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E-methanol for shipping: quality considerations for reduced environmental impact

Fuels - Alternative & New Fuels

Päivi Aakko-Saksa, VTT Technical Research Centre of Finland

Mårten Westerholm, VTT Technical Research Centre of Finland
Christer Söderström, VTT Technical Research Centre of Finland
Rasmus Pettinen, VTT Technical Research Centre of Finland
Matti Reinikainen, VTT Technical Research Centre of Finland
Leonidas Ntziachristos, Aristotle University Thessaloniki
Dimitris Kolokotronis, Aristotle University Thessaloniki
Athanasios Dimaratos, Aristotle University Thessaloniki
Nikolaos Papadis, Aristotle University Thessaloniki

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ABSTRACT

The marine sector significantly contributes to global warming, urging the establishment of ambitious targets to reduce greenhouse gas (GHG) emissions from shipping. Given the sector's reliance on internal combustion engines, advances in fuel technologies are critical, with key considerations including safety and fuel availability.

Electrofuels present a promising near-zero GHG emission solutions in view of their potential geographical availability and production volumes. The EU project "UP-TO-ME" is developing technologies to produce e-methanol from the CO2 point-sources by a fully autonomous, self-optimizing, and compact technology. The UP-TO-ME project also studies end-use aspects of e-methanol as marine fuel, focusing on minimum fuel specifications, particularly regarding the exhaust aftertreatment systems (EATS). The study utilized retrofitted high-speed methanol dual-fuel (DF) engines below 1MW, suitable for archipelago transportation and linking also to ground-transport. The work included experimental combustion analysis and emission measurements that provided the necessary data for the development of engine and EATS simulation models. The emission measurements paid special attention to carcinogenic formaldehyde and climate-warming black carbon emissions, while the sensitivity of the EATS to fuel impurities, including metals, was also assessed. The quality of e-methanol is yet to be established, and the first batches of UP-TO-ME e-methanol provides this data.

1 INTRODUCTION

The marine sector significantly contributes to global warming, and hence ambitious targets are established to reduce its greenhouse gas (GHG) emissions. Given the sector's reliance on internal combustion engines, advances in fuel technologies are critical. Methanol is a promising alternative fuel for shipping. Today, the methanol on market is almost solely fossil methanol produced from natural gas. However, electro-methanol produced from captured CO_2 and hydrogen or from bio-based materials could be carbon-neutral or even carbon-negative assisting to achieve near-zero GHG emissions. Electro-methanol has potentially wide geographical availability and significant production volumes.

Methanol is a good fuel for spark ignited (SI) engines, since its octane number is high. In contrary, low cetane number of methanol creates challenges in compression ignition (CI) engines, which dominate marine sector. Good features of methanol address high flame speed, high latent heat of vaporization, high hydrogen and oxygen contents without carbon-carbon bonds enabling soot-free combustion. On the other hand, methanol is flammable, its volumetric energy content is low, it has tendency to evaporate and its vapor pressure is low hampering the cold starting. Methanol is also corrosive and its lubrication properties are weak. Special requirements are set for lubricating oil when using methanol as engine fuel. Solubility of methanol in diesel is low, but its solubility in water is good [1][2]. Generally, the features of methanol would enable developing high-performance internal combustion engines with low exhaust emissions.

Methanol has a long history as an engine fuel. It was used during gasoline shortages in Germany and France during wars, and widely in the 1970s and 1980s during the oil crises and in the beginning of lead ban in many countries. By the mid-1990s, over 21 000 flexible fuel vehicles (FFVs) were running using M85 fuel containing petrol and up to 85% methanol in the US. When gasoline prices fell, so did the interest on methanol fuels. Today, methanol is used for vehicles in China (M15-M100) [1] and also in racing (e.g. Indy cars). In automotive sector, fuel standards for methanol are available, for example in the US (M51-M85, ASTM D5797), Italy (A20), Israel (M15, M3), India (M15) and China (M100, M85). For marine methanol, the first fuel standard was published in 2024 "Marine methanol standard - Specification of methanol as a fuel for marine applications, ISO 6583". The IMPCA specifications define a single grade of chemical methanol [3], while three methanol grades are defined in ISO 6583 since some equipment are more sensitive to methanol quality than the others.

In the marine sector, methanol is used in 4-stroke medium-speed engines, while methanol 2-stroke dual-fuel engines are regarded mature: 173 methanol-capable containerships were on order in 2024 [4]. Retrofit methanol dual-fuel (DF) is an attractive option, enabling introducing methanol in the present fleet with fast and cost-efficient conversions while maintaining fuel flexibility by enabling both methanol and diesel operation in DF engines [5]. For large engines, retrofit concepts are available on market and also used, e.g. Wärtsilä's retrofit solution in Stena Germanica. Maersk has announced of converting 11 of its large ships to DF methanol operation. The Seaspan and Hapag-Lloyd announced installation of 15 MAN B&W S90 retrofit solutions to DF ME-LGIM. COSCO and CMA CGM have also announced of methanol conversions of their containerships [4]. The large engines use DF direct injection concept. The 4-stroke medium-speed engines operating with the injection of liquid methanol and pilot fuel at the end of the compression stroke, which is available from Wärtsilä and HiMSEN, covering 3500 to 5220 kW power range. The MAN B&W ME-LGIM low-speed engine operates also on direct injection mode, with an injection of liquid methanol and pilot fuel at the end of the compression stroke, currently available in the power range of 5.4-82 MW. WinGD is developing a multi-fuel strategy for its 2-stroke engines [4].

In this study, the focus is on smaller vessels using high-speed engines below 1000 kW. Methanol engines for this segment are sparse. One option is the single-fuel concept using methanol containing additives for ignition and lubrication [6]. Enmar Engines' single-fuel methanol CI engine is on market at power class of up to 415 kW [7]. This engine uses M97 fuel containing methanol and 3% of additives for lubrication and ignition and it meets IMO Tier III limits, while the industrial M97 engine (up to 330 kW) meets EU Stage V standard even without an SCR. NO_x emissions are lower by 50-70% compared to a typical diesel engine, particulate matter (PM) emissions are low, and no sulphur oxides (SO_x) are emitted.

Similarly to large engines, dual-fuel engines are interesting for vessels. Methanol dual fuel technology for high-speed engines can follow many principles [8][9]. A conversion kit for converting diesel engines (up to 1000 kW) to methanol-diesel dual-fuel operation (port injection of methanol) is on market by Enmar engines. We studied end-use aspect of this concept in the engine experiments carried out at VTT with Volvo Penta D16 retrofitted by Enmar Engine to prototype dual-fuel DF methanol engine for vessels. Furthermore, the capability of the retrofit exhaust aftertreatment system (EATS) from Proventia to remove emissions from the methanol DF engine was explored. A wide set of emission measurements were included, and special attention was paid to carcinogenic formaldehyde and climate-warming black carbon emissions. The emission measurements provide the data for the development of engine and EATS simulation models. The emission results of this task are compared with those from conventional marine diesel engine and IMO Tier II and Tier III standards. Besides basic methanol, another methanol batch with the properties mimicking e-methanol was studied.

This work has been conducted within the “UP-TO-ME” project. The EU project “UP-TO-ME” develops technologies to produce e-methanol from the CO_2 point-sources by a fully autonomous, self-optimizing, and compact technology. The retrofitted high-speed methanol DF engine was studied in search for suitable options for archipelago transportation and linking also to ground-transport.

2 METHODS

2.1 Engine

At VTT, tests were carried out on an engine test cell designed for heavy-duty transient testing up to 570 kW.[7] The engine was Volvo Penta D16 650 hp variable speed engine from 2008 without SCR (Table 1, Figure 1). The engine was retrofitted to methanol by Enmar Engines with their dual-fuel kit designed for converting diesel engines (up to 1000 kW) to methanol DF operation. In this retrofit prototype dual fuel methanol/diesel engine concept, low pressure port fuel injection (PFI) of methanol is used. Volvo Penta D16 is an in-line 6-cylinder, 16.1-liter, charge air cooled marine diesel engine using a high-pressure unit injector system, overhead camshaft and a twin-entry turbocharger.

Table 1. Volvo Penta D16 methanol engine.

Characteristics	Volvo Penta D16
Nominal power, kW	478
Nominal torque, Nm	3263
Number of cylinders	6
displacement, L	16.1
Compression ratio	17.5:1
Fuel system	Electronic unit injectors, Twin entry turbo with charge air cooler

2.1.1 Exhaust emission control system

For the methanol DF engine studied, a retrofit exhaust aftertreatment system was installed: Proventia’s NOxBUSTER™ NRMM retrofit system, which consists of DOC+DPF+SCR to reduce PM and NO_x emissions. This system is Proventia’s generic product and is not specifically designed for methanol DF engine in question.

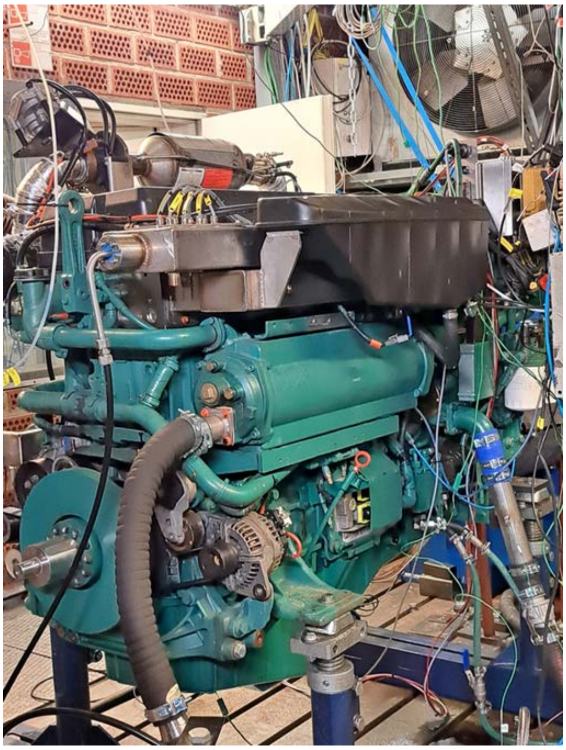

Figure 1. Volvo Penta D16 retrofitted methanol dual-fuel engine installed at VTT.

2.1.2 Methanol and fuel standards

Fossil methanol for the tests was purchased from Algol. This methanol, abbreviated “MeOH A”, is of chemical grade according to the IMPCA specification in Table 2.

With methanol fuel abbreviated “MeOH B”, we mimicked e-methanol and impurities allowed by the methanol specifications due to for example possible contaminations from previous cargos. The impurities added included chloride (2 mg/kg), ethanol (150 mg/kg), acetone (30 mg/kg) and acetic acid (30 mg/km). To mimick e-methanol, we added in “MeOH B” 2% water and copper (1 µg/L). For e-methanol, marine methanol grade C (MMC) of ISO 6583 standard is interesting, since it allows higher water content than the other methanol grades (Table 2). However, cost savings in e-methanol production would be achieved with a limit of max. 2 % of water content. MMC has wider tolerances also on some other of the characteristics than water content as compared to two other qualities of ISO 6583, namely MMA based on IMPCA specifications and additional requirements on lubricity and cleanliness (particle count) or MMB based on the IMPCA specifications.

Table 2. Specifications of the methanol (IMPCA 2015) and ISO 6583 MMC grade.

Characteristics	IMPCA MeOH A	ISO 6583 MMC MeOH B
Purity on dry basis, wt%	min 99.85	min 99.7
Density at 15 °C, kg/m^3		795.0-798.0
Specific gravity 20/20*	0.791-0.793	
Acetone, mg/kg	max 30	max 30
Ethanol, mg/km	max 50	max 150
Hydrocarbons*	pass	
Colour, Pt-Co	max 5	
Sulphur content, mg/kg	max 0.5	max 10
Water, wt%	max 0.1	max 0.5
Acidity as acetic acid, mg/km	max 30	max 30
$KMnO_4$ test at 15 °C, min	min 60	
H_2SO_4 wash test, Pt-Co	max 30	
Chloride as Cl^-, mg/kg	max 0.5	max 2.0
Fe in solution, mg/kg	max 0.10	
Distillation range (760 mmHg), °C	max 1.0	report
Non-volatile matter, mg/L	max 8	
TMA, aromatics	optional	

*No units.

2.2 Emission measurements

Gaseous emissions, including NO_x, NO_2, N_2O, NH_3, CO_2 and CO and formaldehyde were measured on-line at 1 second intervals using the Fourier transformation infrared (FTIR) equipment (Rowaco). Sample was wet raw exhaust gas at temperature of 180 °C.

Black carbon (soot) measurements were conducted with AVL Micro Soot Sensor (MSS, photoacoustic method). Non-volatile, solid particle number (PN) emissions were measured with DEED+CPC system according to EU Stage V legislation. In addition to particles above 23 nm (PN23), particles above 10 nm (PN10) were also measured. Particle size distribution was measured by ELPI downstream eDiluter. Dilution air for eDiluter was dried, filtered and heated.

Total particulate matter (PM) emissions were measured by collecting PM on filters with the AVL partial flow dilution and sampling system. Partial flow dilution system combined with gravimetric sampling of exhaust particulates is a standardised procedure (ISO 8178). Pallflex TX40, Fluoropore and quartz filters were used for PM collections depending on analyses carried out from filters.

Carbon content of PM was determined by using thermal-optical analysis (TOA), which quantitatively analyses the total carbon (TC) content of PM. For the TOA, PM was collected with quartz microfiber Tissuquartz filters pre-cleaned for two hours at 850 °C followed with several days stabilisation. Instrument was Sunset Laboratories Inc's model 4L. In the TOA method, temperature and gas atmosphere is adjusted while continuously measuring the transmission of a laser through the sample matrix. Organic carbon, the original EC, and that produced by the pyrolysis, are oxidized to CO_2, which is then converted to methane and detected by the FID. Methane is injected into the sample oven providing the calibration of each sample analyzed to a known quantity of carbon. Saccharose is used as an external standard. EUSAAR2 protocol (EN 16909) was used.

Concentrations of emission species are presented per cubic meter in standard temperature and pressure, 273.15 K, 100 kPa (per Sm^3).

2.3 Test cycle

Test cycles included load modes from ISO 8178 cycles E2, E3, D2 and C1. Type E is addressed for marine applications, type D2 for generating sets on board of ships and trains and type C1 for compression-ignition engine powered non-road machinery and industrial equipment. The design of the load mode matrix enables calculations with the weighing factors of several test cycles. However, maximum load was not reached due to the limited fuel system of the test setup in respect of lower energy content of methanol than that of diesel fuel. Additionally, some loads were not sufficiently stabile for measurements (see Table 3). Hence, the results at eight load modes (Figure 2) are presented in Figures 3, 5, 6, 8 and 9, while load modes and weighing factors of ISO 8178 cycles E2, E3, D2 and C1 were used in calculations for Figures 4, 7 and 10.

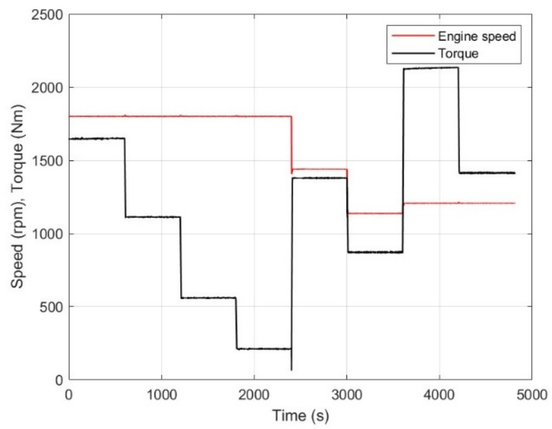

Figure 2. Engine speeds and torques in eight load modes (12 load modes presented in Table 3).

3 RESULTS

3.1 Replacement of diesel fuel with methanol in retrofitted engine concept

The fuel consumption in the different load modes for Volvo DH16 retrofitted methanol DF engine are shown in Table 3. Depending on the engine load, replacement of diesel fuel by methanol was up to 40% (reduced diesel fuel consumption on mass basis). The engine was running smoothly at almost all load modes, except some loads where conditions were unfavorable for combustion of substantial amounts of both methanol and diesel fuel.

In the retrofit dual fuel concept studied, port injection of methanol is used. Lower replacement of diesel fuel is reported with port injection of methanol than with methanol direct injection. Yin et al. [8] found the maximum energy substitution of 50% by methanol with port fuel injection due to roar combustion, while the substitution was up to 80% with the direct injection, respectively [8]. In the study by Dierickx et al. [9] on retrofitting of a methanol DF engine, boundary factors for increasing the energy replacement by methanol included partial burn, knocking and misfire [9]. One limitation of the engine studied relates to its unit injector system, which further limits increasing the diesel replacement by methanol.

Table 3. Diesel and methanol fuel consumption in different load modes when using a) diesel fuel only and b) in dual-fuel mode using diesel fuel and methanol.

Speed/ Torque (%)	Speed (rpm)	Power (kW)	Diesel only (kg/h)	Diesel/ MeOH (kg/h)	Diesel replace-ment (%)
M1: 100/75	1800	311	68	46/39	32
M2: 100/50	1800	210	47	32/38	33
M3: 100/25	1800	105	27	24/12	13
M4: 100/10	1800	40	16	16/0	0
M5: 80/50	1439	208	43	28/33	36
M6: 63/25	1137	104	22	13/20	40
M7: IM 75[1]	1206	269	56	44/22	23
M8: IM 50[1]	1206	179	35	24/26	35
M9:100/100[1,2]	1800	422	93	72/38	22
M10:91/75[1,2]	1643	317	67	49/39	28
M11:IM 100[1,2]	1206	354	75	63/21	15
M12:Idle[1,2]	600	0.5	1.4	1.4/0.8	0

[1]Unstable running. [2]Not included in eight modes.

3.2 Gaseous emissions with MeOH A, MeOH B and EATS

Emissions are formed in methanol DF combustion as a result of incomplete combustion leading mainly to unburned fuel (methanol), CO, formaldehyde and particle emissions, while the NO_x emissions are formed from nitrogen of intake air in high combustion temperatures.

Engine-out NO_x concentrations varied depending on load mode, being at the highest level at intermediate engine speed, modes 7 and 8, reaching almost 2 g/Sm^3 (Figure 3). Differences in the NO_x concentrations between MeOH A and MeOH B were not significant, indicating that the water content of 2% and impurities of fuel did not affect the NO_x emissions.

The EATS efficiently reduced emission species in all load modes studied. Slightly higher NO_x emissions with the EATS in mode 7 than in other modes was due to unstable engine operation in an intermediate speed, which affected the SCR urea injection.

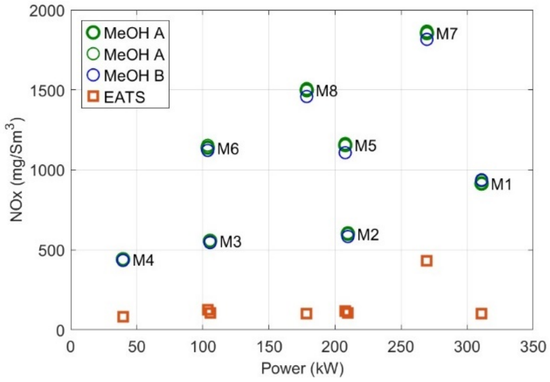

Figure 3. NO_x concentrations at eight load modes. MeOH A results are presented as averages of replicate tests in two measurement sets.

The NO_x emissions upstream and downstream the EATS over modified ISO 8178 cycles E2, E3, D2, C1 and 8 load modes are presented in Figure 4.

The NO_x concentration results obtained in individual load modes are reflected in the emissions over the modified test cycles (Figure 4). Engine-out NO_x emissions from retrofitted methanol DF based on Volvo D16 engine were 4-6 g/kWh. For comparison, the engine-out NO_x emissions of a modern non-road diesel engine reported in one study was approx. 10 g/kWh [10]. Hence, there seems to be potential to reduce engine-out NO_x emissions of a high-speed diesel engine with retrofit methanol dual-fuel combustion, even in the prototype phase of development. Reduced NO_x emissions are explained by cooling effect of methanol.

With the EATS, the NO_x emission level was 0.7 g/kWh from the retrofitted methanol DF engine over 8 load modes. Fridell et al. reported that the NO_x

emissions for Stena Germanica, retrofitted with dual-fuel methanol medium-speed engine and the selective catalyst reduction (SCR), were as low as 0.53 g/kWh [11].

The engine-out NO_x emissions were low for the retrofitted methanol DF engine and further substantially reduced with the EATS.

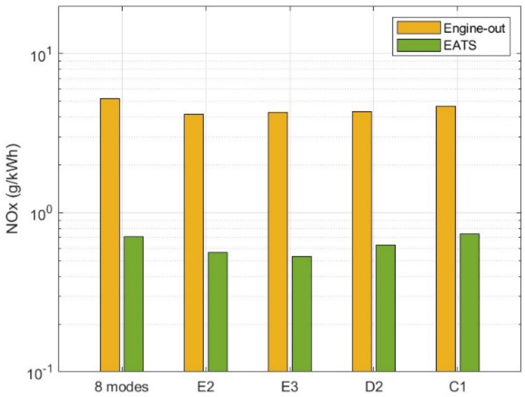

Figure 4. NO_x emissions over ISO 8178 cycles and 8 modes (Table 3), retrofitted prototype high-speed methanol DF engine.

3.3 CO, THC and formaldehyde emissions with MeOH A, MeOH B and EATS

CO, THC (mainly unburned methanol) and formaldehyde concentrations were substantial upstream the EATS of the retrofitted methanol DF engine. Only at the 10% load mode, in which engine runs with diesel fuel only, these concentrations were low. CO concentrations reached almost 3.7 g/Sm^3, THC concentrations 1.5 g/Sm^3 and formaldehyde concentrations 350 mg/Sm^3 (Figures 5 and 6). Unburned CO and THC emissions represented approximately 5% of the fuel consumption over the 8 load modes. Negligible concentrations of CO, THC and formaldehyde were found downstream the EATS, respectively.

Differences in CO, THC and formaldehyde concentrations in exhaust were not significant between MeOH A and MeOH B fuels. Water content of 2% or copper traces and other impurities of fuel MeOH B did not affect these emission results.

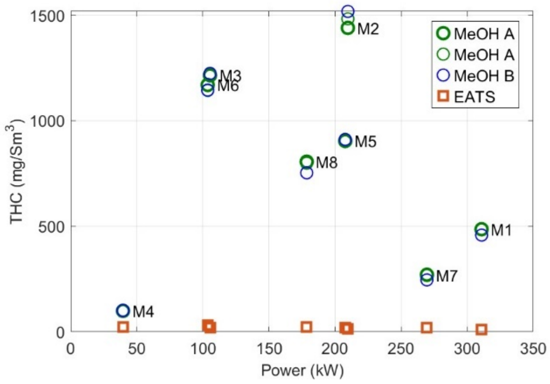

Figure 5. Total hydrocarbons (mainly methanol) emission concentrations at eight load modes. MeOH A results are presented as averages of replicate tests in two measurement sets.

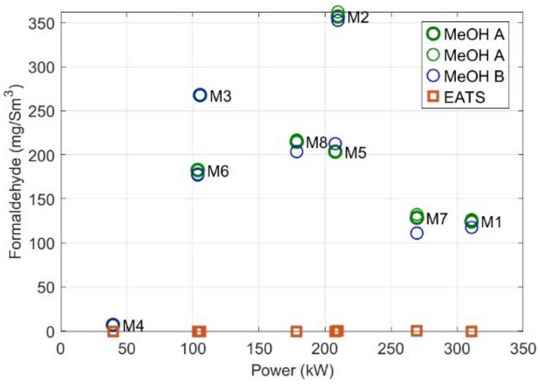

Figure 6. Formaldehyde concentrations at eight load modes. MeOH A results are averages of replicate tests in two measurement sets.

Engine-out formaldehyde emissions were high, approx. 1.1 g/kWh, from the retrofitted methanol dual-fuel Volvo DH16 engine over eight load modes, however, with the EATS, no formaldehyde emissions were detected (Figure 7). Reportedly, engine-out formaldehyde emissions from a modern non-road diesel engine have been below one tenth of that observed here from engine-out position [10].

With the EATS, formaldehyde emissions were negligible for the retrofitted methanol dual-fuel studied here. For Stena Germanica equipped with the SCR, formaldehyde emissions were reportedly 0.002 g/kWh [11], which is also a low emission level. Carcinogenic formaldehyde emission is of special concern for methanol fuels.

Notably, engine-out formaldehyde emissions were efficiently reduced with the EATS in this study.

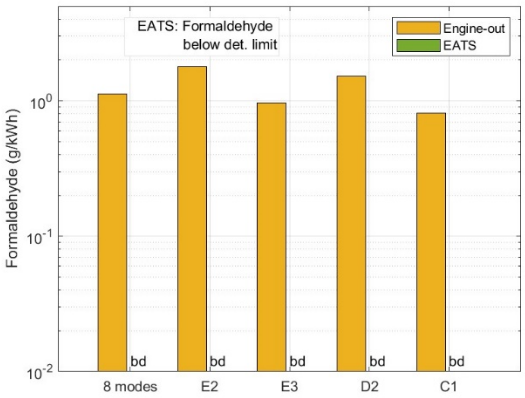

Figure 7. Formaldehyde emissions over ISO 8178 cycles and 8 modes (Table 3), retrofitted prototype high-speed methanol DF engine.

3.4 Particle emissions with MeOH A, MeOH B and EATS

Black carbon concentrations were clear at all loads measured, up to 22 mg/Sm³. The highest BC concentrations were observed at intermediate speed modes 7 and 8, while these concentrations were below 10 mg/Sm³ in other load modes (Figure 8). Differences in BC concentrations in exhaust between MeOH A and MeOH B were not significant, although some spread these results were observed between fuels.

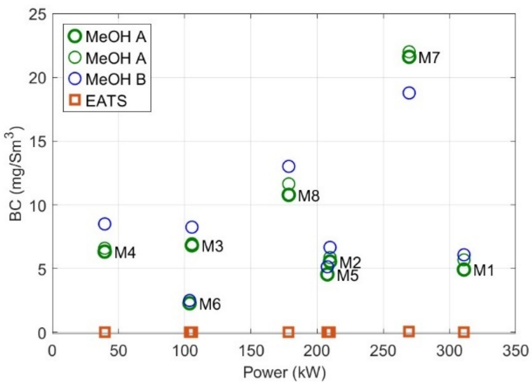

Figure 8. Black carbon concentrations at eight load modes. MeOH A results are averages of replicate tests in two measurement sets.

Black carbon emissions from the retrofitted methanol dual-fuel Volvo DH16 engine, engine-out position, varied from 0.03 g/kWh to slightly above 0.05 g/kWh (Figure 9). With the EATS, BC emission was only 0.0001 g/kWh. In a study reporting engine-out emissions from a modern non-road diesel engine, BC emissions were approx. 0.003 g/kWh [10], which is a lower level than that observed from the retrofitted methanol DF engine upstream EATS. In the study on Stena Germanica equipped with the SCR, BC emissions were reportedly below 0.01 g/kWh [11], while the EATS studied here removed BC almost completely.

Black carbon emissions from retrofitted methanol DF Volvo DH10 engine were high at intermediate speed load modes (Figure 8), which explains the elevated BC emissions over eight modes.

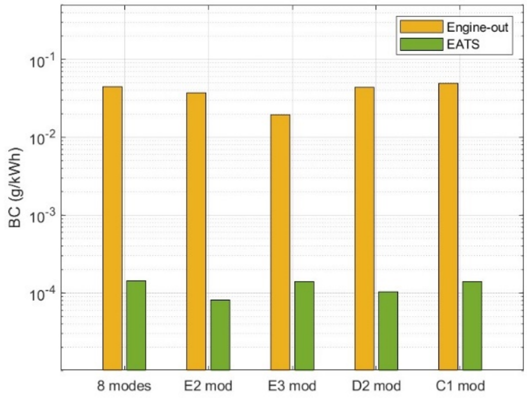

Figure 9. Black carbon emissions over modified ISO 8178 cycles (8 modes included), retrofitted prototype high-speed methanol DF engine.

For the retrofitted methanol DF Volvo DH16 engine upstream the EATS, non-volatile PN (>23nm) emissions reached almost level of 1.6 x 10^{13} #/kWh, while with the EATS this emission level was only 2.2 x10^{11} #/kWh (Figure 10). Engine-out PN23 emission level of the retrofitted methanol DF engine was close to that reported for a modern non-road diesel engine: nvPN (>23 nm) emissions below 3 x 10^{13} #/kWh [10]. Evidently, EATS is needed for this type of retrofitted methanol DF high-speed engine to reduce particle emissions. The EATS studied reduced the particle emissions to an appropriate level for the retrofitted methanol DF engine.

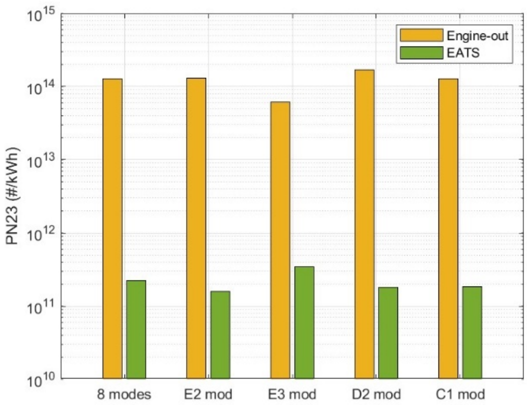

Figure 10. Particle number, PN23, over ISO 8178 cycles and 8 modes (Table 3), retrofitted prototype high-speed methanol DF engine.

3.5 Conversion efficiency of the EATS

The efficiency of the EATS for reducing different emissions species is presented in Figures 11 and 12. Conversion efficiencies of the EATS were particularly high for THC, methanol, CO, formaldehyde and particle emissions, while the EATS was less efficient for NO_x emissions.

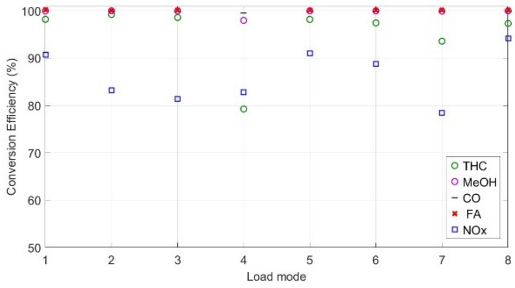

Figure 11. Conversion efficiencies of the EATS for gaseous emissions in eight load modes, retrofitted prototype high-speed methanol DF engine. FA = formaldehyde.

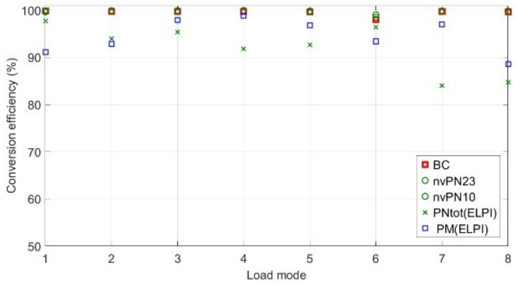

Figure 12. Conversion efficiencies of the EATS for particle emissions in eight load modes, retrofitted prototype high-speed methanol DF engine.

4 MODELING ACTIVITIES

The experimental research of naval engines and EATS is a trustworthy, but costly and time-consuming procedure. That is why the development of computational models capable of simulating a complete engine cycle is necessary in order to investigate new alternative fuels, like methanol, or new combustion modes like dual fuel.

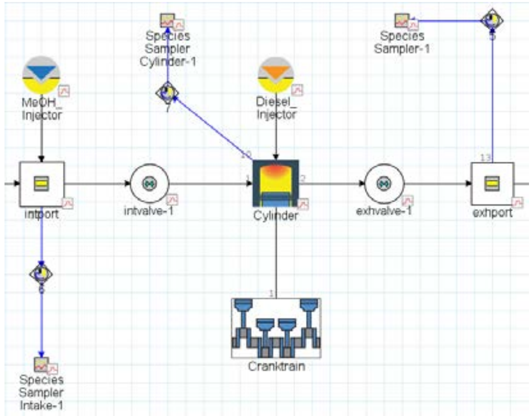

Figure 13. GUI of the 1-cyl DF MeOH GT model

In the context of the present work a computational model of a dual-fuel engine was built in GT-Suite, as shown in Figure 13. To build the model and validate its results, information about engine specifications and experimental data from Dong [12], were used. This work demonstrates the operation of a dual-fuel port injected retrofit methanol engine. Some of the most important engine and test factors of the model are listed in the following Table 4.

Table 4. Engine and test characteristics.

Parameter	Characteristics
Engine type	4-Stroke single cylinder
Diesel supply	Common rail direct injection 15°BTDC
Methanol supply	Port Injection at air Intake 320° BTDC
Engine displacement	1.4 L
Compression ratio	16.7
Fuel to air ratio	0.4
MEF	70%

Engine cylinder template consists of all the commanding equations for the combustion model, heat loss model and in cylinder fluid flow. For heat exchange, the Woschni model (Equation 4) [15] and for combustion, a dual fuel model are used. This combustion model consists of three basic heat release equations [14], two for the pilot diesel combustion, corresponding to the premixed and diffusion phases (Equation 1 and 1), and one for premixed combustion of methanol (Equation 3).

$$\frac{dm_{pre}}{dt} = C_{pm} m_{pre} \left\{ u_{pre} \left(t - t_{ign} \right) \right\}^2 f_{pre}\left(\phi, EGR\right) \tag{1}$$

$$\frac{dm_{diff}}{dt} = C_{diff} m_{diff} \frac{\sqrt{k}}{\sqrt[3]{V_{cyl}}} f_{diff}\left(y_{O_2}\right) \tag{2}$$

$$\frac{dm_{bf}}{dt} = \frac{m_{uf}}{\tau} + \dot{s}_s m_{bf} \tag{3}$$

$$h_{c(\mathrm{Woschni}^*)} = \frac{K_1 p^{0.8} w^{0.8}}{B^{0.2} T^{K_2}} \tag{4}$$

At the cranktrain template all the information about the type of the engine, the engine speed, the geometry of cylinder are defined. Two different types of injectors are used. At the methanol (port) injector, timing of injection, injector delivery rate and fuel ratio of the engine are defined. Also, at diesel (direct) injector the timing of injection, the injected fuel mass and the injection profile pressure at each crank angle degree of injection were defined. Finaly, all the initial condition of environment, the pressure and temperature of air after turbocharger and the intake / exhaust valves timing are defined as experimental setup suggests and showed at the following Figure 14.

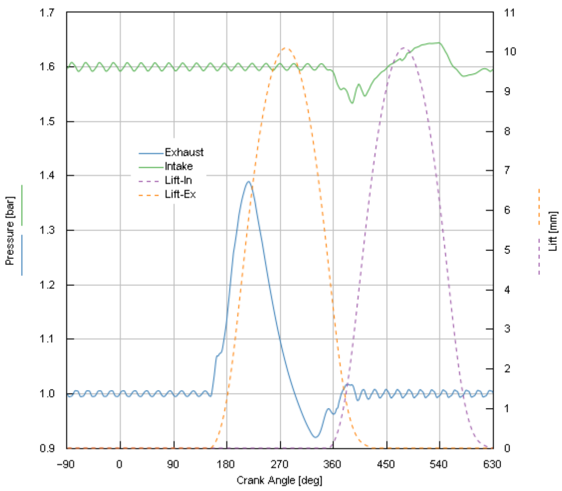

Figure 14. GT model intake / exhaust valves movement, intake and exhaust pressure evolution in a complete engine cycle.

At calibration procedure, the ignition delay, diffusion and premixed coefficients have been adapted, as a result of minimizing the burn rate RMS error between measured and predicted data. Also, detailed chemical kinetics mechanism usage achieved a higher number of predicted species. The chemical kinetics mechanism [13] imported file in use consists of 53 species and 176 reactions while GT-Suite can predict concentration of only 13 species, products of combustion, based on chemical equilibrium calculation. The end result of predicted pressure and heat release rate had satisfactory agreement with experimental results, with average error of 0.7% for pressure prediction (Figure 15).

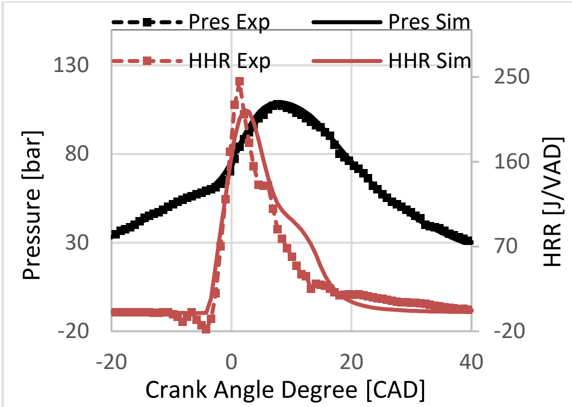

Figure 15. Comparison between experimental and predicted data of pressure and heat release rate for a Dual Fuel MeOH PFI retrofit engine.

5 CONCLUSIONS

Electrofuels present a promising solution to mitigate contribution of shipping to global warming. The EU project “UP-TO-ME” develops a process to produce e-methanol from the CO_2 point-sources by an autonomous technology. In this work, we studied the retrofitted high-speed methanol dual-fuel (DF) engine suitable for smaller marine segment. The retrofitted prototype was based on the Volvo Penta D16 variable speed engine. Furthermore, we studied efficiency of the EATS, Proventia’s NOxBUSTER™ NRMM retrofit system (DOC+DPF+SCR), to reduce emissions from this engine. The emission results provide the data for the development of engine and EATS simulation models.

Depending on the engine load, replacement of diesel fuel by methanol was up to 40% (mass basis). In this dual fuel concept using port injection of methanol, the replacement of diesel fuel is limited. Engine was running smoothly in most load modes in dual-fuel methanol diesel operation, however, there were load-dependent differences in performance of the engine. Unstable running in some load modes indicated that combustion was not optimal in the presence of substantial amount of both methanol and diesel fuel.

There seemed to be potential to reduce engine-out NO_x emissions of the high-speed engine with methanol dual-fuel combustion, even in the prototype phase of retrofit concept for this type of engine. However, the engine-out emissions, especially formaldehyde and particle emissions, were at significant level emphasising the need for an efficient exhaust aftertreatment system for this retrofitted dual-fuel engine using methanol. The EATS studied proved to be very efficient and it reduced the exhaust emissions from the engine to negligible levels. The combination of methanol engine and an efficient EATS enable introduction of methanol retrofit technology without harming health, environment or climate.

Methanol engine concept for small vessels are sparse. The dual-fuel methanol diesel concept studied here enables a replacement of diesel fuel by methanol to the extent depending on the retrofitted engine. With the EATS, exhaust emissions can be reduced efficiently. Further development is needed to increase the share of methanol in the retrofitted dual-fuel engine.

6 DEFINITIONS, ACRONYMS, ABBREVIATIONS

BC: Black carbon

bd: Below detection limit

DF: Dual-fuel

EATS: Exhaust aftertreatment system

FA: Formaldehyde

HC: Hydrocarbon

IMO: International Maritime Organization

NOx: Nitrogen oxides

PN: Particle number

SCR: Selective catalytic reduction

Sm^3: Cubic meter in standard conditions of 273.15 K and 100 kPa

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9 CONTACT

Päivi Aakko-Saksa, VTT. E-mail: paivi.aakko-saksa@vtt.fi.