SUMMETH

SUMMETH – Sustainable Marine Methanol

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Engine Technology, Research, and Development for Methanol in Internal Combustion Engines

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ABSTRACT

This report describes the experimental investigation of several different methanol engine concepts in the range of 250 to 1200 kW with respect to performance and emissions. The investigated concepts are compared with each other and also with other methanol engine concepts to rank the merits and challenges. The results show that methanol can be used efficiently as a fuel on-board ferries, and other vessels, with the potential to reduce greenhouse gas, soot and NOx emissions.

SUMMETH PROJECT SUMMARY

SUMMETH, the **Su**stainable **M**arine **Meth**anol project, is focused on developing clean methanol engine and fuel solutions for smaller ships. The project is advancing the development of methanol engines, fuel system installations, and distribution systems to facilitate the uptake of sustainable methanol as a fuel for coastal and inland waterway vessels through:

- developing, testing and evaluating different methanol combustion concepts for the smaller engine segment
- identifying the total greenhouse gas and emissions reduction potential of sustainable methanol through market investigations
- producing a case design for converting a road ferry to methanol operation
- assessing the requirements for transport and distribution of sustainable methanol.

The SUMMETH project consortium consists of SSPA Sweden, ScandiNAOS, Lund University, VTT Technical Research Centre of Finland, Scania AB, Marine Benchmark, Swedish Transport Administration Road Ferries, and the Swedish Maritime Technology Forum.

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1 INTRODUCTION

The objective of the WP3 was to identify the best engine concept for methanol operation in internal combustion engines for rapid market introduction and implementation in a long term perspective, considering cost and energy efficiency together with minimized environmental impact.

The role of WP3 was to study the performance and emissions for conventional methanol engine concepts such as port-fuel injected spark-ignited engines (PFI-SI) and advanced methanol engine concepts such as Methanol-Diesel compression ignition of methanol fuel with additive (MD95), partially premixed combustion (PPC) and direct injected spark ignition engine (DI-SI). In more detail, the work was divided in two Tasks: 3.1 and 3.2 described below.

Methanol fuel properties

Methanol has several properties that are interesting from an engine combustion perspective. It has high octane rating, high heat of vaporization, high oxygen content in its molecule but only about half of the energy content of, for instance, diesel fuel (Tuner 2016). The high heat of vaporization of alcohols leads to a reduction of temperature in the charge, which can be exploited for improved cylinder filling and reduced compression work. Another interesting and beneficial property of methanol is the comparably high molar expansion that provides additional pressure during the chemical reactions but without additional heat. Methanol can also be blended with ethanol and gasoline.

The lower energy content of methanol, compared to gasoline or diesel fuel, does not only mean that more fuel needs to be carried on-board a ship, but also that the engine fuelling system needs to be designed to accommodate higher fuelling rates. The volumetric energy content of methanol is, however, much higher than for gaseous fuels or batteries.

Engine operation with methanol is associated with a couple of other challenges. Alcohols are more corrosive than either gasoline or diesel fuel. Methanol containing water is the most aggressive while higher alcohols are increasingly less corrosive (Yuen et al. 2010). To avoid corrosion stainless steel, and Teflon is recommended. Metals like lead, zinc, copper, aluminum and magnesium, as well as some elastomers, plastics and rubber should not be used in contact with methanol. The low lubricity of methanol requires additives in the fuel to avoid problems with diesel type fuel pumps and injectors – unless bespoke units are used. Methanol is a solvent and can also form acids during combustion which could lead to higher demands on lubricant additives and possibly more frequent oil changes. Unlike gasoline or diesel fuel, neat methanol is a single-component fuel with single specific vapor pressures and boiling points that make for more challenging low-temperature cold starts. It can be difficult to vaporize enough fuel to reach an ignitable mixture.

Methanol offers reduced probability for soot emissions due to the oxygen present in the fuel. Together with the reduced combustion temperature, methanol offers an attractive way to operate compression ignition (CI) engines with reduced emissions of both NOx and soot compared to regular diesel fuel. Spark ignited (SI) engines typically run stoichiometric with a three-way catalyst (TWC) that effectively reduces the emissions of HC, CO, and NOx. Engine out emissions of methanol, formaldehyde, acetaldehyde, and acetic acid can be high and might require an effective catalyst to be limited at the tailpipe. This problem is more common in port fuel injected engines, where crevices may prevent complete combustion, and can largely be avoided with direct injection (DI) operation.

Task 3.1 Use of neat Methanol in spark Ignited (SI) and partially premixed combustion (PPC) engines (Task Leader LTH)

The high octane rating and strong cooling effect from the heat of vaporization makes methanol less prone to engine knock or pre-ignition, and therefore well suited as a spark-ignition “Otto” engine fuel. Spark-ignited (SI) engines are otherwise commonly known as “gasoline” engines (figure 1). The reduced knock tendencies can be exploited with an increase in compression ratio leading to both higher efficiency and higher power output compared to gasoline operation. Methanol has therefore historically found a use in high power applications such as racing cars and fighter aeroplanes. During the energy crisis in the 1970s methanol was considered one of the promising alternative fuels and intensive research and fleet studies lead to the development of port-fuel injected engines that could run on either M85 or gasoline (Brinkman et al. 1990, STU 1987, Richards 1990). The M85 engine technology was later used for the currently more established E85 vehicles, since methanol and ethanol have quite similar properties. Methanol is in commercial use today in China with regional variations from M5 to M100. M5 to M30 are used directly in standard gasoline engines while M85 and M100 are used in dedicated methanol vehicles (Chen et al. 2014).

The high octane rating of methanol does not naturally suit compression ignition (CI) diesel engine operation. CI engines, used with alcohols, are therefore operated with combinations of increased compression ratios, ignition improvers, inlet air heaters or assisted ignition from glow plug. Also hot residual gases have been employed. The work by Caterpillar on methanol CI engine trucks is a good example of how glow plugs can be applied to support ignition (Richards 1990). Another approach, selected by Wärtsilä for Stena Germanica and also by MAN, is to use a pilot injection of diesel fuel to ignite the bulk of methanol fuel (Haraldson 2015, MAN 2015).

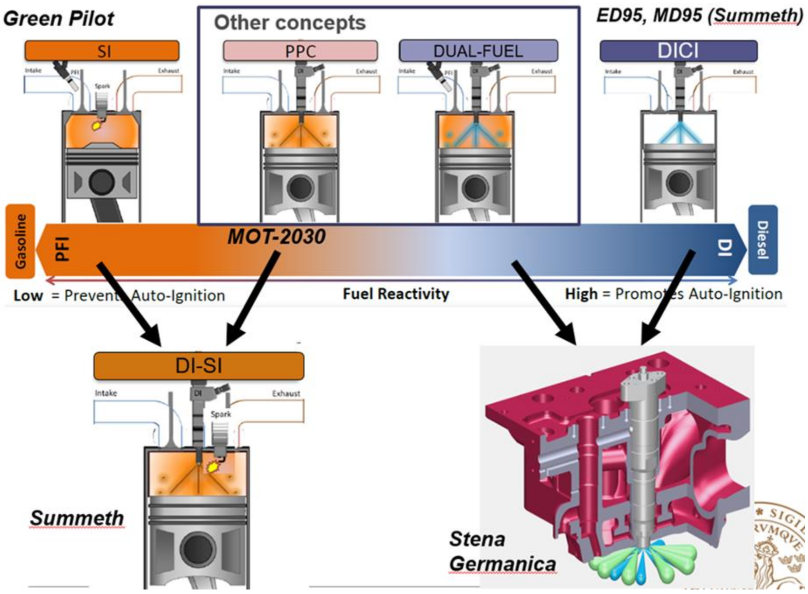

Figure 1. Overview of methanol engine concepts.

Partially premixed combustion is a so called low temperature combustion concept that exhibits substantial fuel flexibility, with liquid fuels, by tailoring the injection strategy towards the auto-ignition properties of the fuel. Typically, there is a separation of the direct injection event and the auto-ignition combustion and by injecting the fuel at a precise point during the compression, combined with air dilution and high amounts of residual gases and a fuel with some resistance to auto-ignition, fully premixed or fully heterogeneous conditions can be avoided. This leads to low emissions of soot, NOx, HC and CO together with very high efficiency (Manente el al. 2009, Shen et al. 2013, Tuner et al. 2014). PPC has been investigated with a number of fuels such as gasoline, naphtha, ethanol and also under other names such as, for instance, gasoline compression ignition (GCI) (Cho et al. 2017), and partially premixed compression ignition (PPCI) (Cheng et al. 2014). PPC with methanol fuel has so far, however, only been investigated by Lund University and the results are reported in section 2.1 (Shamun et al. 2016, Svensson et al. 2016, Shamun et al. 2017, Pucilowski et al 2017).

Task 3.2 Use of Additized Methanol in Diesel Engine (Task Leader VTT).

One option to use alcohols in diesel cycle is Scania's engine using ethanol with ignition improver and lubricity additive (ED95). This concept has been used since 1985 in over 600 buses supplied by Scania to several countries. The modifications of diesel engines include increased compression ratio (28:1), a special fuel injection system and a catalyst to control aldehyde emissions (Hedberg 2007). The fuel used in ethanol buses in Sweden, called Etamax D, which contains hydrated ethanol, 5.0 % m/m ignition improver ("Beraid"), denaturants and corrosion inhibitor additive. (SEKAB brochure, Westman 2005; Hedberg 2007). Today several companies provide the ignition improver additive for the ED95 concept. Munsin et al. (2012) found glycerol ethoxylate additive to produce higher NOx and lower soot than the commercial additive. The best cetane improver for methanol in the past was nitrate-based Avocet (Jennings & Short 2016), however, showing increased corrosion, explosion, toxicity, insufficient lubricity and elevated NO_x emissions. 2% Avocet and 7% Beraid has resulted in the same ignition delay as Avocet alone. In 2015, Akzo Nobel released a patent application for a methanol soluble alkylene oxide adduct of glycerol for anhydrous fuel (Lif 2015). Recently, ammonium nitrate was suggested as a cetane enhancer for methanol, as well as e.g. dimethyl ether (DME), PEG-nitrate, octyl nitrate, hydrazine and hydroxylamine nitrate in a fuel containing also water and lubricity additive and organic amines as anti-corrosion agents (Jennings & Short 2016). For diesel fuel, ignition improvers are typically nitrates, nitrites and organic peroxides (Nylund et al. 2005).

The MD95 concept using commercial ED95 additive was preliminarily screened at VTT by Nylund et al. 2015). In this task, fuel concepts with different additives and recipes were studied and engine optimisation was initiated with the intake manifold injection. Measurements of cylinder pressure parameters, engine performance and emissions enables rating of different development paths. For example, high emissions of unburned fuel and rough engine running indicate inefficient combustion process.

The results from the engine testing of various concepts were then compiled to identify which of the concepts that are best for a quick market introduction and to analyse implementation in the long-term perspective with respect to energy and cost efficiency and environmental impact.

2 Use of Neat Methanol in Spark-ignited and PPC engines (Task 3.1 Summary)

Task 3.1 contains experimental studies with a conventional PFI-SI methanol engine that were conducted by ScandiNAOS, and with advanced methanol engines such as DI-SI and PPC conducted by Lund University. All the used engines have a capacity of around 13 liter and can provide power outputs in the range 250 kW to 700 kW.

2.1 DISI AND PPC ENGINES

Experimental setup

Three engines were used at Lund engine laboratories. Most of the research was conducted on a Scania D13 engine modified for single cylinder operation to facilitate control and measurement of the operating conditions with greater detail. The single cylinder engine was used with two different cylinder heads; one standard D13 cylinder head for PPC and also methanol diffusion combustion and one specifically designed and built by Lund University for this project for DI-SI operation (Björnestrand 2017). To investigate the characteristics of direct injected methanol combustion, another single cylinder Scania D13 engine with optical access to the combustion chamber was used. A complete six-cylinder Scania D13 engine adapted for PPC operation was used to measure power and emissions for the complete operating range with gasoline. These results were used to scale the performance of methanol PPC from the single cylinder engine. All engines were connected to emission analysers for quantification of NOx, particulate matter, CO and HC. For the advanced particulate characterization studies a cooperation was performed with Aerosol-technology at Lund University and DTU in Denmark.

Performance

PPC provides the highest recorded indicated efficiencies (>53%) that we are aware of for a methanol engine (Shamun et al. 2017). The indicated efficiency of methanol PPC is thus exceeding those of the best diesel engines, by around two percentage points (Tuner 2016). The combustion characteristics of methanol PPC show a very rapid combustion that, however, can be controlled with split injection strategies or through late injection diffusion combustion (Shamun et al. 2016, 2017). Although the PPC experiments with a complete engine demonstrate high efficiency and low emissions throughout the load and speed range, the PPC concept is still at a level of a research concept that lacks maturity. Cold starting is one of the challenges (Shamun et al. 2017).

DI-SI can be run either homogenous premixed through early injection or through stratified late injection. Stratification provides very high indicated efficiencies (>51%) but has a narrow range between knock and misfire where stable operation can be achieved (Björnestrand 2017). The heat release characteristics for stratified DI-SI are beneficial with a moderate increase and very quick ending which offers a more silent combustion and also an increased time for expansion that improves efficiency (Björnestrand 2017). DI-SI offers better options than PPC for near time implementation.

Emissions

It was demonstrated that neat methanol operation does not form any carbon-based soot and that the particulate levels are 3-4 orders of magnitude lower than for diesel engines (Svensson et al. 2016, Shamun et al. 2016, Shamun et al. 2017, Tuner 2016). The lack of soot means that engine operation strategy can focus on reducing other emissions and for PPC it is possible to reach 0.12 g/kWh HC, 0.8 g/kWh CO, 0.3 g/kWh NOx and 0.000004 g/kWh particulates and thus meet the stringent EURO VI levels without any exhaust aftertreatment during steady-state operation. Stratified DI-SI operation with EGR does not soot either and can provide low emissions of NOx with reasonable levels of HC and CO (Björnestrand 2017). The emissions advantage is not as strong as for PPC but good enough for SECA regulated areas. It is possible to run DI-SI with stoichiometric operation to enable a three-way catalyst (TWC) for even lower emissions than above reported for PPC.

2.2 PFI-SI METHANOL ENGINES

Experimental setup

A pilot boat has been converted to run on methanol. This included adaption of a pilot boat, which considers many technical systems on board. Among these are the tanks, piping and safety systems. The conversion to methanol operation will show how a smaller vessel can be methanol powered in practice, which demonstrates how emission reductions can be achieved.

Two engines have been converted to run on 100% methanol. One Weichai, originally CNG powered, and one Scania, originally diesel powered. Both engines have been modified to run as SI (spark ignited) and PFI (port fuel injected). Both are six cylinders with total cylinder volume of 12-13 L.

Emission measurements have been performed for the modified Weichai engine, which produces a rated output power of 313 kW and is optimised for high efficiency, combined with a rating for long life. It runs lean with lambda from 1.2 at low loads to lambda 1.5 at high loads. Emissions measurements on the Scania engine will be carried out in early 2018 as part of the GreenPilot project and will be reported later in the year.

The Weichai engine has been run in a dyno and installed in the boat. NOx measurements were carried out in the dyno while NOx and PM/PN measurements were done onboard. Four load points were logged: 1400 RPM, 1800 RPM, 2000 RPM and 2200 RPM. These load points correspond to 31%, 64%, 91% and 100% of MCR (maximum continuous rating). The load points correspond to the prescribed procedure for an emission measurement according to the ISO 8178 E3 – cycle.

Emissions

Lowest recorded NOx emission load point is at full load (313 kW), which was measured to 1 g/kWh. In a certification procedure four of the load points will be weighted and summed together according to prescribed procedure. Calculated according to IMO standard the NOx emission factor is 1.38 g/kWh. Calculated according to EU procedure, the emission factor is 1.77g/kWh.

Engines with NOx emissions under 1.96 g/kWh fulfil IMO Tier III NOx limit and under 1.8 g/kWh the engine also fulfils the upcoming EU regulations on inland waterways.

Particle mass is regulated in upcoming EU regulations. The limit is 0.015 g/kWh. Recorded and weighted particulate mass is 0.0000282 g/kWh meaning that emissions regulation is fulfilled with a margin of 99.99%.

Performance

Results indicating braked fuel efficiency of 38 to 40% for higher loads.

The engine performs similarly to a conventional diesel with respect to efficiency and torque output. Emissions of NOx and particulates are low compared to diesel engines.

The work environment was also considered. By sound test it was determined that the noise level is 6 dB lower for a methanol engine compared to a similar diesel engine. The difference is greatest at 850 rpm, corresponding to slow driving. The difference was reduced when noise from the turbo chargers was intensified at higher engine speed.

The PFI SI technology is simple, proved to work in most passenger cars since the 90s and recognised as cheap. Supply systems such as fuel, injectors and sensors can be of simple type with low pressures needed.

Demonstrating that this, potentially fossil free, fuel will generate low emissions of NOx and PM, in a PFI SI is of great importance. The technology exists, and it is mature. Taking the step to real applications is easy.

3 USE OF ADDITIZED METHANOL IN DIESEL ENGINE (TASK 3.2 SUMMARY)

VTT has a Scania ethanol engine (Scania EEV Ethanol DC9 270 hp) installed in the test bench, and an option to use an additional intake manifold injection system. Several MD95 fuel concepts with different additives and recipes were studied in a Scania engine in a standard configuration, and tests with the intake manifold injection to reduce the need for an ignition improver. Cylinder pressure parameters, engine performance and emissions were measured to enable rating of different development paths. The details of work are provided in Aakko-Saksa et al. 2017.

Fuel blending was based on the additives selected basing on literature (Aakko-Saksa et al. 2012; Nylund et al. 2005). Four ignition improvers were selected, as well as two esters and three oxygenates. Solubility tests were conducted, and then the preliminarily screening of the ignition characteristics of fuel blends using a constant volume combustion chamber (AFIDA in ASG). One of the fuels was blended with dry methanol, while the other fuels contained appr. 5.5 wt% water. AFIDA indicated improvements in the ignition characteristics for some of the new MD95 recipes, although the ED95 fuel was better than any of the methanol blends tested. Ignition characteristics of fuels increased with the increasing amount of ignition improver and using dry MD95. Three methanol blends were selected for the engine tests: MD-1 (with additive A), MD-2 (with additive C and FAME), MD-3 (with additive C+FAME+ether). ED95 was studied as a reference. For actual wet blends FAME separated at least partially, which was not seen in the solubility testing with dry methanol. The intake manifold injection study was conducted with MD-4 and MD-5 having low concentrations of additives. MD-6 contained nitrate additive.

Emission measurements using the ESC test cycle showed differences between the test fuels. The CO emission was substantially lower for all MD candidates than for the ED95 fuel, and also lower aldehyde emissions were observed for methanol than for ethanol blends. Unburned alcohol was present in exhaust both for the MD and ED fuels. NOx emissions were slightly lower for the MD fuels than for ED95. Flame temperature of methanol is lower than that of ethanol (Piel 1990), which probably explains this difference. By default, methanol fuels without carbon-carbon bonds do not enhance soot formation. In these tests material was observed on the PM filters, but it was not black. This material on the filters with alcohol fuels indicated presence of unburned additives. Earlier experience has shown that this kind of semivolatile liquid constituents can be easily removed by oxidation catalyst (Aakko et al. 2000). Particle number emissions were relatively high for the MD-fuels and a catalyst may also reduce these emissions. With nitrate-based additive in MD-6 fuel, the engine did not start.

Cylinder pressure analysis showed that the duration of injection was longer with methanol than with ethanol. In some operation points, the engine management seemed to adjust boost pressure accordingly. The engine operated steadily with all fuels and the experienced cylinder pressure deviation was normal. Pressure rise rate with all fuels remain low, resulting in moderate combustion noise. Longer duration of injection causes increased combustion times for MD. The higher reaction speed combined with better mixing of MD however explains the faster heat release in the late combustion phase. The peak heat release with both fuels were, however, similar. The difference in IMEP figures between ED95 and MD was relatively small.

Intake manifold injection tests: ED95 fuel was injected in the intake manifold for two fuel blends (MD-4 and MD-5) containing less ignition improver additive than the other fuels. These test fuels had particularly poor ignition quality. Utilising manifold injection a fuel blend with poor ignition can be used. Also here much more stable cylinder pressure was achieved when the intake manifold injection was utilized for the MD-4 and MD-5 fuels. However, in this non-optimized system no exhaust emission benefit was achieved. The system needs improvement in both flow design and main injection functionality to show the potential of the concept.

Overall, several MD95 methanol blends were clean burning, and combustion was good in the Scania EEV Ethanol DC9 270 hp. The best performance was observed for the same type of ignition improvers as used in the ED95 concept. For both fuels, MD95 and ED95, high masses on particulate filters were observed and concluded to originate from the unburned additives. This “liquid PM” is assumedly removed by the oxidation catalyst that belongs to the commercial Scania alcohol engine concept. Catalyst may also reduce particle number emissions that were elevated for the alcohol fuels. When fuel was injected in the intake manifold, concentration of ignition improver additive can be reduced. However, the system needs improvement and optimisation to show the potential of the concept. Overall, the results show that the MD95 concept can be a potential solution to introduce environmentally friendly renewable methanol for smaller ships on the condition that engine materials and other related issues are handled.

4 DISCUSSION AND CONCLUSIONS

Table 1 shows an estimation of the relative merits and challenges with the various methanol engine concepts versus conventional diesel engines.

One of the benefits with diesel engines is the extreme ruggedness. Although methanol engines can be expected to be robust enough, none of them are expected to match a conventional diesel engine, except maybe for the DI-Dual-Fuel concept (used on Stena Germanica). Fully premixed engines such as PFI-SI and Dual-Fuel are more exposed to in-cylinder corrosion if the engines are used frequently with start-stopping without proper warming up. The PPC engine is still a research concept and has poor low load operation quality which currently ranks it worst in terms of robustness.

Retrofitting refers to modifying an existing on-board diesel engine to operate on methanol. The on-board conversion of the Stena Germanica engines is a good example of retrofitting (Haraldson 2015). The motivation to retrofit an engine is to limit cost but if the engine is too old or the modification expensive it might be more cost effective to replace the complete engine, especially for smaller engines. All the concepts introduce challenges when it comes to retrofitting. How severe the challenges are, depend also on the generation of the engine to be modified. Apart from that the fuel system with tank, pumps, injectors etc. needs to be upgraded, MD95 requires different pistons, while PFI-SI, DI-SI needs new pistons and cylinder heads adapted for spark plugs. The dual-fuel concept also needs adaption with new pistons and a secondary fueling system, while the DI-Dual-Fuel might get away with a secondary fueling system and advanced fuel injectors thus leaving the base engine intact. PPC is possibly the closest to use diesel engine hardware, but needs an EGR system and an advanced fuel injection system, and considering the immaturity of the concept the requirements for retrofitting are currently quite uncertain.

Table 1. Comparison of various methanol engine concepts 250-1200 kW. DICI Diesel is the reference technology. All other technologies in the table use methanol and are compared with DICI Diesel.

Engine type	Robustness	Efficiency	Power	Noice	HC	CO	NOx	soot
DICI Diesel	0	0	0	0	0	0	0	0
DICI Diesel with particulate filter / SCR	0	-	0	0	0	0	++	++
MD95 with oxidation catalyst	-	0	-	0	0	0	+	+
MD95 with particulate filter / SCR	-	-	-	0	0	0	++	++
PFI-SI Lean burn	-	0	-	++	-	-	++	++
PFI-SI TWC	-	-	0	++	++	++	++	++
DI-SI Lean burn	-	+	-	+	-	-	+	++
DI-SI TWC	-	0	0	+	++	++	++	++
Dual-Fuel	(-)	--	-	+	--	--	0	+
DI-Dual-Fuel	0	0	0	0	-	-	+	+
PPC	--	++	0	-	0	0	++	++

0 = similar performance with methanol as with DICI Diesel

- *– = worse performance with methanol than with DICI Diesel*
- *+ = better performance with methanol than with DICI Diesel*

Diesel engines are known for their high efficiency and thus low fuel consumption. Methanol engines can be even more efficient than diesel engines, but since hardly any are used commercially there is little long term operation data to depend on (Tuner 2016, Björnestrand 2017, Shamun et al. 2017). Direct injected lean operated concepts such as DI-SI, DI-Dual-Fuel and PPC are estimated to have similar or higher efficiency as diesel engines while concepts running at stoichiometric conditions to accommodate a three-way catalyst for ultra-low emissions are expected to have lowest efficiency (Tuner 2016, Björnestrand 2017).

Cost of operation depends mainly on the fuel consumption of the engine and considering the uncertainty of the relative price between diesel fuel and methanol fuel the comparison is only done between the methanol engines. PPC has demonstrated the highest efficiency in laboratory conditions and if this materializes in a commercial engine it will probably have the lowest operating costs. Both DI-SI and DI-Dual-Fuel have good potential for low operating costs. Additives needed for the MD95 increase fuel price to some extent, however, this effect could be minimized using the intake manifold injection.

The power levels are expected to be similar to that of diesel engines but with some limitations for the MD95 concept due to the very high compression ratio and for the PFI-SI engine due to risk of knock.

Diesel engines are quite noisy, while especially PFI-SI engines are known to be quite silent. DI-SI and the Dual-fuel concepts can be more silent than diesel engines while PPC typically has a more aggressive combustion that can be noisy.

When it comes to the emissions, methanol has a distinctive advantage compared to most fuels. The high oxygen content of methanol means that neat methanol fuel will not produce carbon based soot in engine combustion. This feature can also be exploited to operate methanol engines in a way to suppress other emissions. Dual-Fuel and DI-Dual-Fuel depend on diesel pilot, which leads to some soot emissions, but still far lower than for conventional diesel engine operation. For MD95, there is no soot emissions, but some unburned additives are seen on particulate filters. DI-Dual-Fuel and MD95 concepts can reduce NOx down to approximately 2 g/kWh. Even lower NOx can be achieved by the use of lean operation, EGR or aftertreatment devices. For current SECA regulations, lean operation will be sufficient, which relaxes the need for expensive EGR or aftertreatment devices. HC and CO emissions will be produced for engines that depend on premixed or partially premixed operation. Levels can be acceptable with engine control strategies or with the use of low-cost oxidizing catalysts.

For a short term implementation, the conventional PFI-SI engine for lean operation and with an oxidizing catalyst is probably the most dependable, clean and most affordable concept. The MD95 is another option that likely can be implemented within short time. Dual-Fuel and DI-Dual-Fuel concepts would probably need longer introduction time for this engine size class. PFI-SI with stoichiometric operation and TWC (M85) is also a proven technology that can be applied for neat methanol use, but due to lower engine efficiency probably not preferred as such for ships. For long term implementation a mode-shifting PPC/DI-SI engine with oxidizing catalyst can possibly offer the lowest operating costs and strongest reduction of emissions and GHG.

5 REFERENCES

Aakko, P. Westerholm, M., Nylund, N-O, Moisio, M., Marjamäki, M., Mäkelä, T. and Hillamo, R. 2000. IEA / AMF Annex XIII : Emission performance of selected biodiesel fuels - VTT ’ s contribution. Research Report ENE5/33/2000.

Aakko-Saksa, P. et al., 2012. Future Combustion technology for synthetic and renewable fuels in compression ignition engines (REFUEL), Aalto University publication series SCIENCE + TECHNOLOGY 21/2012,

Aakko-Saksa, P., Westerholm, M., Pettinen, R., Söderström, C., Roslund, P., Piimäkorpi, P., Koponen, P., Murtonen, T. and Niinistö, M. 2017. Methanol with additives for diesel engines – VTT's contribution to the SUMMETH project. Draft manuscript 18.12.2017.

Björnestrand, L. "Efficiency and emissions analysis of a methanol fuelled direct injection spark ignition heavy duty engine". Master Thesis, Lund 2017.

Brinkman, N.D., Ecklund, E.E., Nichols, R.J. "Fuel Methanol – A Decade of Progress". Society of Automotive Engineers, Inc. 1990. ISBN 1-56091-011-9., 60.

Chen, H., Yang, L., Zhang, P.-H., Harrison, A. The controversial fuel methanol strategy in China and its evaluation (2014) Energy Strategy Reviews, 4, pp. 28-33

Cheng, X., LI, S., Yang, J., Dong, S. et al., "Effect of N-butanol-Diesel Blends on Partially Premixed Combustion and Emission Characteristics in a Light-duty Engine," SAE Technical Paper 2014-01-2675, 2014, https://doi.org/10.4271/2014-01-2675.

Cho, K., Latimer, E., Lorey, M., Cleary, D. et al., "Gasoline Fuels Assessment for Delphi's Second Generation Gasoline Direct-Injection Compression Ignition (GDCI) Multi-Cylinder Engine," SAE Int. J. Engines 10(4):1430-1442, 2017, https://doi.org/10.4271/2017-01-0743.

Haraldson L., "Methanol as fuel", Methanol as Fuel & Energy Storage Workshop. Lund, Sweden, 2015, http://www.lth.se/fileadmin/mot2030/filer/12._Haraldsson_-_Methanol_as_fuel.pdf

Hedberg, R., 2007. The Scania Ethanol Story - 25 years of experience in sustainable transport. In XVI International Symposium of Alcohol Fuels, 8 January 2007. p. 20.

Jennings, J.R. & Short, G.D., 2016. Enhanced fuel and method of producing enhanced fuel for operating internal combustion engine.

Lif, A., 2015. A methanol-based diesel fuel and the use of an ignition improver. , pp.2–4.

MAN. MAN demonstrates two-stroke methanol engine. 2015. url: http://www.motorship.com/news101/engines-and-propulsion/man-demonstrates-two-stroke-methanol-engine.

Manente, V., Johansson, B., Tunestal, P., and Cannella, W., "Effects of Different Type of Gasoline Fuels on Heavy Duty Partially Premixed Combustion," SAE Int. J. Engines 2(2):71-88, 2010, doi:10.4271/2009-01-2668.

Moirangthem, K., 2016. Alternative Fuels for Marine and Inland Waterways, Available at: http://publications.jrc.ec.europa.eu/repository/handle/JRC100405.

Munsin, R., Yossapong, L., Sumrerng, J., Masataka, M. and Hidenoriet, K., 2012. Investigation of Effects of Ignition Improvers on Ignition Delay Time of Ethanol Combustion with Rapid Compression and Expansion Machine. Available at: http://papers.sae.org/2012-01-0854/.

Nylund, N-O., Murtonen, T., Westerholm, M., Söderström, C., Huhtisaari, T. and Singh, G., 2015. Testing of various fuel and additive options in a compression-ignited heavy-duty alcohol engine. In The 21st International Symposium on Alcohol Fuels, 10 March 2015 , Gwangju, Korea. pp. 1–15.

Nylund, N.-O. Aakko, P., Niemi, S., Paanu, T. and Berg, R. 2005. Alcohols / ethers as oxygenates in diesel fuel: Properties of blended fuels and evaluation of practical experiences, IEA Advanced Motor Fuels. Available at: http://www.iea-amf.org/app/webroot/files/file/Annex Reports/AMF_Annex_26.pdf.

Richards, B., "Methanol-Fueled Caterpillar 3406 Engine Experience in On-Highway Trucks," SAE Technical Paper 902160, 1990, doi:10.4271/902160

Sam Shamun, Mengqin Shen, Lund University; Bengt Johansson, King Abdullah Univ of Science & Tech; Joakim Pagels, Anders Gudmundsson, Per Tunestal, Martin Tuner, Lund University., ”Exhaust PM Emissions Analysis of Alcohol Fueled Heavy-Duty Engine utilizing PPC”., SAE Int. J. Engines 9(4):2016, doi:10.4271/2016-01-2288

Sam Shamun, Martin Tuner, Can Hasimoglu, Ahmet Murcak, Per Tunestal, Oivind Andersson., ” Investigation of Methanol CI Combustion in a High Compression Ratio HD Engine using a Box-Behnken Design” Fuel 209C (2017) pp. 624-633, doi: 10.1016/j.fuel.2017.08.039

Sam Shamun, Maja Novakovic, Vilhelm Malmborg Berg, Calle Preger, Mengqin Shen, Maria E. Messing, Joakim Pagels, Martin Tunér and Per Tunestål.,” Detailed Characterization of Particulate Matter in Alcohol Exhaust Emissions” COMODIA June 2017

Shen, M., Tuner, M., and Johansson, B., "Close to Stoichiometric Partially Premixed Combustion -The Benefit of Ethanol in Comparison to Conventional Fuels," SAE Technical Paper 2013-01-0277, 2013, doi:10.4271/2013-01-0277.

Shen, M., Tuner, M., Johansson, B., and Cannella, W., "Effects of EGR and Intake Pressure on PPC of Conventional Diesel, Gasoline and Ethanol in a Heavy Duty Diesel Engine," SAE Technical Paper 2013-01-2702, 2013, doi:10.4271/2013-01-2702.

STU ”Project M100 – A Test with Methanol-Fueled Vehicles in Sweden”. STU Information no. 640 – 1987. ISBN 91-7850-213-6

Svensson, E., Li, C., Shamun, S., Johansson, B. et al., "Potential Levels of Soot, NOx, HC and CO for Methanol Combustion," SAE Technical Paper 2016-01-0887, 2016, https://doi.org/10.4271/2016-01-0887.

Tuner, M., Johansson, T., Aulin, H., Tunestal, P. et al., "Multi Cylinder Partially Premixed Combustion Performance Using Commercial Light-Duty Engine Hardware," SAE Technical Paper 2014-01-2680, 2014, doi:10.4271/2014-01-2680.

Tuner, M., "Review and Benchmarking of Alternative Fuels in Conventional and Advanced Engine Concepts with Emphasis on Efficiency, CO_2, and Regulated Emissions," SAE Technical Paper 2016-01-0882, 2016, doi:10.4271/2016-01-0882.

Westman, B., 2005. Ethanol fuel in diesel engines for energy efficiency Projected CO 2 -emissions from road transport in EU. In pp. 1–7.

Yuen, P., Villaire, W., and Beckett, J., "Automotive Materials Engineering Challenges and Solutions for the Use of Ethanol and Methanol Blended Fuels," SAE Technical Paper 2010-01-0729, 2010, doi:10.4271/2010-01-0729.