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Transportation Research Procedia 72 (2023) 3664–3671

Transportation Research Procedia

www.elsevier.com/locate/procedia

Transport Research Arena (TRA) Conference

The FASTWATER Demonstrator: Retrofitting a Harbor Tug Boat to Methanol/Marine Gas Oil Dual-Fuel Operation

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Abstract

FASTWATER, with its full name: "FAST Track to Clean and Carbon-Neutral WATERborne Transport through Gradual Introduction of Methanol Fuel: Developing and Demonstrating an Evolutionary Pathway for Methanol Technology and Take-up", is a project funded by the European Union under the Horizon 2020 framework which aims at reducing greenhouse gas emissions from waterborne transport by promoting renewable methanol as a marine fuel. Renewable methanol is a promising fuel not only because it is carbon-neutral, but also because it has the potential to lower the emissions and increase the efficiency of engines. Moreover, the existing fleet can also take advantage of using methanol as fuel with minor modifications. This paper will demonstrate this by going through the process of retrofitting a tug boat from the Port of Antwerp-Bruges, into dual-fuel, methanol and marine gas oil operation.

Keywords: FASTWATER; marine; methanol; carbon-neutral; retrofit; dual-fuel engines

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10.1016/j.trpro.2023.11.554

1. Overview

International Maritime Organization (IMO, 2021) recently published the fourth greenhouse gas (GHG) study, which estimated that from 2012 to 2018, total shipping, including international, domestic and fishing, accounted for close to 3% of total anthropogenic GHG emissions. Moreover, it shows a steady rising trend and a potential to increase another 40% by 2050 with the ever increasing need for intercontinental trade. To counteract this, IMO has set the shorter-term target of 40% reduction of carbon intensity (CO2 emission per transport work) by 2030, and a longer-term target of 50% reduction of annual GHG emissions and 70% of the carbon intensity by 2050, compared to 2008 levels. Meanwhile, IMO has also implemented measures to fight pollutant emissions. From 2020 the sulfur content in marine fuel is limited below 0.5% against the previous limit of 3.5%, and kept below 0.1% in an emission control area.

It is downright clear that improvement of combustion engines alone cannot achieve this drastic GHG reduction goal, what the marine industries need is de-fossilization of the fuel. Hydrogen, ammonia, liquefied methane etc. are all being investigated for this purpose. Among all the potential candidates, methanol has several properties that makes it particularly fit for the marine industries, as will be explained next.

1.1. Why methanol?

One of the greatest advantages of methanol compared to other potential candidates for future marine fuels (mentioned above), is the relatively low capital expenditure requirement for retrofitting the existing fleet. Since methanol is liquid at ambient temperature and pressure, this saves the need of an insulated tank that maintains the low temperature for gaseous fuels to preserve their liquefied state, and only minor modifications are needed for methanol fuel storage and bunkering. Furthermore, methanol is already one of the top five chemical commodities shipped worldwide, 88 out of the world's top 100 ports already have the infrastructure in place and are available to bunker methanol fuel. Besides, methanol is miscible with water and can biodegrade rapidly, these features greatly reduce its potential harm to aquatic ecosystem (despite its toxicity to humans).

Methanol is also a very promising fuel in terms of emission and efficiency (Verhelst et al., 2019). Its high heat of vaporization can help cool down the combustion chamber and substantially lower NOx emissions. It has only one carbon atom and that is bonded to an oxygen atom, so it produces no soot when combusted. Soot has long been considered extremely harmful to human health but it also contributes significantly to global warming due to the radiative forcing (Bond et al., 2013). These properties virtually eliminate one of the most resilient enemies of conventional diesel engines, the NOx-soot trade-off, and this gives more room for the engines to be optimized for efficiency. In addition, methanol engines have no methane slip issue as faced by most LNG engines at the moment. Methane also contributes significantly to global warming. All these features, plus the fact that methanol fuel has no sulfur content, imply that methanol is a future-proof fuel because it can be used already today to meet the requirement of the IMO 2020 sulfur cap, and it has great potential to meet the ever more stringent emission regulations that may include soot and methane in the near future.

However, none of the above would make sense if the methanol is continuously produced from fossil resources. Today, methanol is mostly produced from steam reforming of natural gas. It was estimated that the lifecycle carbon footprint of this so-called grey methanol exceeds 100 g CO2eq/MJ, which is already higher than the 94 g CO2eq/MJ of fossil fuel defined by EU in its latest renewable energy directive (Studio Gear Up, 2021). If methanol is produced from coal, the lifecycle carbon footprint can even be triple of fossil fuel. Nonetheless, methanol can be produced with multiple sustainable pathways (IRENA, 2021). Natural gas can easily be replaced by biomethane and synthesis gas can also be collected from the gasification of biomass such as forestry residue and the biogenic fraction of municipal solid waste, both greatly reduce the lifecycle carbon footprint of the end product to below 40 g CO2eq/MJ. Of course, the scalability of these production pathways may cause concerns due to the natural constraint of the biomass availability. E-methanol, on the other hand, produced with the reaction of hydrogen from electrolysis and carbon dioxide from carbon capture, will be a more promising pathway for large scale production. However, according to the same study (Studio Gear Up, 2021), the lifecycle carbon footprint from this production pathway is largely dependent on the renewable mix of the electricity grid. If the e-methanol is produced with the EU grid today (assumed at 275 gCO2eq/kWh), the lifecycle carbon footprint will be even higher than grey methanol, but if 100% of the electricity comes from solar photovoltaic power, the lifecycle carbon footprint will drop to 4.4 g CO2eq/MJ.

1.2. FASTWATER

As the full name of the project suggests, FASTWATER (FASTWATER, 2022) aims to initiate a fast transitionary path to move waterborne transport away from fossil fuels, and reduce its pollutant emissions to zero impact, through the use of methanol fuel. This will be achieved by developing the relevant technologies and demonstrating methanol-fuelled vessels. This will be achieved with a consortium that has a strong track record with methanol projects (particularly for waterborne transport) and covers the entire value chain including shipyards, a ship owner, engine manufacturers, an equipment supplier, a classification society, a methanol producer, a major port and research institutes.

Fig. 1 shows the four vessels that will be demonstrated within the 4-year duration of the project. The one on the left is the topic of this paper, the harbour tugboat from Port of Antwerp-Bruges, which is scheduled to be retrofitted to methanol and marine gas oil (MGO) dual-fuel operation in the second half of 2022. The one on the top right corner is a pilot boat from the Swedish Maritime Administration that runs on methanol with 3% ignition enhancer (MD97), which was launched on December 2021 and is in service already. The one on the middle right is a dual-fuel coast guard vessel that will be built by Super Toys with the help of the National Technical University of Athens. The one on the bottom right corner is a river cruise ship from Meyer Werft that will be demonstrated as a conceptual study for such a ship operating on methanol.

By working on these demonstrators, the FASTWATER project will help its partners launch commercially available, universal, and scalable retrofit solutions for four-stroke marine engines in the power range of 200kW to 4MW to operate with methanol. These demonstrators will also show the entire chain from renewable methanol production, distribution, bunkering to finally ships sailing on it. This will in turn contribute to clarifying the rules and regulations around using methanol as a marine fuel as they are still not in a mature stage without practical examples such as these demonstrators of different vessel types. Apart from these dual-fuel and MD97 demonstrators, the FASTWATER project also aims at developing next generation combustion engines that run on 100% methanol for both spark-ignition and compression-ignition type of operations (respectively at Ghent University and Lund University).

Fig. 1 Four demonstrator vessels within the scope of FASTWATER (a) The dual-fuel harbour tugboat from Port of Antwerp-Bruges. (b) The MD97 pilot boat from Swedish Maritime Administration. (c) The dual-fuel coast guard vessel from Super Toys. (d) The conceptual study of a dual-fuel river cruiser from Meyer Werft.

2. Retrofitting Process

2.1. Tugboat from Port of Antwerp-Bruges

The target vessel that will undergo the conversion is a 20-series tugboat owned by Port of Antwerp-Bruges with the following features:

Table 1 The main features of a 20-series tugboat

Year of building	2002
Classification	Inland navigation vessel
Length overall	29.5 meter
Engine power	2x 1945 kilowatt
Bollard pull	55 tons
Running hours	3500 hours/year

Preceding the FASTWATER project proposal, a preliminary feasibility study was carried out by a third-party for such conversion. The final findings of this study were positive as the conversion proved to be possible without major structural adjustments of the tugboat, the estimated cost for the retrofit was acceptable, and the impact of the retrofit on the autonomy of the tugboat was acceptable (approximately 14 days of autonomy as standard). The study also pointed out that there are no regulations yet for vessels running on alternative fuels, thus a derogation needed to be requested, as explained next.

2.2. CESNI approval

Rhine-based inland navigation craft must comply with the Central Commission for Navigation on the Rhine's (CCNR) regulations, which had previously forbidden the use of methanol as a fuel. To receive the necessary dispensation, this methanol tugboat project was therefore first presented and discussed with the representative of the inland shipping authority in Flanders (De Vlaamse Waterweg). As a result of this consultation and a request of the Belgian delegation, the project was then submitted to the CESNI (Comité Européen pour l'Elaboration de Standards dan le domaine de la navigation Intérieure), the European committee that administers overall standards for inland navigation, to request the derogation of the class approval & inland navigation vessel certificate (ES-TRIN). The clearance process, which took 18 months of detailed negotiations, was finally agreed by the European Commission in May 2021.

2.3. Risk Assessment

The risk assessment includes both HAZID and HAZOP, which stand for hazard identification, and hazard and operability, respectively. A HAZID study is a methodical 'creative brainstorming' technique used to identify hazards and operational issues associated with a design or process while a HAZOP study is a methodical technique used to identify hazards and operational issues associated with a process or the integration of a design into another system. Together they covers everything onboard the ship, such as pipe sizes and routing, number of filters, type of pump and even maintenance and safety equipment.

The main risks associated with using methanol are:

- A fire/explosion event if it accumulates within its flammable/explosive limits in the presence of an ignition source. Methanol is flammable between 6% and 36% of volume in air.
- Methanol is considered toxic to persons. Short Term Exposure Limit (15 minutes) is 250 ppm; Long Term Exposure Limit (8 hours) is 200 ppm.

It is therefore critical that leaks are prevented where possible. The measures taken to avoid leakage are discussed in the fuelling system section.

In HAZOP study, many of the recommendations generated were related to confirmation on the system design and safety philosophy. It was discussed that a large number of 'loss of containment' events could be attributed to the bunkering hose assembly. It was agreed that the standard/certification for the bunker hose should be confirmed, including its design and burst pressures. It was also noted that when completing testing on the hose integrity, that it should cover the entire hose assembly to be used for bunkering (e.g. end connections/couplings etc.) to ensure suitability and resistance to surge pressures. In the event of a methanol leak it was considered that a suitable response would be to dilute the fluid to mitigate the potential fire risk. It was therefore recommended that a fire hose is readily available (pressurized) for use during bunkering and that this is included in the bunkering procedures. It was noted that there is the potential for insufficient purging of the engine to occur, which could result in the accumulation of a flammable/explosive atmosphere. It was recommended that upon shutdown of the methanol fuel system the control system should confirm that the purging cycle has been completed correctly, with an alarm generated if this has not been achieved.

2.4. Fueling system

The safe operation of the methanol system relies on a number of layers of protection, such as ventilation and nitrogen inerting to prevent the accumulation of a flammable/explosive atmosphere, liquid and gas detection systems and emergency shutdown systems. It was noted during the HAZID study that many hazards had already been addressed by the methanol system design which uses a double-walled pipe in the supply line from the methanol pump room to the engine. Leaks can still occur due to a number of reasons and damage mechanisms. It is therefore important that the pressure between the inter barrier space of the double-walled piping system is kept close to vacuum and is constantly monitored to detect leakage, and that any areas with a single-walled boundary to a system containing methanol have detection systems installed. In addition, these spaces and spaces containing methanol should have the provision to be drained, purged and ventilated, to the point where they are safe for persons to enter. If a methanol leak occurs within a space that can be filled with water, this will dilute the mixture and reduce the risk of a fire.

To address the concern of the bunkering hose assembly from HAZOP study, the entire bunker line - from the bunker station through the fuel preparation room to the methanol tank - is routed to be self-drained. A drip-free coupling is equipped on the bunker station side. On the bulkhead between fuel preparation room and methanol tank, a remote control valve is installed. The end in the methanol tank should be close to the tank bottom to minimize splashing. The bunker station is on the afterward, starboard side of the deck. The pipe connections are surrounded by a coaming to collect leakages. Potential leakage is collected with manual means. The bunker station consists of a bunker pipe, a drain emptying pipe and a tank vapor return. Bunker connection and drain connection are of the drip-free type. The vapour return will be specified according to the supplier's standard. The fuel preparation room is located in one of the original fuel tanks and the space above. The side spaces are separated and are to be part of the cofferdam. The only access to the fuel preparation room is through a manhole on the aft deck and may not be accessible during towing operation. All equipment inside the fuel preparation room is remote control, access or maintenance during operation is not needed. Loose floor plates are arranged on top of the bottom web. The fuel preparation room bulkhead toward the main engine room is insulated. Methanol fuel is stored in a 13 m^3 integrated tank surrounded by a cofferdam. The tank is located aft of the fuel preparation room. A coating is used to protect the steel from the methanol fuel. The tank is equipped with a level indicator which is connected to the control system. A separate high-high alarm system is installed for the bunkering procedure. All connections to the tank are installed inside the fuel preparation room and above the highest tank level. All necessary pipes inside the tank are designed to avoid siphon effects and unnecessary free fall of methanol. Nitrogen is used to blanket the tank as well as purging the fuel pipe. Therefore, a nitrogen generator is to be installed onboard. This poses a risk of asphyxiation in the event that a leak from the nitrogen system displaces oxygen in spaces which persons access. Therefore, low oxygen detectors should be installed in any areas that the nitrogen piping passes through, unless a justification is provided that natural ventilation would be sufficient to prevent a risk of asphyxiation. Also, the nitrogen generator room should have an independent forced ventilation system, with a minimum of 6 air changes per hour.

Each main engine is supplied by an independent methanol supply system. The concept relies on a pressurized loop, which included pump, filters, manual drain valves, and pressure regulator. There will be one filter on each side of the fuel pump, 50 micron upstream and 20 micron downstream of the pump. The pressure indicators are installed between pump and finer filter, as well as after the one-way valve. In case of any alarm related to a safe methanol operation, the relevant alarm will raise and the system turns back to MGO mode. From the pressurized side, a single feed line is routed directly to the main engine. The supply line should be double walled in the main engine room section. On the single feed line, a methanol mass flow meter and a master valve are installed, which is part of the engine safety concept. The double walled pipes are monitored for leakage detection according to the pipe manufacturer standard.

2.5. Dual fuel engine

Introducing methanol into conventional compression-ignition marine engines can be done in several different ways (Dierickx et al., 2018). Methanol can either be mixed directly with MGO, injected directly in the combustion chamber under high pressure, or injected in the intake manifold under low pressure (the so-called fumigation concept). The mixing concept was shown to be disadvantageous due to an unalterable MGO/methanol ratio and, more importantly: their very limited miscibility (Kumar et al., 2013). The direct-injection concept was already commercialized by MAN in their large two-stroke engines (Mayer et al., 2016). However, it requires two separate injectors thus led to a complex modification of the cylinder head. On the other hand, literature showed that the fumigation concept in general demonstrated higher brake thermal efficiency at medium to high load, and lower NOx and PM emissions. The compromised low-load efficiency and cold start issues can be mitigated with diesel-only operation; and higher CO and hydrocarbon emissions can be mitigated with an oxidation catalyst (Tutak et al., 2015, Yao et al., 2017).

The consortium of the FASTWATER project has gained experience from the past involvement in an earlier EU-funded Horizon 2020 project, LeanShips (LeanShips, 2019), that the fumigation concept is a feasible, and relatively low-cost retrofit solution, mainly thanks to the low-pressure methanol fuel supply system (fuel pumps and injectors) and it also provides the full redundancy by enabling switching instantaneously between MGO-only and dual-fuel operation (Dierickx et al., 2019). Hence both of the engines onboard of the tugboat will be converted to dual-fuel operation with the fumigation concept.

It was then discovered that the methanol injector in the intake manifold is a critical part for the retrofit because the cylinder of the tugboat engine is 8 times larger than the engine converted in LeanShips, and an injector capable of the required fuel flow rates for such engine size was not commercially available. Development work of the methanol injector has been started based on a concept available in the market with the assumption that scaling the nozzle geometry would be sufficient to achieve the required discharge along with its required characteristics for the engine to run smoothly under dual-fuel mode. However, it was found that there was no pronounced jet break-up, which means atomization and vaporization were not sufficient to form a well-mixed charge before it reaches the cylinder. This is especially difficult for methanol as it has a higher heat of vaporization compared to other fuels (Dierickx et al., 2021). To tackle this, fluid-dynamic simulations and optical tests have been carried out with extensive state-of-the-art analysis such as the droplet size distribution measurement shown in Fig. 2.

Fig. 2 Droplet size distribution measurements for one of the prototype injectors

As can be seen from the comparison of the original engine and the retrofitted engine in Table 2, several other features were planned on the engine side to promote better methanol vaporization and air-fuel mixing such as increasing the charge air temperature and installing a turbulence inducer in the intake manifold. The compression ratio was also increased to enable higher temperature in the combustion chamber before ignition and thus achieve more stable combustion. From the results on single-cylinder test engine, the retrofitted full-sized engine is expected to achieve methanol energy fraction (MEF) in the range of 70%, which is defined as the ratio of the methanol energy to the total amount of fuel energy in the cylinder as shown in Eq. 1. The full-sized engine being tested on the test bench can be seen in Fig. 3.

$$MEF = \frac{\dot{m}_{methanol} \times LHV_{methanol}}{\dot{m}_{methanol} \times LHV_{methanol} + \dot{m}_{MGO} \times LHV_{MGO}} \tag{1}$$

Table 2 Comparison of the original engine and the retrofitted engine

	Original	Retrofit
Compression ratio	12	~14
Charge air temperature	55°C	~85°C
Methanol injection pressure	n/a	~8 bar
Turbulence inducer	No	Yes

Fig. 3 Full engine on the test bench

3. Conclusions and perspectives

Methanol as a marine fuel is gaining traction. This is especially true after Maersk, one of the largest container shipping companies worldwide made the big announcement (Maersk, 2021) that they will introduce multiple ocean-going vessels to operate on carbon-neutral methanol, and they also engage in strategic partnership with renewable methanol producers across the globe to secure the fuel supply for these newbuild ocean-going vessels (Maersk, 2022). Engine manufacturers also respond rapidly, most major players are either planning or already have methanol related products on the market. This proves that the potential of renewable methanol as a very critical piece of the puzzle for future waterborne transportation has been recognized by the industry leaders, and the FASTWATER consortium shares the similar vision with them that the first movers must establish a steady foundation of the entire value chain so the peers can follow suit.

As can be seen with the lifecycle analysis referenced in this paper, renewable electricity for e-methanol production may still be limited currently but bio-methanol can already fill the gap and contribute significantly to GHG reductions today. After the renewable electricity mix in the grid grows to a certain level, e-methanol will take over and become more competitive both in terms of cost and carbon footprint. Needless to say, this needs to be based on that demands also grow accordingly and the momentum is maintained.

This highlights the importance of this methanol-powered harbor tugboat, which currently undergoes engine retrofit and fuel systems installation, followed by the on-board performance and emission measurement of dual-fuel operation compared with diesel-only operation. This is scheduled for late 2022 with the launch event scheduled early 2023. Upon the successful demonstration of the harbour tugboat reported here, the Port of Antwerp-Bruges plans to have half of its h Emil Jansson et al./ Transportation Research Procedia 00 (2022) 000–000arbor tug fleet converted to methanol operation, i.e. a further 10 vessels. The other half will likely be replaced by newbuilds, which will also be required to sail on non-fossil fuel, with methanol a top candidate. This will strengthen the role of the port authority as booster of the energy transition, and gain credibility by setting an example and disseminating the gained knowledge to other port authorities around the world.

Acknowledgements

This paper is part of FASTWATER project, which stands for "FAST Track to Clean and Carbon-Neutral WATERborne Transport through Gradual Introduction of Methanol Fuel: Developing and Demonstrating an Evolutionary Pathway for Methanol Technology and Take-up". The project has received funding from the European's Horizon 2020 research and innovation program (Contract No.:860251).

References

Bond, T.C. et al., 2013. Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of geophysical research: Atmospheres*, *118*(11), pp.5380-5552. https://doi.org/10.1002/jgrd.50171.

Carbon footprint of methanol, Studio Gear Up, January 2022.

Coulier, J. et al., 2016. Using alcohol fuels in dual fuel operation of compression ignition engines: a review. In *28th CIMAC World Congress on Combustion Engine* (pp. 1-12). CIMAC.

Dierickx, J. et al, 2018. Strategies for introducing methanol as an alternative fuel for shipping. In *7th Transport Research Arena TRA 2018 (TRA 2018)* (pp. 1-10). Ghent University.

Dierickx, J. et al., 2019. Efficiency and emissions of a high-speed marine diesel engine converted to dual-fuel operation with methanol. In *CIMAC World Congress on Combustion Engine* (pp. 1-14). CIMAC.

Dierickx, J. et al, 2021. Retrofitting a high-speed marine engine to dual-fuel methanol-diesel operation: A comparison of multiple and single point methanol port injection. *Fuel Communications*, *7*, p.100010. https://doi.org/10.1016/j.jfueco.2021.100010

FASTWATER, 2020-2024. FAST Track to Clean and Carbon-Neutral WATERborne Transport through Gradual Introduction of Methanol Fuel: Developing and Demonstrating an Evolutionary Pathway for Methanol Technology and Take-up. https://fastwater.eu/

Fourth IMO Greenhouse Gas Study, International Maritime Organization, 2020.

Innovation Outlook : Renewable Methanol, International Renewable Energy Agency, 2021.

Kumar, S. et al., 2013. Advances in diesel–alcohol blends and their effects on the performance and emissions of diesel engines. Renewable and Sustainable Energy Reviews, 22, pp.46-72. https://doi.org/10.1016/j.rser.2013.01.017

LeanShips, 2015-2019. Low Energy and Near to zero emissions Ships. https://www.leanships-project.eu/home/

Lindstad, E. et al., 2020. LNG and cruise ships, an easy way to fulfil regulations—versus the need for reducing GHG emissions. *Sustainability*, *12*(5), p.2080. https://doi.org/10.3390/su12052080.

Maersk, A.P. Moller - Maersk accelerates fleet decarbonisation with 8 large ocean-going vessels to operate on carbon neutral methanol, August 2021, https://www.maersk.com/news/articles/2021/08/24/maersk-accelerates-fleet-decarbonisation

Maersk, A.P. Moller - Maersk engages in strategic partnerships across the globe to scale green methanol production by 2025, March 2022, https://www.maersk.com/news/articles/2022/03/10/maersk-engages-in-strategic-partnerships-to-scale-green-methanol-production

Mayer, S. et al, 2016, June. Performance and emission results from the MAN B&W LGI Low-Speed Engine Operating on Methanol. In *CIMAC Congress* (pp. 6-10).

Tutak, W. et al., 2015. Alcohol–diesel fuel combustion in the compression ignition engine. *Fuel*, *154*, pp.196-206. https://doi.org/10.1016/j.fuel.2015.03.071

Verhelst, S. et al., 2019. Methanol as a fuel for internal combustion engines. *Progress in Energy and Combustion Science*, *70*, pp.43-88. https://doi.org/10.1016/j.pecs.2018.10.001

Yao, C. et al., 2017. Methanol fumigation in compression-ignition engines: a critical review of recent academic and technological developments. Fuel, 209, pp.713-732. https://doi.org/10.1016/j.fuel.2017.08.038