change the general correlations of the dual-fuel combustion process completely. During this measurement campaign, the potential of the admixture of hydrogen to reduce methane slip and CO_2 emissions could be proven. Furthermore, the beneficial combustion properties of hydrogen support the burn-through of the methane and offer more flexibility in the adjustment of various operating parameters for combustion process development regarding emission regulations.

The engine itself didn't have to be adapted to the hydrogen operation. Only an adapted pilot injection strategy on the basis of the thermodynamic analysis was required to hold the CoC constant and prevent knocking and excessively high NO_X emissions.

3.2 Increased Compression Ratio

The approach for the investigations on the increased compression ratio was to simulate a VCR system that can adjust the compression ratio during engine operation to increase efficiency when the engine is running at lower load points. The goal is to reduce GHG emissions and operation cost through fuel consumption and CO_2 pricing. Since such a VCR system isn't available for the single cylinder engine at the present time, the adjustments had to be done through hardware component adjustments.

Preliminary investigations were carried out with a 0D/1D model of the engine to define the range of CR that should be investigated on the SCE. The results of the knock model are shown in figure 7.

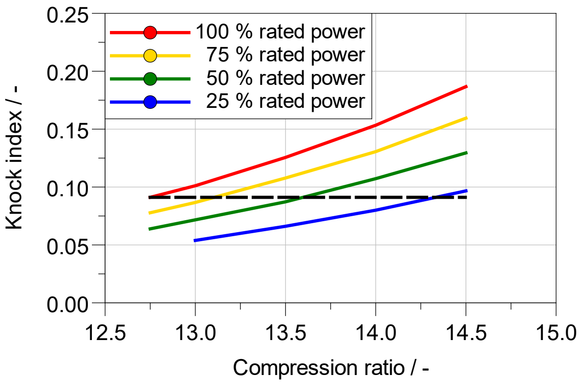

Figure 7. Results for knock index from a 0D/1D engine model at different engine load points depending on the compression ratio.

Since knocking is the main limiting factor for the design of dual-fuel engines, the knock index at full load with standard CR (12.75) is considered to be the allowed maximum. The results of the 0D/1D simulation showed that at the lowest load point, compression ratios of up to 14.5 could theoretically be used with just a small increase of knocking compared to full load with standard CR. At 50 % rated load, a CR of around 13.5 would lead to knock levels around the considered maximum. The 0D/1D simulation resulted in an efficiency benefit of 1.3 % (ca. 0.5 percentage points) considering the test cycle for marine applications type E2 with CR = 13.5 used at the two lower load points. The load points were weighted for the mean value based on table 5 [14].

Table 5. Weighting factors to calculate mean values for the entire load profile at constant speed (generator curve) according to E2 test cycle for marine applications [14]

load	%	25	50	75	100
factor	-	0.15	0.15	0.5	0.2

On the SCE, engine experiments were carried out with one thicker intermediate plate in the connecting rod compared to the standard setup, and with another piston crown with a comparable geometry at a higher epsilon without any intermediate plate. These combinations led to compression ratios of 13.15 and 14.39 to be available for experimental investigations. Since the aim of this technology package within the research project TEME2030+ is to improve efficiency in lower load points, the experiments were carried out at 25 % and 50 % rated engine load.

In figure 8, the detailed analysis of several measurement series with the above-mentioned compression ratios at 50 % engine load is shown. While there was no clearly visible effect of the compression ratio on NO_X and CH_4 emissions, the CO_2 emissions, and therefore also the total GHG emissions, showed deviations between the different measurement series. The measurements had to be carried out over a longer period of time due to the necessary hardware replacements to adjust the compression ratio. During this time, the exhaust gas analyser had to be exchanged for maintenance and the different spectrometers showed some implausible deviations. Therefore, no analysis of the measured emissions is presented. According to [4], a higher efficiency at higher CR leads to a decrease of the specific NO_X emissions in part load operation. With a certain degree of uncertainty because of the different exhaust gas measuring systems, no contrary observations could be made during the investigations on the single cylinder engine. It is therefore assumed that, considering the IMO Tier III limit for NO_X emissions, approximately the same CoC can be used for engine operation at slightly higher CR's. Therefore, knocking is the only limiting factor to be considered in the following derivations.

To analyse the effect of the compression ratio at 50 % load, two variations of the center of combustion with different pilot quantities (70 and 85 mg/shot) are shown for each CR. The variation of the CoC was performed by adjusting the pilot injection timing. Other engine parameters like pilot quantity and charge air pressure were held constant and are shown in table 6.

Table 6. Operation parameters for investigations of the effects of compression ratio at different load points in figures 8 and 9.

Load	%	50		25	
Figure	-	8		9	
pm_i	bar	10.8		6.4	
CoC	°CAaTDC	varied		varied	
p_{CA}	bar_{abs}	2.05		1.25	
T_{CA}	°C	45		45	
PQ	mg/shot	70	85	60	85
	e.-%	≈3.2	≈3.8	≈4.3	≈6.2
p_{Rail}	bar	1200		1200	

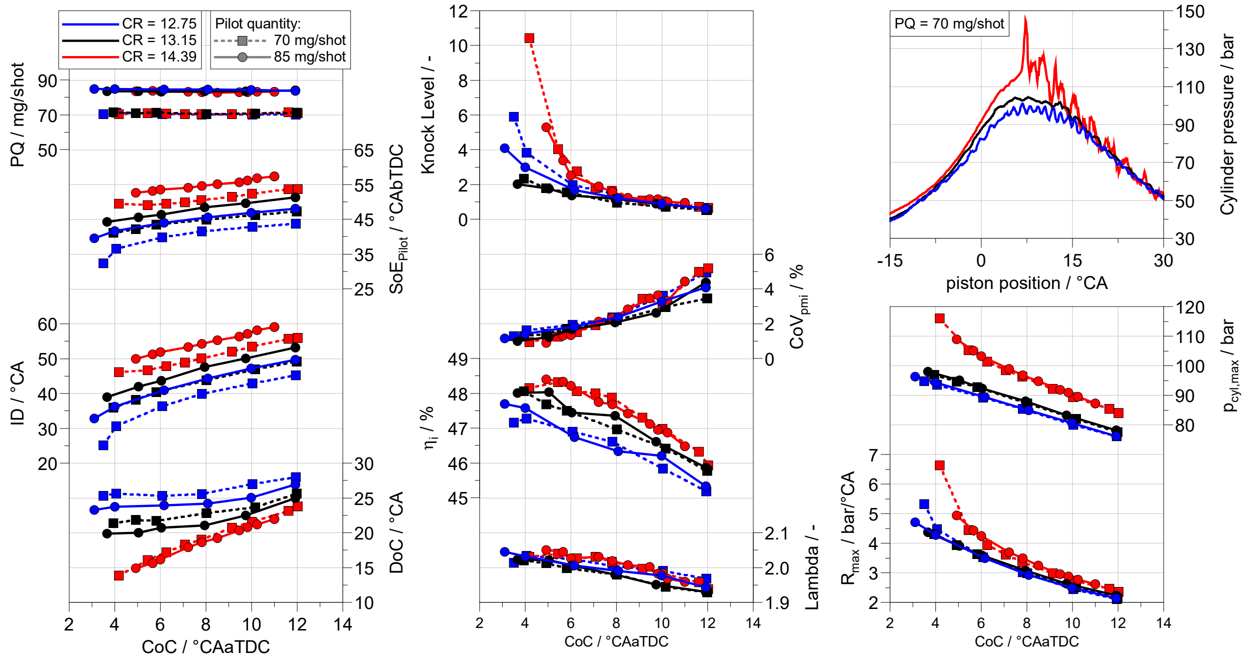

Figure 8. Influence of the compression ratio based on center of combustion variations with different pilot fuel quantities at 50 % engine load and other operating parameters held constant according to table 6.

The following effects can be observed for an increased compression ratio:

- Duration of combustion decreases due to the higher pressures and therefore higher temperatures during the combustion. While at the lower compression ratios, a higher pilot quantity also shortens the DoC by 1-2 °CA, at the highest CR, the difference in pilot fuel quantity has no significant impact on the DoC any more.
- To maintain a constant CoC with the same amount of pilot fuel, the injection had to be advanced to extend the ignition delay and retard the SoC.
- With a higher pilot quantity, the injection has to be placed even earlier to keep the CoC constant, as already known from several investigations [3,12].
- An unexpected effect can be observed in the knock level: at early CoC's, the knock levels with a CR of 13.15 were lower than at 12.75. At CR 14.39 the knock level increases strongly towards early CoC. From 8 °CAaTDC towards later CoC, there is no more significant difference between the varying compression ratios.
- The CoV$_{pmi}$ shows no significant differences in operation stability between the different compression ratios. The limit of 3 % for unstable engine operation is reached at CoC between 9 and 10 °CAaTDC for this set of operation parameters.
- The first step in CR leads to an efficiency benefit of ca. 0.5 percentage points over the whole range of CoC. The second step leads to nearly the same benefit although the increase of epsilon is even higher than in the first step.
- Charge air pressure and thus lambda was kept constant, with a slight decrease of lambda towards later CoC due to the efficiency losses of the late combustion, meaning more fuel had to be injected to maintain constant power.
- In the lower right diagram, the mean values for peak pressure and maximum pressure gradient are shown to quantify the increase due to the change of CR. From 12.75 to 14.39, peak pressure rises by ca. 10 bar and pressure gradient rises by ca. 0.5 bar/°CA. Since it is only a part load operation point, there is plenty of space to the tolerated limit and none of this increase is critical. Towards early CoC, the difference increases due to the stronger knocking.
- To investigate the unexpected effect in the knock level, the single cycle with the highest knock level for each CR is shown in the top right diagram. For the compression ratio of 14.39, a clearly knocking combustion with a knock amplitude of over 20 bar can be observed. At the lowest CR, the pressure oscillations begin well before TDC. According to [3], this can be

defined as ringing combustion triggered from the diesel ignition, which is misinterpreted as knocking but is not as harmful. At the medium CR only very weak oscillations can be observed matching the lowest knock levels overall.

Next, the 25 % load point is analysed the same way. The results for CoC variations with 60 and 85 mg/shot pilot quantity for each compression ratio are shown in figure 9. Other operation parameters can be taken from table 6. Again, emissions are not analysed due to the implausible deviations between the two different exhaust gas analysers.

For pilot timing, ignition delay and duration of combustion, the same correlations apply for 25 % load. Again, the resulting knock levels are not as expected. At this load point, even at the highest compression ratio, the knock level is lower than at the standard CR. The detailed presentation of the single cycle with the highest knock level for each CR shows the reason: At 14.39, even though very weak, but clearly knocking combustion can be observed. At the lower compression ratios, again, ringing combustion, that lead to higher knock values, takes place.

The CoV_{pmi} again is very consistent throughout the different epsilons. The indicated efficiency in this comparison has a higher scattering, but the overall benefit is on the same scale, with slightly higher differences of almost up to 2 percentage points from the lowest to the highest CR at a CoC of 4 °CAaTDC. At this 25 % load point, the step from 12.75 to 13.15 seems to have more impact than the further increase to 14.39.

To summarize the observations from both analysed load points, a theoretically available benefit in indicated efficiency of around 1-2 percentage points could be proven for the lower load points by an increased CR from 12.75 to 14.39.

The approach was to increase the compression ratio with knock level as a limiting factor. The results show that significantly stronger knocking only occurred at 50 % load at early CoC. At 50 % load and a CoC of 8 °CAaTDC or later and at 25 % load over the whole range of CoC, the knock levels were on the same scale or even lower with the increased CR.

Nevertheless, when knocking becomes too strong, a shift towards later CoC can be considered. For example, at 50 % load (figure 8) with standard CR of 12.75, the engine could be operated at a CoC of 4 °CAaTDC with an acceptable amount of knocking. An increased CR of 14.39 at the same CoC would exceed the knock limit of 10. Therefore, the CoC can be retarded by 1-2 °CA to reduce knocking while maintaining a significant benefit in efficiency.

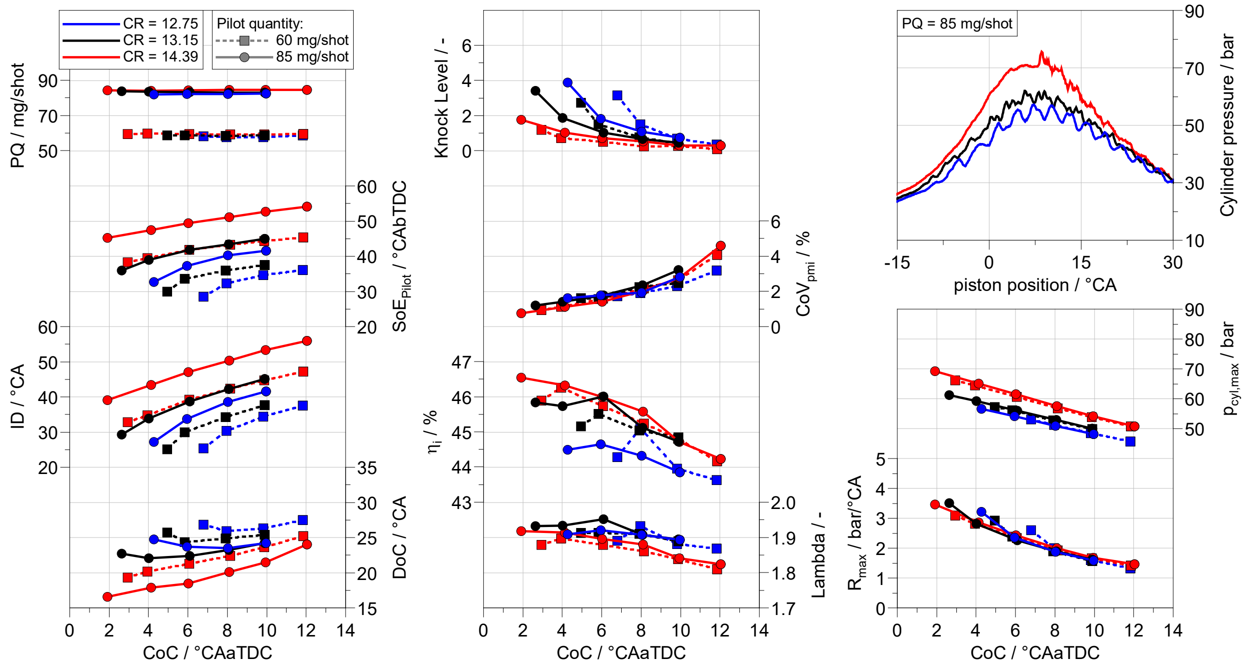

Figure 9. Influence of the compression ratio based on center of combustion variations with different pilot fuel quantities at 25 % engine load and other operating parameters held constant according to table 6.

Since knocking was not that big of a problem, even higher compression ratios could be possible to maximise the efficiency benefit. Further research on the single cylinder engine will follow. Further investigations will also follow at 75 % engine load, which is the most important load point within the type E2 test cycle according to table 5.

The unexpected findings regarding the sometimes even decreasing knock level at higher epsilons can be explained with the help of previous investigations regarding the occurrence of ringing and knocking combustion in dual-fuel engines. The variation of the air fuel ratio, which, like the compression ratio, influences the overall combustion conditions, led to strong knocking at low values and unexpectedly rising knock levels at high values. These higher knock levels could be traced back to ringing combustion that was misinterpreted as knocking. The ringing combustion, also appearing as an oscillation in the cylinder pressure, was caused by the late pilot injection needed for early CoC at poor firing conditions through the lean mixture [3,9]. It is reasonable to assume that this correlation also applies when considering a variable compression ratio. To draw further conclusions from this, there is probably an optimum compression ratio for each load point and the control approach on the base of an adjusted pilot injection strategy originally designed for changing gas qualities can also be applied to the use of VCR systems. Using the gas mixing unit, the investigations for different gas qualities were possible without any hardware adjustments to the engine itself. Since experimental investigations with different compression ratios on the SCE are linked to several reconstruction phases, the effort required for full factorial studies is relatively high. During the current research project, the focus was therefore only on preliminary investigations to quantify the potential in general.

The combination of different fuel gas qualities and a variable compression ratio using a combined control approach would offer more advantages in terms of highest efficiency at various gas qualities since the compression ratio is the main design parameter directly linked to the expected gas composition as the gas quality and composition directly affects knock levels.

4 CONCLUSIONS

During the research on medium-speed dual-fuel engines conducted by the Department of Piston Machines and Internal Combustion Engines of the University of Rostock, various approaches to reducing GHG emissions were investigated, using both experimental and simulation-based methods. The focus was on CO_2, the dominant GHG, and CH_4, which is particularly critical due to its high global warming potential (GWP) of 28 over a 100-year horizon.

This paper examines two measures to reduce GHG emissions: hydrogen admixture to the fuel gas and increasing the compression ratio to improve part-load efficiency. Both strategies were analyzed independently.

Hydrogen admixture offers significant potential to reduce GHG emissions through two primary mechanisms. Firstly, as a carbon-free fuel, hydrogen can substitute a part of the carbon-based fuel (e.g., natural gas in this case), directly reducing CO_2 emissions in proportion to its energetic share. Secondly, hydrogen enhances the combustion of the remaining natural gas, substantially reducing methane slip. This effect is particularly pronounced at low hydrogen shares during part-load operation. Improved combustion completeness and shorter combustion durations also increase efficiency, further lowering GHG emissions. For instance, with an energetic hydrogen share of 12%, methane slip in part-load could be reduced by approximately 60%, resulting in a total GHG reduction of around 20%.

Moreover, hydrogen allows more flexibility in engine operation parameters, such as the center of combustion or air fuel ratio. This flexibility facilitates optimization for targets like fuel consumption or emissions. Hydrogen admixture also mitigates the NO_X-CH_4 trade-off, enabling adjustments based on specific applications with different objectives, such as compliance with emission regulations or CO_2 pricing.

The study demonstrates the significant potential of hydrogen admixture in medium-speed dual-fuel engines to support long-term climate goals and transition towards sustainable propulsion systems or power supply. Notably, these benefits were achieved without hardware modifications to the engine or fuel system. Only adjustments to the pilot injection strategy, based on thermodynamic analyses within the engine control unit, were required. Consequently, this technology is well-suited for retrofit solutions in existing dual-fuel engines with common rail pilot systems. However, each application should be evaluated individually, particularly regarding hydrogen availability, as even small hydrogen admixtures yield overproportionally benefits.

Separately, the study also explored the effects of increasing the compression ratio to improve part load efficiency. Experiments were conducted using hardware modifications on the research engine to simulate a variable compression ratio system.

Raising the compression ratio from 12.75 to 14.39 resulted in an efficiency gain of approximately 1 percentage point in lower to medium part load operation. With the chosen engine parameters, no significant issues with knocking combustion were observed up to 50% engine load. Although no substantial NO_X increase was expected, this could not be definitively confirmed due to inconsistencies in exhaust gas measurement systems. Further research at higher loads and with increased compression ratios is necessary, also to evaluate potential NO_X increases to quantify the actual efficiency gain particularly with regard to NO_X conformity in emission control areas. While current developments focus on two-stage VCR systems, the findings highlight the additional potential benefits that multi-stage or continuously variable systems could offer.

Medium-speed dual-fuel engines demonstrate significant potential to contribute to achieving long-term climate goals, particularly in reducing GHG emissions in both marine and stationary applications.

The two separately investigated measures and further technologies can also be combined to maximise the overall benefit. To fully exploit the potential of dual-fuel engines in meeting climate targets, a holistic approach is essential. In addition to the measures explored in this study, further advancements in internal combustion engine technologies and advanced combustion concepts should be pursued. Similarly, exhaust aftertreatment solutions, such as SCR or methane oxidation catalysts, can further reduce methane slip and NO_X emissions, ensuring compliance with increasingly stringent environmental regulations.

By integrating these complementary strategies, medium-speed dual-fuel engines can play a key role in the transition towards sustainable propulsion and power generation, offering a versatile and scalable solution to meet the demands of a carbon-neutral future.

5 DEFINITIONS, ACRONYMS, ABBREVIATIONS

°CA: Crank Angle Degrees

CH_4: Methane

C_3H_8: Propane

CO_2: Carbon Dioxide

CoC: Center of Combustion

CoV_{pmi}: Coefficient of Variation of pm_i

CR: Compression Ratio

DF: Dual-Fuel

DoC: Duration of Combustion

ECU: Engine Control Unit

EGR: Exhaust Gas Recirculation

FTIR: Fourier Transform Infra-Red

GHG: Greenhouse Gas

GWP: Global Warming Potential

H_2: Hydrogen

HP: High Pressure

ID: Ignition Delay

IMO: International Maritime Organization

LNG: Liquefied Natural Gas

LPDF: Low Pressure Dual-Fuel

MPDI: Medium Pressure Direct Injection

NGC: Natural Gas Chromatograph

NO_X: Nitrogen Oxide

p_{CA}: Charge Air Pressure

PFI: Port Fuel Injection

pm_i: Mean Indicated Pressure

PQ: Pilot Quantity

p_{Rail}: Rail Pressure

SCE: Single Cylinder Engine

SCR: Selective Catalytic Reduction

SoC: Start of Combustion

TCA: Charge Air Temperature

TDC: Top Dead Center

VCR: Variable Compression Ratio

6 ACKNOWLEDGMENTS

The authors would like to thank the German Federal Ministry for Economic Affairs and Climate Actions for funding the project TEME2030+ (project number: 03SX537C). Furthermore, our thanks go to FVTR GmbH, Schaller Automation GmbH & Co. KG, M. Jürgensen GmbH & Co KG, Kolbenschmidt GmbH, Kompressorenbau Bannewitz GmbH, Sick AG and Umicore AG & Co. KG for supporting this project.

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Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag