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Ethanol: a viable alternative fuel option

Fuels - Alternative & New Fuels

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ABSTRACT

Ethanol is being considered as a potential option in the shipping industry's efforts to reduce carbon emissions and transitioning towards a decarbonized future. Ethanol is gaining a lot of interest especially from Brazil, where ethanol has been used as fuel for road vehicles for decades. By utilizing ethanol as a fuel in combustion engines, the industry can make significant strides towards meeting its carbon emission reduction targets.

The main concern when running ethanol as fuel is its potential impact on engine performance and compatibility. Ethanol has a lower volumetric density compared to traditional fossil fuels. As a result, more ethanol is required to achieve the same energy content as fossil fuels. The reduced density can result in reduced power output and decreased fuel efficiency, as well as impact factors such as storage capacity. Furthermore, ethanol's corrosive properties may require modifications or upgrades to engine components to ensure compatibility and prevent damage. According to the paper, an efficient utilization of ethanol as fuel in combustion engines will be demonstrated.

Although ethanol generally is considered safe for use as a fuel, aspects such as flammability, corrosiveness and material compatibility should be taken seriously. Ensuring safety when utilizing ethanol as a fuel requires the engine system and operation to be designed with safety as a key feature.

This article will review different ethanol engine concepts in terms of performance and safety. The issues concerning the use of ethanol as combustion engine fuel will be addressed. This article aims to showcase the safe and efficient utilization of ethanol in engines, highlighting its potential to drive the shipping industry towards a decarbonized future.

1 INTRODUCTION

As the decarbonisation of the marine industry progresses, engine technologies capable of utilizing methanol, ammonia and hydrogen have become available. With the number of vessels sailing on sustainable fuels increasing, the demand for these fuels is growing rapidly. The availability of sustainable fuels varies from continent to continent and the pricing remains challenging for commercial use. To stay on track with International Maritime Organization's (IMO) green house gas reduction targets and keep operational costs competitive, additional sustainable options are required.

Bioethanol is being considered as one promising solution that can offer an affordable path in reducing carbon emissions from shipping. On tank-to-wake basis CO2 emissions can be expected to be reduced by 3-5% compared to operating on fossil Light Fuel Oil (LFO). With bioethanol well-to-wake CO2 emissions can be reduced up to 80% in a standard route from Brazil to Europe, according to Raízen's initial studies review [1]. The European Union's Renewable Energy Directive specifies default values for greenhouse gas emissions savings for bioethanol, ranging from 28% to 76%. The variation in savings percentages is influenced by factors such as feedstock type, production processes, and regional agricultural practices [2].

The well-to-wake emissions reduction will be heavily dependent on the production method of the bioethanol. In addition to the emissions produced and abated during production of ethanol, the land use where the biomass is produced plays an important role for sustainability. The biomass production shall not jeopardize primary food or feed production and result in land use change, either directly or indirectly according to IMO's sustainability criteria [3].

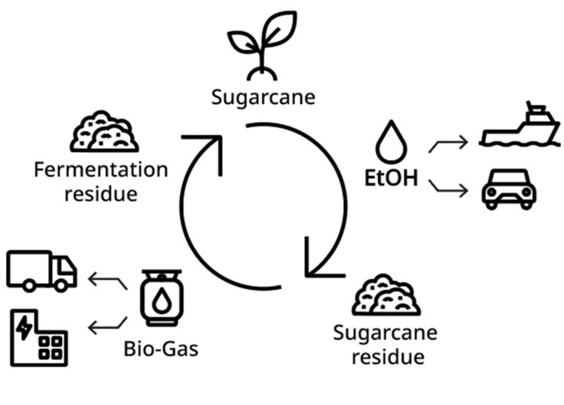

Figure 1. Circular economy model in sugarcane ethanol production

In Brazil, there are operational examples of circular economy practices within the sugarcane ethanol production industry, as illustrated in Figure 1. These examples highlight the potential for sustainable bioethanol production. The process begins with the production of sugar and ethanol from sugarcane. The residual plant materials, known as bagasse and vinasse, can be repurposed as a fertilizer for the sugarcane fields or as a feedstock for biogas production through anaerobic digestion. The digestate resulting from biogas production, along with other fermentation residues, can be utilized to enhance soil biomass in the plantation. The primary outputs of this process, biogas and bioethanol, serve multiple purposes. Biogas can be converted into electricity, while bioethanol can be used as a sustainable transport fuel. This integrated approach not only maximizes resource efficiency but also contributes to the reduction of greenhouse gas emissions, promoting a more sustainable and circular bioeconomy [4, 5, 6].

Ethanol has been utilized to reduce carbon emissions in the automotive sector for an extended period, particularly in Brazil, where it has significantly contributed to making road transport more sustainable. While ethanol is a well-known fuel for smaller high-speed engines, its application in larger medium-speed engines within the shipping industry has not been extensively investigated. This paper addresses the technical challenges associated with the use of ethanol as a fuel for combustion engines. Key issues include the lower energy density of ethanol compared to traditional fossil fuels, which can result in reduced engine performance and efficiency. Additionally, ethanol compatibility with existing methanol engines will be covered.

The objective of this paper is to showcase the safe and efficient utilization of ethanol in marine engines, emphasizing its potential to drive the shipping industry towards a decarbonized future. By addressing these technical challenges, the research aims to contribute to the broader adoption of ethanol as a viable alternative fuel in the maritime sector.

2 ETHANOL PRODUCTION AND AVAILABILITY

The global annual production of ethanol is currently approximately 110 million tons, with the United States and Brazil being the two largest producers, followed by the European Union and China, as illustrated in Figure 2. In comparison, the marine sector consumes a total of approximately 350 million tons of heavy fuel oil (HFO) and distillate fuel combined annually. Considering that the energy content of ethanol is about two-thirds that of HFO and distillate fuel, the total current ethanol production would equate to approximately 20% of the total marine fuel demand.

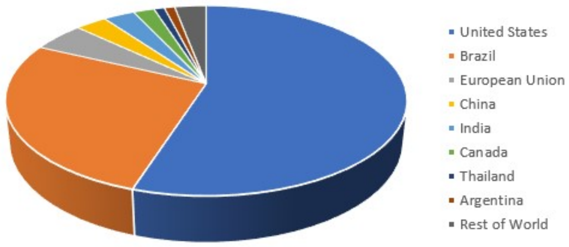

Figure 2. World fuel ethanol production by region [6]

Approximately 90% of the ethanol produced globally is utilized as fuel, predominantly blended with gasoline. The high demand for ethanol in gasoline blending could potentially constrain its availability for the marine sector. The geographical availability of ethanol is also uneven, with higher accessibility in regions possessing well-established production facilities and related infrastructure. Ethanol, being the most extensively used biofuel for land-based transportation, is stored at numerous large fuel and chemical hubs. Currently, there are no ethanol-powered ships in operation, necessitating the development of port infrastructure specifically for ethanol handling and storage.

Sugarcane is a major global energy crop, traditionally used for bioethanol, sugar, and bioelectricity production. The high demand for biofuels has increased production, driven by rising fossil fuel prices, environmental impacts, global warming, concerns about greenhouse gas (GHG) emissions, and increasing governmental incentives. In 2018, sugarcane ethanol production ranked second with 30 billion liters, while the primary feedstock for ethanol was coarse grains (i.e., corn) with 61 billion liters. Together, these two feedstocks account for 84% of the world's ethanol production.

Worldwide sugarcane production reached about 1.86 billion tons in 2021, with 75% of this production concentrated in Brazil, India, China, Pakistan, and Thailand (respectively, 38.5%, 21.8%, 5.8%, 4.8%, and 3.6% of the global production). Brazil produced 75% more sugarcane than India but similar amounts of refined sugar (38.1 million tons in Brazil and 35.8 million tons in India during the same period). These figures highlight the importance of sugarcane bioethanol in Brazil, where more than half of the sugarcane, about 55%, is converted into biofuel. This also indicates the potential for other countries, particularly India, to add a clean fraction of biofuel to their automotive fleets, with an estimated production capacity of 30 billion liters of ethanol annually.

Brazilian production areas are mainly located south of the Amazon Rainforest, avoiding competition with native forest areas. South-Central Brazil is the heart of the country's sugarcane production and industry. In addition to the technological potential, Brazil has extensive land available for production, using about 100,000 square kilometers for plantations, which is less than 1.2% of the national territory. Various by-products and wastes are generated in sugarcane mills, such as sugarcane bagasse, straw, leaves, molasses, vinasse, and CO_2. Developing integrated processes using these residual fractions could enhance the viability and sustainability of sugarcane processing units through biorefinery approaches under a circular bioeconomy [7].

3 ETHANOL AS A MARINE FUEL

Ethanol is increasingly being considered as a viable alternative fuel for marine engines. From a technical perspective, ethanol and methanol share similar properties, allowing for the application of comparable technical solutions. For dual-fuel engines designed to operate on both conventional fuels and methanol, minor modifications can enable the use of ethanol as well. Below are detailed notes and solutions related to ethanol engine technology.

Marine Engine Technology Solutions for Ethanol:

- Viscosity: Ethanol has a different viscosity compared to traditional marine fuels, necessitating the selection of appropriate fuel injection equipment.

- Fuel Injection Capacity: Due to the varying energy content of different fuels, it is crucial to ensure that the fuel injection system has adequate capacity.

- Ignition: Ethanol has a lower cetane number than traditional marine fuels, requiring the use of pilot fuel for reliable ignition.

- Corrosion: Ethanol can be corrosive, making the correct choice of materials and/or the use of corrosion inhibitors essential.

- Safety: Properties such as low flashpoint, flammability, and explosion risk must be addressed in accordance with existing regulations and technical solutions.

Despite containing carbon, ethanol can be considered a carbon-neutral fuel when produced from renewable sources. Approximately 95% of the ethanol produced globally is bioethanol. Compared to methanol, ethanol has a higher energy content, which positively impacts the required fuel tank volume for vessels. The table below illustrates key considerations and energy content-related facts regarding the differences between traditional and sustainable marine fuels.

Table 1. Fuel properties

Fuel type		LFO	EtOH	MeOH
Boiling temperature @ 1 bara	[°C]	160	78.4	64.7
Density (liquid) @ 20°C	[kg/l]	0.83	0.789	0.78
Lower Heating Value - LHV	[MJ/kg]	43.0	26.7	19.9
Latent heat of evaporation	[MJ/kg]	0.25	0.85	1.10
Stochiometric Air/fuel ratio	[kg_{air}/kg_{fuel}]	14.5	9.00	6.47
Stochiometric Air/fuel ratio	[kg_{air}/MJ_{fuel}]	0.34	0.34	0.33
Adiabatic flame temperature (1bar 20°C)	[°C]	2104	2238	1949
Maximum laminar burning velocity	[cm/s]	20	50	52
Minimum auto ignition temperature	[°C]	400	423	455
Ignition energy	[mJ]	0.2	0.28	0.14

The main properties of Light Fuel Oil (LFO), ethanol, and methanol are presented in Table 1. While the properties of ethanol and methanol are similar, bioethanol typically contains various contaminants such as sulphur, chlorides, and water. The concentration of water in bioethanol typically ranges from 5-10 %-m. The presence of these contaminants in varying concentrations can significantly impact corrosion and material wear properties, necessitating further research to understand these effects comprehensively.

Ethanol is well researched in combination with Port Fuel Injection (PFI) with both premixed Otto combustion and diffusive Diesel combustion. For dual-fuel high-speed engines utilizing ethanol fumigation in the intake manifold, substitution ratios of up to 80% of the fuel energy have been reported [8], showing promise that ethanol could provide significant reductions in carbon emissions.

As is typical with methanol PFI technologies, challenges such as lubrication oil dilution and engine knock need to be carefully considered in the engine concept. Ethanol, which requires a higher boiling temperature compared to methanol, may necessitate higher receiver temperatures to avoid wall wetting and prevent fuel impingement on the cylinder liner. The combination of higher receiver temperatures and ethanol’s lower latent heat of evaporation can result in increased sensitivity to engine knock compared to methanol. Despite these potential challenges, an engine designed for methanol operation should be capable of accommodating ethanol with minimal modifications.

Research on ethanol in diffusive combustion with Direct Injection (DI) is not widely available. Kim et al. have reported positive results on engine emissions when blending ethanol with diesel on a high-speed common-rail automotive engine [9]. While showing promise for ethanol, the blending ratios were low, reaching 10 %-v at most.

To increase the understanding on both ethanol in diffusive combustion and requirements of ethanol-methanol capable engines, Wärtsilä carried out a test campaign covering basic combustion research and multicylinder engine tests. The methodologies employed and the results obtained are detailed in the following chapters.

4 COMBUSTION RESEARCH UNIT TEST WITH ETHANOL

Ethanol and methanol were evaluated using a Combustion Research Unit (CRU) to compare their ignition and combustion properties in a diffusive combustion process, both with and without the addition of LFO as a pilot fuel. The test aimed to analyze the ignition and combustion properties of these alternative fuels under controlled conditions.

4.1 Test method

Anhydrous ethanol sample used in the test had purity of >99.5%. IMPCA grade methanol sample used in the test had purity of >99.9%. LFO reference fuel complied with fuel requirements in ISO 8217:2017.

In the test procedure, the fuel is injected into a constant volume combustion chamber which is heated and pressurized according to two different test conditions:

1. Temperature: 550 °C & Pressure: 55 bar

2. Temperature: 590 °C & Pressure: 70 bar

During combustion of the fuel, the pressure increase in the combustion chamber is measured and plotted against time for evaluating the combustion properties and determining parameters including e.g. ignition delay and main combustion period. The parameters and explanations on combustion pressure trace are presented in Figure 3.

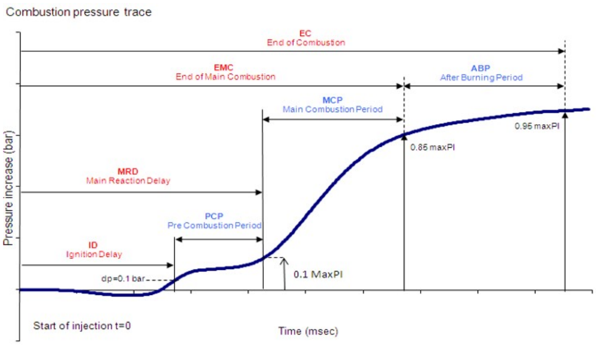

Figure 3. Explanation of pressure trace analysis and parameters

4.2 CRU test results

Neither ethanol nor methanol ignited in the test chamber without pilot fuel under test condition no. 2, which was expected based on earlier experiments on the CRU with methanol. The tests were continued with LFO pilot ignition and the chamber conditions adjusted for test condition no. 1.

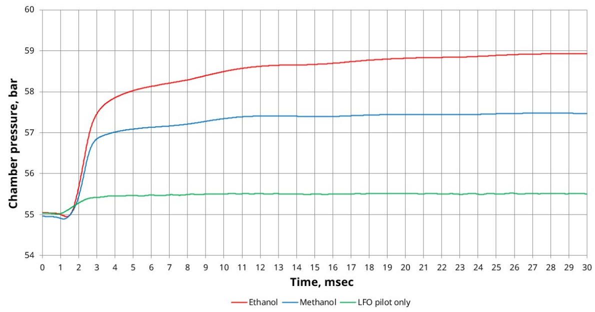

Figure 4. Pressure trace, test condition 1

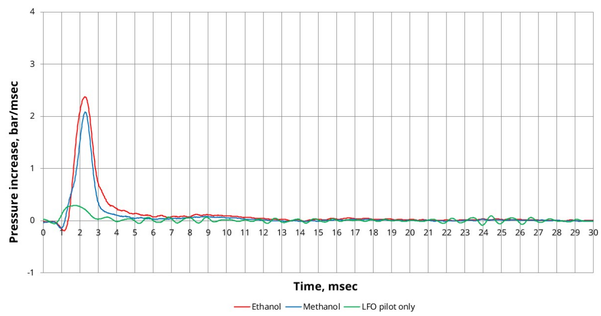

Figure 5. Pressure rise rate, test condition 1

Parameters determined from the pressure traces presented in Figure 4 and Figure 5, at test condition 1 with pilot fuel, indicated that the Ignition Delay (ID) is at a similar level for both ethanol and methanol. However, the Main Combustion Period (MCP) and After Burning Period (ABP) were observed to be longer for ethanol compared to methanol.

This suggests that while the initial ignition characteristics of both fuels are comparable, ethanol exhibits a more prolonged combustion process. The extended MCP and ABP for ethanol could imply differences in the combustion kinetics and energy release profiles between the two fuels. These findings are significant as they may influence the overall efficiency and emissions characteristics of engines operating on ethanol versus methanol.

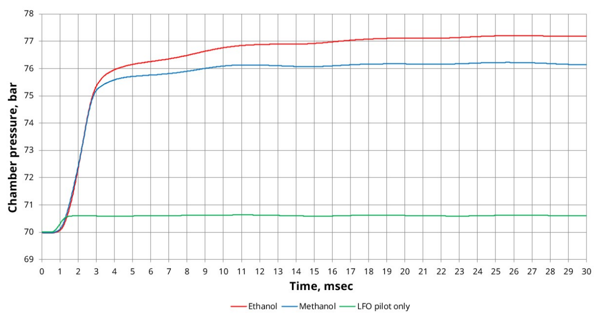

Figure 6. Pressure trace, test condition 2

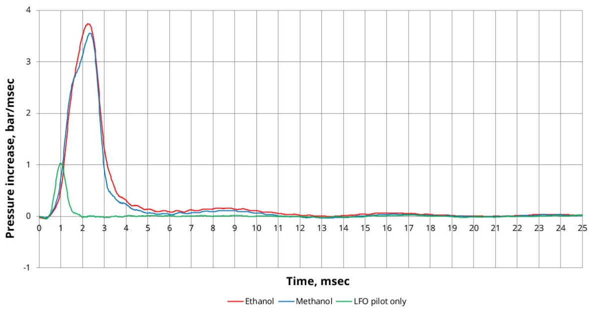

Figure 7. Pressure rise rate, test condition 2

Parameters determined from the pressure traces presented in Figure 6 and Figure 7 under test condition no. 2 with pilot fuel indicated that the ID for ethanol is similar to that of methanol, although the ID for methanol was marginally shorter. The MCP and ABP were observed to be longer for ethanol compared to methanol under these conditions.

Based on the results of the CRU-tests, ethanol exhibits a similar ignition delay to methanol in diffusive combustion process utilizing pilot fuel ignition. The extended combustion duration of ethanol may be attributed to its chemical properties and combustion characteristics. The observed increase in peak pressure, although minor, aligns with the thermodynamic expectations given ethanol's lower latent heat of evaporation. These findings suggest that ethanol can be a viable alternative to methanol in multi-cylinder engines, potentially offering similar performance metrics with minimal adjustments to the existing engine configuration.

5 MULTI-CYLINDER ENGINE TEST WITH ETHANOL

The objective of the engine test was to determine if a methanol optimized engine can use ethanol as a drop-in fuel, how the performance of the engine will change with ethanol and what areas need to be further developed to better accommodate operation on ethanol.

5.1 Test engine

Table 2. Wärtsilä 32M main technical data

Main technical data	
Cylinder bore	320 mm
Piston stroke	400 mm
Cylinder output	580 kW/cyl / 560 kW/cyl
Speed	750 rpm / 720rpm
BMEP	28.9 bar
IMO	Tier II or III

The engine utilized for these ethanol tests was a six-cylinder Wärtsilä 32M, specifically developed for dual-fuel methanol operation. The main features of this engine are presented in Table 2. The engine is turbocharged, intercooled and equipped with on/off type variable inlet valve timing.

The methanol fuel system comprises an external high-pressure pump that feeds a common-rail system capable of achieving an injection pressure of 600 bar. The diesel injection system is supplied by a camshaft-driven jerk-pump, which allows the use of both HFO and LFO, with compatibility for most biodiesel types as well. The layout of the fuel system is illustrated in Figure 8 [10].

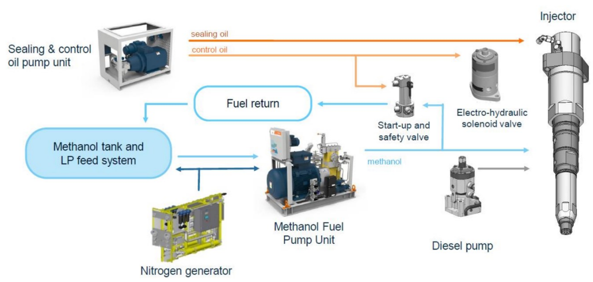

Figure 8. Wärtsilä 32M fuel system

Both LFO and methanol are injected through a common injector body, which contains separate needles (3 pcs) for methanol arranged in a circular pattern, and a central needle for LFO injection. The injection nozzle is designed with 9 holes for methanol and 10 holes for LFO, ensuring efficient and precise fuel delivery.

The control oil is utilized to actuate the system's methanol fuel needles within the injector. Its primary function is to transmit the opening force generated by the solenoid and to dampen any potential vibrations in the needle movement.

The sealing oil serves to prevent the low viscosity methanol fuel from leaking past the needle into the injector body. Consequently, the sealing oil pressure must always exceed the fuel injection pressure. Due to the pressure differential between the fuel and the sealing oil, a small quantity of sealing oil will enter the needle seat, providing lubrication and thereby enhancing the service life of the nozzle.

5.2 Test method

The engine tests were conducted using anhydrous grain ethanol, which contained approximately 3%-

m of 2-methyl-1-propanol (isobutanol) as the legally mandated denaturing agent. Additionally, residual methanol, estimated to be around 5%-m of the ethanol-methanol fuel mixture, was present in the tank prior to bunkering ethanol. To ensure a homogeneous mixture, the fuel was circulated using a transfer pump installed in the tank.

A sample of the thoroughly mixed fuel was then taken and analyzed at Wärtsilä’s in-house fuel laboratory. The results of the fuel analysis are presented in Table 3.

Table 3. Analysis results of the ethanol-methanol fuel mixture

Sample ID		24022	24023
Sample type		Ethanol	Ethanol
Sample label		Truck 7.2.2024 Ethanol	MeOH/Ethanol After circulation 8.2.2024
Water content	wt%	0.318	0.151
HHV	MJ/kg	29.91	29.34
LHV	MJ/kg	27.13	26.58
Carbon	wt%	52.3	51.4
Hydrogen	wt%	13.1	13

The test matrix involved operating the engine under varying loads and engine speeds to evaluate the performance characteristics of ethanol and methanol as fuels. The observed variations between ethanol and methanol were consistent across different nominal engine speeds and when the engine was operated according to the nominal propeller curve.

The performance characteristics of the engine running on ethanol were compared to those of the engine running on methanol under standard settings. Importantly, no modifications were made to the engine’s automation system, hardware, components, or turbocharger specifications for these tests, ensuring a direct back-to-back comparison of the two fuels.

5.3 Test results

When comparing the injection durations for ethanol and methanol as illustrated in Figure 9, it is observed that ethanol exhibits an injection signal approximately 500μs shorter than methanol at high Break Mean Effective Pressures (BMEP). Below 16 bar BMEP, the difference in injection duration is reduced, yet ethanol consistently maintains a shorter signal. This outcome is anticipated due to ethanol's higher energy density relative to methanol.

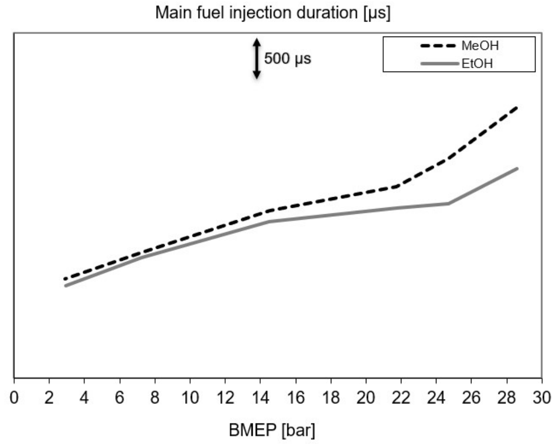

Figure 9. Main fuel injection duration

Typically, a shortened injection duration at the same BMEP could be expected to lead to shorter combustion duration and lower fuel consumption in the context of diffusive combustion. However, this expectation does not hold true when comparing ethanol and methanol, which have distinct combustion properties.

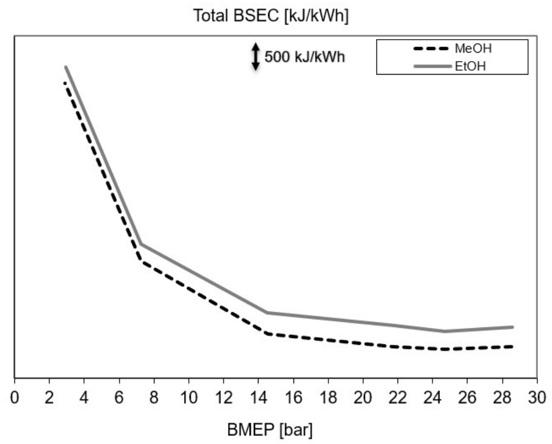

Figure10. Total BSEC

As illustrated in Figure 10, the total Break Specific Energy Consumption (BSEC), including pilot fuel, is approximately 500 kJ/kWh higher when operating on ethanol compared to methanol. This difference is consistent across the load range from 2.9 bar BMEP to 28.9 bar BMEP, although some variations can be observed at different loads.

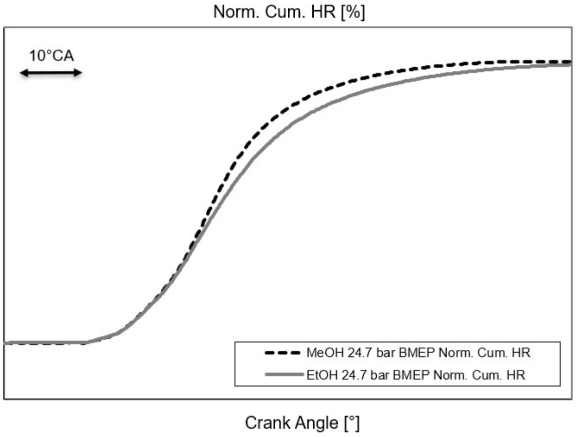

Figure 11. Normalized cumulative heat-release

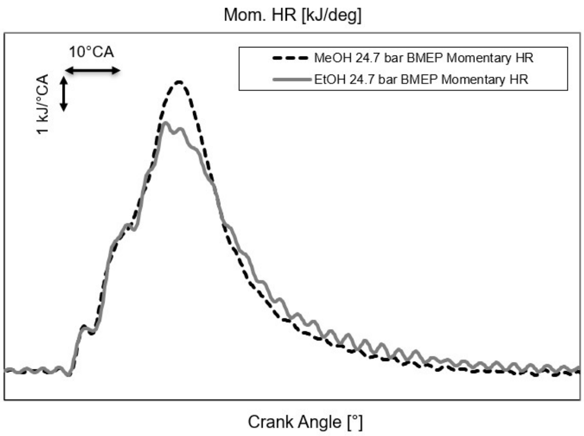

Figure 12. Momentary heat-release

A partial explanation for the disconnect between injection duration and fuel consumption can be found when observing the Heat-Release (HR) graphs illustrated in Figures 11 and 12. While the ignition delay for both fuels is similar, as was also observed in the CRU tests, the cumulative HR is slower with ethanol. When examining the momentary HR, the peak HR rate is approximately 1.5 kJ/°CA lower for ethanol. This indicates that ethanol's burning velocity differs significantly from that of methanol, which contributes to the observed discrepancies in fuel consumption. Indications of lower burning velocity were seen in the CRU tests, and similar behavior was observed on the multicylinder engine, confirming the validity of using the CRU to predict a fuel's impact on engine performance.

The maximum laminar burning velocities reported in the literature for ethanol and methanol indicate that ethanol burns slightly slower than methanol, although the difference in peak velocities is not significant. Specifically, values up to 50 cm/s for ethanol and up to 52 cm/s for methanol have been reported [11, 12]. Despite the similarity under controlled conditions and under moderate pressures, the fuels exhibit markedly different behavior under conditions typical for an engine utilizing direct injection and diffusive combustion.

The slower burning velocity and longer heat-release were also evident in the charge air pressure, shown in Figure 13. At high BMEP values the difference between ethanol and methanol was about 0.5 bar, decreasing towards lower BMEP values. At 28.9 bar BMEP the charge air pressure exceeded the maximum mapped value which resulted in the exhaust waste gate opening, explaining why the charge air pressure is the same with both fuels.

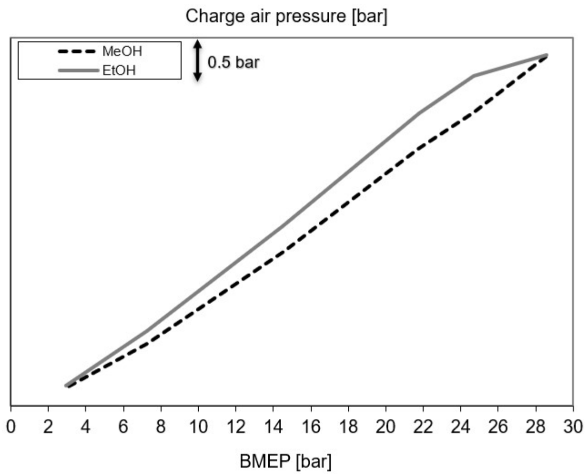

Figure 13. Charge air pressure

Approximately 6 bar higher firing pressures were observed when operating on ethanol. This increase can be attributed to elevated compression pressure, which is a result of the increased charge air pressure.

Only small variations in the exhaust gas temperatures were observed. With the exhaust waste gate closed, largest difference measured between the fuels was approximately 10°C as seen in Figure 14. The larger difference seen at 28.9 bar BMEP is caused by the exhaust waste gate being open to limit the charge air pressure.

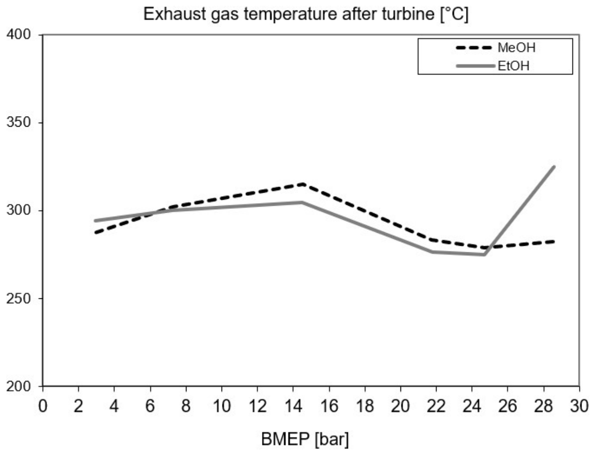

Figure 14. Exhaust gas temperature after turbine

Nitrogen Oxide (NOx) emissions when operating on ethanol were observed to be 50-100 vol-ppm lower compared to methanol. However, due to the higher exhaust gas mass flow associated with ethanol, the specific NOx emissions are approximately at the same level as those of methanol, as illustrated in Figure 15. When calculating the emissions for the ISO 8178 D2 test cycle, ethanol produced a weighted NOx emission that was 0.2 g/kWh lower than that of methanol. For IMO certification purposes it could be proposed to consider methanol as the worst-case fuel in terms of NOx emissions, if the same engine is to operate also on ethanol.

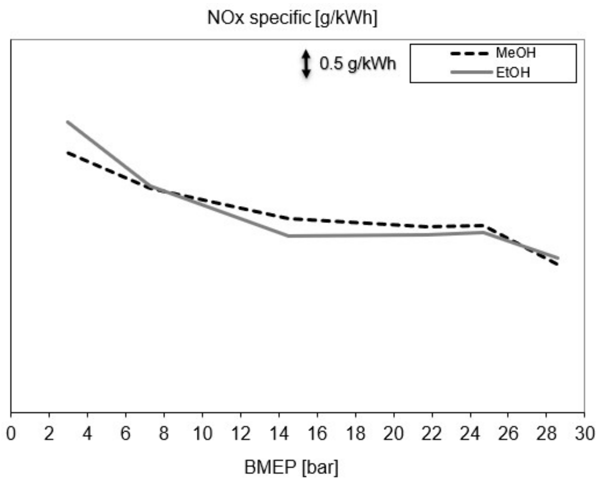

Figure 15. Specific NOx emissions

The Total Hydrocarbon (THC) emissions measured were mainly similar between the two fuels. At 2.9 bar BMEP, an increase of roughly 100 vol-ppm was observed, as seen in Figure 16. The response factor of the hydrogen Flame Ionization Detection (FID) method varies between different fuel types. Alcohol fuels typically have a response factor of less than 1. The energetic fuel share of ethanol and methanol is roughly 92% at 28.9 bar BMEP decreasing to roughly 50% at 2.9 bar BMEP. The change in fuel share will cause variation in the exhaust gas matrix. Consequently, this potential interference should be taken into account when interpreting the THC emissions results for alcohol-based fuels.

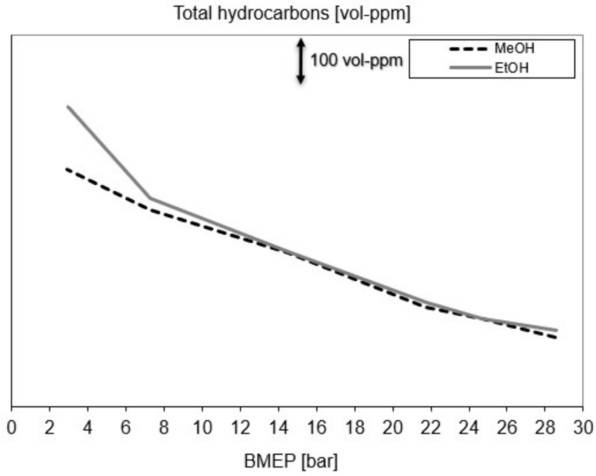

Figure 16. Total hydrocarbon emissions

In addition to the FID a Fourier Transform Infrared (FTIR) measurement device was used. FTIR allows for the detection of a broader range of gaseous components compared to traditional devices typically used for THC measurements. Shown in Figures 17 and 18, unburnt fuel and formaldehyde emissions were measured during the test.

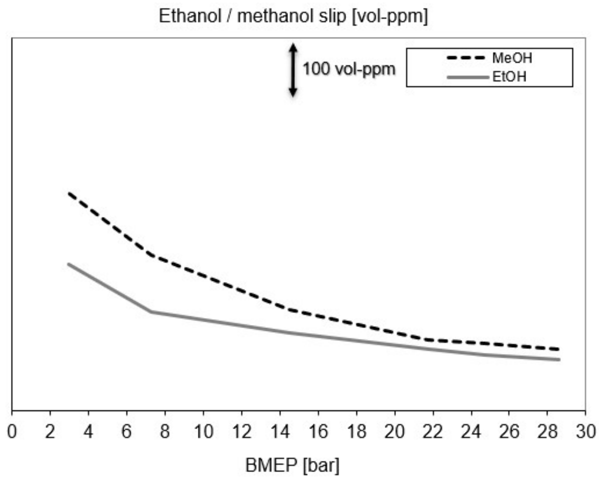

Figure 17. Unburnt ethanol and methanol emissions

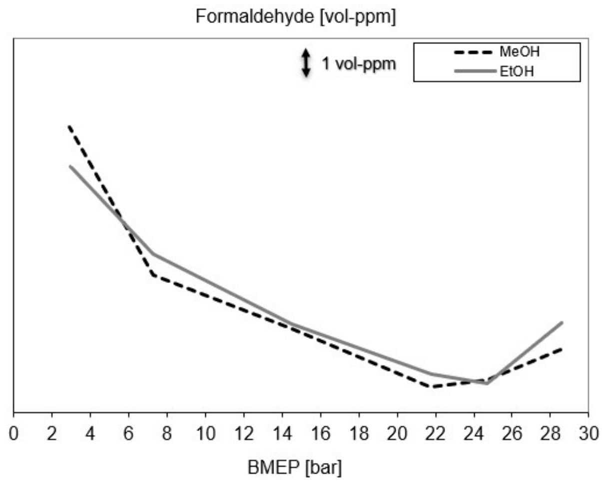

Figure 18. Formaldehyde emissions

The concentration of unburnt main fuel was reduced by over 100 vol-ppm when operating on ethanol. Considering the longer heat-release and higher fuel consumption with ethanol this is unexpected. At the same time Carbon Monoxide (CO) emissions increased by roughly the same amount, indicating that the combustion kinetics are somewhat different between these fuels in diffusive combustion.

Formaldehyde emissions were similar both with ethanol and methanol, only minor variations were observed, while absolute values remained well below 20 vol-ppm.

Particulate matter (PM) emissions were measured with an AVL Micro Soot Sensor. This device provides the possibility to perform on-line measurements of particulate mass. However, it can only measure the solid particulates, and the impact of organic carbon is not included in the measured mass. Roughly 4 mg/m^3 increase was observed at low BMEPs with ethanol, shown in Figure 19. Above 22 bar BMEP the difference between ethanol and methanol was negligible.

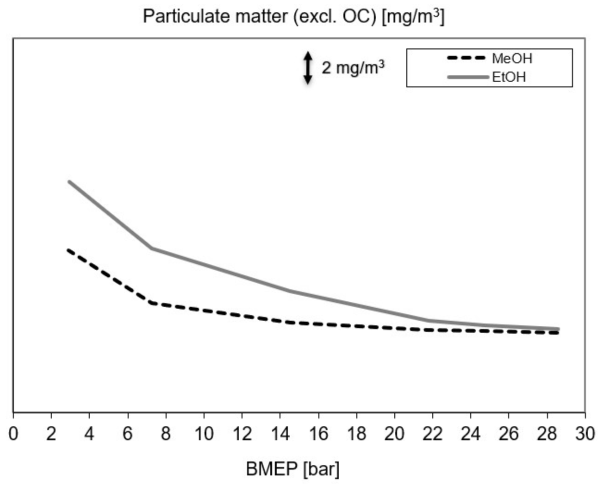

Figure 19. Particulate matter emissions

These test results highlight the importance of considering the specific combustion characteristics of different fuels when evaluating their performance in internal combustion engines. Despite theoretical similarities their performance can vary significantly in practice.

6 CONCLUSIONS

Due to its similarity with methanol, ethanol can be considered a viable option as a marine fuel. The availability of bioethanol is higher compared to many other sustainable fuel options today. However, competition with other bioethanol consumers, such as blending with gasoline for automotive use, can constrain its availability. The electrification of passenger cars worldwide may alleviate this challenge.

Geographical accessibility to ethanol varies greatly, meaning its use as the sole sustainable option may not be feasible everywhere. However, for vessels equipped with multifuel-capable engines, ethanol could serve as an additional option, especially for global operations.

Ethanol can be utilized in a methanol-optimized engine; however, this results in a penalty in thermal efficiency. The use of ethanol requires further development and separate optimization to achieve optimal performance.

On a general level, three possible development paths for ethanol-capable engines can be proposed, in order of shortest time-to-market:

1. **Methanol Engine Running on Ethanol**: This approach involves using a methanol engine to run on ethanol. While there is an efficiency penalty when using ethanol, the NOx emissions are similar for both fuels. This path offers the quickest

time-to-market due to the minimal modifications required.

2. **Injection nozzle and Turbocharger Optimization**: This development path focuses on optimizing the injection nozzle and turbocharger to accommodate both ethanol and methanol. Although there may be an efficiency penalty when using methanol, this approach allows for dual-fuel capability with improved performance characteristics for each fuel.

3. **Advanced Multifuel Engine**: The most sophisticated development path involves creating an advanced multifuel engine with adaptive combustion controls and redundancy in injection pressure capacity. This design can accommodate the variations in burning velocity of ethanol and methanol, ensuring optimal performance and efficiency for both fuels. This path, while offering the most advanced solution, has a longer time-to-market due to the complexity of the required technology.

These development paths provide a strategic framework for advancing ethanol-capable engine technology, each with its own set of trade-offs and benefits.

7 DEFINITIONS, ACRONYMS, ABBREVIATIONS

BSEC	Break specific energy consumption
CO	Carbon monoxide
CO2	Carbon dioxide
CR	Common rail
CRU	Combustion research unit
DI	Direct injection
FID	Flame ionization detection
FTIR	Fourier transform infrared
HFO	Heavy fuel oil
HR	Heat-release
IMO	International maritime organization
IMPCA	International methanol producers and consumers association
LFO	Light fuel oil
LHV	Lower heating value
NOx	Nitrogen oxides
PFI	Port fuel injection
PM	Particulate matter
THC	Total hydrocarbons

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