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Retrofit and Experimental Evaluation of a Conventional Marine Diesel Engine for Dual Fuel Diesel-Methanol Operation

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Abstract
Strict emission laws and energy security concerns have resulted in a variety of alternative ideas applicable to internal combustion engines. In this work, a conventional four-stroke six-cylinder marine diesel engine was retrofitted for diesel-methanol dual fuel operation and a number of experimental studies were conducted to evaluate the combustion, performance, and emission characteristics. The retrofit effort involves the mounting of six methanol injectors on custom-made injector ports, installed before the cylinder head air intake port and after the intercooler. The methanol injection is controlled via a separate ECU, which works in parallel with the original one. Initial tests were carried out after the retrofit, to verify the successful dual fuel operation. The results indicate the success of the retrofit process since the engine thermal efficiency was retained or improved in some cases and NOx emissions were greatly reduced.

***Keywords*: Dual Fuel, Diesel, Methanol, Combustion, Engine, Emissions**

1. Introduction

Compression ignition (CI) diesel engines have dominated major areas of industry as power generation units due to their high efficiency, durability, and reliability. Nonetheless, tight pollution rules and ever-increasing diesel fuel prices have increased interest in technical solutions that reduce pollutants and improve fuel efficiency for such CI engines. Furthermore, it is fairly known that under typical diesel settings, the margins for emission and efficiency improvement have been reached, thus more radical alternatives, such as full or partial substitution of diesel fuel as the primary energy source, are being investigated.

A viable alternative that is gaining momentum is the use of oxygenated fuels in addition to ordinary diesel for dual-fuel combustion in CI engines [1]. Methanol is one of these fuels that is being studied extensively due to its low cost, existing developed distribution network, and relatively easy storage. Although the cetane number (CN) for methanol is quite low (i.e., 3 to 5) [2], numerous approaches for implementing a Diesel Methanol Dual-Fuel (DMDF) engine have been presented in the literature [3]. Compression engines that were retrofitted for dual-fuel diesel methanol operation, usually have lower NOx and Soot emissions while their performance is maintained at the same levels as in diesel-only operation [3].

The retrofit concepts are divided into those in which methanol is injected directly into the combustion chamber with a separate or the same injector as diesel fuel, [4], and those in which methanol is injected into the intake air before the cylinder, mainly referred to as port injection [5].

The option of direct mixture and injection of methanol at diesel engines has been examined and implemented in [6], [7] and [8]. For the direct mixture, results have indicated that the mixture ratio could not exceed 20 % due to the miscibility problem and the lower heating values, Furthermore, methanol direct injection could result in higher methanol substitution ratios, and better control of the combustion process via the adjustment of injection timing. However, this option is more to be implemented as a retrofit since it requires either modification on the cylinder head for the installation of the new injectors or the replacement of the existing injectors with ones that can inject both fuels.

On the other hand, methanol port injection is a much easier and more affordable solution as a retrofit option. The retrofit can be applied either with the installation of injectors at a specific point at a single point or at multiple points. The first approach is the single-point injection (SPI), in which the injectors are placed at a single point in the intake manifold. In this approach, the fuel is injected at a steady rate. Then the fuel is mixed with air and a homogeneous mixture is injected inside the cylinder. This concept has been implemented in [5], [9] and [10]. The second approach is the multi-point injection (MPI), in which the injectors are placed close to the cylinder intake port, (one or more injectors per cylinder). The fuel is injected during the intake stroke; thus, the injector opens and closes one time for each cycle. Works involving engines retrofitted with this concept are presented in [5], [11] and [12].

The benefits and drawbacks of each method are reported in detail in [5]. In this work, a diesel engine was retrofitted by applying both approaches. In brief, it was reported that in the SPI approach, the installation of the injector is easier since its position is usually more reachable. However, several factors should be considered such as mixing length for methanol, the avoidance of methanol condensation, and the proper fuel distribution for all the cylinders. These have led to the need for the installation of a cooler bypass, leading to a more complex retrofit. On the other hand, in the MPI approach the position of the injectors is not so reachable, and small retrofits such as the repositioning of the cooler are required. However, since methanol is injected right before the intake port, no further alterations are needed with respect to the previously mentioned factors. With respect to engine performance and emissions, the following advantages are noted for the MPI, the maximum methanol energy fraction (MEF) is greater for MPI, during the SPI operation and especially when the inter-cooler was offline, engine knocks were observed, thermal efficiency is better at low MEFs for MPI and better at higher MEFs for SPI, NOx emissions were lower for all the tests for MPI operation.

In the present research work, a conventional diesel marine high-speed engine is retrofitted for dual-fuel diesel methanol operation, and its operational results are experimentally verified. In Section 2, the technical aspects of the retrofit concept are presented, and in Section 3 the research method is described. In Section 4, the experimental results are presented while in Section 5 the results until now are discussed.

2. Retrofit Concept and Procedure

2.1. Technical Aspect of Retrofit Concept

In this work, a conventional marine engine was retrofitted to dual fuel operation by installing low-pressure methanol injectors at the engine's airpath before the cylinder intake port. The engine specifications are depicted in Table 1. With respect to previous works, it was decided that the MPI concept is appropriate for the engine in this work. The main reason for this choice is that the SPI operation could result in combustion knocks which can damage the engine, and the requirement for explicit control of the engine cooling system. Furthermore, as previously stated, previous works indicated superior performance of the engine in terms of emissions and performance for the MPI concept.

Table 1: Engine Specifications

Model	Mercury D-Tronic 4.2
Cylinders	6
Compression Ratio	16.5
Bore x Stroke	94 mm x 100 mm
Displacement	4.2 L
Diesel Injection System	Electronic Distribution Pump
Maximum Torque /Speed	548 Nm / 2650 rpm
Rated Power/Speed	186 kW / 3800 rpm
Boost Pressure	100-124 kPa

The main technical challenge for the retrofit is the installation position of the injectors, which is an important design aspect since it directly affects the performance of the engine. Furthermore, there are restrictions regarding the installation i.e., the injector's mounting position must be physically reachable. Previous works indicate that for MPI concept it is beneficial for the methanol to be injected close to the intake valve port with respect to the engine's performance, due to the cooling effect of methanol's increased latent heat of evaporation [3].

The engine that was retrofitted in the scope of this work has a reversed flow cylinder head, i.e., the intake and exhaust ports are located at the same site of the cylinder head and are connected to a common intake-exhaust manifold. Furthermore, on top of the intake/-exhaust manifold, the intercooler is located, thus blocking any intervention on the cylinder ports. For this reason, to install the methanol injectors, the intercooler was lifted by approximately 10 cm. At the created interval between the intake ports of the intercooler and intake exhaust manifold, six custom-made injector hubs were installed.

These hubs are composed of two parts, the first of which is mounted on the manifold and supports the intercooler. The injector is mounted on the second part which is respectively fitted in the first part. The reason for not directly mounting the injector on the first part is the necessity for the option to change the spray cone angle relative to the intake port, without dismounting the intercooler and remanufacturing the whole hub. As depicted in Fig. 1, the injector cannot be projected to the intake port from the position that the injector is mounted. Hence there is the possibility for the need for the injector angle to be readjusted. The final angle of the injector was selected to be such that the spray angle reaches the furthest before hitting the intake port walls. In this case, the methanol should have sufficient time to be dispersed at the intake air current and form the homogenous mixture before reaching the walls.

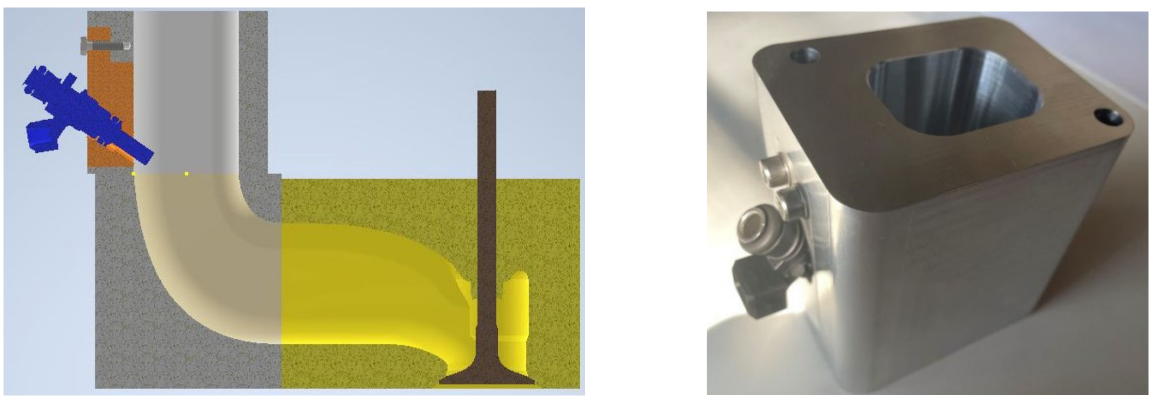

Fig. 1: Methanol Injectors Hubs.

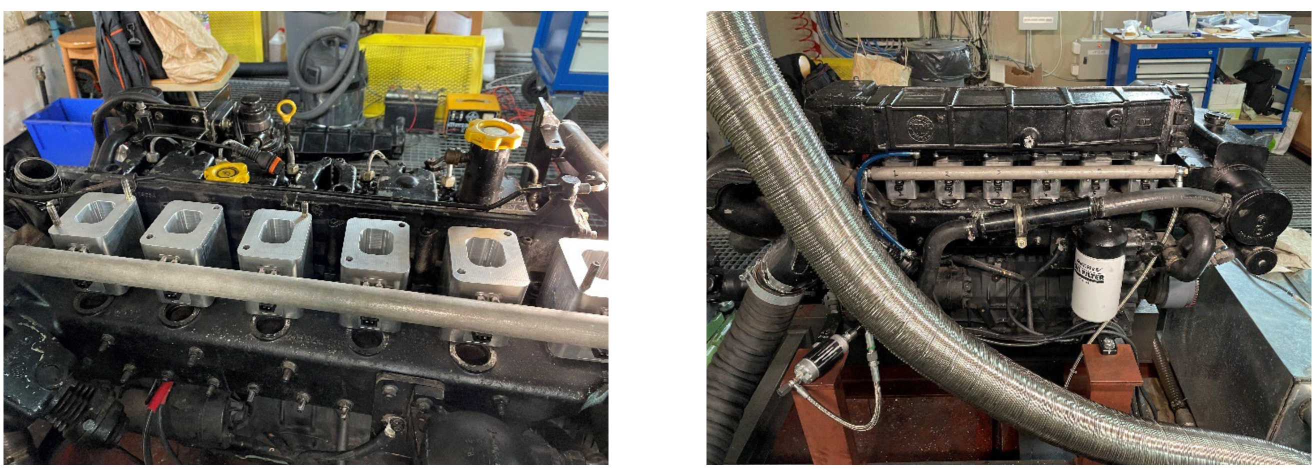

Fig. 2: Methanol Injectors Hub and Common Rail System as installed at the engine.

For the methanol injections, the Bosch EV14 injectors were selected. These injectors are widely used for gasoline port injection in the automotive industry, and they are methanol-compatible. The model variation selected for the present application was based on the capacity of the injector to deliver sufficient methanol quantity for 80 % energy substitution at the maximum speed and power of the engine, during the time window in which the intake valve is open. The methanol is supplied to the injectors via a low-pressure common rail system. This system is composed of a methanol-compatible fuel pump and a pressure regulator that maintains the fuel pressure at 8 bar. It should be noted that the methanol common rail pressure is higher than those of similar retrofit projects. The high pressure was selected to fulfil the requirement for the maximum injection quantity at higher rotating speed to be met. The methanol fuel system is controlled via a separate ECU which is manufactured by HEINZMANN GmbH & Co. KG. The particulars of the methanol system are depicted in Table 2.

Table 2: Methanol System Specifications

Injector Model	EV14
Injector Maximum Capacity	1000 cc/min
Injector Spray Cone Angle	30 deg.
Methanol Pump Capacity	200 l/h at 8 bar
Common Rail Pressure	8 bar
Methanol ECU	Heinzmann

Furthermore, some other minor retrofits were conducted for the methanol injection. Mainly a camshaft encoder was installed to synchronise the methanol injections. The methanol ECU is to work in parallel with the original Bosch ECU of the engine. The diesel injection is controlled indirectly by the ECU with respect to the throttle position. Direct control of the diesel injection timing and quantity is not possible via the Bosch ECU.

2.2. Engine Setup

In an effort to validate the engine retrofit, an experimental test-bed was set up at the Laboratory of Marine Engineering at NTUA. The engine is connected to an AVL-Zoellner water brake with a maximum load capacity of 1200 kW and 4000 rpm. The whole testbed is controlled and monitored in real-time by a dSpace DS1103 controller board, programmed under the Matlab/Simulink environment. The already installed engine sensors, i.e., intake manifold pressure, intake temperature, diesel pump injection quantity and timing, and injector needle lift were recorded during testing.

Furthermore, several other sensors were also installed on the engine to monitor its performance. A Kistler 6052C in-cylinder pressure transducer was installed at the engine's glow plug port to monitor the in-cylinder pressure during combustion. The signal is recorded via a charge amplifier by a National Instruments DAQ unit at 500 kHz. Other measurements present in the test bed include NOx/oxygen, fuel mass flow, turbocharger speed, torque, and rotational speed. The NOx/oxygen sensor is the automotive standard NGK SmartNOx wide-range linear λ sensor installed 1 m downstream from the ICE turbine. The testbed schematic is shown in Fig. 3.

3. Research Method

To characterize the dual fuel operation the Methanol Energy Substitution Ratio (MESR) is introduced and is defined as the percentage of methanol energy contributed to the system to the total energy from both fuels~~:~~

$$MESR = \frac{\mathrm{m_{MeOH}} \times Hu_{MeOH}}{\mathrm{m_{MeOH}} \times Hu_{MeOH} + m_{diesel}Hu_{diesel}} \quad (1)$$

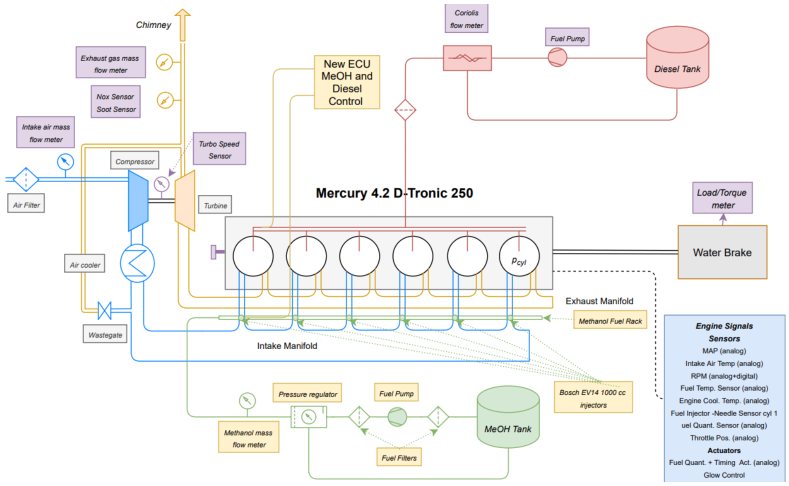

Fig. 3: Schematic diagram of the Experimental Setup.

where m_{MeOH}, and m_{diesel} are the methanol and diesel mass flows and Hu_{MeOH}, and Hu_{diesel} are the lower calorific values of diesel and methanol.

Furthermore, the Brake Thermal Efficiency is also calculated and utilized:

$$BTE = \frac{P_e}{\mathrm{m_{MeOH}} \times Hu_{MeOH} + m_{diesel} Hu_{diesel}} \tag{2}$$

where P_e is the engine power delivered at the water brake.

In this study, methanol of 99.95 % purity and diesel fuel with less than 50 ppm sulfur content were used. The combustion analysis was conducted via the pressure signal obtained by the in-cylinder pressure sensor. For each measurement, 100 combustion cycles were obtained, amplified, filtered, and averaged. The crank angle was measured by a magnetic pickup sensor. The Heat Release Rate (HRR) was calculated based on the first law of thermodynamics:

$$\frac{dQ}{d\theta} = \frac{\gamma}{\gamma - 1} \cdot P \cdot \frac{dV}{d\theta} + \frac{1}{\gamma - 1} \cdot V \cdot \frac{dP}{d\theta} \tag{2}$$

where Q is the heat release, θ is the crank angle, P is in-cylinder pressure, V is the instantaneous cylinder volume, and γ is the heat ratio.

The heat ratio depends on the mixture composition and temperature. However, for simplicity reasons and in accordance with similar works [5], [11] γ was considered constant at 1.35.

4. Experimental Results

The evaluation of the performance of the engine was conducted by adjusting the engine throttle setpoint since no direct control of the diesel system was available. The load was adjusted by a constant valve command to the water brake, which corresponds approximately to 120 Nm load. Afterward, via the methanol ECU, the methanol injection quantity was steadily increased, and measurements were conducted. The crank angle-based Results are depicted in Fig. 4 while the time-based measurement results are depicted in Fig. 5.

It can be noted from the results that the methanol is successfully injected into the engine, and part of the load is provided by its released heat during combustion. The maximum MESR that was reached during experiments was 35 %. Further increase was not pursued because the Engine ECU decreased the diesel quantity and consequently reduced the engine speed. The thermal efficiency of the engine remains at the same level as at the diesel mode or even increases for MESR by around 25 %.

The combustion measurements are consistent with the results from previous works, for diesel and dual fuel operation. As can be observed, the ignition delay increases with the percentage of MESR. This can be explained by the methanol's large latent heat of vaporization, which decreases the cylinder temperature, resulting in a decrease in the rate of oxidization of the diesel fuel. Furthermore, combustion duration decreases for higher MESR. The reason for this is that methanol and air have formed a homogenous mixture. Therefore, after diesel ignition, the combustion is characterized by a premixed phase, leading to a shorter combustion duration.

NOx emissions were heavily decreased with the introduction of methanol by 50 % in ppm values. This is consistent with the results from previous published works. The formation of NOx in combustion engines is mainly influenced by temperature and oxygen concentrations. Methanol vaporization decreases the cylinder temperature, leading to a reduced NOx production rate. Furthermore, the increased combustion delay is beneficial for the dispersion of diesel fuel, which leads to lower concentrations and hence lower temperatures locally.

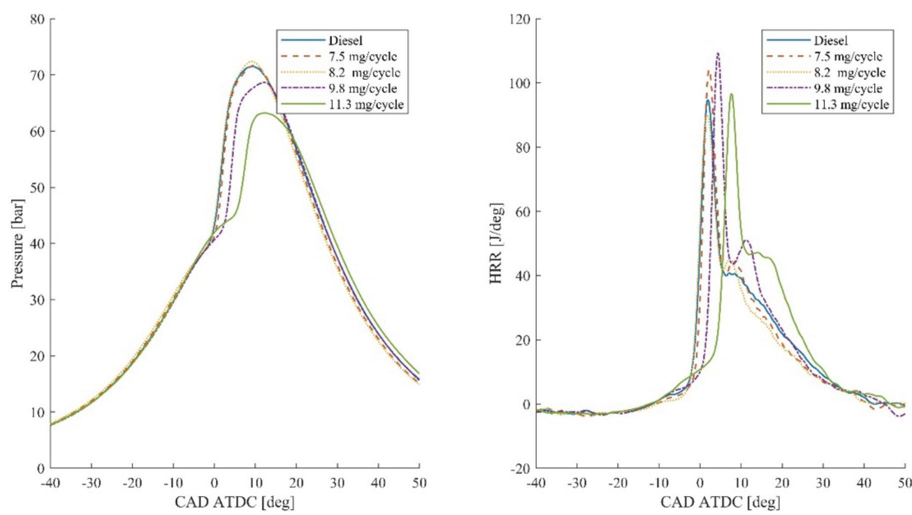

Fig. 4: CAD Based Measurements.

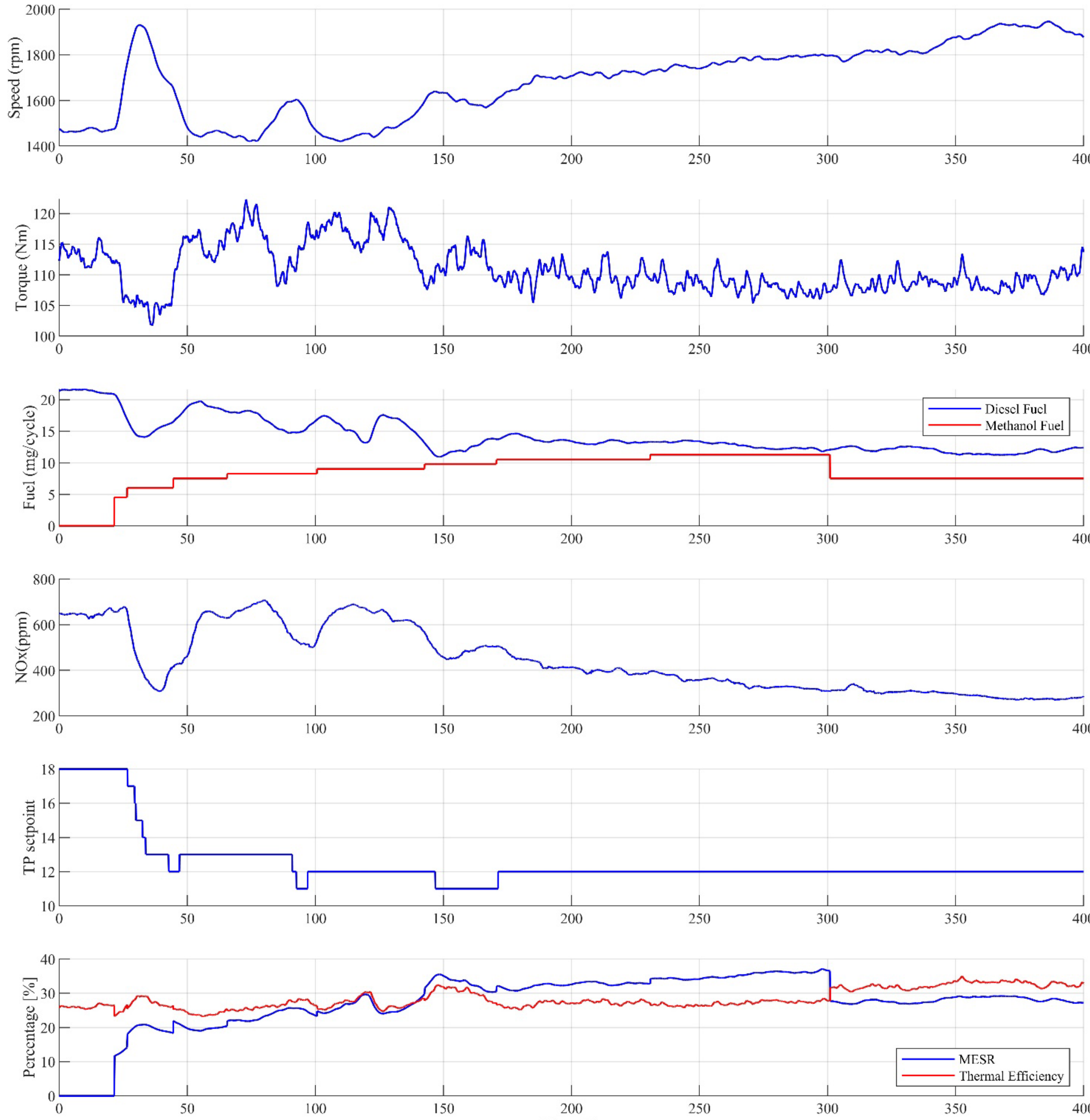

Fig. 5: Time-Based Measurements.

5. Conclusions

In the present work, the retrofit effort, and experimental results from the conversion of a conventional marine diesel engine to a dual-fuel diesel methanol are presented. To retrofit the engine, minor conversions to the intake air path along with the installation of a few custom-manufactured parts were conducted. These retrofits were solely based on the design of the present engine.

Experimental validation of the engine was successful, achieving a 35 % MESR. Furthermore, engine performance was maintained since the brake thermal efficiency was nearly the same as in diesel mode. Finally, NOx emissions were dramatically decreased up to 50 %, in ppm values with the methanol injection.

Acknowledgments

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