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# A Methanol Fueled Marine Engine Simulator for Fast Craft Applications

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**Abstract.** The paper presents a thermodynamic simulator of a marine four-stroke medium speed engine, fueled by methanol. The study stems from the current lack of information on methanol marine engines, whereas there is a growing interest in this type of alternative fuel, also in the maritime field. The numerical model, developed in Matlab©-Simulink© language and structured in a modular form, is derived from a natural gas marine engine simulator, developed by the authors and already described and validated in a previous research study. In the methanol engine model, for the in cylinder phenomena calculation, the zero dimensional actual cycle approach is adopted, while the turbocharger compressor and turbine are simulated by their performance maps. After a short description of the original natural gas simulator, the paper reports the variations introduced for adapting the engine model to the methanol fuel mode. The obtained outcomes are compared with data referring to a dual fuel natural gas engine, available in the literature. This comparison, between the simulated results of the two fuel modes of the engine, aims at highlighting the differences in efficiency and carbon dioxide emissions, in order to improve the environmental impact of the medium and high-speed vessels.

**Keywords.** Marine engine, methanol fuel, natural gas, simulation, $CO_2$, efficiency

## 1. Introduction

Environmental sustainability is becoming a major challenge for the maritime industry as increasingly stringent rules are issued by international bodies. To reduce the greenhouse effect on the planet, not only the carbon dioxide ($CO_2$) emissions are tackled but also a reduction in emissions of nitrous oxide ($N_2O$) and methane ($CH_4$) is necessary as they present a Global Warming Potential (GWP) higher than $CO_2$ and respectively equal to 29.8 e 273 on a 100-year base. The International Maritime Organization (IMO), in fact, has introduced increasingly stringent regulations regarding the main air pollutants such as $NO_x$ and $SO_x$ whose emission limits are reported in Annex VI of the MARPOL Convention [1].

In response to the decarbonization target signed by the United Nations in the "Paris Agreement", the IMO has set ambitious goals in terms of emission reduction. The goals, in terms of greenhouse gas (GHG) emission and carbon intensity reduction are based on the emissions registered in 2008. These goals can be summarized in a reduction in the absolute annual GHG emissions from international shipping by at least a half by 2050, and a reduction in the carbon intensity of the ships ($CO_2$ emissions per transport work) by at least 40% by 2030 and 70% by 2050. Meanwhile, the European Union has set even more ambitious goals in terms of GHG emission reduction, including the shipping sector in the Emission Trading Scheme (ETS) and leaning toward climate neutrality in 2050.

Energy efficiency measures such as more efficient hull forms based on CFD simulations, air lubrication systems, waste heat recovery systems [2-5], batteries and hybrid devices [6, 7] can reduce emissions from ships but cannot meet the ambitious goals of emission reduction up until marine propulsion systems are based on fossil fuels. Hence, further progress is primary in the development of marine engines fueled by green alternative fuels (i.e. produced from renewable sources and ensuring zero emissions in the life cycle). Different alternative fuels are going to enter the maritime field and they are characterized by different chemical and physical properties. The most promising fuels are: natural gas (NG or LNG), methanol, ammonia, and hydrogen. Natural gas is by far the most employed alternative fuel, even though it allows only for a small reduction in GHG emissions and it has to be stored in pressurized and insulated tanks, which are space and weight demanding. The same considerations regarding storage can be assumed for hydrogen and ammonia. Hydrogen is a gas at room temperature and it is liquid at -253°C or pressures ranging from 350 -700 bar (depending on temperature), while ammonia can be stored as a liquid at a temperature of -33°C. As a fuel ammonia is suitable for Spark Ignition (SI) ICEs and Compression Ignition (CI) engines in Dual Fuel configuration, with the injection of a pilot fuel (MDO); nevertheless, ammonia is extremely toxic resulting in a challenging integration of the system on small craft likely to be used for passenger transport [8]. On the other hand, studies on marine ICE fueled by hydrogen are still ongoing both for SI and CI ICEs and commercial applications are not available. That is why methanol has been assumed as a suitable solution for High Speed Craft (HSC) application and a simulation of a SI methanol fueled engine is presented in this paper.

Methanol is an alcohol whose chemical formula is $CH_3OH$ and it is liquid at room temperature, making it suitable to be stored in common fuel tanks. This is a crucial advantage in the HSC as this type of vessels are particularly sensitive to displacement variations. As it has only one carbon atom (C), methanol cannot easily form pollutant compounds as PM (Particulate Matter) [9] which are characteristic of long-chain hydrocarbons and they are a major concern for HSC, expected to sail in coastal areas. The combustion process of methanol produces $CO_2$, but in a wider perspective, the life cycle emissions are strongly dependent on the production process: green methanol, which allows for a net-zero emission over the entire life cycle, can be obtained from biomass since the $CO_2$ emissions from the combustion are compensated by the $CO_2$ absorbed by the growing crops.

Methanol as fuel has a long history in the automotive industry while in the marine sector has been used as fuel for chemical (methanol) tankers and in a few recent cases for Ro-Pax vessels and new container ships. The research on methanol use as fuel onboard ships is going fast as it is suitable for different applications and converters. The recent development of new technologies such as the Fuel Cell has paved the way for new projects and opportunities. Fuel cells are a viable solution for yachts and small craft [10] as they ensure no noise and vibration. On the other hand, in applications where a higher power density is required (i.e. high speed craft), an ICE is considered to be the most suitable solution. Unfortunately, in literature there are few publications concerning marine engines running by methanol, most of which refer to technical and economic studies concerning the conversion to methanol (or dual-fuel) of two and four-stroke marine diesel engines [11].

In this work, starting from a marine four-stroke NG engine simulator (already developed from the authors in [12]), the same is converted to employ the methanol as fuel, in order to compare the NG engine performance with the methanol solution. The choice of starting from a NG engine is because NG engine thermodynamic cycle (Otto) is the same of the methanol one.

The development of a simulator, reproducing the whole behavior of a four-stroke engine, is particularly useful to assess the performance of high-speed vessels. Mainly in these applications, as planing and semi-planing hulls, the engine working points can significantly differ from the propeller curve traditionally considered in steady-state conditions. From this point of view, it is very important to analyze the behavior of the engine in its entire working area, especially for testing a new technology based on an alternative fuel such as methanol.

## 2. NG engine simulation model

Figure 1 shows the NG four-stroke engine Matlab-Simulink® model, already described and validated in a previous authors' work [12]. Therefore, no commercial software specifically dedicated to engine simulation [13, 14] has been used but each component and phenomenon have been simulated through mathematical approaches chosen by the code developers. The main drawback of this approach is the lack of an in-depth representation of the combustion process that does not allow, for example, the estimation of polluting emissions. However, this method allows a simpler use and computational management of the code, which can allow for example an adequate coupling between engine behavior and boat motions [15].

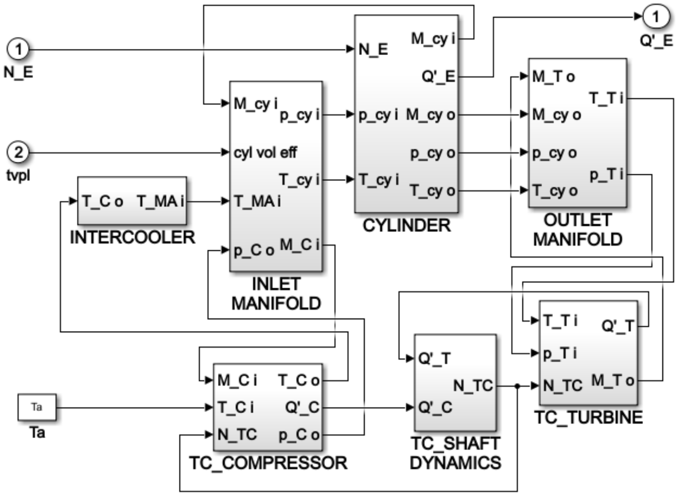


**Figure 1.** NG/methanol engine model in Matlab-Simulink® environment.

As shows in the figure, the engine model is organized in a modular form and each module simulates the performance of the pertinent engine component, i.e.:

- Cylinder
- Intercooler
- Inlet/outlet manifold
- Turbocharging (TC) compressor
- TC turbine
- TC shaft dynamics

Each model block is modelled by a filling and emptying zero-dimensional approach. Steady-state performance maps and algebraic/differential equations simulate the engine components performances. The ideal gas equation is adopted for the fluid model, with specific internal energy and enthalpy functions of both temperature and fluid composition.

A more detailed description of the engine simulator is reported in a previous paper of the authors [12], therefore, hereinafter a brief engine model description is just reported.

The main input data of the engine simulator are: geometric data, cylinders number, intake and exhaust valve characteristics together with opening/closing timing, compressor and turbine performance maps and rotor inertia, room temperature and fuel characteristics. The engine working condition is defined by the rotational speed and the throttle valve pressure loss. The main simulator output is the engine torque.

The cylinder actual Otto-Miller cycle is determined, as the variation of the crank angle value, by a single zone zero dimensional approach.

The Wiebe equation is adopted to the combustion heat release ($x_b$), determined for each value of the crank angle $\vartheta$:

$$dx_b = 1 - \exp\left[-a\left(\frac{\vartheta - \vartheta_{ign}}{\Delta\vartheta}\right)^m\right] \tag{1}$$

where $a$ and $m$ are numerical constants; $\vartheta_{ign}$ is the combustion start crank angle and $\Delta\vartheta$ is the overall combustion crank angle.

### *2.1. NG model application and validation*

The NG engine simulation is applied to Rolls-Royce Bergen series, NG marine C26:33L8PG [16], with Maximum Continuous Rating (MCR): 2430 kW@1000 rpm.

Simulation results, for different load and rpm values, are reported in [12], showing a good agreement between calculated and reference data: medium errors are less 2% with peak values less 4%.

## 3. Methanol engine simulation

The C26:33L9PG NG engine simulator is applied to simulate the same engine fueled by methanol. Tab. 1 reports the main characteristics data of the two fuels.

**Table 1.** NG and methanol data [11]

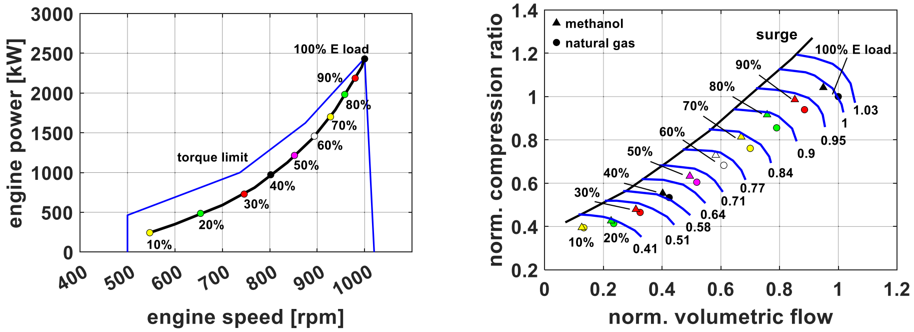
| Data | Natural Gas | Methanol |
|---|---|---|
| Carbon content (wt%) | 75 | 37.5 |
| Carbon content (wt%) | - | - |
| Lower heating value (kJ/kg) | 49000 | 20100 |
| Stoichiometric air fuel ratio | 17.5 | 6.5 |

The two engine simulators maintain the same thermodynamic cycle type (i.e. Otto-Miller), MCR speed and power, geometrical data and turbocharges characteristics. The methanol engine model tuning is finalized to obtain the better efficiency in all the considered working conditions and the same MCR brake power of the NG engine.

The changes in the NG engine original model to make it suitable for running by methanol are described in the following. As regard the equivalence ratio ($\varphi = \alpha_s/\alpha$, where $\alpha$ is the air fuel ratio and $\alpha_s$ the stoichiometric one), in the NG engine $\varphi$ is equal to 0.5 [12], while the methanol fuel mode requires $\varphi$ equal to 1 [17]. In both fuel modes, the respective equivalence ratio values are maintained constant in every working condition. After ignition, being the methanol flame propagation speed greater than NG one [9], in the Wiebe equation the combustion crank angle duration is 15% reduced in comparison with NG one. In order to obtain the same MCR brake power, in the methanol engine a different poppet valve tuning is adopted, to reduce the cylinder volumetric efficiency by increasing the inlet valve closing delay after the bottom dead center. Again compared to the NG engine, a new ignition start crank angle setting, versus engine speed, is defined in order to maximize the gross indicated mean effective pressure (i.m.e.p.) in all working conditions of the engine. In particular, the advance of the combustion start crank angle was reduced by $1 \div 1.5$ degrees, compared to the values used in the NG engine model.

## 4. Simulation results and comparison

In order to compare the results of the two simulation models and subsequently for a first validation of the methanol engine simulator, ten working conditions are considered, in terms of engine power and speed on the theoretical propeller curve. As shown in Figure 2a, the ten working conditions cover an engine power range between 10% and 100% of MCR, with steps equal to 10%. Being the methanol model derived from the NG one, with the same MCR, it is considered that also the torque limit curve in Figure 2a is common to the two fuel modes.

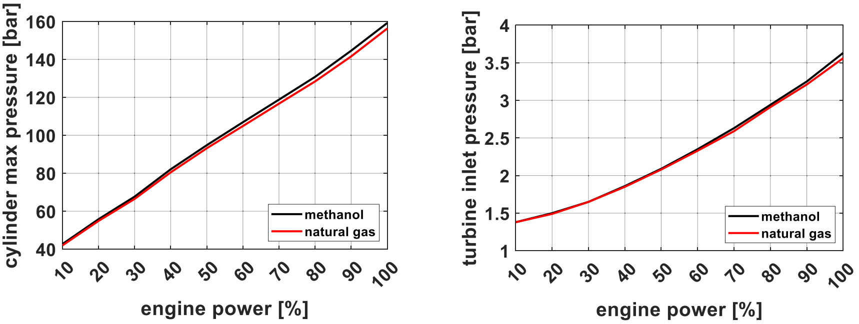


(a) (b)

**Figure 2**. NG and methanol working conditions in the load diagram (a) and compressor maps (b).

Figure 2b reports the ten engines working conditions in the turbocharger (TC) compressor maps, normalized by dividing each characteristic by the correspondent value referring to the MCR working condition in the NG mode. The figure shows that in the methanol mode, at the same engine load, the compressor works at a greater pressure ratio and a lower volumetric flow in comparison with the NG condition.

The higher air supply pressure in the methanol mode involves a higher maximum pressure inside the cylinders, as shown in Figure 3a, and consequently a higher pressure at the TC turbine inlet (Figure 3b).



a b

**Figure 3.** Cylinder maximum pressure (3a) and TC turbine inlet pressure (3b) in NG and methanol mode.

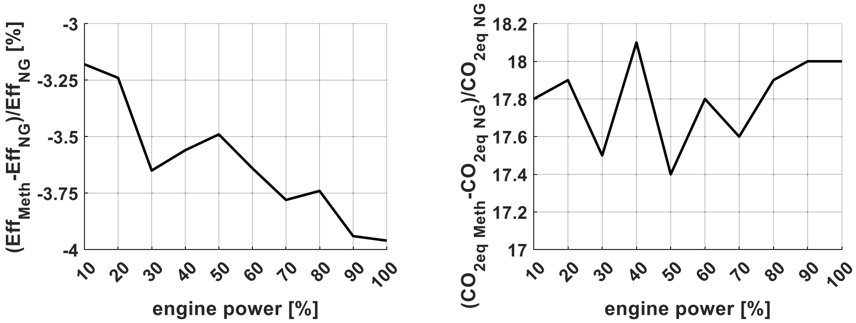
The engines efficiency ($\eta_E$) and its engine percentage difference ($\Delta x/x$) are expressed by:

$$\eta_E = \frac{P_E}{M_f H_i} \tag{2}$$

$$\frac{\Delta x}{x} = \frac{x - x_{NG}}{x_{NG}} 100 \tag{3}$$

where: $P_E$ is the engine brake power; $M_f$ and $H_i$ the fuel mass flow rate and its lower heating value respectively; $\Delta$ is the difference; $x$ is the generic variable and $x_{NG}$ the generic variable referred to the NG fuel at the same engine load of the variable $x$.

Figure 4a reports the percentage difference in engine efficiency of the two fuel modes:



a b

**Figure 4**. Percentage difference in engine efficiency (7a) and $CO_{2\,eq}$ emission (7b).

The data reported in Figure 4a show a greater efficiency of the NG engine; this difference decreases from about 4% up to slightly greater 3% as the engine load decreases.

The equivalent carbon dioxide ($CO_{2\,eq}$) mass flow rates are determined multiplying the Well-to-Tank carbon fuel coefficient ($CF_{eq}$) [18] of each fuel (NG and methanol) by the respective mass flow rate value.

Figure 4b reports a greater $CO_{2eq}$ mass flow rate of the methanol mode in comparison with NG, between 17.4% and 18.1%, depending on the engine load.

In order to assess the efficiency performance of a marine propulsion system, the whole fuel consumption map of the engine should be available, especially in high-speed planing hulls, where the required power of the propeller can significantly differ from the traditional cubic law. For this reason, Figure 5 shows the comparison in terms of NG specific fuel consumption between simulation results and data sheet, while Figure 6 illustrates the methanol fuel consumption map derived by simulation. From Figure 5 it is also possible to appreciate the reliability of the developed simulator for the NG mode, while some considerations about the numerical validation of the methanol engine model are reported in the next paragraph.

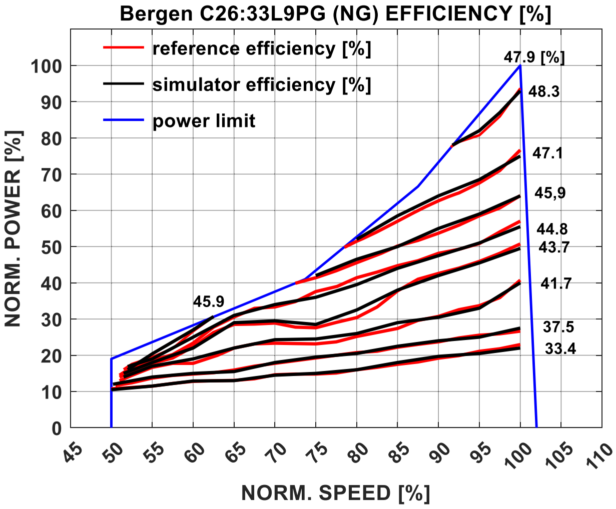


**Figure 5.** Specific fuel consumption map of the NG engine: comparison between data sheet and simulation.

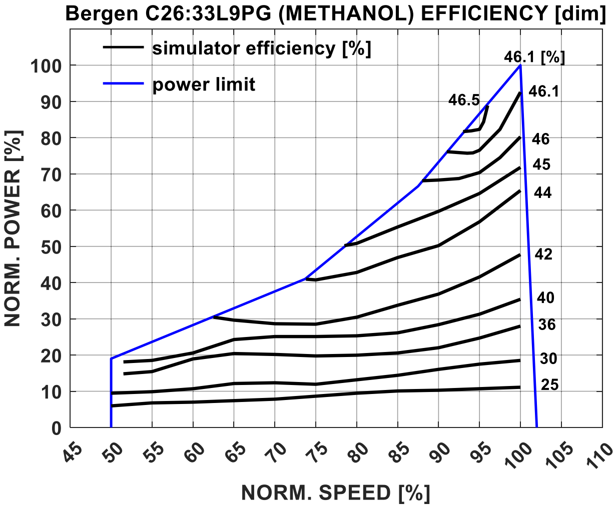


**Figure 6.** Specific fuel consumption map of the methanol engine

### *4.1. Methanol engine model validation*

In order to validate the methanol fueled engine mathematical model, the authors found in literature just one article [19] reporting data for the comparison between methanol and NG. Specifically, [19] reports data of a two-stroke engine MAN 9S90 ME-C, 37.62 MW@72 rpm, converted to operate by NG (using 1.5% MDO as pilot fuel) or methanol (5% MDO pilot fuel).

$CO_2$ emission data pertinent to methanol engine show a 29.2% emission value greater than NG fuel mode. The data displayed in Figure 4b show a difference in $CO_{2eq}$ emission between the two fuels of about 10% less, referred to the same difference values reported in [19], again in favor of NG. Considering the significant differences in power and working principles between the two engine types (i.e. two-stroke engine in [19], four-stroke engine in the present paper), the difference in $CO_2$ emission values between [19] and Figure 4b seems to provide a first positive indication regarding the reliability of the methanol engine simulator.

## 5. Conclusions

Starting from an existing marine four-stroke NG engine simulator, developed and already validated by the authors, the same thermodynamic model has been modified to predict the performance of the same engine powered by methanol, a fuel type that arouses much interest for an upcoming marine use.

All modifications made to the original model of the NG fueled engine are reported in this article together with the comparison of the simulations results, obtained by the methanol and NG engine models, for different values of the delivered power at different rpm. The comparison allows an evaluation of the differences that the two fuel types involve on the global performance of the two engines (i.e. overall efficiency, carbon dioxide emission) and on the main components (i.e. cylinder, TC compressor and turbine). Another interesting result of the study is the reproduction by simulation of the whole methanol fuel consumption map of the engine, particularly useful for a proper engine-propeller matching of planing or semi-displacement vessels.

Currently, the limited amount of information regarding the operating data of methanol fueled engines does not allow a detailed validation of the methanol engine simulation model, which the authors will carry out as soon as experimental data will be available.

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