D3.17 Evaluation report on application of methanol: compression ignited vs dual fuel

Synergetics | Synergies for Green Transformation of Inland and Coastal Shipping

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Release Approval

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Executive Summary

Methanol is considered to be one of the main options to reduce the climate and environmental impacts from shipping. Different methanol engine technologies exist, and it is relevant to compare the performance of different concepts to understand where and how they are best applied.

As part of Work Package 3 Demonstration (WP3) of the SYNERGETICS project, ScandiNAOS AB (abbreviated SNAOS in the following) is tasked with demonstrating the performance of marine dual fuel (DF) and compression-ignited methanol (MD97) engines. These two engines are compared based on four criteria: engine power, engine efficiency, diesel replacement ratio and emission levels. Tests are conducted according to ISO 8178 standard.

The MD97 methanol engine outperforms DF engine in 3 out of 4 categories: Diesel replacement ratio, emission levels, and engine efficiency. In category of engine power output, MD97 shows lower maximum output per displacement.

The compression ignited MD97 engine offers several advantages, particularly in terms of environmental impact and efficiency. It enables close to the total replacement of fossil fuel with renewable methanol, it reduces harmful emissions such as NOx, CO, hydrocarbons and reaches the IMO Tier III emission levels without the need for an after-treatment system. The engine also achieves a 2% to 6% better efficiency and simplifies operations by requiring only one fuel system. Additionally, it is not in the same way as the DF engine sensitive to harmful methanol-knock under high loads and exhibits lower cylinder and cycle-to-cycle variations. However, one downside is its lower maximum output for similar size engines.

The dual-fuel methanol engine offers the option of conversion of existing diesel engines and provides fuel flexibility but faces several challenges. At high loads, it is sensitive to knocking and at high methanol substitution rates, significant cycle-to-cycle variations can occur. The dual-fuel concept can also give large cylinder to cylinder variations. These issues can contribute to lower efficiency and higher emissions compared to the MD97 methanol engine. The diesel part of the fuel in the DF engine will still produce soot, particularly under high load conditions. To reach the optimum performance and minimize the environmental impact of a DF engine more development will be needed. Despite the current downsides, the DF concept is well worth developing further due to the retrofit possibility that enables the introduction of renewable fuel for existing engines, potentially increasing the speed of transition towards sustainable shipping.

The best engine option for a particular application will depend on the specific conditions in each case. The following should be considered as general reflections.

The single fuel compression ignited engine will typically be the best option for propulsion of smaller vessels that operate in a defined area with a regular home port, where regular distribution of methanol and additives can be organized. Under these conditions the benefits of the concept e.g. high diesel replacement, no after treatment system and no need for multiple fuels onboard, can be fully appreciated. For larger vessels operating in less defined areas the higher power output and fuel flexibility, that dual fuel engines provide, can be an advantage. It will also be easier to find the required space for tanks for different fuel as well as for after treatment systems in a larger vessel.

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1. | Introduction

1.1 Objective

The objective of this report is to present, evaluate and compare the results of performance tests done on two similar methanol engines against four criteria: power, efficiency, emission levels and diesel replacement fraction. One engine is a dual fuel, port injection engine and the other is a single fuel, compression ignited MD97 methanol engine.

1.2 Brief description of the methanol concepts compared

There are several ways to utilize methanol in internal combustion engines. The first thought might be to use it in a spark ignited Otto engine since the fuel characteristics of methanol, i.e. high octane and low cetane number, resemble the characteristics of petrol. This concept alternative is typically used in cars and in smaller land-based application but has, however, not been considered in this case, since the baseline has been existing marine diesel engines. The required hardware such as cylinder heads for sparkplugs and high energy ignition system has not been available for the particular engine candidates. With the spark ignited engine alternative eliminated, the remaining main option is compression ignited single or dual fuel engine.

Single fuel engines will run on fuel from one fuel tank and will not require diesel as pilot fuel for ignition. Dual fuel engines need, in addition to the methanol feed, also separate diesel fuel supply to ignite the methanol when in "dual fuel" mode. Note that the dual fuel engine used in this study is also able to run in "diesel only" mode.

Most dual fuel engines today are based on a diesel engine. When adopted to dual fuel, the diesel fuel system is kept, and a methanol fuel system is added. It is either sprayed directly into the cylinder with a fuel injector fitted in the cylinder head or before the cylinder in the intake air with one or several injectors. The first alternative is called direct injection and the second is called port injection. For the port injection concept, the methanol is mixed with the inlet air before it enters the cylinder. The fuel-air mixture is compressed and close to top dead centre the diesel is injected, initiating the ignition.

All concepts have aspects worth considering and are described in more detail in deliverable D3.16., while the focus in this report is to compare two specific concepts:

- Dual fuel port injection engine (DF)
- Single fuel compression ignited methanol engine (MD97)

1.2.1 Dual fuel port injection technology (DF)

All major marine engine suppliers have dual fuel engines where methane gas (LNG) can replace a significant part of the HFO or MGO. Since the methane is in gas phase it is easier than for the liquid methanol to get a good mix with a uniform distribution. The methane is either introduced via a mixing unit arranged at considerable distance upstream the air inlet manifold or via one or several injectors at the intake manifold. The premixed methane-air mixture will enter each cylinder when its inlet valve is open. When the inlet valve is closed, the piston will compress the premix and close to the top dead centre the diesel fuel will be injected and ignited by the heat from compression and in turn ignite the methane-air mixture.

In the case of methanol-diesel DF engine, the upstream gas mixer is not an option. The methanol has to be injected into the air inlet manifold. Both single point and multi point injection can be considered. For a good performing engine, it is critical to get as similar fuel-air mixture both between all cylinders and between consecutive ignition cycles, as possible. For the best control of the flow of methanol into each cylinder, it is beneficial to place one injector per cylinder as close as possible to the inlet valve of each cylinder. This can be a challenging engineering task to find a good location without obstructing the air flow of the original air inlet manifold too much. In diesel only mode, the engine runs on the standard normal diesel cycle. When switched to methanol mode, the engine runs on a dual fuel combustion cycle.

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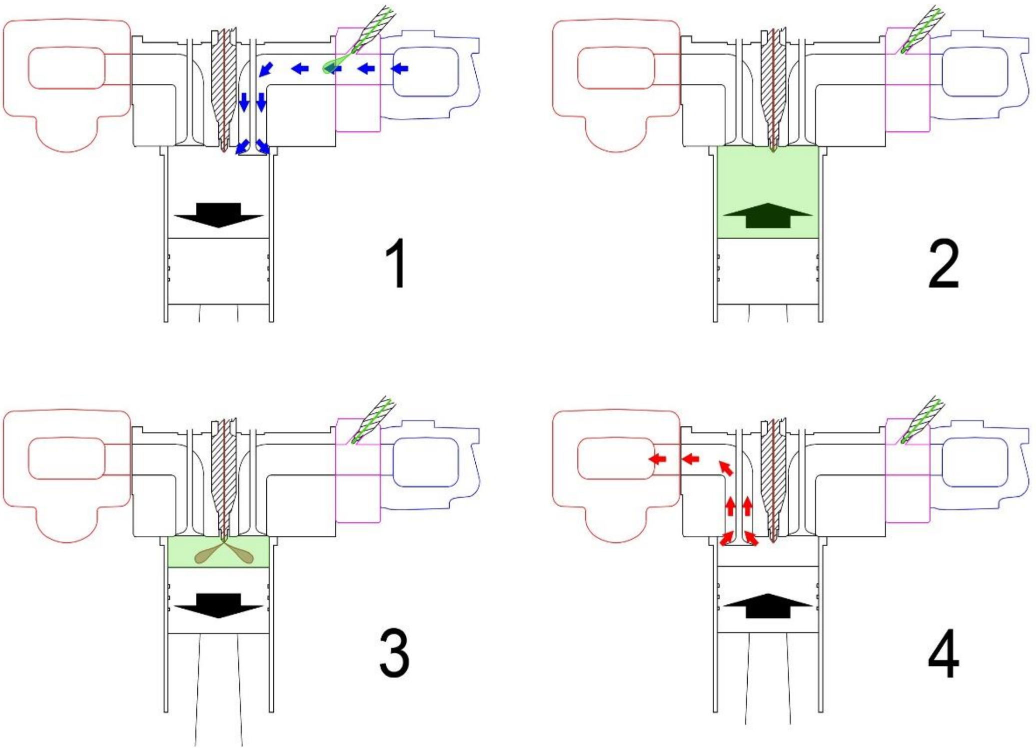
A diesel engine typically operates lean, i.e. there is an excess of air compared to fuel and the power is controlled by the fuel amount injected. In dual fuel mode, where the methanol is pre-mixed with the air, there is a risk that the fuel mixture becomes too lean i.e. below the flammability limit of methanol. For this reason, also in dual fuel mode the engine will operate on diesel only when the engine is subject to very low power demand, where the mixture is very lean.



1 | The combustion principles of 4-stroke port injected engine with diesel pilot ignition

1. The piston moves down, methanol injects from the port into the inlet air
2. The piston moves up and compresses the air-methanol mixture, temperature and pressure are increased
3. Close to TDC, diesel is injected as pilot fuel and ignites the compressed methanol air mix in the cylinder. The piston is then pushed down by the expansion of the hot gases.
4. The exhaust gases are pushed out through the exhaust valve.

The key task when converting a diesel engine to dual fuel operation is to find the best possible location for the fuel injectors. The challenges will vary depending on the engine design. For a typical V type engine, the available space between the cylinder banks is very limited and the modified air inlet manifold typically will have to stay within the boundaries of the original manifold but still host the fuel injectors for each cylinder and a double walled fuel rail. A straight engine with external air inlet manifold on one side and exhaust on the other (crossflow) provides better access. Some engines have the air distribution integrated in the cylinder head. In these cases, modification of the cylinder head will be required to fit the methanol fuel injectors for a multi-point port injection concept.

The diesel engine to be converted in this case, was a straight engine with an external air inlet manifold. The new manifold was re designed to make space for the fuel injectors together with the fuel rail in an explosion proof enclosure. The coolant tank had to be repositioned, and new brackets fitted to attach the methanol control unit. Software was developed for the methanol injection control unit to communicate with the original diesel ECU and to calculate the methanol quantity to be injected depending on the speed and torque of the engine.

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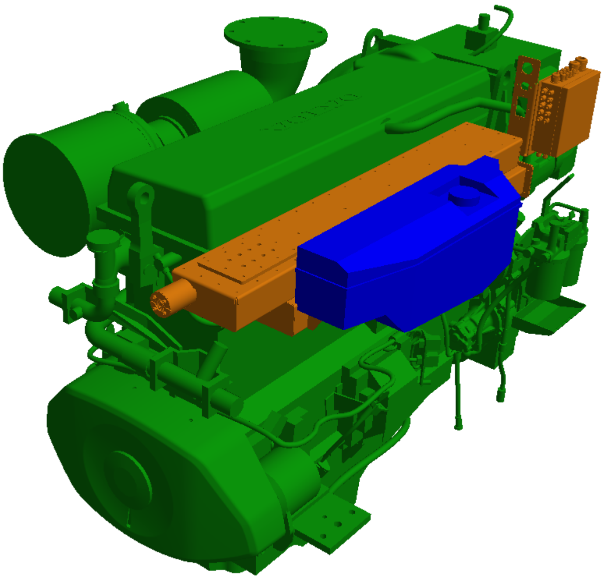
After the development of the mechanical hardware and the methanol control unit including wiring to the original diesel ECU and programming of the basic functionality, the next step was to define the methanol fuel map. The fuel map determines the amount of fuel to be injected into the engine at different operating conditions. To generate the various operating conditions, the engine is rigged in a test dyno where the speed and torque resistance can be varied as well as environmental conditions such as the temperature of the inlet air and cooling water.

The objective of the engine dyno campaign was to test the functionality of the methanol control unit, maximize the diesel replacement ratio, reduce NOx and maintain high engine efficiency. The tests included functionality of the control units to enter and exit dual-fuel mode as well as handling of transient loads. Tuning of methanol quantity was done in an iterative process to find optimum performance considering limiting factors such as misfiring, knocking and emissions.

To maximize the impact of the development work performed in the project, the intention was to make the conversion kit as generic as possible. The position and fitting of fuel injectors and arrangement of the fuel rail will have to be customized for each engine type but, components, control unit and control concept are generic and easy adoptable to in principle any diesel engine.



2 | 3D model of DF engine

Figure 2 shows the 3D model of a DF engine that has been tested in the scope of this task.

1. Base engine (green)
2. Coolant tank repositioned (blue)
3. Modified air inlet manifold housing, methanol fuel rail, fuel injectors and the dual fuel control unit fitted aft of the air inlet manifold. Developed and designed by SNAOS (orange)

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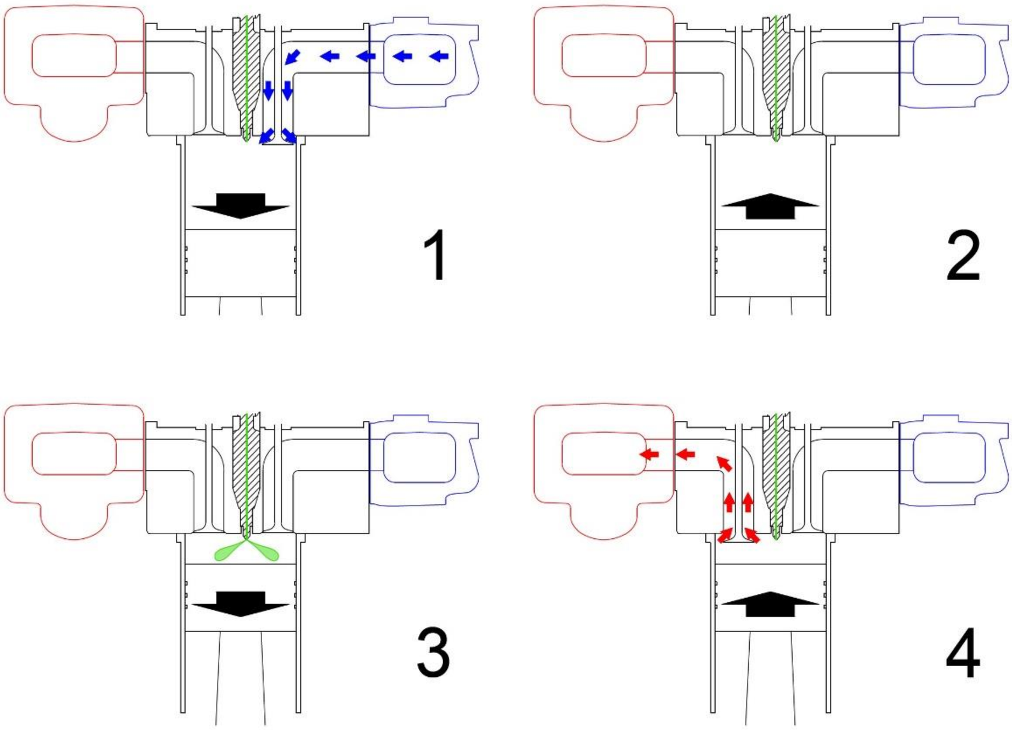
1.2.2 Single fuel, compression ignited methanol MD97 engine

Single fuel compression ignited methanol engine runs on MD97 fuel, which is a fuel mixture developed by SNAOS. It contains 97% methanol, 3% ignition improver and 0.1% lubricant, see table 2 for specification. Compression ignition is not the obvious choice for a methanol engine since neat methanol has a low cetane number and a high octane number. The cetane number indicates how quickly fuel ignites under compression and the higher the number, the smaller is the ignition delay. The octane number measures the fuel resistance to pre-ignition which can cause knocking – the higher the number, the more resistant is the fuel against knocking. These characteristics make methanol more suitable for spark ignited Otto combustion. However, by adding an ignition improver the characteristics of methanol are changed, so it can be used as single fuel in a compression ignited engine. Moreover, the compression ratio was increased compared to a standard diesel engine. This increment of compression ratio limits the specific output of this type of engine. Scania developed this concept for ethanol in the 1980s and has used it extensively for busses and trucks. Ethanol and methanol have comparable combustion characteristics, and the concept has now been adopted for marine and industrial compression ignited methanol engines. In figure 3, the principle of methanol compression ignited engine is illustrated.



3 | The combustion principle of compression ignited methanol engine

1. The piston moves down, and air enters the cylinder
2. The piston moves up and compresses the air, temperature and pressure are increased
3. Methanol with ignition improver and lubricant are injected and ignited, piston moves down
4. The emission gases are pushed out through the exhaust valve.

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4 | Compression ignited methanol (MD97)

The concept is based on the modification of Scania marine and industrial engines by using original Scania components from their ethanol (ED95) bus and truck engines.

Today Enmar Engines is selling compression ignited methanol engines that use MD97 fuel. The engines are based on the Scania marine and industrial engines but with several modifications, including alcohol fuel injectors and higher compression pistons. With the ignition improver, the engine can run on diesel cycle with methanol and provides similar performance as a diesel engine with high efficiency while fulfilling IMO Tier III NOx emission levels without after treatment system.

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2. Execution of the engine comparison

2.1 Engine technology comparison

Two concepts are tested and compared: MD97 (compression ignited, single fuel, methanol) and DF (dual fuel, port fuel injection, diesel-methanol). Note that MD97 is a developed product available on the market from Enmar Engines company while the methanol DF concept is in development phase for this engine size. Engines are tested in specialized facilities equipped with an engine dynamometer and data collecting tools for precise engine performance measurements. The test points are chosen according to the ISO 8178 standard.

The objective of the test was to compare the characteristic performance of the two concepts to better understand how they can be applied in the best way to contribute to a reduction of the climate and environmental impact. Engine data can be found in Table 1

Table 1 | Engine data

		MD97	DF
No of cylinders		6	6
Displacement	l	12.7	12.8
Bore	mm	130	131
Stroke	mm	160	158
Compression ratio		25	17
Injection system		Common rail	Common rail

2.2 Experiment set-up

Relevant characteristics to test and compare:

- Engine power
- Engine efficiency
- Fuel ratio – diesel replacement ratio energy-wise
- Emissions

Engine power

Engine power is a function of speed [RPM] and torque [Nm], measured by dynamometer. Power is then easily calculated as:

$$P[kW] = \frac{T * n * 2\pi}{60 * 1000}$$

Where P is power in kilowatts [kW], T is torque in Newton meters [Nm] and n is rotational speed in revolutions per minute [RPM]. This formula is derived from the basic relationship between power, torque, and angular velocity, with a conversion factor to account for the units. As per ISO 8178 standard, tests are done at constant speed of 1500 RPM.

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Engine efficiency

Engine efficiency refers to how effectively the engine converts input energy stored as chemical in the fuel tank to useful output, mechanical work. In general, engine efficiency can be viewed from different perspectives, such as thermal efficiency, overall efficiency (thermal × mechanical) and specific fuel consumption (SFC). In this case, thermal efficiency and SFC will be taken into consideration. Thermal efficiency is the ratio of useful work output to heat input, provided by the fuel. It is calculated as:

$$\eta_{thermal} = \frac{Power\ output}{Lower\ heating\ value * Fuel\ flow} \times 100\%$$

Where power output is calculated from measured torque at the test bed and heat input is fuel consumption rate multiplied by lower heating value (LHV) of the fuel.

Specific fuel consumption is another criterion for efficiency evaluation, and it is defined as:

$$SFC\ \left[\frac{g}{kWh}\right] = \frac{Fuel\ flow\ rate\ [\frac{g}{h}]}{Power\ output\ [kW]}$$

Lower the SFC, better the efficiency. Test bed is equipped with AVL fuel mass flow meter for fuel flow rate measurement with a built-in accuracy check and calibration.

Fuel ratio

Fuel ratio criterion is introduced to see how performance parameters change related to which fuel and in what fractions is fed to engines. In this comparison, it is defined as diesel replacement fraction by energy, calculated as ratio of energy provided by methanol over the total fuel energy:

$$Fuel\ ratio = \frac{Energy\ from\ methanol}{Total\ energy\ from\ fuel}$$

To emphasize the difference between energy-wise and volumetric fuel ratios here is an example: assume total of 100 litres of fuel is consumed, out of which 90 litres is methanol and 10 litres is diesel. In that case, diesel replacement fraction by volume is 90%. However, due to different energy content of methanol (15,6 MJ/l) and diesel (35,8 MJ/l), the same consumption case corresponds to diesel replacement ratio of 80% by energy. In the results section, two engines are compared based on energy-wise replacement fraction also named methanol energy fraction.

Emissions

Measured emissions produced by combustion of fuel are NOx, CO, CO2, O2 and HC. On the test bed, these are measured as part per million (PPM) of the exhaust gas mass flow by a HORIBA analyser. Exhaust gas mass flow and emissions calculations are done according to IMO Nox Technical code 2008 to determine relevant values in g/kWh for the emissions.

Test dyno

The engine dyno facility is a specialized testing environment designed to evaluate and optimize the performance of internal combustion engines. Engine dyno tests are used in research and development of new engines, performance optimization and tuning, quality control for rebuilt or repaired engines, emissions testing and certification, benchmarking and comparative analysis. Main benefits of testing engines in a dyno facility are obtaining precise and repeatable results, detecting and correcting issues before engine installation, optimization of performance and reducing time for after-installation testing.

The facility enables testing engines in a controlled environment, separate from the consumer, taking precise measurements of engine's performance characteristics such as torque output, fuel efficiency, emissions, temperature and pressure readings.

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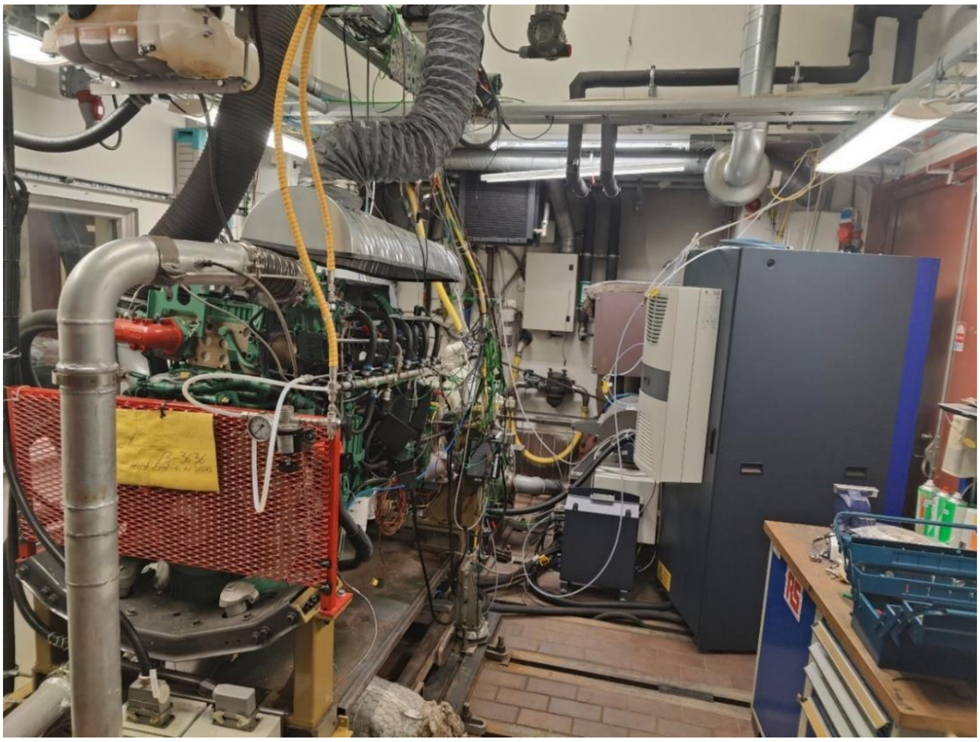
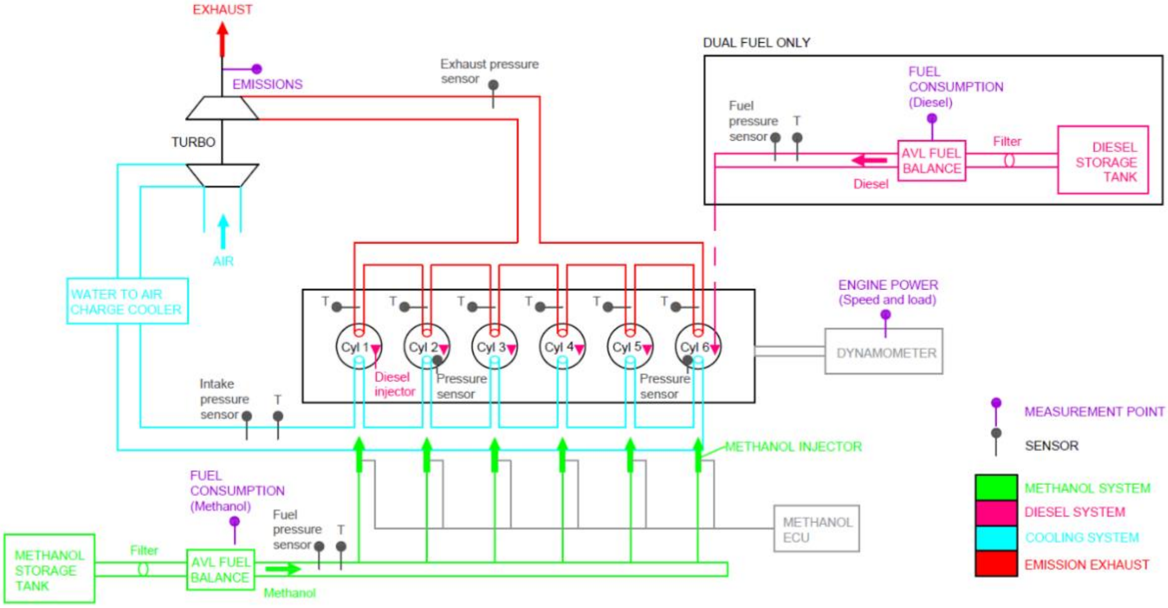
Key components of an engine dyno facility are: dynamometer, test cell, cooling and fuel systems, data acquisition and control. Dynamometer measures engine torque across various RPM ranges and applies controlled loads to simulate real-world conditions. The engine is mounted in a dedicated test cell featuring soundproofing, windows for observation and controlled environment for consistent testing conditions. Cooling and fuel systems manage engine temperatures and handle different fuel types and pressures. Lastly, computerized data logging systems offer real-time monitoring of multiple engine parameters and ability to make adjustments during testing. Figure 5 shows a picture of the arrangement and Figure 6 shows the schematic set-up at test dyno.



5 |Arrangement of the engine in the test dyno



6 | Engines measurement points

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Fuels

When testing DF engine, fuels used are methanol and diesel of standardized specification, IMPCA for methanol and K1 for diesel. Test on the MD97 engine is done using MD97 methanol fuel, with a specification developed by SNAOS. MD97 test fuel characteristics can be found in Table 2.

Table 2 | MD97 Test fuel data

Fuel component	Target mix (w/w)	Acceptable mix (w/w)
Methanol (IMPCA)	96.9%	96.35-97.05%
Beraid 3555M$^{1)}$	3.0%	2.90-3.50%
Armolube 211$^{1)}$	0.1%	0.05-0.15%
Alt. Ethomeen O/12$^{1)}$ (Replaces Armolube 211)	0.1%	0.05-0.15%
Density	ISO 3675	0,795-0,810 kg/dm3
Specific energy		19.9 MJ/kg

2.3 Test programme

A defined test programme ensures that engine tests are conducted in a standardized and consistent manner across different engines and testing facilities. This allows for reliable comparisons and reproducible results. This test programme is set by ISO 8178 – international standard for exhaust emission measurements of non-road internal combustion engines. The standard includes collection of steady-state engine dynamometer test cycles designated as different types (C1, C2, D1 etc). The test done in this case is of type D2 – for constant speed (1500 RPM), generating sets with intermittent load. Five test modes are defined, see Table 3.

Table 3 | Test modes definition as per ISO 8178

Test modes, Type D2	Torque	Weighting factor
Mode 1	100%	0,05
Mode 2	75%	0,25
Mode 3	50%	0,30
Mode 4	25%	0,30
Mode 5	10%	0,10

Each mode has a corresponding load point that is assigned a specific weighting factor to represent importance in the overall emissions calculation. The engine is operated at each mode for a sufficient time to achieve thermal stability. Emissions are then measured at each mode and then combined using the weighting factors to produce a single weighted average emission value for each pollutant.

In the engine dyno facility, the engine is run at a constant speed of 1500 RPM and load induced on engine is being increased until the engine reaches its maximum torque for mode 1. The speed of 1500 RPM is chosen to enable comparison with generators that are most often operated at the same speed. For the following modes, the engine continues to run at the same speed, and the load is reduced to achieve 75%, 50%, 25% and 10% of established maximum torque.

The two engines are similar but not identical. In order to get the relevant results for comparison, the performance at the similar brake mean effective pressure (BMEP) has been compared.

For engines of similar volume, the rated output of the MD97 engine is lower than for the DF engine but for comparison they have been operated at similar load points.

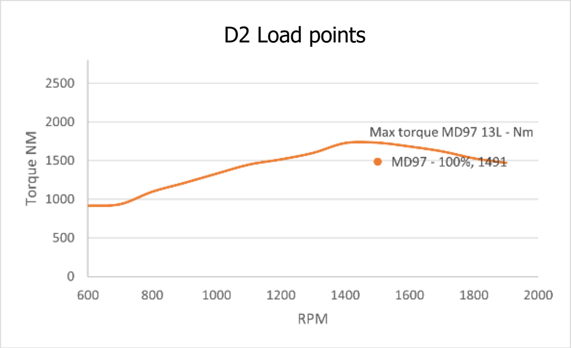
2.4 Test results

In this chapter, test results of MD97 methanol compression ignited engine and dual fuel methanol diesel port injection engine are presented and evaluated. Tests are conducted in 5 modes for each engine as per ISO 8178 standard. In each mode, 4 main criteria are evaluated: engine power, engine efficiency, methanol fraction and emissions. Fuel flow data is plotted as specific fuel oil consumption in grams per kilowatt hour. The same graphs also show mass and volumetric fuel flow data, pointing to methanol fraction amount. Emissions specific rates of CO, NOx, THC and soot are measured at the end of exhaust (see figure 6) and plotted. Additionally, for each case, cylinder pressure data, mean cylinder gas temperature and heat release data are provided for a closer look in engine behaviour. Cylinder gas temperature is derived from pressure data and plotted over a range of crank angle degrees (CAD), where 0 marks top dead centre. Cycle variations are measured and plotted in blue, while mean is calculated and plotted in orange. Lastly, heat release data graph shows heat released, rate of heat release per CAD and fuel injection timing in relation to CAD.

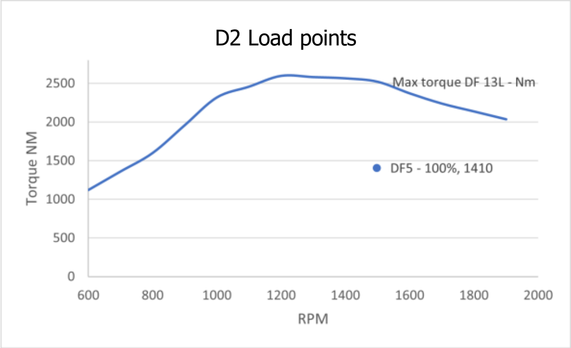
2.4.1 Mode 1

Mode 1 represents engine's maximum (100%) rated torque at a constant speed of 1500 RPM for the MD97 engine. To manage transient there need to be a spare capacity of 10% the engine max torque referred to as "overload", or 110% power load point.

Figures on the left show the results for MD97, and on the right for DF engine. As stated before, for similar size engines the rated output of the DF engine is higher than for the MD97 engine but for comparison they have been operated at similar load points with similar break BMEP. In mode 1, DF engine BMEP is 13.63 bar and for MD97 it is 14.69 bar.



7 | MD97 engine load point at mode 1



8 | Dual fuel engine load point at mode 1

Comparing figures 7 and 8, we can see the engine max torque curve (orange) is higher for DF engine than MD97, meaning DF can produce more torque for the same RPM speed. Therefore, on engine power output criteria, DF outperforms MD97. This is mainly due to the higher compression ratio needed for MD97 which limits the maximum torque of the engine.

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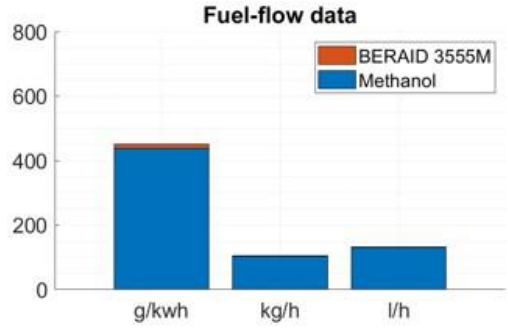
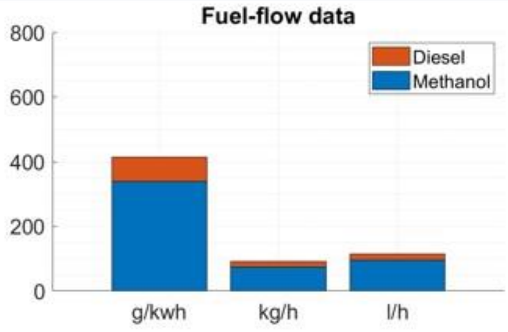
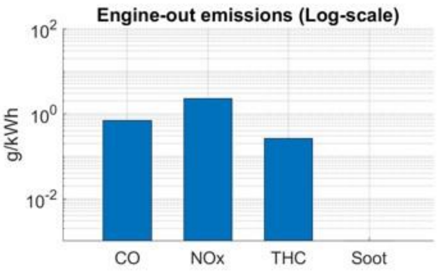


9 | MD97 engine fuel flow data at mode 1

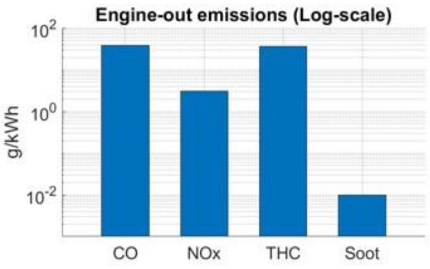


10 | MD97 engine fuel flow data at mode 1

Figures 9 and 10 show fuel flow data. The first column on the graph represents specific fuel consumption, the second one fuel mass flow per hour and third one volumetric flow per hour. The graphs show that MD97 has slightly higher consumption rate at about 430 g/kWh compared to 405 g/kWh. For DF engine, 67% diesel replacement ratio is achieved. With power output, fuel consumption rates and LHV information for methanol and diesel, thermal efficiency can be calculated. For MD97, thermal efficiency reaches 40%, and for DF 36%.



11 | MD97 engine out emissions at mode 1



12 | Dual fuel engine out emissions at mode 1

Figures 11 and 12 show emissions measured at the end of exhaust, note the scale is logarithmic. Overall, MD97 emissions are considerably lower than DF. An AVL Micro Soot meter shows that soot is not produced during operations on methanol-only. Carbon oxides and unburnt hydrocarbons are much higher at DF operation, while NOx are about twice as high for DF as MD97. For the DF engine a small part of the unburnt hydrocarbons is fomaldehyde. Formaldehyde is cancerogenic and there is an emerging discussion regarding what emission levels of formaledhyde should be accepted. Formaldehyde is easy to reduce in an oxidation catalyst and the reduction is effective also at low exhaust gas temperatures, which make the high emission level managable.

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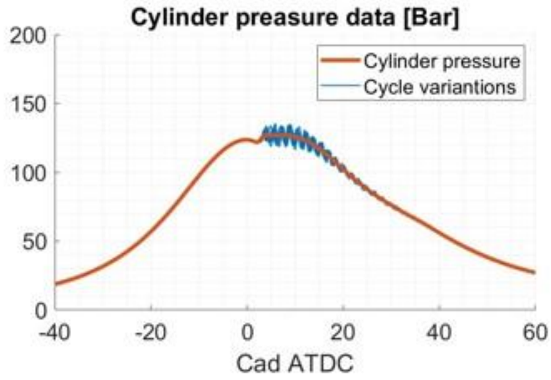
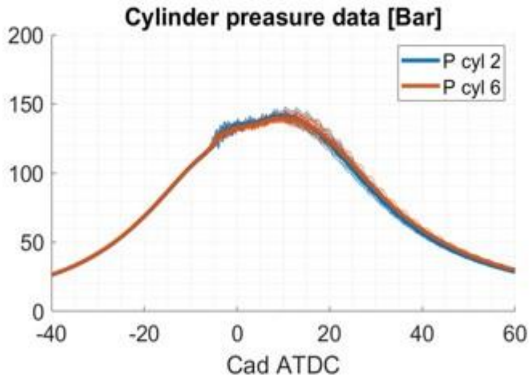
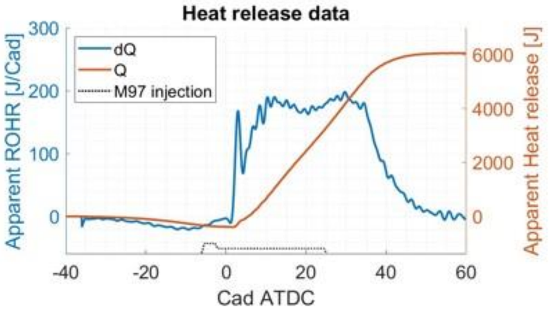


13 | MD97 engine cylinder pressure data at mode 1

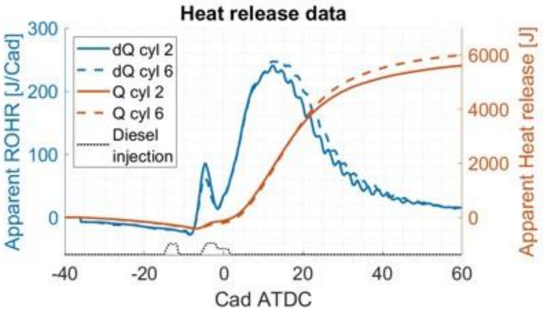


14 | DF engine cylinder pressure data at mode 1

Figures 13 and 14 show pressure inside the cylinder over the course of engine cycle expressed as crank angle position (CAD). Note that 0 on x-axis marks top dead center (TDC) piston position, i.e. farthest from the crankshaft. It can be seen that the pressure starts to rise at -40 CAD in both cases, peaking just after TDC and before 20 CAD. Note that MD97 engine has uniform distribution between cylinders, while in DF case, cylinder 2 is representable of all cylinders and cyl 6 represents worst case scenario.



15 | MD97 engine heat release data at mode 1



16 | DF engine heat release data at mode 1

Figures 15 and 16 show heat release data and timing of fuel injection. In case of MD97, black dash line represents injection of methanol and in DF case, injection of diesel. This is because in the first case methanol is the only fuel that is about to be ignited by compression (see previous pressure graphs for the same CAD interval) and in DF case, timing of diesel pilot fuel that will enable the ignition is important to optimize for. Apparent rate of heat release (ROHR) shows the rate at which heat is released (blue) during combustion process. Apparent heat release (orange) shows the cumulative heat released over the combustion process, starting at 0 and ending at final value of total heat released. As MD97 has only one injection and DF has two (pilot and main), ROHR curve of MD97 has only one spike while DF one has two. Due to lower heating value of methanol compared to diesel, MD97 engine needs to have injectors opened for much longer duration than in DF case, given similar injector size and rail pressure. This results in a more spread out rate of heat release.

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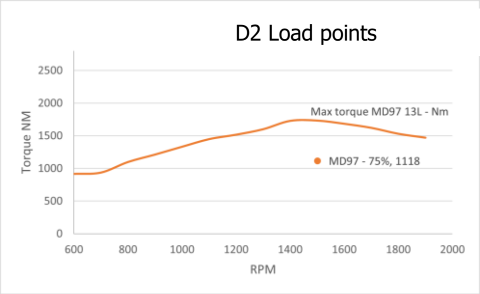
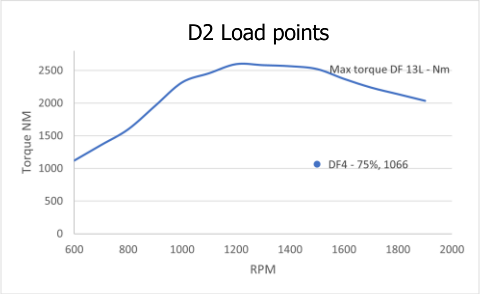
2.4.2 Mode 2

Mode 2 represents 75% of maximum torque. Be reminded, maximum torque of MD97 engine is taken as the reference for both engines so the similar BMEP comparison is possible. In mode 2, DF engine BMEP is 10.3 bar and for MD97 it is 11.01 bar.

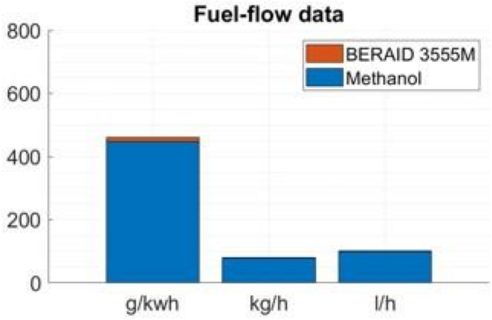
In this mode, all trends continue as in mode 1. New information to note from this regimen is that thermal efficiency of MD97 decreased to 39% and DF increased to 37% compared to mode 1. Still, MD97 outperforms DF. Furthermore, methanol energy fraction in DF engine decreased to 64%.



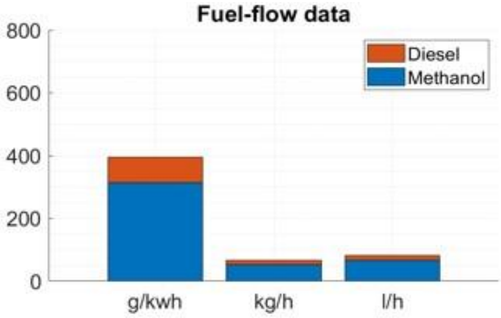
17 | MD97 engine loadpoint at mode 2



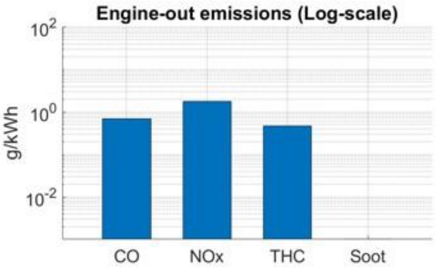
18 | Dual fuel engine loadpoint at mode 2



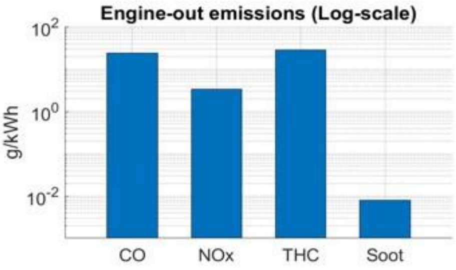
19 | MD97 engine fuel flow data at mode 2



20 | Dual fuel engine fuel flow data at mode 2



21 | MD97 engine out emissions at mode 2



22 | Dual fuel engine out emissions at mode 2

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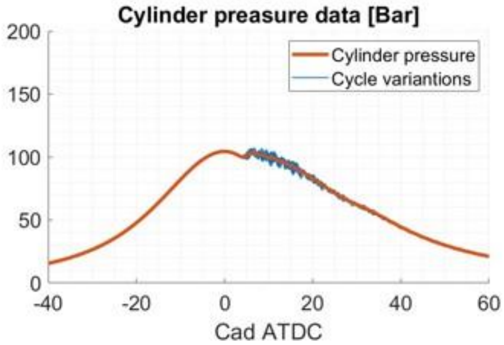
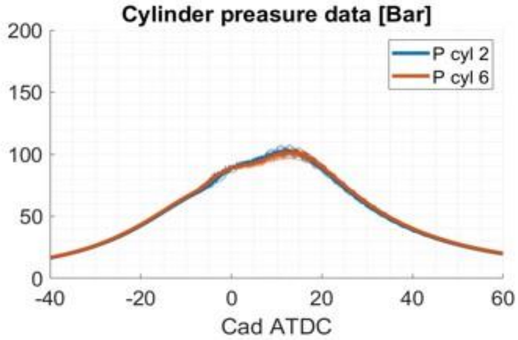
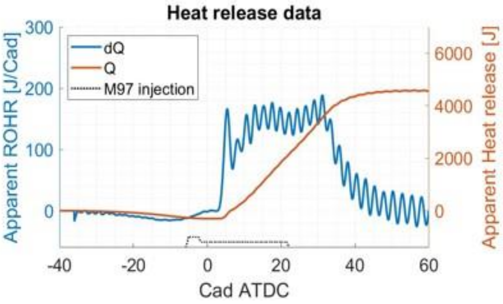


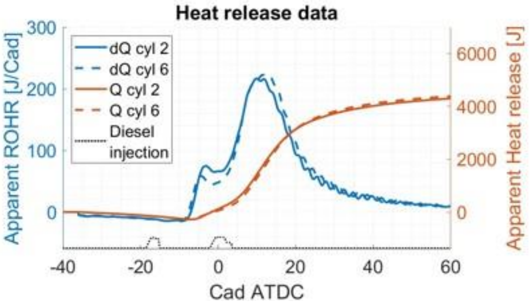
23 | MD97 engine cylinder pressure data at mode 2



24 | Dual fuel cylinder pressure data at mode 2



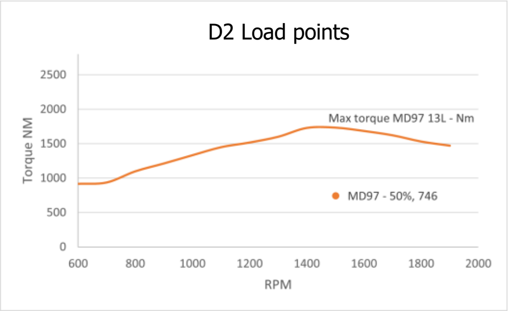
25 | MD97 engine heat release data at mode 2



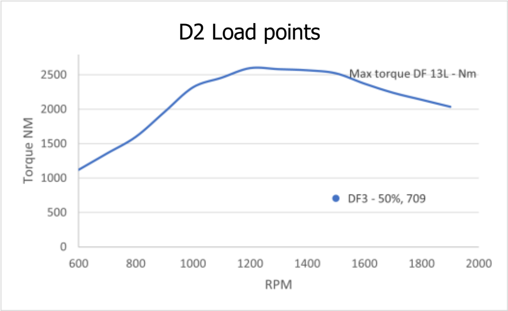
26 | Dual fuel heat release data at mode 2

2.4.3 Mode 3

Mode 3 represents 50% of maximum torque. In this mode, DF engine BMEP is 6,86 bar and for MD97 it is 7.35 bar. In this mode, all trends continue as in previous modes. Thermal efficiency and diesel replacement ratio keep dropping with decreasing loads. MD97 thermal efficiency is now 37% and DF is 34%. Diesel replacement ratio achieved in DF engine is 62%.



27 | MD97 engine loadpoint at mode 3



28 | Dual fuel engine loadpoint at mode 3

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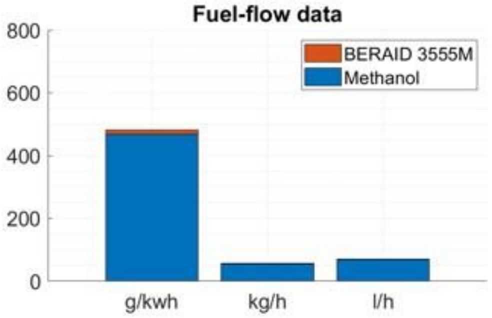
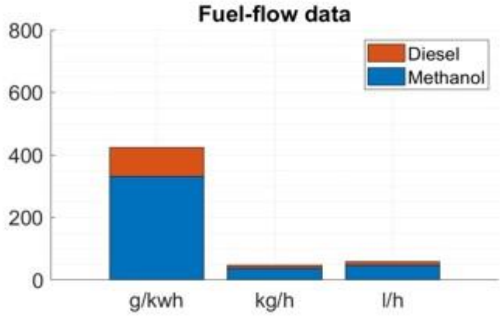
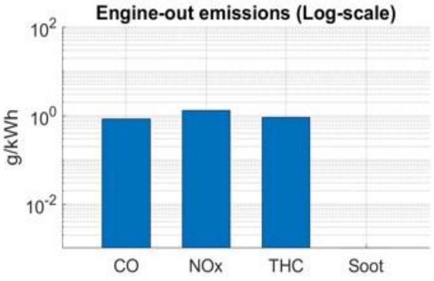


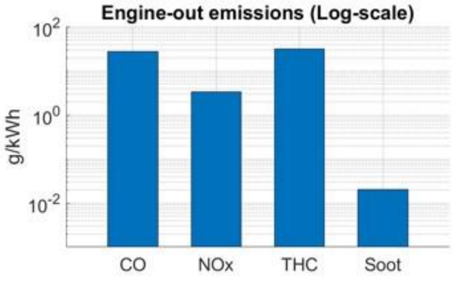
29 | MD97 engine fuel flow data at mode 3



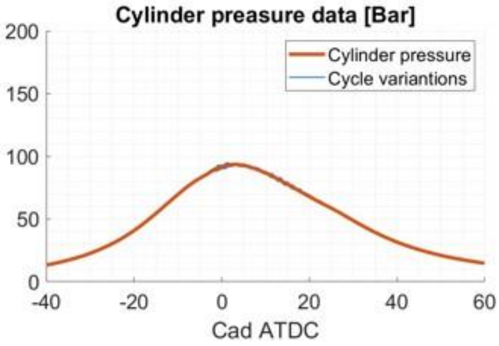
30 | Dual fuel engine fuel flow data at mode 3



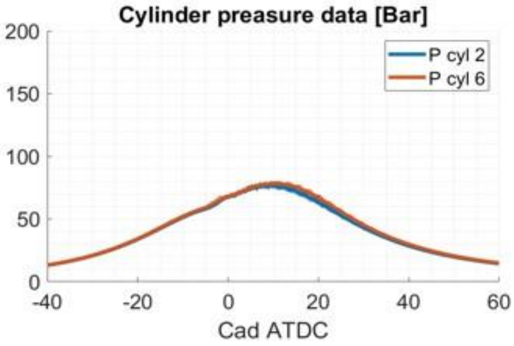
31 | MD97 engine out emissions at mode 3



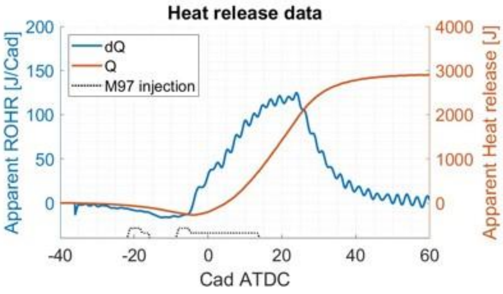
32 | Dual fuel engine out emissions at mode 3



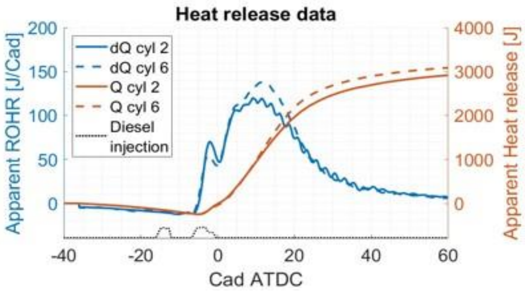
33 | MD97 engine cylinder pressure data at mode 3



34 | Dual fuel cylinder pressure data at mode 3



35 | MD97 engine heat release data at mode 3



36 | Dual fuel heat release data at mode 3

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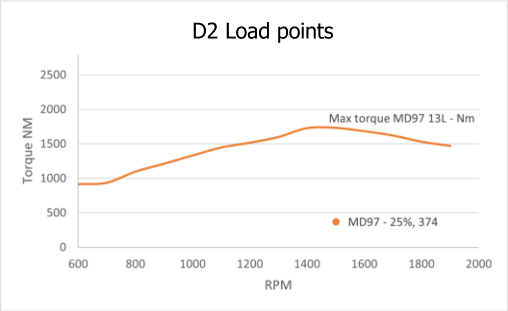
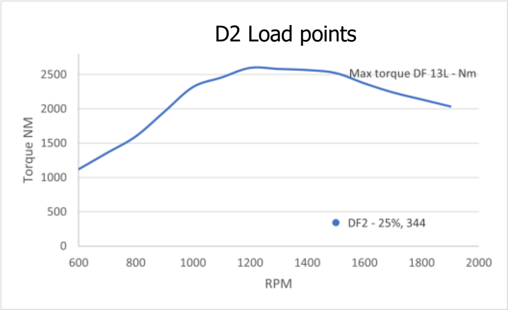
2.4.4 Mode 4

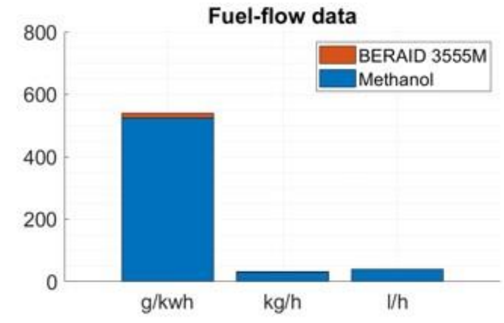
Mode 4 represents 25% of maximum torque. DF engine BMEP is 3.33 bar and for MD97 it is 3.68 bar. In this mode, thermal efficiency further decreased and is calculated to be 33% for MD97 and 27% for DF engine. However, diesel replacement ratio in DF engine increased to 68%, almost the same value as at highest load.



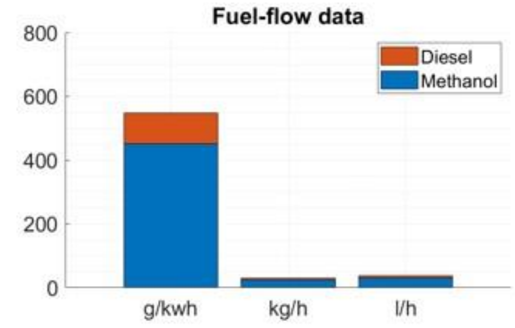
37 | MD97 engine loadpoint at mode 4



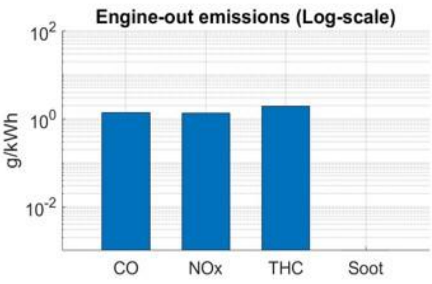
38 | Dual fuel engine loadpoint at mode 4



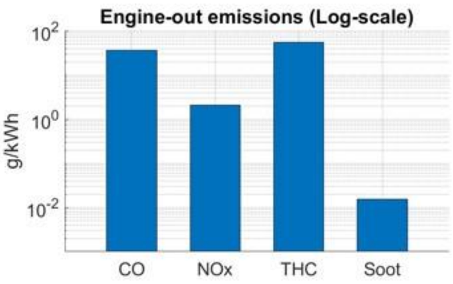
39 | MD97 engine fuel flow data at mode 4



40 | Dual fuel engine fuel flow data at mode 4



41 | MD97 engine out emissions at mode 4



42 | Dual fuel engine out emissions at mode 4

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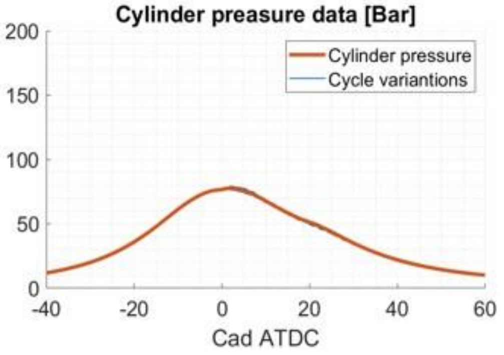
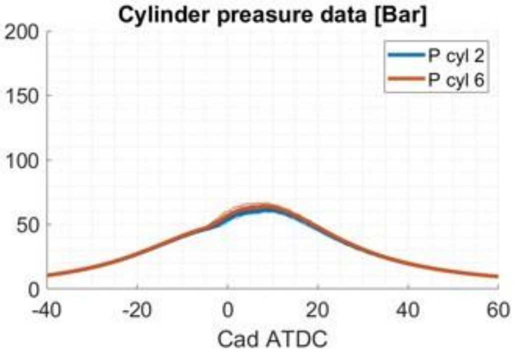
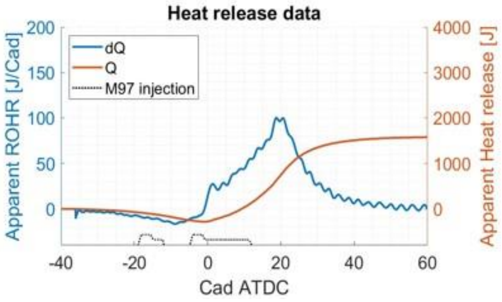


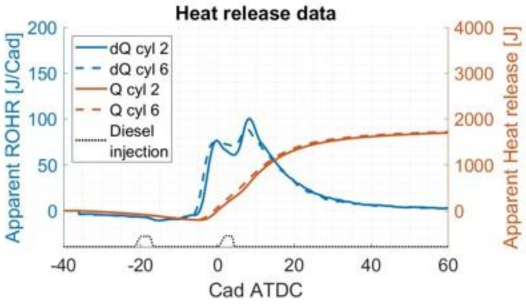
43 | MD97 engine cylinder pressure data at mode 4



44 | Dual fuel cylinder pressure data at mode 4



45 | MD97 engine heat release data at mode 4



46 | Dual fuel heat release data at mode 4

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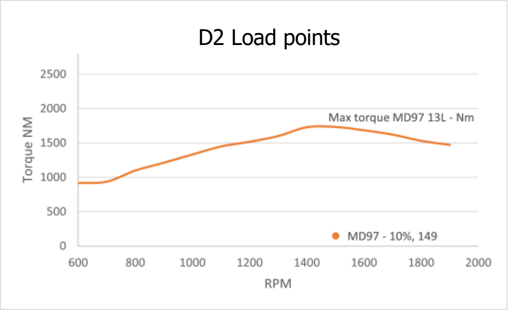
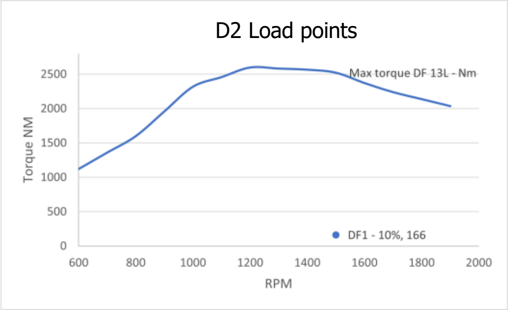
2.4.5 Mode 5

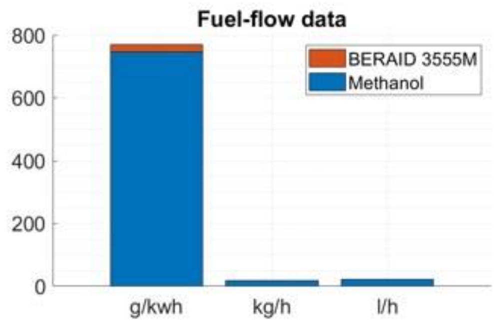
Mode 5 represents 10% of maximum torque. DF engine BMEP is 1.6 bar and for MD97 it is 1.46 bar. In this mode, thermal efficiency further decreased and is calculated to be 23% for MD97 and 19% for DF engine. However, diesel replacement ratio in DF engine increased to its maximum over all the modes reaching 71%.



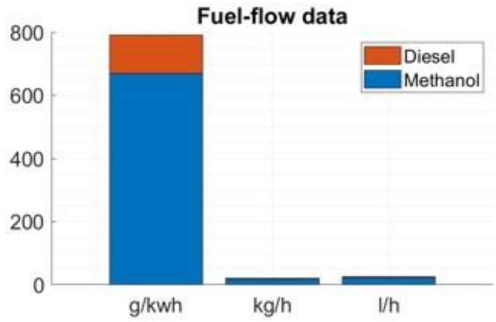
47 | MD97 engine loadpoint at mode 5



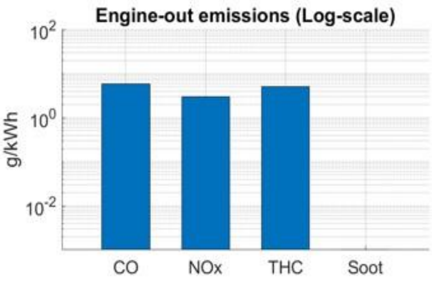
48 | Dual fuel engine loadpoint at mode 5



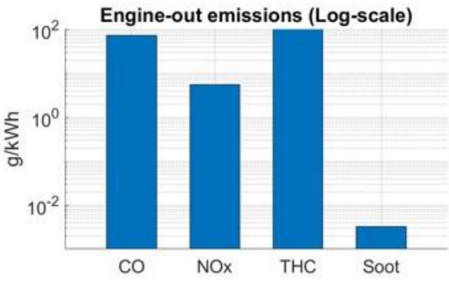
49 | MD97 engine fuel flow data at mode 5



50 | Dual fuel engine fuel flow data at mode 5



51 | MD97 engine out emissions at mode 5



52 | Dual fuel engine out emissions at mode 5

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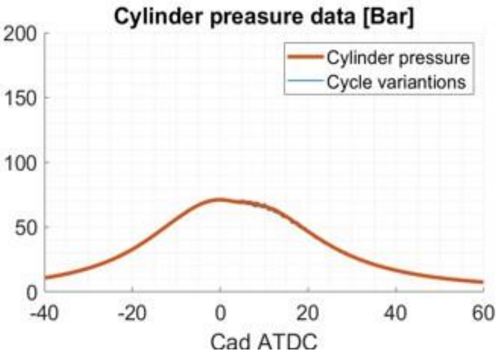
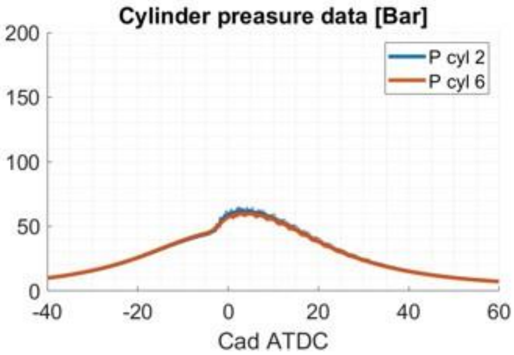
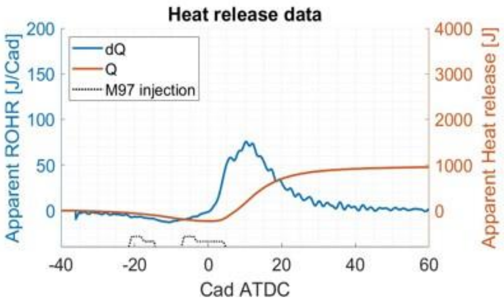


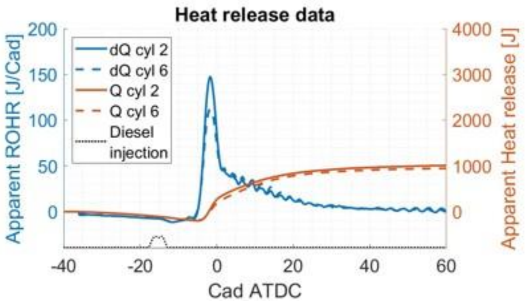
53 | MD97 engine cylinder pressure data at mode 5



54 | Dual fuel cylinder pressure data at mode 5



55 | MD97 engine heat release data at mode 5



56 | Dual fuel heat release data at mode 5

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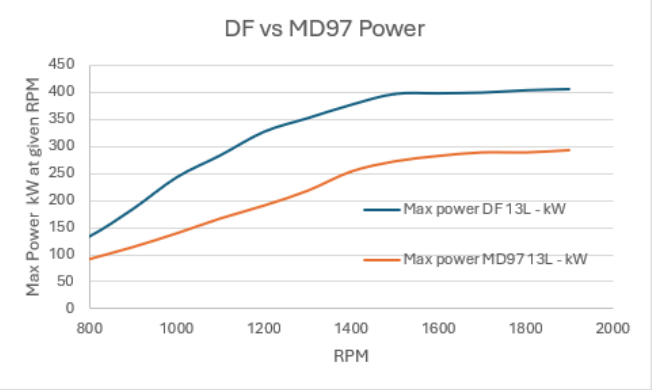
2.4.6 Summary of test results

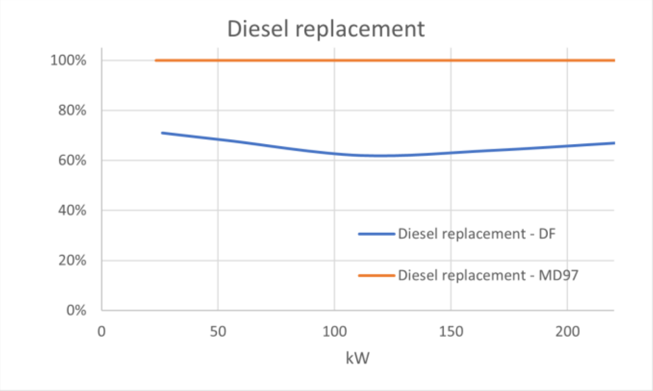
Engine dyno tests yield extensive datasets providing deep insights to different phenomena during combustion: timing of fuel injection, heat release data, pressure measurements etc. These are shown and discussed in previous chapters. To emphasize resulting key performance indicators, figures showing maximum power output, diesel replacement ratio, thermal efficiency, CO, NOx and total hydrocarbons emissions for both engines across loads are shown separately in this chapter.

One of the most important parameters of a propulsion system is maximum power output available from the engine at different speeds. This maximum power is the only observed criterion in which DF engine outperforms MD97, as can be seen in figure 57. DF peaks at power output of 400 kW, while MD97 can reach 300 kW at maximum.



57 | DF vs. MD97: Power output

Diesel replacement shows the ratio of energy provided by methanol over the total fuel energy. Considering MD97 is a single fuel methanol engine and all energy comes from methanol, assigned value is 100%. DF engine provides a diesel replacement ratio between 60% and 70% over the full load range. Normally the replacement ratio will decline towards the maximum power of a DF engine but in this case the 100% power refers to the maximum power of the MD97 engine with lower rating, therefore the curve does not show such decline. The optimization of the diesel replacement ratio is an iterative process where tuning of the parameters is done in a systematic way considering fuel efficiency, emission, knocking etc. The time available in the test dyno only allowed for an initial campaign and more time in the test dyno will most likely provide a better replacement ratio in the magnitude of 2-5% percent units.



58 | DF vs. MD97: Diesel replacement ratio energy-wise

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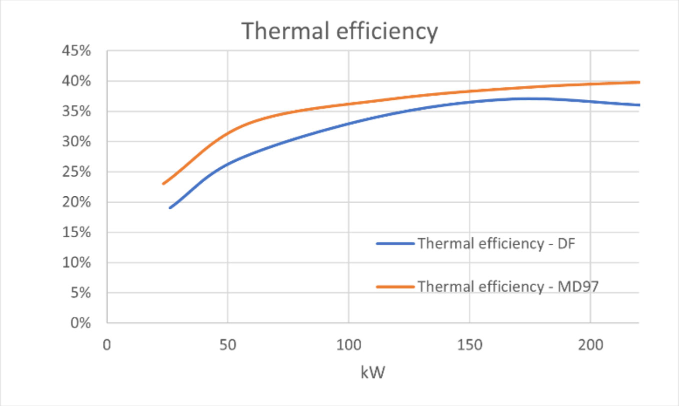
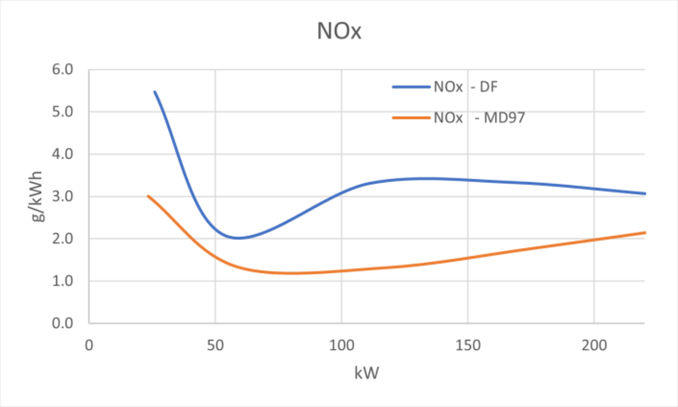
Thermal efficiency represents the fraction of heat energy successfully converted to useful mechanical work. The first thing to notice on figure 59 is that DF engine curve is lower than MD97 across all loads. This shows MD97 engine is more efficient than DF under all load conditions. MD97 peaks at 40% efficiency, while DF peaks at 36%. Both values are comparable to traditional Diesel engines and there is no indication of losing efficiency because of methanol.



59 | DF vs. MD97: Thermal efficiency

NOx emissions are the most regulated among measured ones in this test. Once again, MD97 produces less emissions across all loads. Both engines produce the highest specific emissions at the lowest loads, after which they quickly decline to the overall minimum values at 25% load – 2.1 g/kWh from DF engine and 1.33 g/kWh from MD97 engine. MD97 emissions gradually increase from 25% load all the way to the end, while DF shows a steep increase between 25% and 50% load. Between half load and full load, DF emissions are slowly decreasing however, not at a rate to reach a breakpoint with MD97. The MD97 engine meets the IMO III requirements of a weighted average of 2 g/kWh without after treatment system. For the dual-fuel engine the NOx emissions are about half of a diesel engine but still required and SCR system to meet the IMO Tier III requirements.



60 | DF vs MD97: NOx emissions

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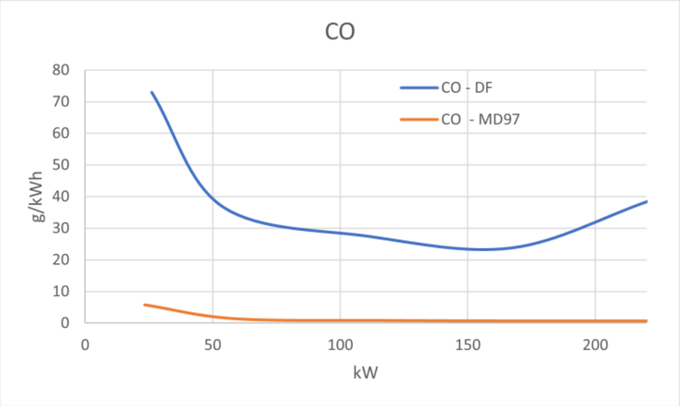
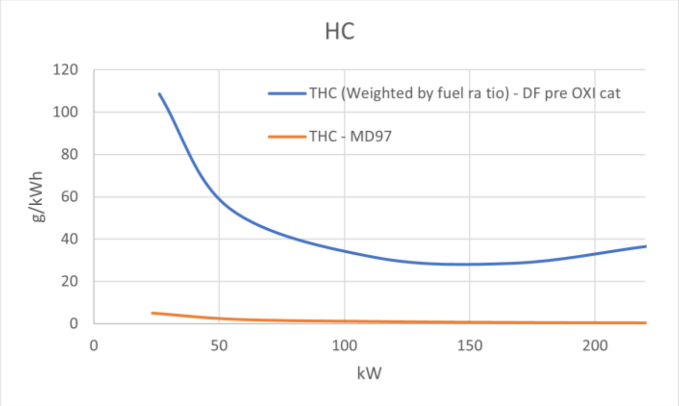
The emission of CO and hydrocarbons HC are indication of the amount of fuel that are not completely combusted in the engines and they are following the same pattern. The CO emissions are significantly higher for DF engine, across all loads. MD97 emits almost negligible amounts nearing zero at all load conditions. On the other hand, DF produces the maximum amount of CO at lower loads, peaking at 73 g/kWh after which emissions show steep decline until 25% load. As load increases from 25% to 75%, CO emissions gradually decrease, reaching minimum of 24 g/kWh. At the highest load, DF engine produces 39 g/kWh CO. This amount is about half the maximum emissions that occur at minimum load.



61 | DF vs. MD97: CO emissions

Total hydrocarbon emissions refer to release of various HC compounds into the atmosphere. Curve trends of THC emissions are, as mentioned, largely alike to the CO ones: MD97 hoovers around zero, while DF curve starts with a peak at a low load, rapidly decreases until about half load, after which it gradually increases again. As in all other emission categories, MD97 produces significantly less amounts of emissions.



62 | DF vs. MD97: Total hydrocarbon emissions

It is noticeable that the emissions of CO and HC are much higher for the dual fuel engine. However, vast majority of those emissions can be eliminated in an oxidation catalyst.

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3. Conclusions

The comparative analysis of MD97 methanol compression ignited engine and the dual fuel (DF) methanol-diesel port injection engine highlights key performance and environmental differences between two solutions. Both engines are tested at five load points according to ISO 8178. Engines are compared based on engine power, efficiency, fuel ratio, and emissions.

The MD97 engine demonstrates better thermal efficiency, achieving a 2-6% improvement over the DF engine. However, MD97 engine exhibits a lower maximum power output per displacement compared to the DF engine, which may limit its applicability in high-power demand scenarios. It is important to note that this study compares two similar engines, both featuring 13 L cylinders. However, a single-fuel methanol engine is also offered in a 16 L variant. The 16 L MD97 engine delivers a maximum power output of 415 kW, which slightly exceeds that of the DF 13L. This suggests that adequate comparable power output is achievable with methanol alone, albeit at the cost of larger dimensions. The DF engine, while offering higher power output capability, shows higher cycle-to-cycle variations at high loads and larger cylinder-to-cylinder variations. These variations can impact operational stability but with further optimization it should also be possible to reduce them. DF engine offers a good trade off between meeting high power requirements and lowering environmental impact as much as possible. The MD97 engine is a marketed and certified product offered by Enmar Engines since a number of years, the DF is a newer product in development phase. The efforts to enhance both the fuel ratio and engine performance are ongoing.

In terms of emissions, MD97 outperforms DF in all measured categories: CO, NOx, THC and soot. MD97 does not even require aftertreatment system to reach IMO Tier III emission levels for marine applications which is a considerable benefit, saving space and cutting down on maintenance work due to fewer components. Total hydrocarbons emissions produced from methanol contain formaldehyde which is considered to be a problematic emission since it is classified as a group 1 carcinogen substance by the International Agency for Research on Cancer (IARC). However, the formaldehyde emission can be reduced by 99% by introduction of an oxidation catalyst. The DF engine system, while more complex due to dual fuel storage and management, provides operational flexibility and redundancy. This can be advantageous in scenarios where fuel availability or pricing fluctuates. Therefore, DF engines can be considered a good solution in transitioning phase of industry where infrastructure for methanol supply is still under development and the retrofit potential could save the older fleet from scrapping earlier than desired due to continuously stricter environmental regulations. Although this report focuses solely on engines, required ship design modifications must be taken into account to fully grasp what utilizing methanol or methanol-diesel engines onboard vessels entail. These aspects are covered by IMO Interim Guidelines in more detail and include extensive safety considerations resulting with some additional equipment such as heat and gas detectors, oxygen and/or nitrogen sensors, double structural boundaries around spaces containing methanol such as cofferdams around tanks and double walled piping.

In conclusion, while the MD97 engine system presents a better option from emission and efficient perspective, the DF engine system offers flexibility and higher power output. The choice between these solutions will depend on specific operational requirements, regulatory constraints, and long-term fuel availability considerations. In both cases, the main message is the technology is ready to be applied.

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