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Methanol as a Fuel in Shipping: Review and Outlook to ICE Research Within MENENS

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Abstract. Waterborne transportation has long been the backbone of global trade, with the reciprocating internal combustion engine (ICE) as the dominant power source. In the efforts to decarbonize shipping, methanol has emerged as a promising alternative fuel due to its easy storability and favorable combustion characteristics compared to non-carbon fuels such as hydrogen and ammonia. In the MENENS project, one of the research objectives is to better understand, further develop, and demonstrate different engine technologies that can employ methanol fuel in marine-sized engines. This study reviews maritime stakeholder research on methanol fuel for marine ICEs, emphasizing the chosen injection and ignition strategies across different engine technologies. In this paper, we aim to identify research gaps concerning methanol as a marine engine fuel, and provide insight into the initiatives and proposed research direction within MENENS.

Keywords: Internal combustion engine (ICE) · Shipping · Methanol · Alternative fuel · MENENS

1 Introduction

Using synthetic 'net-zero carbon fuels' in reciprocating internal combustion engines (ICEs) of marine vessels appears to be a promising route to decarbonize shipping [1]. Among many proposed alternative fuels, methanol is seeing an ever-increasing interest to power both existing and newbuild ships, as for instance demonstrated by the large container vessels recently ordered by Maersk fueled by green methanol [2]. Methanol's liquid state at standard temperature and pressure (STP), relatively low investment cost [3], and scalable net-zero production pathways [4] make it a promising fuel solution and a potential catalyst for the transformation to sustainable shipping.

While several combustion strategies can be employed to use methanol in ICEs, high pressure direct injection (HP-DI) of methanol appears the most

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appealing for large-bore marine engines [5], facilitating methanol's combustion in a diffusion manner. However, for smaller-bore four-stroke marine engines, the cylinder head's space constraints and cost of an extra DI system for methanol call for alternative strategies. One option is the premixed combustion mode using port fuel injection (PFI) of methanol, ignited by a spark in mono-fuel (MF) spark-ignition (SI) engines or pilot fuel in compression ignition (CI) engines. However, understanding of these technologies, particularly premixed dual-fuel (DF) CI engines with combustion modes varying from premixed to partially premixed and diffusion combustion, is still limited.

This study provides a short review of research into methanol as a marine engine fuel. First, we explore the chosen injection and ignition strategies and their resulting combustion mode across the various engine technologies. Second, we highlight some of the existing research gaps in marine ICEs fueled with methanol. Finally, we discuss the future research to be undertaken in the MENENS project to fill these gaps. This paper provides a guidance for future research on mono-fuel SI and DF CI engines and their associated combustion modes, aiming to enable methanol fuel adoption in a wider range of marine applications.

2 The Sustainable Fuel of Methanol in Shipping

2.1 Alternative Marine Fuels

Sustainable fuels can power not only the current, but also the next generation marine engines. The adoption of natural gas (NG) in marine ICEs can reduce their environmental impact, including CO_2 emissions, without abating their performance. However, NG remains a fossil fuel, thus insufficient for shipping to rely on to meet the decarbonization targets set by the International Maritime Organization (IMO). Therefore, sustainable fuels, either produced by biomass or renewable electricity, have been the central focus of recent research and development (R&D) efforts in shipping [1]. Currently, R&D mainly focus on three alternative fuels: methanol, ammonia, and hydrogen [6]. Challenges with the combustion characteristics, emissions, and toxicity of ammonia still hinder its rapid adoption in marine ICEs. Similarly, challenges with hydrogen's low energy density and wide flammability limits inhibit its potential for fast application on board of ships, especially for larger (ocean-going) vessels [7]. Consequently, methanol (see [5] for properties) continues to gain momentum for widespread use in the maritime sector, including both deep-sea and inland-shipping applications.

2.2 Sustainable ICE Operation with Methanol

Methanol's liquid state at STP and the potential for net-zero carbon engine operation using renewable methanol make it a popular sustainable shipping fuel solution [4]. Additionally, methanol has the potential to eliminate the inherent trade-off between nitrogen oxide (NOx) and soot emissions in marine diesel engines due to its high latent heat of evaporation and the absence of carbon-to-carbon molecules [5]. Lastly, the sulfur-free nature of methanol relieves ICE operations from sulfur oxide (SOx) emissions, rendering the need for scrubbers unnecessary. These benefits have placed methanol at the forefront of (R&D) efforts in shipping.

3 Methanol Trajectory in Marine Engine Applications

The long use of methanol as an ICE fuel in automotive applications and the potential of large-scale production of green methanol has drawn great attention from the maritime industry since the last decade. This has resulted in many initiatives towards the R&D of methanol-fueled engines for marine applications.

3.1 Consortium Projects

To provide a comprehensive overview of the research efforts, a chronology of previous and current research initiatives on methanol-fueled marine ICEs was compiled. Figure 1 presents the timeline of the consortium projects investigating methanol application in marine engines.

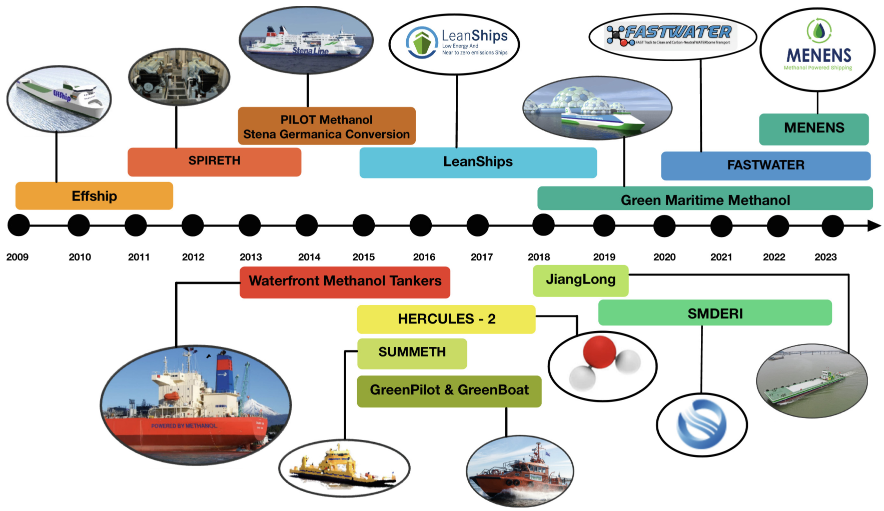

Fig. 1. Timeline of projects on methanol-fueled marine ICEs (Image courtesy MENENS project, produced using Notability.)

The Effship project initiated the efforts to explore methanol fuel [8] and the promising results derived from its evaluation resulted in the first experimental investigation of methanol in the subsequent SPIRETH project [9]. In SPIRETH, a diesel engine was converted to run on DI and diffusion combustion of both methanol and diesel, paving the way for the first on-board application in the Stena Germanica ferry where four Wärtsilä four-stroke medium-speed diesel engines were successfully converted to operate on methanol. A single dual-channel (DC) HP injector is employed to inject both fuels in the cylinder [10].

The HERCULES-2 project, where the WinGD manufacturer was involved, initiated the efforts to build efficient and environmentally friendly two-stroke engines capable of switching between different alternative fuels, including methanol [11]. Another initiative came from MAN and the Waterfront project to build seven new tanker vessels propelled by two-stroke engines powered by methanol [12]. In both two-stroke engine concepts, high pressure DI strategy was used for both diesel and methanol fuel for their subsequent diffusion combustion.

In the following years, more initiatives emerged, including the SUMMETH project focused on experimentally investigating alternative engine concepts, such as SI, to employ methanol in smaller ship applications [13]. This project also helped ScandiNAOS to build its new MD97 methanol engine employing methanol with an ignition improver to combust in the diffusive mode. Following SUMMETH, GreenPilot project was carried out to demonstrate the feasibility of converting small vessels to use methanol in SI engines [14]. In parallel, the GreenBoat project was initiated, focusing on the application of those engines in recreational crafts. The Shanghai Marine Diesel Engine Research Institute (SMDERI) also initiated its efforts to convert a commercial diesel engine to operate in diesel-methanol under diffusion combustion [15]. Table 1 provides an overview of several methanol-fueled marine engines currently available on the market. Furthermore, it is worth noting that most marine engine manufacturers have committed to introducing new methanol-fueled engines in the near future.

Table 1. Methanol-fueled marine ICEs by engine manufacturers

Engine Manufacturer	Engine Model	Type	Power range (kW)	Methanol Injection	Combustion mode	Ref.
Wärtsilä	W32 M	4x-stroke Medium Speed	3,480 - 9,280	HP-DI DC single injector	Diffusion DF	[10]
MAN	ME-LGIM	2-strokeLow-speed	4,000-60,000	HP-DI separate injector	Diffusion DF	[12]
WinGD	X-DF-M	2-strokeLow-speed	38,700-77,400	HP-DI separate injector	Diffusion DF	[11]
ABC	DZD MeOH	4-strokeHigh-speed	1,326 - 3,536	LP-PFI	Premixed DF	[16]
SMDERI	CS series	4-strokeMedium-speed	1,230 - 1,760	HP-DI separate injector	Diffusion DF	[14]
ScandiNAOS	MD97	4-strokeHigh-speed	150 - 450	HP-DI ignition improver	Diffusion MF	[17]

The LeanShips project was established to showcase methanol's potential as an ideal retrofitting choice, opting for the low-pressure (LP) PFI strategy operating the engine under the premixed combustion of methanol-air ignited by pilot diesel [18]. Following LeanShips' research output, the ongoing FASTWATER project was launched, where engine manufacturer Anglo Belgian Corporation (ABC) is also involved, to establish the feasibility of both converted and new-build vessels to run on methanol fuel [19]. The premixed DF combustion concept was also explored in a converted diesel engine in a project led by Jianglong and other knowledge institutions [20]. In the Green Maritime Methanol project, alternative strategies to use methanol in marine engines, such as a heavy-duty (HD) SI engine and a CI engine with diesel-methanol blends, were studied [21,22].

4 Research Challenges and Contributions Within MENENS

In continuation of these research efforts, the MENENS project, a Dutch consortium initiative, was established with a focus on accelerating the energy transition in shipping by developing methanol-based solutions. One of the objectives of the project is to better understand, further develop and demonstrate potential ICE technologies that can employ methanol as a marine fuel [23].

4.1 ICE Combustion Strategies and Experimental Research

In DF CI engines, there are primarily two ways for methanol combustion: premixing it with air and ignite it with pilot diesel in a process reminiscent of the Otto cycle, or combusting both methanol and diesel in a diffusive mode. The diffusion combustion approach is currently popular in methanol marine engines, especially large-bore low-speed ones. The premixed combustion concept is better suited for smaller marine engines with cylinder head constraints. However, combustion challenges, such as knocking at high loads and misfire at low loads, restrict maximum attainable Methanol Energy Fraction (MEF). Options to overcome such challenges and increase maximum MEF remain relatively unexplored, thus calling for further research into premixed DF CI engines. Further, alternative premixed MF strategies, such as using methanol in HD SI engines, can be more suitable for certain marine applications considering the trade-off between performance and emissions.

Based on the remaining challenges, one of the objectives of the MENENS project is to further explore the potential of premixed combustion concepts of methanol for marine engine applications. Exploring the capabilities of a MF methanol strategy in HD SI engines is imperative. Furthermore, we seek to draw conclusions regarding premixed combustion variances related to the methods of combustion initiation, whether it be pilot fuel flame or spark. These insights can also guide our optimization efforts for the premixed DF CI engine, potentially accelerating the sustainable transformation of the current fleet operated by the diesel engine. For this reason, two marine engines, a medium-speed CI and a high-speed SI engine, will be converted to operate on PFI methanol in the coming year. The HD SI engine and its main characteristics are shown in Fig. 2 and Table 2, respectively, located in the Appendix A.

5 Conclusions

Methanol fuel can power both existing and next-generation marine engines. However, challenges such as maximum attainable MEF and combustion stability in premixed DF engines limit its broader adoption. Using methanol in HD SI engines remains understudied, including emission characteristics for such premixed combustion concepts. To this end, research gaps have been identified within MENENS, leading to the goal of further understanding and developing premixed combustion concepts with high MEF for enabling the adoption of sustainably produced methanol in medium- to high-speed engines in the marine industry.

A Appendix - Experimental Setup

Fig. 2. The HD Marine four-stroke SI engine experimental setup in Den Helder, Netherlands (Image courtesy MENENS project.)

Table 2. Characteristics of the HD Marine SI engine

Parameter	Value	Unit
Number of Cylinders	8	-
Bore	170	mm
Stroke	190	mm
Geometric Compression Ratio	12:1	-
Rated Speed	1500	rpm
Rated Power	500	kWe

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