ZURICH, MAY 19 – 23, 2025

2025 | 108

Experimental investigations of a methanol dual-fuel combustion process for marine engines

Fuels - Alternative & New Fuels

Karsten Stenzel, WTZ Roßlau

Phillip Thorau, WTZ Roßlau
Leon Beckmann, WTZ Roßlau
Frederick Schirrmeister, WTZ Roßlau
Dr.-Ing. Christian Reiser, WTZ Roßlau
Prof. Dr.-Ing. Bert Buchholz, University of Rostock

ABSTRACT

This paper explores the use of methanol as a potential fuel for high-speed engines to provide a retrofit solution for existing propulsion systems in the maritime sector. With global temperatures rising, there is an urgent need for action to reduce CO2 emissions. This also accounts for international shipping, which is responsible for a significant proportion of global emissions. Against this background, methanol is emerging as a promising marine fuel, with its favorable storage properties and high energy density.

In this study, a methanol-diesel dual-fuel combustion process with port fuel injection was investigated. This combustion technology can be used well as a retrofit solution due to the minimal intervention in the existing engine architecture. For this reason, extensive thermodynamic investigations were conducted as part of a publicly funded research project at WTZ Roßlau. This involved the use of a single-cylinder research engine with a bore diameter of 175mm, where numerous parameters, such as charge air temperature, excess air ratio and combustion centre, were examined and their influence on engine performance, exhaust gas emissions and combustion stability were assessed.

The initial tests showed that the simple substitution of diesel fuel with methanol without adjusting the engine configuration is already limited at moderate methanol energy fractions due to prolonged ignition delay and high-cylinder pressure gradients. However, by optimising the operating parameters, significantly higher methanol fractions of over 90% can be achieved, with 96.5% possible at full load operation. The study also examined key parameters, such as the center of combustion and excess air ratio, which significantly affect engine performance and emissions. The results suggest that earlier combustion positions and lower excess air ratios improve efficiency, combustion stability and methanol emissions, although further optimization is required. Future research will focus on different compression ratios, valve timing and investigating other technologies such as exhaust gas recirculation, low-pressure methanol direct injection and a mono-fuel combustion process with spark plug ignition.

The findings of this study show that methanol has great potential as a retrofit fuel for marine engines, contributing to a more sustainable shipping industry while meeting global emission reduction goals. Further investigations will be needed to refine the process and optimize fuel mixture formation to improve combustion stability and reduce unburnt methanol emissions.

1 INTRODUCTION

According to the IPCC report from 2018 [1], human-induced global warming of 1.5°C was expected to be reached around 2040. Contrary to this prediction, this level of global warming was already exceeded in 2024 [2]. A warming of more than 1.5°C compared to pre-industrial times has far-reaching environmental consequences, in particular a rise in sea levels and the more frequent occurrence of extreme weather events [3]. In this context, it must also be expected that so-called tipping points will be exceeded, whereby changes in the climate system are becoming irreversible and self-reinforcing. This development dramatically highlights that reducing greenhouse gas emissions is the greatest challenge of our time, and immediate action must be taken to protect our climate and thus our livelihoods.

This also applies to the maritime sector, which is responsible for 2.8% of global CO_2 emissions, with approximately 105,000 oceangoing vessels of 100 gross tonnes and above [4]. In line with the Paris Agreement, the International Maritime Organization (IMO) strengthened its climate targets in 2023. Compared to the reference year of 2008, it aims to reduce greenhouse gas emissions from shipping by at least 70% in 2040 and reach net-zero greenhouse gas (GHG) emissions around 2050 [5]. To achieve these goals, innovative technologies are required that minimize the use of fossil fuels and at the same time improve the energy efficiency and environmental compatibility of ships. In this context, it is not sufficient to solely equip new vessels with low-emission technologies. The existing fleet must also be converted to more environmentally friendly propulsion systems. This concept, also known as retrofitting, is the key to a cost-effective and future-proof maritime transformation. Dual-fuel combustion systems are often used for this purpose, which offer a high degree of flexibility in fuel selection and allow to switch between fossil fuels and more environmentally friendly alternatives. In addition, if systems fail or if renewable fuels are not available, it is possible to fall back on conventional diesel fuel.

Methanol is a promising fuel for ship applications and is very well suited for retrofitting existing propulsion systems due to its good storage and combustion capabilities. The production of green methanol is possible using a variety of processes, whereby these methods are based on the use of renewable energy sources and sustainable feedstocks. In the following sections, the properties and advantages will be discussed in detail and engine results for a methanol-diesel dual-fuel combustion process will be presented.

2 METHANOL AS A MARINE FUEL

2.1 Methanol production and costs

Methanol already plays an important role in the chemical industry with a production capacity of about 110 million tons per year from more than 90 methanol plants worldwide. It is anticipated that the current production capacity will be sufficient to meet the demand for methanol as ship fuel, as long as the growth remains gradual in the early stages and stays at a moderate level until 2030. [6]. At present most of the methanol is derived from fossil feedstocks (e.g. natural gas or coal) and only around 0.2% is produced from renewable sources, primarily as bio-methanol. Today, methanol is mainly used as a chemical raw material for the production of formaldehyde, acetic acid and plastics. In addition, there is a growing interest in sustainably produced methanol as a fuel in sectors where the possibilities for a climate-neutral transformation are severely limited due to the high energy requirements, such as shipping as well as on-road and off-road applications [7].

Green methanol can be produced as e-methanol using electricity from sustainable sources, such as wind or solar energy, and green CO_2 obtained via direct air capture (DAC). However, production as bio-methanol is also possible, whereby the path via gasification of biomass or through biogas reforming is generally possible. Waste from the forestry and agricultural industries as well as sewage or municipal solid waste can be used as feedstock. Several producers are assessing the potential demand and planning investments to scale up production of green methanol, weather as bio- or e-methanol. Considering the time required to develop production facilities, the first volumes of green methanol are expected to reach the market by 2024/2025, with larger quantities likely available by 2030. The projections for the costs of green methanol vary greatly, depending in particular on the costs of the bio-feedstock, electrolysis and the renewable CO_2 from DAC. Currently, the costs of bio-methanol are significantly lower than those of e-methanol, although comparable prices are expected in the future due to scaling effects and maturing of the technologies (see Figure 1). In order to introduce e-methanol at reasonable costs, co-production of fossil and green methanol is also conceivable. In the forecast for 2050, it is principally possible that the green alternatives will reach the price level of fossil methanol. The mechanisms of carbon credits or the introduction of CO_2 taxes will also have a major impact on energy costs in the future [6], [7], [8], [9].

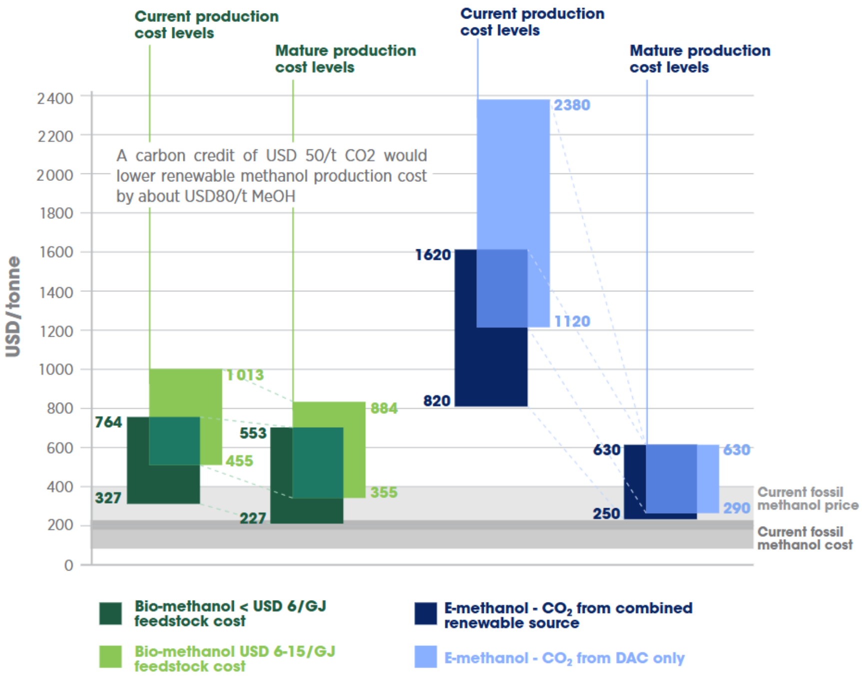

Figure 1. Current and future production costs of bio- and e-methanol [7]

2.2 Methanol properties, advantages and challenges

Methanol is a clear, volatile, colourless, and flammable liquid alcohol. Selected physical properties for diesel fuel, methane, methanol, hydrogen and ammonia can be seen in Table 1. Due to the low flash point of around 12°C, methanol forms an explosive atmosphere above the liquid surface even under ambient conditions [13]. Furthermore, it has a minimum ignition energy of only 0.14 mJ (about half that of methane) [16] and very wide ignition limits of 6.7 to 36% by volume [11], which significantly increase the risk of ignition in the event of leaks and the presence of ignition sources. This results in numerous safety measures, which are set out in the IMO's Interim Guidelines for the safety of ships using methyl/ ethyl alcohols as fuel (MSC.1/Circ. 1621). These include, for example, the inertisation of fuel tanks, the use of double-walled piping, the permanent installation of gas warning as well as fire detectors and many more [14]. In addition, methanol burns with a relatively cold flame that is almost invisible to the human eye in daylight. Due to its higher molecular weight (32 g/mol for methanol and 28 g/mol for air), methanol vapours tend to sink downwards [13]. These can accumulate in poorly ventilated, low-lying or confined areas, such as the bilge in the engine room [8].

Table 1. Selected physical properties for different fuels [7], [10], [11], [12], [13]

Property	Unit	Diesel	Methane	Methanol	Hydrogen	Ammonia
Density at 15 °C	kg/m³	810 – 890	468 (-162°C)	796	70.9 (-253°C)	676 (-33°C)
Boiling temperature	°C	190 – 350	-162	65	-253	-33
Flash point	°C	> 55	-	12	-	-
Autoignition temperature	°C	220 – 300	595	470	560	651
Flammability limits	Vol.-%	1 – 6	5.3 – 15	6.7 – 36	4.1 – 74	16 – 25
Latent heat of vaporization	kJ/kg	233	509	1177	447	1371
Lower heating value	MJ/kg	41 – 43	50	19.9	120	18.8
Volumetric energy density	GJ/m³	36.6	23.4	15.8	8.5	12.7
Stoichiometric air-fuel ratio	kg/kg	14.7	17.2	6.5	34.3	6.05

The key advantage for methanol is that it can be stored in its liquid form under ambient conditions in integrated tanks. Bunkering is therefore comparable with marine fuels, such as heavy fuel oil, whereby only minor adjustments need to be made to existing tanks when compared to the other alternative fuels. These tanks can be made from stainless steel or carbon steel with a methanol-resistant coating, such as inorganic zinc silicate [9]. Since methanol can also have a corrosive effect on other metals such as aluminium, copper, zinc, titanium and their alloys and can also damage plastics, resins and elastomers, it is necessary to select compatible materials [7]. Methanol has with 15.8 GJ/m³ a relatively high volumetric energy density requiring approximately 2.3 times the volume to store the same amount of energy as diesel fuel. However, according to IMO guidelines, a cofferdam is required around integrated methanol tanks. This structural space surrounds the fuel tank and provides an additional layer of gas and liquid tightness, offering protection against external fires and toxic and flammable vapours between the fuel tank and other areas of the ship [17].

Methanol is toxic to aquatic life at concentrations above 1000 mg/l, but it is less toxic than many other marine fuels. Its LC50 for fish is 15,400 mg/l, compared to 79 mg/l for HFO. This means it would take 200 times more methanol than HFO to harm the same number of fish. Ammonia is much more toxic, with an LC50 of just 0.068 mg/l. Also on the human body, methanol is only directly toxic in very high concentrations. However, the human body metabolizes methanol in the liver via the intermediate step of formaldehyde to formic acid, which is the primary toxic metabolite in methanol poisoning. Formic acid can lead to metabolic acidosis, which lowers the pH value of the blood and leads to hyperacidity of the body and thus to metabolic disorders. It also causes damage to the liver, kidneys, optic nerve or brain and, in large quantities, can even lead to death. Ingestion is primarily oral but is also possible via the skin and respiratory system. For these reasons, it is important that the bunker facilities, the fuel supply and propulsion systems on board are designed in such a way that crew members cannot come into contact with methanol. In addition, adequate training for the crew is required as well as knowledge of how to deal with leaks or spillages [13], [15].

2.3 State of the art for methanol ship propulsion and combustion systems

Methanol is already available in over 120 ports worldwide [13]. At 30 of these ports, bunkering is also possible [18], meaning that the necessary fuelling infrastructure is already in place there, with 5 ports being located in China. This development and the major order in 2021 from A.P. Moller-Maersk, the second largest shipping company, for 8 large oceangoing vessels that can run on methanol impressively demonstrate the importance of methanol as a future marine fuel [19]. Maersk is also partnering with 6 companies to increase global methanol capacity, with at least 600,000 tons of e-methanol and at least 130,000 tons of bio-methanol to be produced by the end of 2025 [20]. Since 2021, orders for large ocean-going container ships have progressed further, with Maersk now having 25 orders for methanol-powered container ships, while the global order books already contain more than 100 orders for a wide variety of ship types and numerous operators [21]. Waterfront Shipping, a subcontractor of Methanex, the world's largest producer and distributor of methanol, is pioneering the use of methanol as a marine fuel. Back in 2016, the company chartered one of the world's first methanol-powered ocean-going vessels, the Lindanger, a tanker with a transport capacity of 50,000 DWT [22]. Waterfront Shipping's fleet now already includes 19 methanol-powered ships [13]. Like Maersk's container ships, the methanol tankers are powered by 2-stroke methanol dual-fuel engines from MAN Energy Solutions. The world's first methanol-powered ship was the Stena Germanica, whose 4-stroke engines were converted for methanol dual-fuel operation back in 2015 [23].

The combustion of methanol in engines can generally be classified based on the fuel injection and ignition concepts (see Figure 2). It is possible to burn methanol diffusively or to ignite it with a pilot fuel as well as a spark plug. In ship applications, spark-ignited methanol engines play a minor role and will therefore not be further discussed here. Currently, the focus is strongly on dual-fuel combustion processes, as these offer a high fuel flexibility and operation in diesel mode is possible as a backup option. In this case, the methanol can be injected into the combustion chamber at different pressure levels and times. These processes, known as high-pressure direct injection (HPDI) and low-pressure direct injection (LPDI), require considerable modifications to the engine structure, such as the integration of the injection components into the cylinder head, and in most cases highly complex fuel systems. Port fuel injection (PFI) is much more suitable for converting existing engine systems, whereby the injection components are usually installed in the intake duct in front of the cylinder head and the fuel is injected into the charge air at low pressure. This concept was used in the engine investigations for this paper and is explained in more detail in the following chapter.

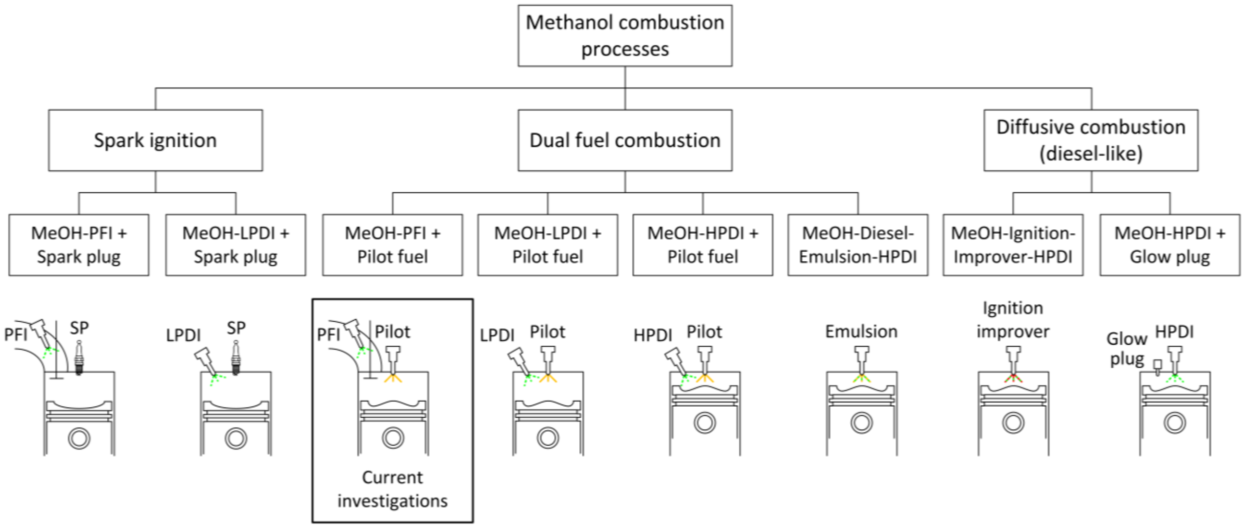

Figure 2. Classification of methanol combustion processes

3 TEST BENCH SETUP AND SINGLE-CYLINDER RESEARCH ENGINE FM18

The engine tests are carried out on the single-cylinder research engine FM18 at WTZ Roßlau. The most important engine parameters are summarised in Table 2 and a picture of the single-cylinder research engine can be seen in Figure 3. The base engine is designed for peak pressures of up to 400 bar and is characterized by a high degree of flexibility with regard to the compression ratio and valve timing. For the experimental investigations in methanol dual-fuel operation, the single-cylinder is equipped with 175D engine components from the project partner MAN Energy Solutions.

Table 2. Engine parameters of the single-cylinder research engine FM18

Parameter	Unit	Value
Stroke	mm	215
Bore	mm	175
Number of cylinders	-	1
Piston displacement	dm^3	5.17
Con rod length	mm	547
Rated power	kW	180
Rated speed	min^{-1}	1800
Number of valves	-	4
Compression ratio	-	(variable)
Camshaft	-	Axially tensioned (variable)

Figure 3. Picture of the single-cylinder research engine FM18

The optimization of the combustion process focuses mainly on engine efficiency, the achievable methanol quantities, combustion stability and exhaust emissions. For this purpose, the single-cylinder research engine is equipped with extensive indication measurement devices in the charge air, exhaust gas, diesel and methanol systems as well as in the combustion chamber. Furthermore, the exhaust gas concentrations are measured with an AVL SESAM i60 FT SII FTIR spectrometer. In addition to the typical species for the combustion process development, this makes it possible to measure the methanol and formaldehyde concentration in the exhaust gas. The specific emissions in g/kWh are calculated using a correlation between the single-cylinder and a reference full-scale engine.

The methanol is injected into the charge air using an IPF-DS200 methanol injector from HEINZMANN. Figure 4 shows the integration of this injector into the charge air segment in front of the engine. The methanol is injected in a suction-synchronized manner, meaning that the intake valves are already open. The fuel pressure must be set to ensure proper atomization while providing enough injection time to mix the methanol into the moving intake air. To prevent methanol from remaining in front of the closed intake valves, a latest possible injection end must be maintained. This is necessary to avoid the scavenging of unburnt methanol during the valve overlap phase. In addition, any remaining mixture could ignite in the following cycle due to the backflow of hot exhaust gases or ignition sources, potentially leading to combustion anomalies. Therefore, the injection duration is extended by starting the injection earlier while keeping the end constant. Nevertheless, it must be assumed that even with an ideal injection timing, not all of the injected fuel evaporates in the intake duct, but liquid methanol also enters the combustion chamber. In addition, a wall film is expected to form on the intake channel and the intake valves. This can be influenced by suitable measures, such as the position of the injector, the adjustment of the spray cone angle or the use of a single or multiple injector concept [24].

In advance to the engine tests, a methanol fuel module developed by the WTZ was installed on the test bench. The schematic structure of this fuel system is shown in Figure 5. The methanol is stored outside the test bench building in an IBC, equipped with a self-priming feed pump. This pump supplies the fuel system with pre-pressure, while the injection pressure is regulated within the methanol module via a booster pump and a frequency converter. Inside the module the fuel temperature is also regulated, with both cooling and heating being possible through a water circuit. The fuel consumption is measured using a Coriolis mass flow meter. A safety shut-off valve is installed directly upstream of the engine, which automatically closes in the event of an emergency stop, cutting off the fuel supply to the engine. Additionally, the test bench is equipped with comprehensive safety features, including gas warning and fire sensors, as well as personal protective equipment for the testing crew, such as portable gas detectors, respirators, methanol-resistant gloves and body suits. In addition, all connecting elements in the methanol module are designed to be permanently leak-proof.

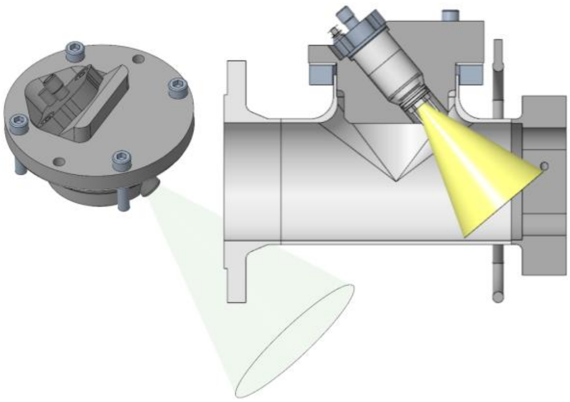

Figure 4. Integration of the methanol injector into the charge air segment

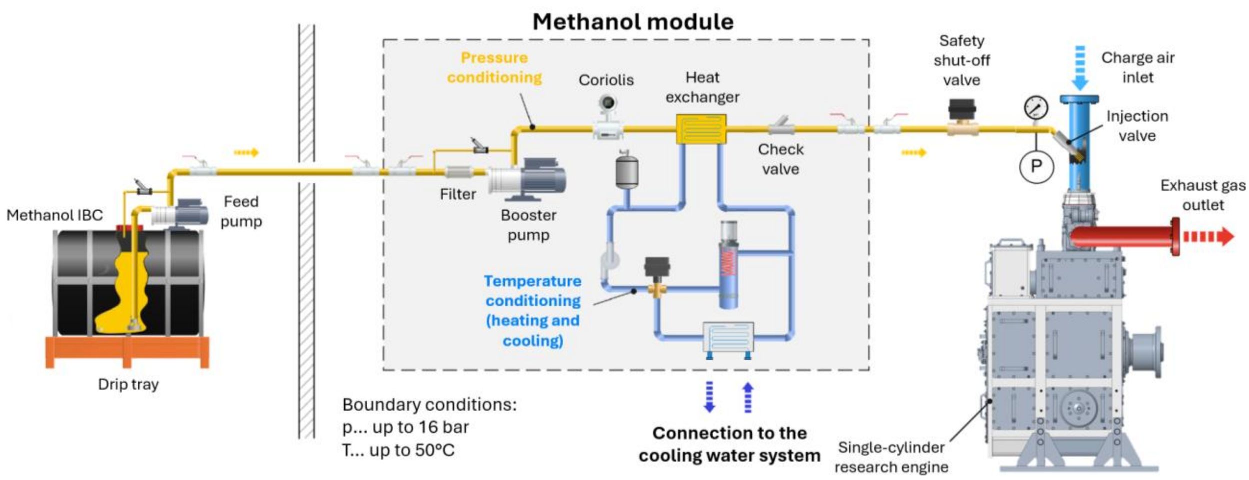

Figure 5. Schematic design of the installed methanol module

4 EXPERIMENTAL INVESTIGATIONS

4.1 Substitution of diesel fuel with methanol

In the first engine tests, the diesel fuel was gradually substituted with methanol at a constant engine load without any adjustments to the engine hardware or the parameter settings, such as charge air pressure and temperature, the start of current (SOC) for the diesel injection and the diesel injection pressure. Figure 6 shows the cylinder pressure, rate of heat release and cumulative heat release for methanol energy fractions of up to 60% at an engine load of 75%. The lower pressure values at the end of the compression stroke indicate that the evaporation of the methanol leads to a strong cooling of the combustion chamber. As a result, the ignition delay is extended with increasing methanol fractions. This means that at the start of combustion, a larger quantity of mixed diesel fuel is immediately burned in an intense premix combustion, which results in high cylinder pressure gradients and pulsations in the combustion chamber.

This is also apparent in the selected engine results in Figure 7. With a methanol energy fraction of 60%, there is a sharp increase in the maximum cylinder pressure gradient, whereby the combustion stability with regard to the coefficient of variation of the maximum cylinder pressure (COV_{pmax}) worsens at the same time and reasonable operation is no longer possible due to increasing component stresses. An advantage is that nitrogen oxide emissions can be significantly reduced by increasing methanol energy fractions due to the lower combustion temperatures. Simultaneously, however, a rise in emissions of unburnt methanol and formaldehyde (HCHO) is also observed. These should be reduced in the further course of the investigations by suitable adjustments to the methanol combustion process or, if not otherwise possible, by applying appropriate exhaust gas aftertreatment technologies. On the one hand, this makes sense with regard to the efficiency of the engine, but also in terms of the health effects of methanol and formaldehyde.

The limitation of the maximum achievable methanol energy fraction with an unchanged engine setup due to the maximum cylinder pressure gradients and combustion stability also applies to the other load points, although these will not be discussed in detail here. An overview of the achievable methanol fractions is shown in Table 3. In each case, the last stable operating point with tolerable maximum cylinder pressure gradients is listed. At low and high engine loads, the achievable fractions are restricted to 40%. At medium loads, slightly higher methanol fractions of 50% can be reached.

The following section discusses possible adjustments to the combustion parameters in methanol dual-fuel operation that can significantly improve the methanol energy fraction, engine performance and exhaust emissions.

Table 3. Maximum achievable methanol energy fraction without adjustment to the engine hardware or parameter settings

Engine load	%	25	50	75	100
Max. MeOH fraction	%	40	50	50	40

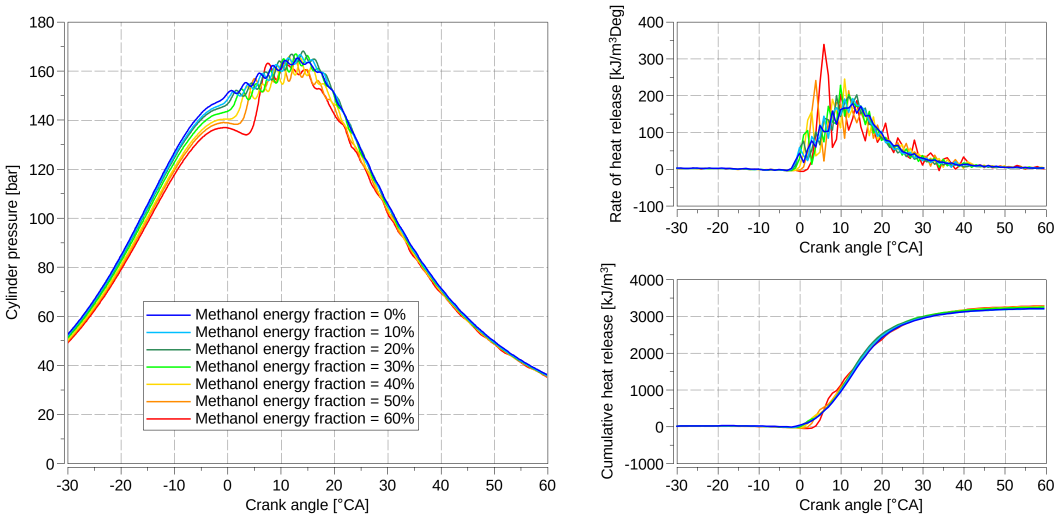

Figure 6. Cylinder pressure, rate of heat release and cumulative heat release for a variation of the methanol energy fraction at an engine load of 75%

Variation of the methanol energy fraction					
Engine load	75 %	**IMEP**	17.2 bar	**Engine speed**	1800 min-1
SOC Diesel	-10 °CA a. TDC	**Diesel pressure**	1600 bar abs.	**Methanol pressure**	5.5 bar abs.
Charge air pressure	4.1 bar abs.	**Charge air temp.**	50 °C	**Scav. pressure**	200 mbar

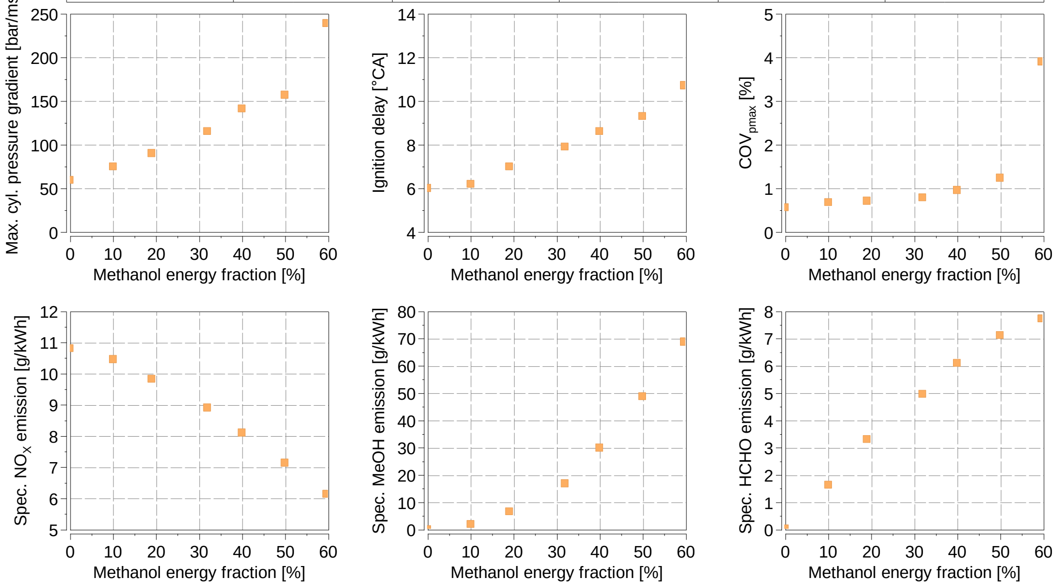

Figure 7. Selected engine results for variation of the methanol energy fraction at an engine load of 75%

4.2 Variation of the centre of combustion

As shown in section 4.1, it is not possible to simply increase the methanol fraction step by step until the smallest diesel pilot quantities are reached. This is limited by the sharp increase in cylinder pressure gradients. Therefore, in the following tests, this limit was bypassed and the engine load was increased by successively raising the methanol content.

The most relevant engine parameters and a selection of measurement results for varying the centre of combustion are shown in Figure 8, where two methanol energy fractions of 94.0 and 92.5 % are compared. In each case, the excess air ratio was kept constant at 2.0 and the engine load at 75%.

Variation of the centre of combustion					
Engine load	75 %	**IMEP**	17.2 bar	**Engine speed**	1800 min-1
SOC Diesel	Var. °CA a. TDC	**Diesel pressure**	1200 bar abs.	**Methanol pressure**	8 bar abs.
Excess air ratio λ	2.0 -	**Charge air temp.**	70 °C	**Scav. pressure**	200 mbar

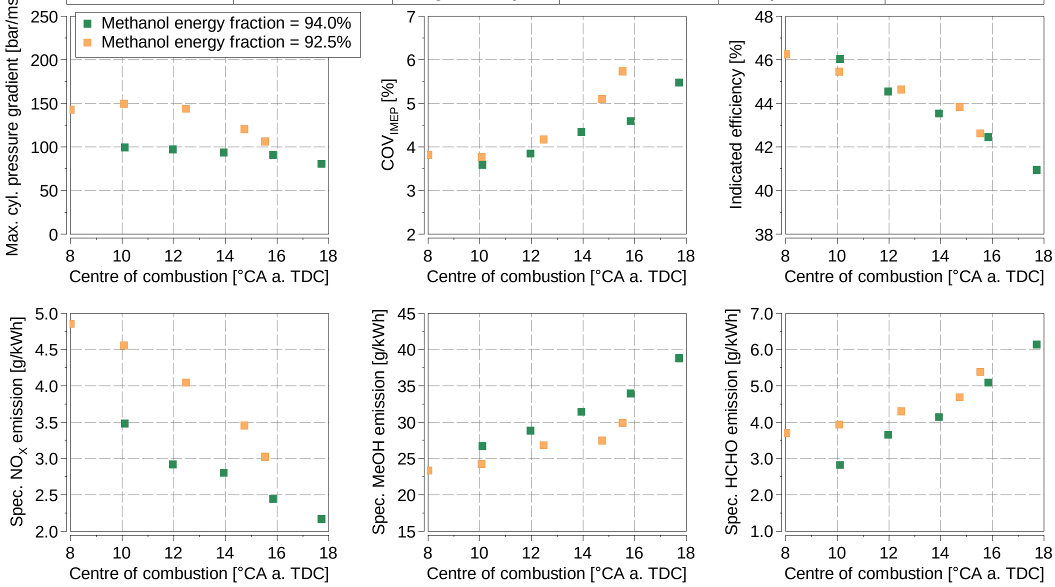

Figure 8. Selected engine results for variation of the centre of combustion at an engine load of 75%

When varying the centre of combustion, the results reveal the well-known effect that the indicated efficiency increases with earlier combustion positions, but at the same time NO_X emissions also rise. This can be explained by thermodynamic advantages on the one hand and higher combustion temperatures on the other. However, this more intensive fuel conversion also leads to a more stable combustion with regard to the coefficient of variation of the indicated mean effective pressure (COV_{IMEP}) and to a lower methanol slip. This also applies to formaldehyde, which is produced as an intermediate product during methanol combustion and is oxidized more completely at the higher temperatures due to the earlier centre of combustion. However, the combustion timing cannot be shifted arbitrarily to an earlier point. At a certain limit, there is a sharp increase in the ignition delay for diesel combustion as a result of the early compression phase and the associated low temperatures. Contrary to expectations, an earlier start of diesel injection will then lead to a later combustion. This effect can be shifted if the diesel pilot quantity is increased, as it is the case with a methanol energy fraction of 92.5%. Higher diesel quantities generally lead to lower ignition delays, as already explained in section 4.1. However, the first combustion phase is dominated to a greater extent by the diesel ignition, which leads to a more intense premix combustion and higher maximum cylinder pressure gradients. Nevertheless, the higher diesel fraction and the more intensive premix combustion also leads to higher NO_X emissions, whereby the methanol slip can be reduced at the same time.

Figure 9 shows the associated cylinder pressure, the rate of heat release and cumulative heat release for the variation of the centre of combustion at a methanol energy fraction of 94.0%. With a constant excess air ratio of 2.0, the higher indicated efficiency and associated lower fuel consumption also require a decreased air mass and correspondingly reduced charge air pressures. This can be easily identified by the lower pressure values at the end of the compression stroke, but the more intensive combustion also leads to shorter combustion durations and higher maximum cylinder pressures. To conclude, it can be stated that with regard to engine efficiency, combustion stability as well as methanol and formaldehyde emissions, it is advantageous to optimize the combustion process to achieve the earliest possible centre of combustion.

4.3 Variation of the excess air ratio

In analogy to the previous engine tests, the influence of the excess air ratio (λ) on the methanol combustion process was investigated in the next step. For this purpose, the engine load was kept constant at 75%, the combustion centre at 12°CA a. TDC, the charge air temperature at 70°C and the scavenging pressure at 200 mbar. A corresponding selection of engine results can be found in Figure 10.

A higher excess air ratio has different effects on the engine behaviour depending on the combustion phase. In the case of diesel pilot injection, an increased λ leads to a more compact spray, as it is injected against a higher density. This compact spray leads to a shorter ignition delay and an intensive ignition phase, which results in higher maximum cylinder pressure gradients. However, the interactions are very complex and described in more detail in [25].

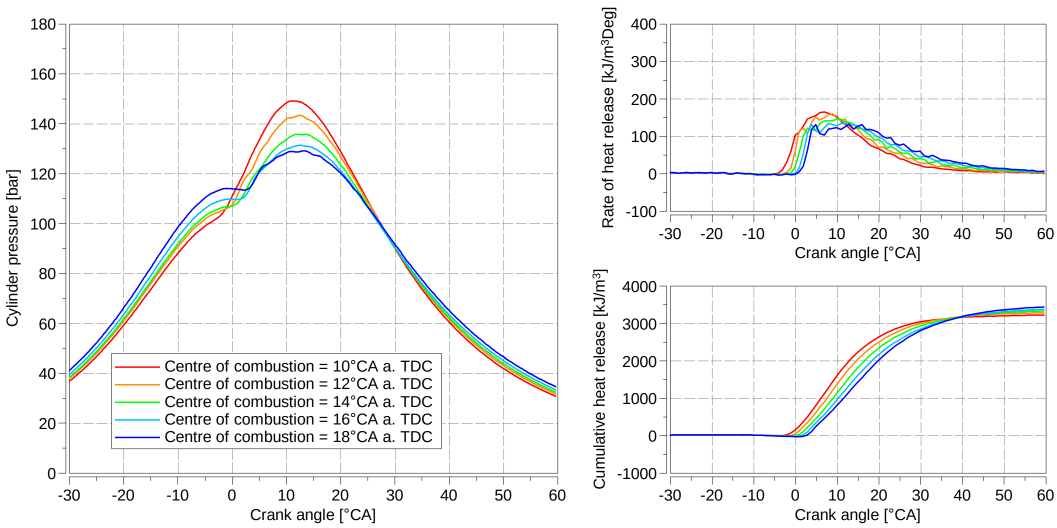

Figure 9. Cylinder pressure, rate of heat release and cumulative heat release for the variation of the centre of combustion at an engine load of 75% and for a methanol energy fraction of 94.0%

Variation of the excess air ratio λ					
Engine load	75 %	**IMEP**	17.2 bar	**Engine speed**	1800 min^{-1}
SOC Diesel	Var. °CA a. TDC	**Diesel pressure**	1200 bar abs.	**Methanol pressure**	8 bar abs.
Centre of combustion	12 °CA a. TDC	**Charge air temp.**	70 °C	**Scav. pressure**	200 mbar

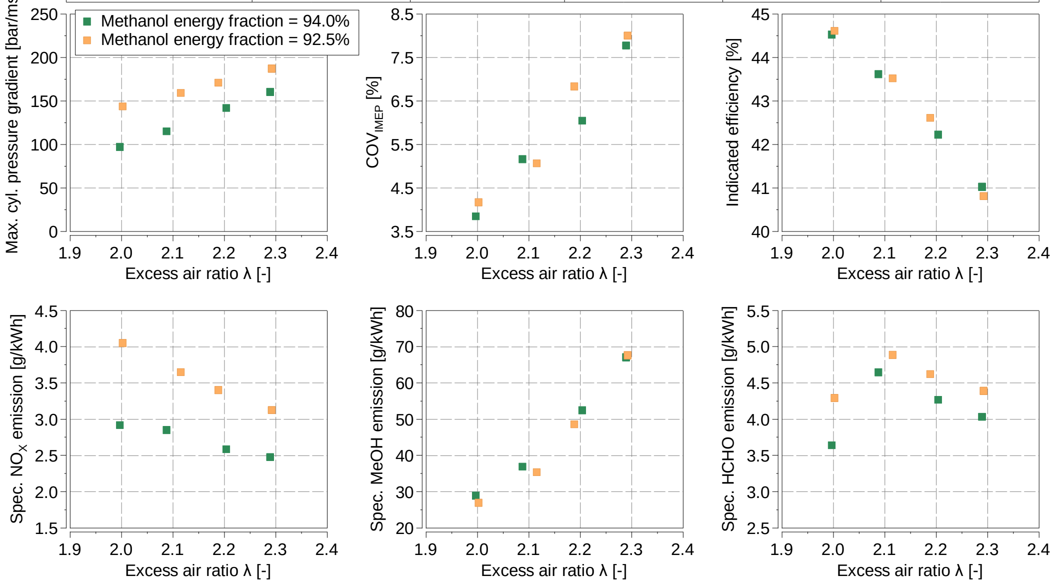

Figure 10. Selected engine results for variation of the excess air ratio at an engine load of 75%

The combustion of methanol is simultaneously delayed by the leaner λ values. As a result, there is a decrease in combustion stability, lower indicated efficiency, and incomplete combustion, leading to increased methanol emissions. However, NO_X emissions can be reduced because of the lower combustion temperatures. The opposing effects, namely the intensive ignition phase and the weakened subsequent combustion phase, result in almost no impact on the overall combustion duration. As already shown in section 4.2, even with the variation of the excess air ratio, higher diesel pilot quantities lead to lower ignition delay, which results in a more intensive first combustion phase and thus also to higher maximum cylinder pressure gradients. Nitrogen oxide emissions also increase, as described before. The achievable lambdas for rich mixtures are once again limited by the ability to adjust the desired centre of combustion and, with greater excess air ratios, by the stability of combustion with regard to COV_{IMEP}. For an ideal combustion process, it makes sense to use rich lambdas in terms of efficiency and combustion stability. Figure 11 shows the associated cylinder pressure, the rate of heat release and cumulative heat release for the variation of the excess air ratio at a methanol energy fraction of 94.0%. The effects described above (intensive first combustion phase, almost constant overall combustion duration) can also be seen there.

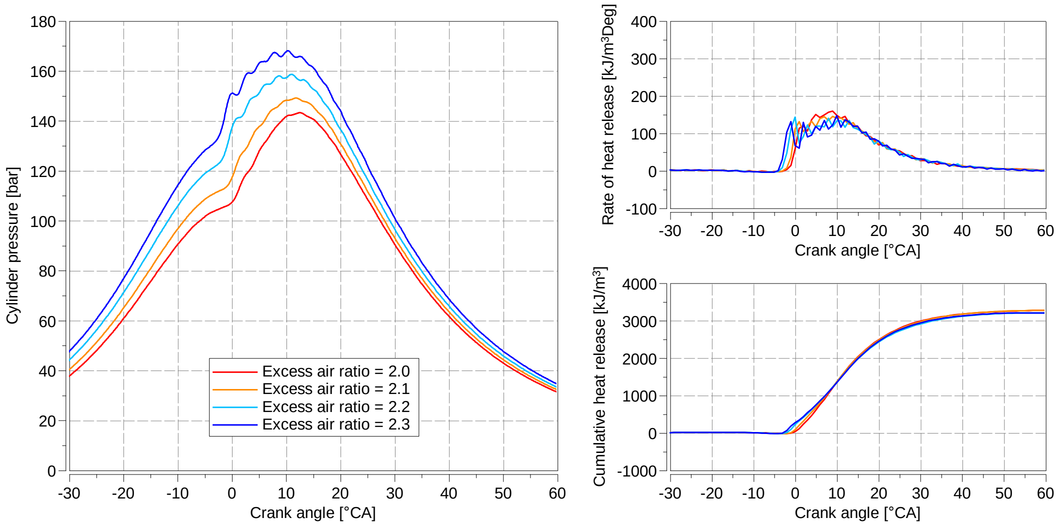

Figure 11. Cylinder pressure, rate of heat release and cumulative heat release for a variation of the excess air ratio at an engine load of 75% and for a methanol energy fraction of 94.0%

4.4 Variation of the engine load in methanol dual-fuel operation

Finally, the investigations are also going to address different load points in the methanol dual-fuel operation. A selection of engine results is summarised in Figure 12. The measurements were taken for a constant centre of combustion of 10°CA a. TDC, a charge air temperature of 70°C and at a rated speed of 1800 rpm. It can be seen that the achievable methanol energy fractions at the higher loads are well above 90%. At the full load point it is even 96.5%. However, only 75% methanol energy fraction can be achieved at 25% load as otherwise the methanol slip increases sharply and early centres of combustion with a high engine efficiency cannot be realised. The maximum cylinder pressure gradients for all load points presented are around 100 bar/ms and the combustion stabilities are also at a good level with a COV_{IMEP} of around 3 % and for the higher load points of less than 5 % with regard to COV_{pmax}. Nevertheless, further investigations should also focus on improving mixture formation and increasing combustion stability. Compared to the initial results in section 4.1, the achievable methanol content at full load could be increased by over 55%, whereby only the operating parameters were optimised and no adjustments were made to the hardware setup. In addition, the NO_X, methanol and formaldehyde emissions are at a very good level. For completeness, Figure 13 presents the cylinder pressure, rate of heat release, and cumulative heat release at the different load points corresponding to the maximum achievable methanol energy fractions previously shown in Figure 12.

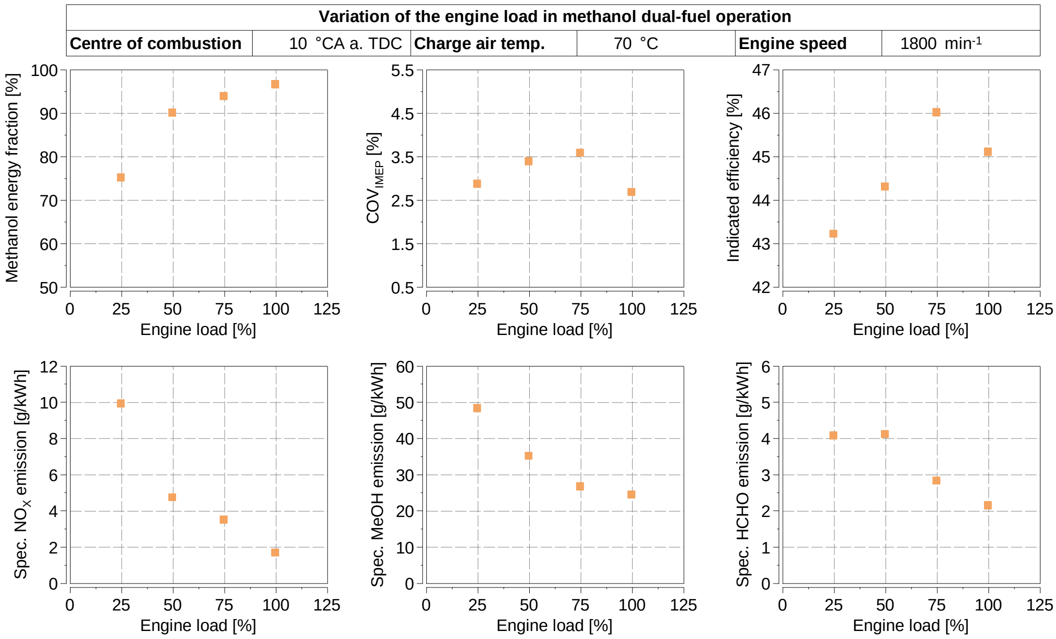

Figure 12. Selected engine results for the variation of the engine load in methanol dual-fuel operation

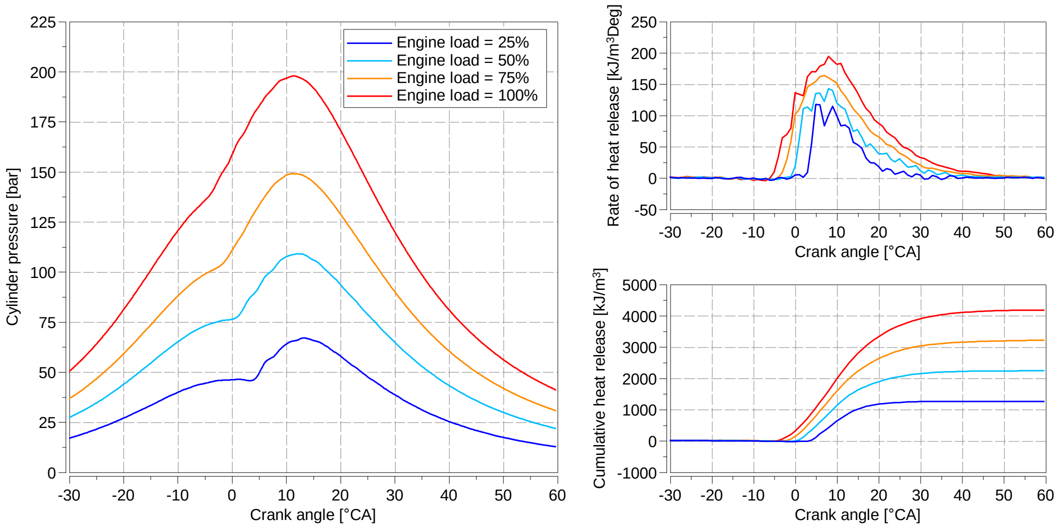

Figure 13. Cylinder pressure, rate of heat release, and cumulative heat release in relation to the maximum achievable methanol energy fractions for varying engine loads in methanol dual-fuel operation

5 CONCLUSIONS AND OUTLOOK

The dramatic rise in global temperatures clearly indicates the urgent need for action to reduce worldwide CO_2 emissions. This also applies to the maritime sector, where innovative technologies are required to limit climate change as quickly as possible. Due to the long service lives of ships, the existing fleet must also be assessed and retrofitted with climate-friendly alternatives. A promising marine fuel for this purpose is methanol, which is characterised by its good storage capabilities in liquid form under ambient conditions, while also having a relatively high energy density. Furthermore, methanol is already available as a chemical in many ports worldwide, although bunkering facilities are currently limited. The recent large orders from global players, such as A.P. Moller-Maersk, also underscore the importance of methanol for the maritime industry, and in particular, series engines are already available in the two-stroke sector, such as those from MAN Energy Solutions. Although the first methanol-fuelled ship was powered by four-stroke engines, further research is still required in this area.

In this paper, a methanol dual-fuel combustion process with port fuel injection for high-speed engines was investigated, which is very well suited as a retrofit solution for existing engine systems. Accordingly, for methanol operation the hardware setup of the diesel application was used without adjustments. The first step for the engine tests was to set up extensive methanol fuel peripherals and to integrate an injector into the charge air segment in front of the engine. In addition, the test bench was equipped with comprehensive indicating measurement technology and an FTIR spectrometer to determine the exhaust gas concentration of different species. Furthermore, when designing the system, special attention was given to the safety features in order to protect both the employees as well as the technical systems and to prevent unintended ignition.

As shown in the initial investigations, the gradual substitution of diesel fuel with methanol is limited by a sharp increase in ignition delay and associated high maximum cylinder pressure gradients. For medium engine loads, methanol energy fractions of only 50 % can be achieved. It is much more effective to bypass this limit and increase the engine load by enhancing the methanol content. In this way, methanol energy fractions of over 90 % can be achieved for the higher loads. The centre of combustion and the excess air ratio were discussed in the paper as important parameters to affect engine performance and exhaust gas emissions. Although earlier centres of combustion lead to higher nitrogen oxide emissions and a slight increase in the maximum cylinder pressure gradients, there are also clear advantages in terms of engine efficiency, combustion stability as well as methanol and formaldehyde emissions. In this context, the diesel pilot quantity has to be considered in particular, as the characteristic map is restricted with smaller diesel quantities and an earlier diesel injection as well as the resulting increased ignition delays then lead to a later combustion position. On the other hand, the diesel quantity is a main driver for nitrogen oxide emissions and maximum cylinder pressure gradients and therefore cannot be increased infinitely. Similar effects are apparent for the excess air ratio. Also in this case, a low λ leads to higher nitrogen oxide emissions, but at the same time advantages can be achieved in terms of indicated efficiency, combustion stability and methanol emissions. For an optimal methanol dual-fuel combustion process, the earliest possible centre of combustion and lowest excess air ratios are therefore recommended.

The results achieved are very promising in terms of effort and performance. In the course of the project, additional investigations will be conducted, focusing on different compression ratios, valve timing, the potential for using an exhaust gas recirculation system, low-pressure direct injection of methanol, and a methanol mono-fuel combustion process with a spark plug. In this context, the methanol mixture formation needs to be optimised in particular in order to improve combustion stability with regard to COV_{IMEP} and to reduce the emission of unburnt methanol.

6 ACKNOWLEDGMENTS

This research is funded by the German Federal Ministry for Economic Affairs and Climate Action on the basis of a decision by the German Bundestag (project no. 03SX585B), which is gratefully acknowledged.

In this context, the authors would like to thank the CliNeR-ECo project partners, MAN Energy Solutions and Technical University of Darmstadt, for their collaboration and support.

cliner eco
climate neutral retrofit engine concepts

Supported by:
Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag

7 DEFINITIONS, ACRONYMS, ABBREVETIONS

COV: Coefficient of variation

DAC: Direct Air Capture

DWT: Deadweight Tonnage

FM18: Single-cylinder research engine 18

GHG: Greenhouse gases

HCHO: Formaldehyde

HFO: Heavy fuel oil

HPDI: High-pressure direct injection

IBC: Intermediate Bulk Container

IMEP: Indicated mean effective pressure

IMO: International Maritime Organization

IPCC: Intergovernmental Panel on Climate Change

LC50: Lethal concentration 50 (concentration of a substance that kills 50% of a test population)

LPDI: Low-pressure direct injection

MeOH: Methanol

NO_X: Nitrogen oxides

PFI: Port fuel injection

pmax: Maximum cylinder pressure

SOC: Start of current

TDC: Top dead centre

USD: US Dollars

8 REFERENCES

[1] IPCC. 2018. *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels.*

[2] Copernicus Climate Change Service (C3S). 2025. *2024 is the first year to exceed 1.5°C above pre-industrial level.*

[3] United Nations Development Programme. 2016. *Pursuing the 1.5°C limit – Benefits & opportunities*.

[4] United Nations Conference of Trade and Development. 2023. *Review of Maritime Transport 2023 – Towards a green and just transition*.

[5] International Maritime Organization. 2023. *Resolution MEPC.33(80) – 2023 IMO Strategy on reduction of GHG emissions from ships.*

[6] DNV. 2023. *Alternative fuels for containerships.*

[7] International Renewable Energy Agency and Methanol Institute. 2021. *Innovation Outlook: Renewable Methanol*.

[8] Lloyd’s Register Group Limited. 2023. *Fuel for thought: Methanol*.

[9] Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. 2022. *Methanol as a marine fuel*.

[10] Schröder, J., Müller-Langer, F., Aakko-Saksa, P., Winther, K., Baumgarten, W., Lindgren, M. 2020. *Methanol as Motor Fuel Summary Report – Appendix I: General issues on methanol as motor fuel*.

[11] Scharl, V. 2024. Dissertation. TUM School of Engineering and Design. *Investigation of Ammonia as Fuel for High-Pressure Direct Injection Combustion*.

[12] De Vries, N. 2019. Ammonia energy conference. *Safe and effective application of ammonia as a marine fuel*.

[13] Methanol Institute. 2023. *Marine Methanol – Future-proof shipping fuel*.

[14] International Maritime Organization. 2020. *MSC.1/Circ.1621 – Interim guidelines for the safety of ships using methyl/ ethyl alcohol as fuel*.

[15] Medicins sans frontiers – Emergency medicine anaesthesia critical care work group. 2023. *Methanol poisoning*.

[16] ClassNK. 2024. *Alternative fuels insight*.

[17] ClassNK. 2023. *Safety Requirements for Construction and Equipment of Ships Using Methanol as Fuel*.

[18] Dolan, G. 2024. Going mainstream. *Bunkerspot*. Volume 21. Number 1: 105-107.

[19] MAN Energy Solutions. 2021. *Milestone Order for World's Largest Methanol Dual-Fuel Engine*.

[20] Öko-Institut e.V. 2023. *Methanol as a marine fuel – Advantages and limitations*.

[21] Nilson, P. 2023. Maersk orders six new methanol-powered vessels. *Ship Technology Global*. Issue 87. September 2023.

[22] Adams, S. DNV GL. 2016. *DNV GL welcomes Lindanger to fleet – world's first methanol fuelled ocean-going vessel*.

[23] Ship Technology. 2015. *Stena Germanica RoPax Ferry*.

[24] Kunkel, C., Hagl, P., Bhuvaneswaran, M., Gross, C., Eppler, F. 2024. Methanol Retrofits for a fast net-CO2 reduction in the Marine Market. Proceedings of *13. Dessau Gas Engine Conference*, Dessau-Roßlau, 228-246.

[25] Pang, K. M., Jangi, M., Bai, X.-S., Schramm, J., Walther, J. H., Glarborg, P. 2019. Effects of ambient pressure on ignition and flame characteristics in diesel spray combustion. *Fuel*, Volume 239, 676-685.