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Strategies for introducing methanol as an alternative fuel for shipping

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Abstract

Although waterborne transport is an energy efficient means of transport, its contribution to greenhouse gas emissions is growing and pollutant emissions are high relative to other forms of transport. Emission legislation on the other hand is catching up by introducing strongly reduced emission limits in the upcoming years, which leads to an urgent need for alternative ways of fueling waterborne transport. In the Horizon 2020 “LeanShips” project, the use of methanol as an alternative fuel for shipping is studied in one of its demonstrators. In the demonstrator, a high speed marine diesel engine is converted for methanol use. This paper discusses the rationale for methanol as an alternative fuel for marine transportation, different possible strategies for operating vessel engines on methanol, their pros and cons, and the approach taken within LeanShips, namely dual fuel operation with methanol port injection. The potential of methanol concerning energy efficiency and pollutant emissions is discussed, as well as other demonstration projects on methanol and next steps for methanol engine developments .

Keywords: methanol; internal combustion engines (ICE); LeanShips; alternative fuels; retrofit

1. Introduction

In the past century the scientific knowledge on climate change increased significantly. In 1938, G.S. Callendar (Callendar, 1938) solved a set of equations linking greenhouse gases and climate change. He found that a doubling of atmospheric CO_2 concentration resulted in an increase in the mean global temperature of 2°C, and he linked increasing fossil fuel combustion with a rise in CO_2 and its greenhouse effects. In the 1950s, these observations were echoed by Plass (Fleming, 1998) but the greenhouse gases of concern remained CO_2 and H_2O. It was not until the 1970s that other greenhouse gases – CH_4, N_2O and CFCs – were widely recognized as important anthropogenic greenhouse gases. The Intergovernmental Panel on Climate Change (IPCC) has published several assessment reports since it was established in 1988; in which it provides a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts. In their first assessment report in 1990 it was stated that there is a natural greenhouse effect which already keeps the Earth warmer than it would otherwise be. Continued emissions of these gases at present rates would commit us to increased concentrations for centuries ahead (Cubasch et al., 2013), hence there is an urgent need to reduce anthropogenic greenhouse gas emissions.

Our current high-tech society owes its success to the presence and consumption of massive quantities of accessible and inexpensive energy sources such as fossil fuels. For many decades, experts have warned of an impending oil shortage. On the basis of the current consumption and the known oil reserves, there is still plenty of oil for the next 50 years. Given the high added value of carbon-based fuels, chemicals and plastics, a carbon free economy is unrealistic. A CO_2 neutral economy that does not prohibit the formation of CO_2 but rather avoids its net release into the atmosphere is a more realistic goal (Martens et al., 2017).

Driven by the increased awareness, the current economy is orienting towards a sustainable one, which is also described by policymakers or enterprises as the Energiewende or energy transition (Hake et al., 2015). From food consumption behavior (more local, less meat) to energy production (renewables) to the transportation industry, to name a few, the consumption, manufacturing habits and primary energy resource usage are evolving to include sustainability.

Huge technological progress has been made in the automotive sector the past decades, on the one hand by the commercial introduction of hybrid and electric vehicles, and on the other hand by the efficiency gains of fossil fueled internal combustion engines (ICEs), not to mention the research and introduction of alternative fuels, such as methanol, ethanol, hydrogen etc. for internal combustion engines. The automotive industry is therefore widely acknowledged as a locomotive industry, able to help upgrade many of its related industries, such as the marine industry (Lin et al, 2009).

This goes hand in hand with the progress made in the energy industry, which is facing challenges with regard to electric grid stability, seasonal electric demand, renewable energy intermittency, etc. This has driven this sector to take up power to gas (P2G) and power to liquid (P2L) concepts in recent years to formulate an answer to the increasing share of wind and solar power supplied to the electric grid (Rosa, 2017). We will come back to the potential link of P2G and P2L with the marine industry later in this paper.

The marine industry was originally only submitted to national legislation in territorial waters. In international seas, national legislation does not rule, which is why the International Maritime Organisation (IMO) has been established in 1952. Since then, it has become an important legislative body for safety and environmental aspects. In 1998, annex VI was introduced to MARPOL, the International Convention for the prevention of Pollution from Ships, containing the first Tier I, which went into force in 2005 and the Tier II and Tier III amendments, which went into force in respectively 2011 and 2016. In 2011, amendments were introduced with measures to reduce emissions of greenhouse gases (GHG). Tier II standards have been met by combustion process optimization, like fuel injection timing, pressure and rate, fuel nozzle flow area, exhaust valve timing and cylinder compression volume. Tier III standards on the other hand require dedicated NO_x emission control technologies, such as various forms of water induction into the combustion process, exhaust gas recirculation or selective catalytic reduction (Ryley et al., 2012).

According to current estimates of IMO, international shipping accounted for about 2.2% of total anthropogenic CO_2 emission volume for the year 2012. The mid-range forecasted scenarios on the other hand show that, by 2050, CO_2 emissions from international shipping could grow by between 50% and 250% depending on future economic growth and energy developments (Smith et al., 2015).

To meet current and future more stringent regulation, marine industry stakeholders are doing research and developing pilot projects to test, on a real scale, potential solutions that can lead to a sustainable marine transport industry. It is in that regard that the Effship project was introduced in 2009, focusing on potential alternative fuels for heavy fuel oil (HFO). Effship concluded that liquefied natural gas (LNG) and methanol were two promising alternative fuels for ICEs in marine vessels (Stenhede, 2013).

The present work is carried out as a part of the LeanShips project (LeanShips, 2017). LeanShips stands for 'Low Energy And Near-to-zero emission Ships'. It is a Horizon 2020 (H2020) project funded by the European Commission aimed at developing green shipping technologies and bringing these to the market. One of the seven demonstrators of the LeanShips project, 'Demonstrating the Potential of Methanol as an Alternative Fuel' aims to demonstrate a high-speed marine diesel engine converted to dual fuel operation on methanol and diesel while achieving significant reductions of emitted pollutants. When LeanShips is mentioned in this paper, it concerns only this demonstrator.

In this paper the principal fuel choice for the demonstration project, methanol, will be discussed, and its features will be compared with HFO and LNG. Different dual fuel approaches in compression ignition engines will be elaborated, followed by results from other demonstration projects on methanol and a brief discussion of other strategies that have not been demonstrated yet in a marine context, but look promising for further increasing efficiency and decreasing emissions. The paper ends with the strategy chosen for converting a Volvo Penta D7, literature results for this strategy and the status at writing of this paper of the LeanShips project.

2. Rationale for methanol as a marine fuel

Maritime transport is currently largely dependent on heavy fuel oil. HFO accounts for approximately 77% of maritime transport fuel used and almost all fuel used by ocean going ships (McGill et al., 2013). Diesel propelled internal combustion engines are the principle means of marine propulsion. The engines are broadly classified into slow speed two stroke, medium speed four stroke, and high speed four stroke engines (Royal Academy of Engineering, 2013). Because of scalability reasons, the maturity of the internal combustion engine technology, and the needed propulsion specifications of ships, the ICE technology will still play a major role in the foreseeable future as the main propulsion technology for ships, perhaps for all but the shortest coastal voyages for which battery electric propulsion will find its applications as well, and given that sustainable fuels or other sustainable measures find their entrance.

In the introduction of this paper we elaborated the framework in which the marine industry is operating and the challenge it is facing. In this section we will elaborate why methanol can play a major role in the future as an alternative fuel for shipping, not only from an engine point of view but also from a holistic and society point of view.

When selecting potential fuels for replacing fossil fuels a vast number of criteria need to be taken into account as for example meeting regulations such as NO_x and SO_x legislation. Reviewing literature shows that each author has its own set of criteria to select alternative fuels.

The three decision criteria proposed by DNV GL are affordability, sustainability and safety (Chryssakis et al., 2015). Affordability has to do with the cost of producing and using a fuel, which was the main driver in the 1950s towards the wide adaptation of HFO (Bengtsson et al., 2012). Sustainability is described by DNV GL as the environmental footprint of using a certain fuel from a lifecycle perspective. In this, it is important to consider not only the utilization of the fuel, but also the fuel production footprint and the ability of the fuel to meet future demands. Safety is the third criterion as major accidents in the early phase of using a new fuel can have a detrimental impact for the future of the fuel (Chryssakis et al., 2015).

According to Verhelst (Verhelst, 2014), although focused on automotive but expandable to maritime transportation, the first criteria for an initial selection of alternative fuels should be that they are sustainable, scalable and compact. The fuel should rely on an infinite energy supply and make use of a closed cycle of resources (i.e. sustainable). It should be scalable, meaning it should use abundantly available and thus cheap resources. And furthermore it should offer a high energy and power density (i.e. compact).

In the Effship project, a project co-funded by the Swedish Innovation Agency and partners, and based on the vision of a sustainable and successful maritime transportation industry (defined as one which is energy efficient and has minimal environmental impacts), workshops and discussions were held with industry stakeholders for determining criteria for future marine fuels: engine manufacturers, shipping companies, naval architects, consultants and researchers. The authors based their criteria on a study of Wang et al. (Wang et al., 2009) who defined four categories of criteria: technical, economic, environmental and social. In the study of Effship social criteria were grouped under 'other' criteria and two more categories were added, namely logistical, and safety and safe handling criteria (Bengtsson et al., 2012).

In this section we will elaborate the rationale for methanol from an environmental, an economical, and an engine point of view. To evaluate potential alternative fuels, we will start by structuring a list of future available fuels derived from Bengtsson et al. (2012) and from Bromberg et al. (2010) according to their primary energy source which gives the following three categories: fossil fuels, electrofuels/synthetic fuels and biomass based fuels. Fossil fuels are crude oil or natural gas derivates, electrofuels/synthetic fuels are made by storing electrical energy from e.g. renewable sources in the chemical bonds of liquid or gaseous fuels, and biomass based fuels use biomass as a feedstock. On the vertical axis the fuels are furthermore categorized according to their physical state at standard temperature and pressure (STP). Note that methanol, hydrogen and di-methyl ether (DME) can be made out of a variety of feedstocks.

	Fossil based fuels	**Electrofuels / synthetic fuels**	**Biomass based fuels**
Liquids	Heavy fuel oil (HFO)[crude oil] Low sulphur HFO [crude oil] Low sulphul distillate diesel fuels [crude oil] Methanol [NG, coal]	Methanol [H2]	Vegetable oils [plants] Biodiesel [vegetable oils] Synthetic diesel [wood] Ethanol [wood, wheat] Methanol [wood, black liquor]
Gases	Liquified Petroleum Gas (LPG)[NG] Compressed Natural Gas (CNG)[NG] Liquified Natural Gas (LNG)[NG] Hydrogen [NG] Dimethyl ether (DME)[NG]	Hydrogen [water] Dimethyl ether (DME)[H2] Ammonia [H2] Synthetic methane [H2]	Biogas [sewage] Dimethyl ether (DME)[wood, black liquoμr]
Solids	Coal		Wood

Figure 1: List of current and alternative fuels structured according to their primary energy source and their physical state at STP. Between round brackets the abbreviation is given and between square brackets the source of which it is produced.

When defining sustainability based on combining the criteria of Verhelst and DNV GL this leads us to the following definition of sustainability: the alternative fuel should rely on an infinite energy supply and make use of a closed cycle of resources (Verhelst, 2014) and the fuel production and utilization should be in quantities that can meet demand, without compromising our future ability to use this fuel (Chryssakis et al., 2015). This last criterion is in line with the scalability criterion of Verhelst who said that the fuel should be abundantly available and thus use cheap resources.

To meet the sustainability criteria in terms of making use of a closed cycle of resources, only electrofuels and biomass based fuels are retained with for electrofuels the side mark that the fuel should be produced using electricity from a CO_2 neutral energy source. Furthermore the fuel should rely on an infinite energy supply, meaning the primary energy source should be abundantly available. Powering the current worldwide fleet of merchant ships with biofuels derived from natural sources such as vegetable oils would require a land area equivalent to that of about twice the size of the United Kingdom (Royal Academy of Engineering, 2013). As this land area is not available solely for farming the necessary biomass feedstock, we can conclude that biomass based fuels will find their entrance but only for limited supply.

This leaves us with electrofuels, a limited set of the initially selected alternative fuels that can replace the majority of the heavy fuel oil usage, namely methanol, ammonia, hydrogen, synthetic methane gas and DME. Ammonia does offer an acceptable energy density and thus appears to be an attractive energy carrier. It is however not a good engine fuel because it is a difficult compound to burn over a wide range of loads such as needed in transport applications. Various tricks are needed mostly by adding in more reactive fuels, to get it to burn reliably (Verhelst, 2014).

Hydrogen is a fuel with excellent engine characteristics (Verhelst, 2013). On top no CO_2 is produced on combustion. Its very low density however makes it not an attractive fuel from an infrastructure point of view (Chryssakis et al., 2015). Synthetic methane gas in its liquefied form, LNG, has the disadvantage of methane slip, of a more restrictive on-board fuel storage system and is less attractive from a fuel distribution, handling and bulk storage point of view. DME on the other hand is, given its high cetane number, suited for use in compression ignition engines. It has similar storage characteristics as liquefied petroleum gas (LPG) (Semelsberger et al., 2005).

As DME is produced in a two-step process where syngas is first converted to methanol, followed by methanol dehydration to DME, it seems to be more interesting to directly use methanol as a fuel. This leaves us with the alternative fuel methanol which is a liquid at STP. Methanol has great characteristics for internal combustion engines. Its high octane number, high flame speed, low flame temperature, and high heat of vaporization make it an excellent fuel for use in internal combustion engines (Vancoillie et al., 2013).

From a primary energy source perspective as well as from the perspective of gradually introducing an alternative fuel, methanol is very suitable given the number of feedstocks that it can be produced from, namely natural gas (current typical feedstock in the West (Bromberg et al., 2010)), coal, biomass and CO_2. Methanol is furthermore one of the most traded chemicals worldwide meaning that the infrastructure is currently present and that the fuel is available worldwide in great quantities (Andersson et al., 2015). In this way methanol can be gradually introduced as a fuel, where the fuel production is in a first stage mainly based on the current production technology with natural gas. Gradually technologies to produce methanol from biomass feedstocks (Södra, 2017) and especially from CO_2 can get maturity and become commercially available (Tran, 2010).

From an economical point of view, methanol is in competition with LNG, HFO with advanced aftertreatment systems such as a scrubber system, and with marine gas oil (MGO). In Andersson et al. (2015), it is concluded that methanol is an attractive alternative from the point of view of fuel storage and bunkering infrastructure costs. Methanol conversion and new-build costs are competitive. The cost of marine methanol is furthermore lower than the equivalent costs of marine LNG, and competitive when compared to emissions abatement measures such as scrubbers and catalysts, as the latter also add to operational costs (Andersson et al., 2015). In a study made by the European Maritime Safety Agency (Ellis et al., 2015), the investment cost for methanol retrofit and new build solutions were estimated to be in the same range as costs for installing exhaust gas aftertreatment (scrubber and SCR) for use with HFO, and below costs of investments for LNG solutions. Compared to MGO, methanol was on an energy basis less expensive from 2011 to 2013. With the low oil prices in 2014 and early 2015, methanol was comparatively more expensive but in late 2015 the price of methanol has started to move closer to the levels of MGO again (Ellis et al., 2015).

A last reason pleading in favour of electrofuels, are the recent P2G and P2L developments in the energy sector. From a cross-industry perspective, an increasing demand in methanol (or other electrofuels) and an increasing construction of renewable energy sources, could stimulate and go hand in hand with the development of P2G and P2L concepts.

3. Methanol in internal combustion engines

In the previous section the rationale for methanol was elaborated and compared to other alternatives for meeting current and upcoming marine legislation. Little was mentioned on the behaviour of methanol in engines. In this section we will discuss the different possible strategies for converting a diesel compression ignition (CI) engine to methanol operation and briefly discuss other promising strategies for introducing methanol as a marine fuel.

The ICEs in vessels are mostly compression ignition engines. Methanol is however an ideal fuel for use in spark ignition (SI) engines, on its own or blended with gasoline, particularly due to its high octane number (low tendency to knock). Its cetane number on the other hand is only about 3 (Yao et al., 2017), which makes methanol not suited for CI engines that require high cetane number fuels (diesel has a cetane rating that ranges from 40 to 55). Additives can be added to methanol to increase the cetane rating close to that of diesel. However, these ignition improvers are typically composed of nitrogen containing compounds such as octyl nitrate and tetrahydrofurfuryl nitrate, many of which are toxic and or carcinogenic (Yao et al., 2017). Therefor other technologies should be applied for operating methanol in CI engines.

3.1. Strategies for converting a compression ignition engine to methanol operation

One of the technologies that burn alcohol fuel in CI engines is called Dual Fuel (DF) operation. Overall, the following DF approaches are used (Mayer et al., 2016; Coulier et al., 2016):

i. Port Fuel Injection (PFI) of methanol, enabling methanol to mix with the charge in the intake, and then being ignited with a (pilot) diesel injection near the top dead centre (TDC). This approach is also called the “fumigation concept”.

ii. One direct injector injecting a premixed mixture of methanol and fuel oil near TDC, using one injector.
iii. One dual direct injector injecting diesel and methanol, separately, near TDC, using one injector with multiple fuel channels and needles.
iv. Two direct injectors, one for injecting diesel and one for injecting methanol.

In all of the above approaches diesel injection is used to ignite methanol, one of the fundamental principles of the dual fuel operation principle. Each of the approaches has its advantages and disadvantages. Approach ii., injecting a premixed mixture of diesel and alcohol fuel, has the advantage that only one injector is needed and that the conversion to dual fuel operation is relatively straightforward. A big disadvantage is that the substitution ratio (amount of diesel replaced by methanol) cannot be changed instantaneously and moreover the substitution ratio is very limited (only a few percent) because diesel and methanol have a limited miscibility (Yao, 2017; Bechtold et al., 2007).

When injecting the diesel and alcohol fuel separately into the cylinder (approach iii. and iv.), the substitution ratio can be changed instantaneously and more diesel can be substituted with alcohol fuel. In approach iv., the downside is that two separate injectors are required, both injecting directly into the cylinder, leading to a complex conversion of the engine (a.o.t. the cylinder head should be modified to enable two injectors instead of one). The two direct injectors approach is chosen by MAN in their MAN B&W LGI engine (Mayer et al., 2016). The design aims at enabling low speed marine diesel engines to operate on a large variety of low flash point fuels, like LPG or methanol.

Approach iii. is a technology developed by Wärtsilä and was used as a retrofit solution for a Wärtsilä-Sulzer 8 cylinder Z40S (see below). The downside of this methodology is that it requires specific technology developments and that it is not a universal retrofit solution.

Compared to approach iii. and iv., approach i., the fumigation concept, is easier to implement because methanol is injected at low pressure (compared to injecting it directly into the cylinder) and no cylinder head modifications are required. In addition, the engine intake is generally (more) easily accessible. This makes it an ideal solution for retrofitting existing engines to operation on dual fuel methanol-diesel (Coulier et al., 2016).

3.2. Other promising strategies for applying methanol in marine engines

The different dual fuel operation approaches discussed above are the main approaches that can be used for operating a compression ignition engine intended for diesel or HFO use, on methanol. These conversion strategies are well suited strategies to gradually introduce methanol as a marine fuel, as they enable the ship operator to still operate on 100% diesel fuel. When methanol starts taking a share of the waterborne transportation fuel, this opens up routes to further optimize its applications.

Dedicated (SI) methanol engines can offer an even better balance between high energy efficiency and ultralow emissions (Vancoillie et al., 2012). A study by M.I.T. showed that methanol engines in trucks could be 25% more efficient than diesel engines, with peak efficiencies potentially attaining 55% to 60% (Cedrone et al., 2013). These high efficiencies were claimed to be possible through the use of fuel reforming, recovering waste exhaust heat to drive endothermic reactions that convert methanol into syngas with a higher heating value than the methanol. Furthermore, the hydrogen-rich syngas allows much more dilution of the fuel-air charge, lowering peak temperatures and thus heat losses, or mitigating knock and thus enabling even higher compression ratios (CR).

Brusstar et al. demonstrated, on a turbocharged diesel engine with a CR of 19.5:1 that was converted to SI operation on methanol, the wide dilution limits of methanol in a strategy using stoichiometric fueling and exhaust gas recirculation (EGR) to control the load, as such reducing throttling losses and enabling three way catalyst aftertreatment. The high compression ratio enabled peak brake thermal efficiencies on methanol of 42%, a 5% relative increase compared to the baseline diesel engine. Shamun et al. obtained a gross indicated efficiency of 53% with a high level of EGR and an optimal combustion phasing. The results were obtained on a Scania D13 engine, utilizing a high compression ratio of 27:1 (Shamun et al., 2017).

4. (Demonstration) Projects applying methanol as a fuel in marine engines

The use of alternative fuels in shipping has been receiving increasing attention as a measure for complying with low sulphur requirements for fuels and reduced emissions of sulphur oxides (Ellis et al., 2015). This has resulted in a number of demonstrations projects in the past decade to investigate the use of methanol. Figure 2 gives a timeline showing the main projects.

Methapu had the overall goal to evaluate the use of solid oxide fuel cell (SOFC) technology and methanol as a means of providing electrical power. The Methapu project was the first project where methanol was tested as a fuel onboard a ship (Ellis et al., 2015) and while doing this project different operational safety rules applicable for other installations and projects using methanol as a marine fuel were developed (Tronstad et al., 2017).

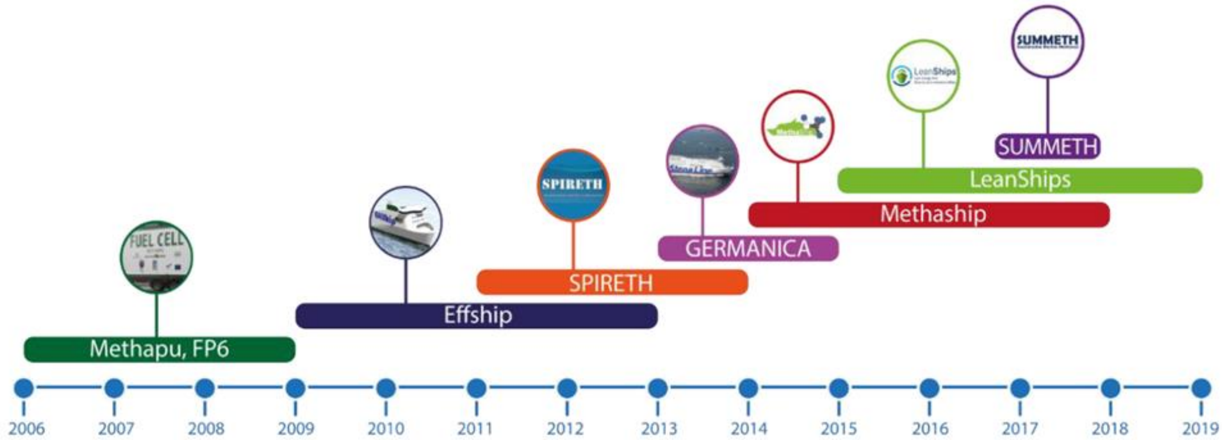

Figure 2: Timeline showing some of the main projects investigating the use of methanol as a marine fuel (Ellis et al, 2015)

The Effship project, already mentioned earlier in this paper, concluded based on study work and laboratory tests that methanol has potential primarily for conversion of existing vessels and that further projects such as Spireth can lead to a wide use of methanol as a marine fuel for the future (Stenhede, 2013). Effship contributed to the IMO's draft IGF Code, the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels, such as methanol.

Spireth was created as a spin-off of the Effship project. The main project findings were that it is feasible to convert ships to operate on methanol and DME based fuels, and that these fuels are a viable alternative to reduce emissions. Arrangements for methanol storage, distribution and handling were furthermore designed, assessed from a safety and risk perspective and installed on the Stena Scanrail (Ellis et al., 2014). A retrofit solution was developed for conversion of a ship's main diesel engine, a medium speed four stroke engine. The dual fuel direct injector approach (approach iii.) was chosen as it was reasoned that this concept offers a cost effective conversion of the engine in combination with superior performance. The outcome of the study in the Spireth project is that direct injection of methanol around TDC and ignition via a pilot diesel is the preferred combustion retrofit concept (Ellis et al., 2014).

During the Spireth project, Stena Line decided to carry out a full methanol conversion of the Stena Germanica, a large RoPax ferry operating between Göteborg and Kiel. The vessel's four main engines, Wärtsilä-Sulzer 8 cylinder Z40S, each with a power output of 6MW, were converted based on the laboratory testing (Ellis et al., 2014). The project was called 'Pilot Methanol' and received support from the EU-TEN-T program (Andersson et al., 2015). On figure 2 it is mentioned as Germanica. During the conversion of the Stena Germanica, which took less than two months, modifications were done to the bunkering line, tanks, pump room, pumps, piping, and the automation system. With regard to capex cost, the conversion was claimed to be relatively simple, around 350 €/kW, using a common rail system with a methanol injection pressure limited to 650 bar and dual fuel direct injectors, and a new engine control system. The existing fuel and part of the ballast tanks were converted to methanol tanks, enabling no loss of commercial space. With regard to maintenance, it is expected that the efficiency and lifetime of components will be similar or better (Stojcevski, 2014). Costs are expected to be about 30% to 40% lower for a second retrofit project (Andersson, 2015).

The Methaship project, a three-year project that started in 2014 and is coordinated by Meyer Werft, is developing designs for a cruise and a RoPax ferry. Bunkering options will also be studied and the designs will be evaluated by Lloyd's Register, partner in the project, to get necessary certification for both concepts (Ellis et al., 2015).

Another key project, not mentioned in the timeline, is the conversion of the MAN engines to dual fuel operation and which are installed in seven new-build methanol tankers built for Methanex and commissioned in 2016. The engines in question are slow speed two stroke 10MW ME-LGI engines that offer a dual fuel solution for low flashpoint liquid fuels as methanol. The first results show NO_x emission decreases of about 30% (Mayer et al, 2016).

Also not mentioned on figure 2 is the GreenPilot Project. GreenPilot started in March 2016 and has the objective to demonstrate that methanol can improve power output and reduce environmental impact on a small vessel. Adaptation works will include replacing the existing engine with a new engine that is converted to methanol operation and modifying a number of auxiliary systems such as the fuel bunker tank and piping, gas and fire detection system, fire suppression system, etc. (Ramne, 2017). Summeth, the most recently started project on the timeline, has the objective to investigate methanol combustion concepts for smaller engines (about 250 to 1200 kW), and to develop a design for a case study ship using these engines (Ellis et al., 2015).

5. LeanShips project

5.1. Approach chosen within LeanShips

Methanol as an alternative fuel has been extensively demonstrated in automotive engines (Vancoillie et al., 2012), but those have always been spark ignition (SI) engines. Introducing dedicated SI methanol engines for shipping would, although technically perfectly feasible, be a major change and prevent uptake. Therefore, LeanShips chose to develop a methanol conversion solution for a diesel engine while maintaining 100% diesel operation capability as this will be more attractive initially for vessel operators. In this way operational costs and pollutant emissions can decrease, and at a later stage dedicated methanol engines can be demonstrated that take full advantage of methanol's unique properties as discussed earlier.

Recent projects have demonstrated the conversion of a low speed two stroke engine (MAN engines in Methanex tankers) and a medium speed four stroke engine (Wärtsilä engine in Stena Germanica), but little has been demonstrated on smaller high speed four stroke engines (Anderssson, 2015). In the LeanShips project, the focus is on converting a Volvo Penta D7, a high speed marine engine. The engine has a rated power of 265 hp at 2300 rpm, has six cylinders, a swept volume of 7,15 l and a compression ratio of 17,6:1.

The aim of the LeanShips project is to demonstrate approach i., the fumigation concept, on a Volvo Penta D7. Approach i. was chosen as it is the easiest way to convert an engine to dual fuel operation. Compared to the other approaches, approach iv. was not an option as there is no space available in the cylinder head for adding a second fuel injector. Approach ii. was not considered because of its technical limitations (limited working range due to low miscibility of methanol and diesel) and approach iii. was not an option because a single dual fuel injector is not available in the market and it would furthermore need complex adaptations to the cylinder head. The advantage of the fumigation concept is furthermore that the operator can still very easily arbitrate between diesel-only operation and dual fuel operation.

The main objectives of the project are to convert the engine to dual fuel operation, to map the engine's potential on power, efficiency and emissions via a detailed engine test bench program and to use in a second stage the obtained data in a life cycle assessment for two pilot study vessels. The conversion will be done in such a way that it can be offered as a retrofit solution. The results of the test bench program will be published towards the end of the project, which is foreseen end of April 2019.

5.2. Engine results with the fumigation concept available in literature

At the beginning of the LeanShips project a literature study was done, giving an overview of research results with the fumigation concept (Coulier et al., 2016). In the study, an overview is given of the performance of the fumigation concept with regard to load variations, efficiency and emissions (NO_x, particulate matter (PM), hydrocarbon (HC), CO and CO_2 emissions).

With regard to load and efficiency the following conclusions were drawn (Coulier et al., 2016):

- The maximum load of the engine is generally not or slightly negatively affected by fumigation, but there are also cases in which an increase of the maximum load of the engine is reported.
- Both for low and high loads there is generally a limit to the substitution ratio. For low loads, there is an upper limit to the substitution ratio because of partial burn and/or misfire when the alcohol-air mixture

becomes too lean. For high loads on the other hand, when more and more diesel fuel is substituted for alcohol fuel, there is a higher degree of premixed combustion and in combination with the inherently higher compression ratio (CR) of a diesel engine this can cause knock.

- With regard to brake thermal efficiency, in most cases, a slight decrease in efficiency is observed at low loads and a slight increase at high loads. In general a lower efficiency can be attributed to a lower combustion efficiency (the amount of the fuel that is burned completely) and a higher efficiency to a faster combustion (closer to the thermodynamically ideal isochoric combustion) and possibly lower heat losses due to lower combustion temperatures.

With regard to emissions the following conclusions were drawn (Coulier et al., 2016):

- A general drop in NOx emissions is observed across the load and speed range with the fumigation concept. This reduction gets more pronounced as the substitution ratio is increased. The main reason for this observation is the cooling effect of the methanol that is fumigated in the intake of the engine, together with the lower flame temperature of methanol.
- Overall, the PM emissions (particulate mass concentration) generally decrease. There is, however, no agreement in literature on the particulate number concentration.
- It can be concluded that the trade-off relation between NO_x and PM emissions that is observed in pure diesel operation, disappears in dual fuel mode.
- CO emissions – an intermediate product of combustion and a measure for incomplete combustion – are higher in dual fuel mode than in pure diesel operation and they also increase with increasing fumigation level, due to the lower temperatures associated with the higher heat of vaporization of methanol.
- Hydrocarbon emissions are higher in dual fuel mode than in pure diesel operation due to PFI effects and a lower combustion temperature, both associated with the fumigation of alcohol fuels.
- No conclusion can be drawn with regard to CO_2 emissions in dual fuel mode. It can however be said that methanol's lower carbon intensity is beneficial for reducing CO_2 emissions.

5.3. Status of LeanShips project

The status at writing of this paper is that the project is finalizing the installation of the retrofit solution on the Volvo Penta D7. First the retrofit solution was designed, including the design of the methanol fuel supply system (pumps, container, fuel rail and injectors) where the focus was on finding suitable methanol-compatible components; the measurement system (pressure sensors, thermocouples and flow meters) and the accompanying data acquisition system for acquiring the engine data to be analyzed; and the engine control unit enabling the engine to operate on dual fuel methanol diesel. The next phase are the bench tests where the aim is to map the engine efficiency, emissions and power output over the entire load and engine speed range of the engine, both on diesel and on dual fuel methanol-diesel, in this way enabling an objective and quantitative data set for comparison of both operation modes.

6. Conclusion

As can be concluded from this paper, there is already quite some work done, both on a scientific and industry level, to introduce new fuels and especially methanol in the maritime industry. Most projects, including LeanShips, focus on converting diesel engines to dual fuel operation and do not chose (for the time being) for methanol-only engines. This is mostly due to the long lifetime of engines, the numerous diesel engines installed on ships, and the fact that this solution allows flexibility on the fuel that is used. Once methanol will be adopted by vessel owners and operators and its market share will be significant, and given an easy bunkering infrastructure at ports, the next step can be to further optimize the engines depending on the experience gained in the first years.

On the other hand, while methanol as a fuel has already proven extensively its advantages in spark ignition engines, the amount of scientific knowledge on dual fuel operation is more limited. In the coming years the focus should be to fill that gap. Within the LeanShips project already a significant gap will be filled with knowledge on the behaviour of methanol in high speed four stroke compression ignition engines. For low speed two stroke engines and medium speed four strokes engines with higher power outputs, there is currently little or no data available in open literature, on for example the behavior of heavy fuel oil compared with methanol.

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7. References

Andersson K., Salazar C.M., 2015. Methanol as a marine fuel report. FCBI Energy, prepared for Methanol Institute.
Bechtold R.L., Goodman M.B., Timbario T.A., 2007. Use of Methanol as a Transportation Fuel. Methanol Institute.
Bengtsson S., Andersson K., Ellis J., Haraldsson L., Ramne B., Stefenson P., 2012. Criteria for Future Marine Fuels. The IAME 2012 Conference, 6-8 September, 2012, Taipei, Taiwan.
Bromberg L. and Cheng W.K., 2010. Methanol as an Alternative Transportation Fuel in the US: Options for Sustainable and/or Energy-Secure Transportation.
Brusstar MJ., Stuhldreher M., Swain D., Pidgeon WM., 2002. SAE paper no. 2002-01-2743.
Callendar, G.S., 1938. The artificial production of carbon dioxide and its influence on temperature. Q.J.R. Meteorol. Soc., 64, 223-237.
Cedrone K., Bromberg L., Cohn D.R., 2013. Ultra-high efficiency methanol engines with advanced exhaust energy recovery. 20th International Symposium on Alcohol Fuels (ISAF), March 26, 2013.
Chryssakis C., Brinks H., King T., 2015. The Fuel Trilemma: Next Generation of Marine Fuels. DNV GL Strategic Research & Innovation Position Paper 03-2015.
Coulier J., Verhelst S., 2016. CIMAC Congress, Helsinki. Document number 20160600501.
Cubasch U., Wuebbles D., Chen D., Facchini M.C., et al., 2013. Introduction of Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
Ellis J., Tanneberger K., 2015. Study on the use of ethyl and methyl alcohol as alternative fuels in shipping. Report prepared for the European Maritime Safety Agency (EMSA).
Ellis J., Ramne B., Falk T., et al., 2014. Spireth – End of project report. Activities and outcomes of the Spireth Project.
Fleming J.R., 1998. Historical perspectives on climat change. Oxford University Press, New York, 208 pp.
Hake J-F., Fischer W., Venghaus S., Weckenbrock C., 2015. The German Energiewende – History and status quo. Elsevier, Energy 92 (2015) 532-546.
LeanShips, 2015-2019. Low Energy and Near to zero emissions Ships. http://www.leanships-project.eu/project/ .
Lin C-W., Chen S-H., Tzeng G-H., 2009. Constructing a cognition map of alternative fuel vehicles using the DEMATEL method. Journal of Multi-criteria decision analysis 16: 5-19.
Martens J.A.,Bogaerts A., De Kimpe N., Jacobs P.A., Marin G.B., Rabaey K., Saeys M., Verhelst S., 2017. The Chemical Route to a Carbon Dioxide Neutral World. ChemSusChem 2017, 10, 1039-1055.
Mayer S., Sjöholm J., Murakami T., et al., 2016. CIMAC Congress, Helsinki, Document Number 20160600407.
McGill R., Remley W.B., Winther K., 2013. Alternative Fuels for Marine Applications.
Ramne B., 2017. GreenPilot – Aim and Background. GreenPilot seminar 2017-06-15.
Rosa R.N., 2017. The role of synthetic fuels for a carbon neutral economy. Journal of Carbon Research.
Royal Academy of Engineering, 2013. Future Ship Powering Options – Exploring alternative methods of ship propulsion.
Ryley T., Chapman L., 2012. Transport and climate change. Transport and sustainability volume 2.
Semelsberger T.A., Borup R.L., Greene H.L., 2005. Journal of Power Sources, Volume 156, Issue 2, Pages 497-511.
Shamun S., Hasimoglu C., Murcak A., et al., 2017. Fuel, Volume 209, Pages 624-633.
Stenhede T., 2013. WP2 Present and future maritime fuels, Effship.
Smith T.W.P., Jalkanen J.P., Anderson B.A., Corbett J.J., et al., 2015. Third IMO GHG Study 2014.
Södra, 2017. https://www.sodra.com/en/about-sodra/press/press-releases/2658273/ .
Stojcevski, T., 2014. Methanol – as engine fuel, status Stena Germanica and market overview. Qatar: Middle East Methanol Forum.
Tran K-C., 2010. Making renewable fuel by carbon recycling.
Tronstad T., Astrand H.H., Haugom G.P., Langfeldt L., 2017. Study on the use of fuel cells in shipping.
Vancoillie J., Verhelst S., Demuynck J., Galle J., Sileghem L., Van De Ginste M., 2012. SAE Paper no. 2012-01-1283.
Vancoillie J., Sileghem L., Verhelst S., 2013. SAE Paper no. 2013-01-1312.
Verhelst S., 2013. International Journal of Hydrogen Energy, Volume 39, Issue 2, Pages 1071-1085.
Verhelst S., 2014. Future Vehicles Will Be Driven by Electricity, But Not as You Think. Proceedings of the IEEE, Vol. 102, No. 10.
Wang J.J., Jing Y.Y., Zhang C.F., Zhao J.H., 2009. Renewable and Sustainable Energy Reviews, Volume 13, Issue 9, Pages 2263-2278.
Yao C., Pan W., Yao A., 2017. Methanol fumigation in compression-ignition engines: a critical review of recent academic and technological developments. Fuel 209 (2017) 713-732.