2024 International Symposium on Power Electronics,
Electrical Drives, Automation and Motion

A preliminary numerical study of a medium speed marine engine fueled by methanol

1st Marco Altosole
Department of Industrial Engineering
University of Naples "Federico II"
Naples, Italy
marco.altosole@unina.it

2nd Maria Cristina Cameretti
Department of Industrial Engineering
University of Naples "Federico II"
Naples, Italy
mariacristina.cameretti@unina.it

3rd Ugo Campora
Department of Mechanical Energy Management and Transportation Engineering
University of Genova
Genova, Italy
ugo.campora@unige.it

4th Roberta De Robbio
Department of Industrial Engineering
University of Naples "Federico II"
Naples, Italy
roberta.derobbio@unina.it

5th Marco Palomba
Department of Industrial Engineering
University of Naples "Federico II"
Naples, Italy
marco.palomba@unina.it

6th Filippo Scamardella
Department of Industrial Engineering
University of Naples "Federico II"
Naples, Italy
filippo.scamardella@unina.it

***Abstract*— The work presents a study of a marine four-stroke medium speed engine fueled by methanol. This study arises from the current interest in developing marine engines with alternative fuels, such as methanol, verifying performance and polluting emissions, in particular CO_2 which also represents a cause of concern in the naval sector. Methanol is considered as a renewable energy source which features some better physicochemical properties compared to the traditional fossil fuels. In fact, methanol has higher laminar flame speed and wide lean-burn limitation, potentially reducing nitrogen oxides, carbon monoxide and unburned hydrocarbon emissions with a higher combustion efficiency. The used approach is based initially on a zero-dimensional model developed in Matlab©-Simulink© language and subsequently on a one-dimensional model through a commercial code that allows the entire engine to be simulated. The results provide the initial conditions for an in-cylinder CFD calculation, via the ANSYS FORTE® code, to study combustion in detail using an alternative fuel such as methanol and introducing adequate kinetic mechanisms. The obtained outcomes are compared with data referring to the same engine fueled by natural gas, available in the engine project guide.**

Keywords— Marine engine, Methanol, Natural Gas, Model, CO_2, Efficiency, CFD

I. Introduction

There is an increasing interest in developing marine engines that use alternative fuels like methanol to decarbonize the shipping sector. Although there are several solutions to make vessels more energy-efficient, the achievement of the goals set by international bodies requires a shift from traditional fossil fuels towards cleaner sources of energy. Methanol is considered a renewable energy source, having better physicochemical properties than traditional fossil fuels. It can be a viable solution to achieve the goal of net-zero Green House Gas (GHG) emissions from shipping pursued by the International Maritime Organization for 2050 [1]. Due to the imposition of stringent international regulations, the development of methanol fueled engines has in fact gained considerable attention, resulting in the study and implementation of several methanol-based solutions for marine ICEs. Methanol, thanks to its characteristics as a fuel, is well suited for use in spark ignition (SI) engines given the high Octane Number and high latent heat of vaporization. Nevertheless, the use of methanol in compression ignition (CI) engines has gained attention too, although it poses several challenges such as the high auto-ignition temperature (double of diesel) and the already mentioned high latent heat of vaporization [2]. These characteristics resulted in the need of a pilot fuel to activate ignition. The direct injection of methanol has been studied by Wartsila and tested in [3] on board a ferry, and MAN [4]. In spark ignition engines, methanol has been used during the 20th century as an anti-detonating agent in racing and aviation engines [5]. In the field of road traction, extensive field testing was conducted in the 1980s-1990s, using vehicles fueled with M85 blend (85% methanol in volume). More recent studies on automotive engines, [6]-[7], still do not exceed 85% and focus on emissions highlighting lower NOx, CO_2 and PM emissions.

Single-fuel engines have been analyzed too and have shown good combustion characteristics and emissions reduction. In [8] a comparison between methanol and gasoline on two flex-fuel engines showed relative efficiency benefits of about 10% for methanol, thanks to more isochoric combustion, less pumping, cooling, and dissociation losses. Lower combustion temperatures allowed also to reduce NOx emission by 5-10 g/kWh. In [9] emissions from a direct-injection spark-ignition methanol engine is analyzed concerning the effects of injection timing, ignition timing, and injection nozzle parameters achieving smokeless combustion and highlighting the importance of these parameters on the combustion and emissions. Regarding large-bore engines, two studies were found in the literature. In [10] a large-bore engine is tested with methanol to assess whether the positive effects seen on automotive engines can be reproduced on large-bore engines as well. The positive results on a 5 liters cylinder (Miller cycle) showed that detonation can be avoided and the use in even larger engines seems possible with a scavenged prechamber layout. The influence of prechamber is investigated in [11] where through a 3D model the influence of fuel-air ratio and ignition timing on combustion and emissions of a marine engine is analyzed by simulation. Both [10] and [11] show that the use of methanol can lead to the formation of formaldehyde potentially hazardous to human health.

In this context, the present work concerns the numerical study of a medium-sized marine engine powered by methanol, considered a fuel of interest in the marine field. The preliminary calculations performed for a maximum load operating point allow a comparison with natural gas (NG) which is the reference fuel for this engine, in terms of combustion characteristics and pollutants.

II. METHODOLOGY

The calculation methodology is based on the integration of different modeling approaches to overcome the absence of experimental data. In general, when the available experimental test cases do not allow an overall view of the engine behavior in its different operating conditions or with different fuels, and cannot provide appreciable inlet conditions in cylinder for 3-D combustion calculations, a one-dimensional model can be used [12]. By modeling the intake, combustion, exhaust system and turbocharger design appropriately, it enables to simulate a wide range of the engine operating conditions. Besides, the 1-D model can provide boundary conditions or in-cylinder initial conditions to CFD tool for in-cylinder three-dimensional computations. The 3-D CFD computations can perform a deeper investigation on the combustion phenomenon and pollutant formation, analyzing the most interesting operating conditions.

Preliminarily, a zero-dimensional model based on Matlab-Simulink tool allowed to verify the feasibility of using methanol as the single fuel for the tested engine. This latter analysis, conducted with reference engine data, provided key insights regarding the supercharging and equivalence ratio values suitable for methanol. Starting from these indications, the 1-D model reproduced various operating points to provide the initial conditions for the CFD calculation at intake valve closure (IVC). In Fig. 1, a simplified scheme of the integrated procedure is reported.

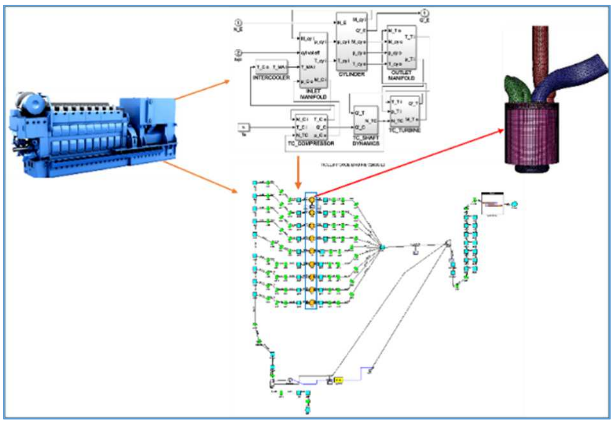

Fig. 1. *Simplified representation of the integrated procedure.*

A. Description of the engine

The engine object of study is a marine engine Rolls-Royce C26:33 L9PG [13] which is a 9-cylinder spark ignition engine supplied with natural gas as fuel injected in the intake manifold. The characteristics of the engine and operating conditions are listed in TABLE I. and TABLE II. .

TABLE I. ENGINE SPECIFICATIONS

Bore [mm]	260
Stroke [mm]	330
Displacement [l]	158
Compression Ratio	11:1
BMEP [bar]	18.5
Rated speed [rpm]	1000

TABLE II. FULL LOAD DATA

BMEP [bar]	18.5
Charge air pressure [bar]	3.8
Charge air temperature [°C]	55
Air flow rate [kg/h]	13100
Fuel flow rate [kg/h]	400
Temperature after turbine [°C]	365

III. ZERO-DIMENSIONAL MODEL

A natural gas four-stroke marine engine simulator developed in Matlab-Simulink® environment, previously described and validated by the authors [14], is shown in Fig. 2. This model was then tuned to be fueled by methanol. Each component and physical phenomenon were simulated using mathematical models chosen by the authors. This method has a major drawback of not providing an in-depth representation of the combustion process, that makes difficult the estimation of polluting emissions. Nevertheless, this approach reduces the computational burden of the code, allowing for an adequate matching between engine behavior and the propeller power request during ship motions. In the hypothesis of maintaining the same thermodynamic cycle, the engine was adapted for the use of methanol. The main changes concerned the Wiebe equation, where the combustion crank angle duration was reduced by 15% in comparison with NG one and the combustion start crank angle was reduced by 1÷1.5 degrees, compared to the values used in the NG engine model. The equivalence ratio (equal to 0.5) was not modified and kept constant in all working conditions. A new ignition start crank angle setting, versus engine speed, was defined in order to maximize the gross indicated mean effective pressure in all working conditions and to obtain the same MCR brake power; in the methanol engine a different poppet valve tuning was adopted, to reduce the cylinder volumetric efficiency [15].

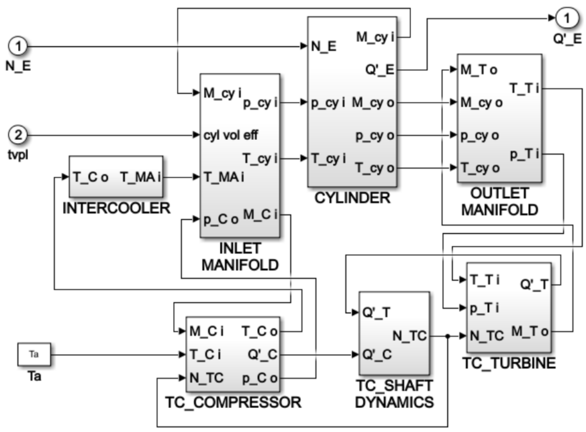

Fig. 2. 0-D model developed in Matlab-Simulink.

TABLE III. 0-D MODEL RESULTS

	0-D NG	**0-D Methanol**
Power [kW] / n[rpm]	2430 /1000	2430 /1000
Specific consumption [g/kWh]	153.2	398.2
BMEP [bar]	18.6	18.5
Efficiency [-]	0.48	0.461
Air flow rate [kg/h]	13160	12540

In TABLE III. the results obtained from the engine simulator in NG and methanol mode are compared.

Results show a slight reduction in efficiency at maximum load and almost analogue BMEP (Brake Mean Effective Pressure). The NG engine simulator has been previously validated through the performance map provided by the manufacturer. Fig. 3 points out a good superposition between the reference simulated maps, with errors below 5% [14].

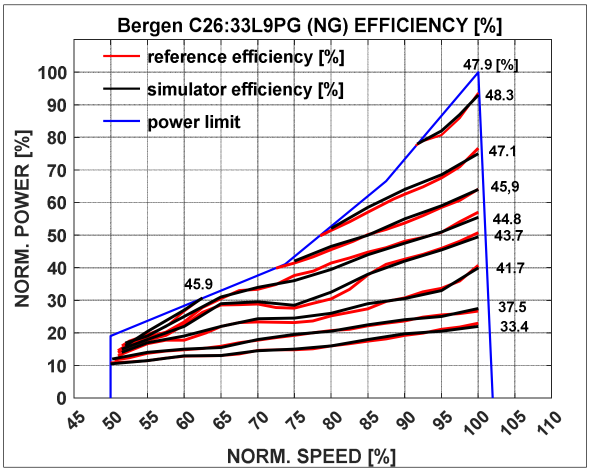

Fig.3 0-D NG model validation on the performance map [13].

IV. ONE-DIMENSIONAL MODEL

To simulate the entire engine more in detail, a 1-D model consisting of nine cylinders with a realistic firing order was created by using a commercial code (Fig.4).

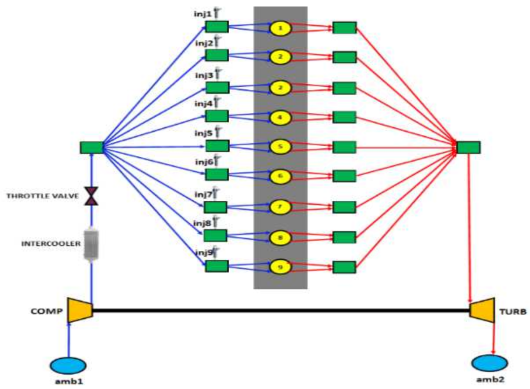

Fig.4 Schematization of the engine.

The 1-D approach used is non-predictive, meaning that combustion was simulated by imposing the Wiebe law (equation 1), which is the same as that used in the 0-D model. Heat transfer inside the cylinder is simulated using the Woschni model. Fuel is injected into the intake port upstream of each of the nine cylinders. Differently from the 0-D model, pressure drops are taken into account through the ducts and a proper valve lift law is considered for the intake and exhaust valves. Furthermore, the presence of the throttle valve can vary the load on the engine. Finally, compressor and turbine scaled maps from the 0-D calculation were used, as experimental data were not available.

$$x_b = 1 - exp\left[-a\left(\frac{\theta - \theta_0}{\Delta\theta}\right)^{m+1}\right] \qquad (1)$$

The fuel used is pure methane as the composition of natural gas is unknown, and initially the operating conditions refer to the maximum load (TABLE II) in order to compare the modelling results with the data supported by the engine technical manual, keeping a constant equivalence ratio (see equation 2) of approximately 0.5 and reducing the fuel flow rate to 368 kg/h to maintain the same input energy, as methane has a higher Lower Heating Value (LHV).

$$\varphi = \frac{\alpha_{st}}{\alpha} \qquad (2)$$

Then, other three operating points at several engine speeds and loads have been simulated with engine fueled by methane following the theoretical propeller curve (Fig. 5) to validate the model. The results are reported in TABLE IV.

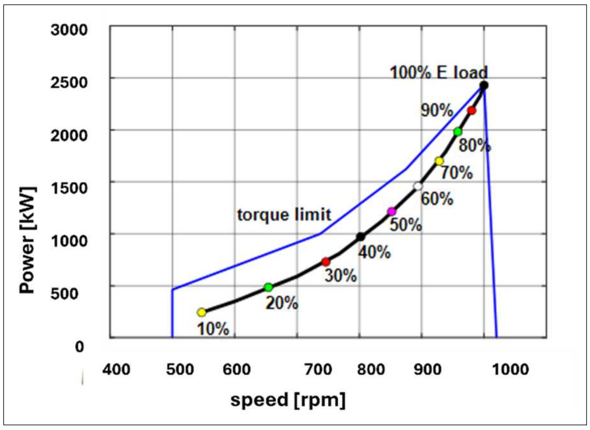

Fig.5. Theoretical propeller curve on the engine diagram.

TABLE IV. 1-D MODEL RESULTS WITH METHANE

	100% Load	80% Load	50% Load	20% Load
Power [kW] / n[rpm]	2430 /1000	1940 /982	1218 /852	493 /654
BSFC [g/kWh]	150.8	151.3	160.9	178.3
IMEP [bar]	19.3	16.2	12.2	7
BMEP [bar]	18.5	15.4	10.9	5.7
Efficiency [-]	0.477	0.475	0.447	0.404
Air flow rate [kg/h]	13536	10799	7157	3224
Fuel flow rate [kg/h]	368	294	196	88

In order to obtain the initial conditions for the CFD calculation at 100% load, the differences of the results between the nine cylinders were preliminary assessed. From the results obtained with the 1-D scheme, as expected, a slight lack of symmetry in terms of mass flow rates can be observed. As a consequence, the pressure curves in Fig. 6 display a minimal difference in terms of peak pressure (2.14%) and of Indicated Mean Effective Pressure (4.04%). This highlights how a detailed CFD combustion study, performed on a single cylinder, can still be significant.

Then, at full load by imposing the same boost pressure of 3.8 bar as in the methane case and targeting the same power, methane was replaced by liquid methanol. This substitution led to a more than doubled fuel flow rate due to the lower LHV (see TABLE V.). The inlet cylinder temperature decreased due to the vaporization of methanol. Additionally, more air was allowed to enter into the engine, resulting in a reduced overall equivalence ratio (about 0.35). However, under these conditions, despite the very lean mixture, it is demonstrated that methanol can burn completely [11].

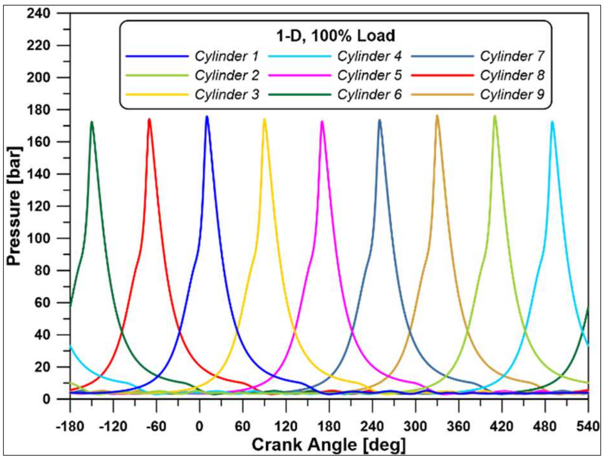

Fig. 6. Indicated pressure calculated in the nine cylinders.

TABLE V. 1-D RESULTS WITH METHANOL 100% LOAD

Power [kW] / n[rpm]	2430 /1000
BSFC [g/kWh]	340.6
IMEP [bar]	19.3
BMEP [bar]	18.5
Efficiency [-]	0.523
Air flow rate [kg/h]	15443
Fuel flow rate [kg/h]	831

To further investigate the behavior of methanol which has very different combustion characteristics from methane, a detailed study of this phenomenon is necessary, namely transitioning to a 3-D CFD simulation. For this calculation, the pressure and temperature conditions at IVC (135°BTDC) of cylinder#1 are considered, then matching the 1-D and multidimensional simulation aims to improve the predictive level of both types of modeling approach.

V. CFD MODELLING

Based on the geometry provided by the manufacturer (Fig. 7) [13], the computational domain consisting of a 30° degrees sector, including only the bowl and the cylinder, was created. Originally, a pre-chamber connected to the main chamber is present, useful to enhance the level of turbulence to ignite in-cylinder lean mixtures. However, for simplicity in these preliminary calculations, the authors have simulated the pre-chamber effects by increasing the level of turbulence to achieve values coherent with literature findings [11], although it does not faithfully reproduce the effects of a real pre-chamber. After a mesh sensitivity analysis, the selected mesh for the following calculations features an average dimension of the cells of 2.6 mm, in line with reference studies [16].

The CFD calculations were conducted via the Ansys FORTE code, which contains a solver for chemical reaction kinetics, employed to perform the CFD-chemistry coupled simulation. In TABLE VI the used models are reported, including the kinetics mechanisms employed for the two examined fuels. The mechanism of methane oxidation was tested in previous works by the authors [17], while the chemical kinetic mechanism for methanol by Pichler and Nilsson [18] is adopted. As mentioned above, the initial conditions at IVC for the three-dimensional calculation are retrieved from the one-dimensional model referred to the first cylinder. Initially, methane was considered, and the results were compared with engine reference data to validate the CFD model.

Then, by replacing methane with methanol, the operating conditions correspond to the engine working at the same boost pressure used in the original natural gas engine, mirroring the 1-D approach, and keeping the same spark ignition time (15°BTDC) of methane case.

Subsequently the calculations are performed by varying the excess air to verify the effect of the equivalence ratio on the development of methanol combustion at the same conditions. In TABLE VII the initial conditions obtained by 1-D model are reported for the five test cases, with pressure remaining constant at 3.95 bar.

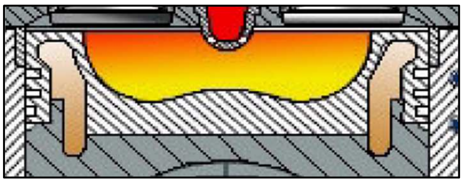

Fig. 7. Bowl geometry [13].

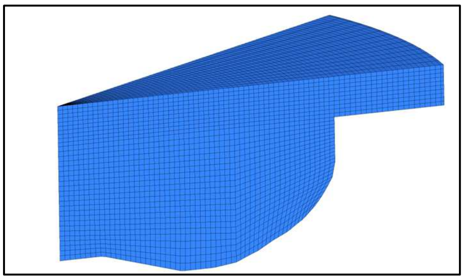

Fig. 8. Domain sector with computational grid.

TABLE VI. CFD MODELS

Fuel	**Kinetic mechanism**	**Turbulence model**	**Laminar flame speed**
Methane	GRI-Mech 3.0	RANS RNG K-ε	Power law formula
Methanol	Pichler [18]	RANS RNG K-ε	FORTE Methanol library

TABLE VII. CFD OPERATING CONDITIONS

Case	**Fuel**	**Temperature at IVC [K]**	**Energy Input [kJ]**	φ
1	Methane	391	69.66	0.46
2	Methanol	337	65.65	0.35
3	Methanol	337	69.27	0.37
4	Methanol	337	74.59	0.4
5	Methanol	337	83.36	0.46

A. CFD Results

Figs. 9 and 10 show the comparison of the in-cylinder pressures and heat release rates with the two fuels used by varying the equivalent ratio for methanol. Increasing the equivalent ratio higher peaks of pressure and heat release are achieved with methanol [19]. Comparing the results obtained with the two fuels, it is worth noting that the heat release rate profile produced by the methanol fuel oxidation has a faster gradient, as reported in [11] and earlier ignition, except in the case with the lowest φ (case#2).

The different combustion development is due to the different methanol characteristics such as the higher laminar flame speed (LFS), as shown in Fig. 11. In fact, the laminar burning velocity influences both the duration of the initial stage of combustion in spark ignition engines and, albeit at a lower level, the main combustion phase governed primarily by turbulent flame propagation [5]. For a detailed analysis of the combustion development, the maximum temperatures reached in the cylinder are shown in Fig. 12, while the temperature and fuel mass fraction distributions for several crank angles are displayed in Figs. 13 and 14. The images confirm that the combustion of methanol is faster and shorter than that of methane, with lower peak temperatures responsible for thermal NO formation.

In TABLE VIII the summary results are reported: the mass fraction burned (MFB) of methane is higher than that of methanol, except for case#2 where the very lean air-methanol mixture exhibits a different behavior.

Finally, comparing the results at the same fuel energy input (case#3), or at the same φ (case#5) with the methane case, methanol shows good efficiency with respect to power output at the expense of higher CO_2 production.

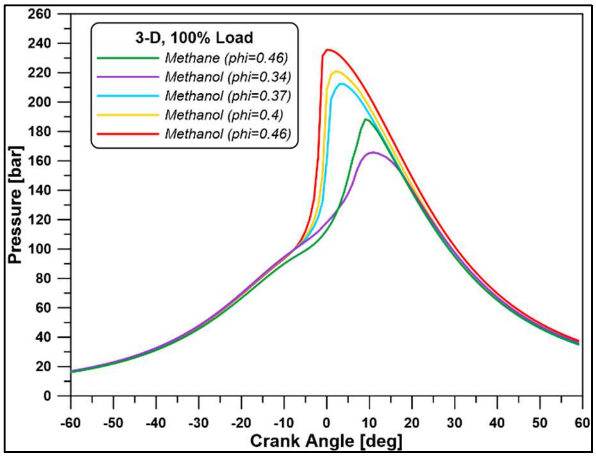

Fig. 9. *Comparison between methane and methanol pressure.*

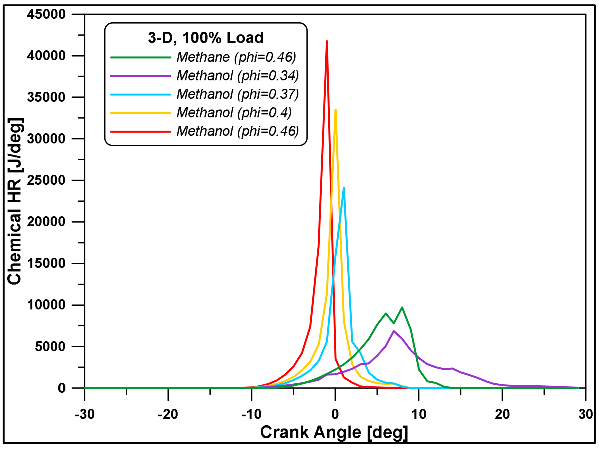

Fig. 10. *Comparison between methane and methanol RoHR.*

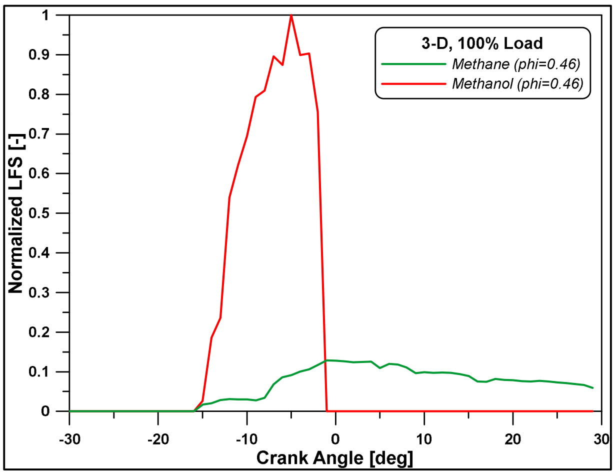

Fig. 11. *Comparison between methane and methanol LFS.*

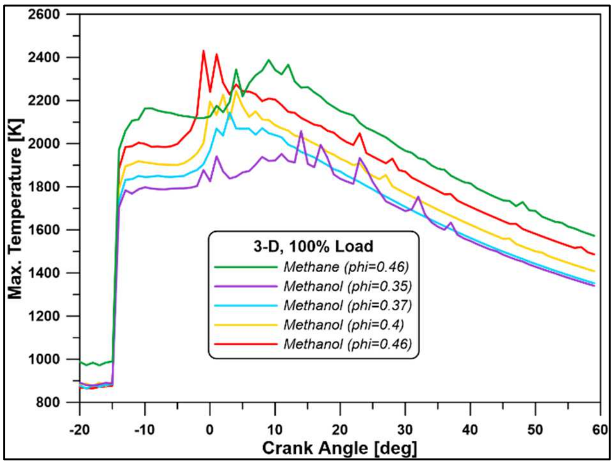

Fig. 12. *In-cylinder maximum temperature.*

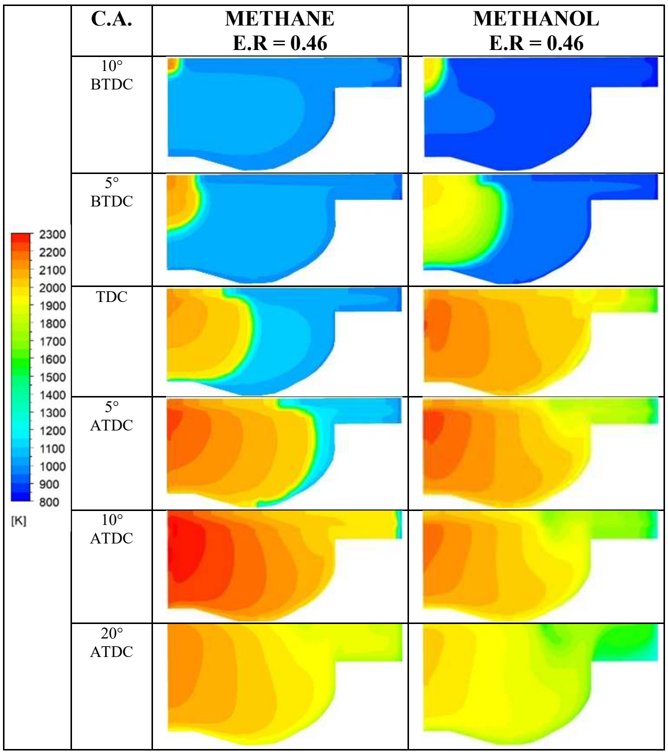

Fig. 13. *Distribution of in-cylinder temperature*

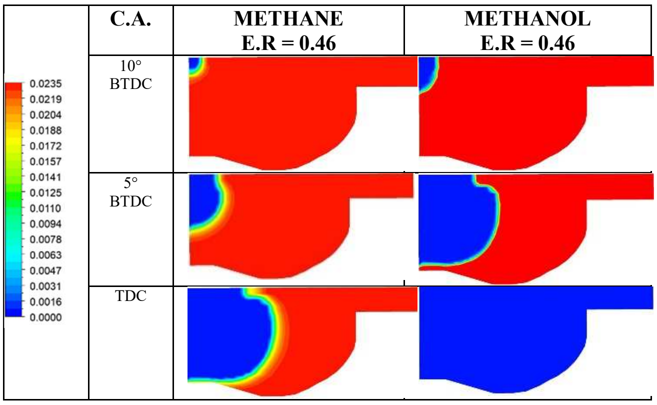

Fig. 14. *Distribution of in-cylinder fuel mass fraction*

TABLE VIII. 3-D MODEL RESULTS

Fuel Case φ	CH_4 *Case#1* **0.46**	CH_3OH *Case #2* **0.35**	CH_3OH *Case #3* **0.37**	CH_3OH *Case #4* **0.4**	CH_3OH *Case #5* **0.46**
Power [kW]	2440	2398	2377	2513	2722
BSFC [g/kWh]	154	342	361	388	434
CO_2 [g/kWh]	428	476	504	542	603
CO [g/kWh]	10^{-5}	1.43	$3*10^{-5}$	$5*10^{-5}$	1.25
Efficiency [-]	0.48	0.51	0.480	0.472	0.457
Ignition Start [°BTDC]	3	4	5	6	7
MFB 10-50	6°	7°	3°	2°	2.5°
MFB 50-90	3°	9°	2°	2°	0.5°

VI. CONCLUSION

The methanol fuel performance and emissions were investigated in a marine spark ignition engine using an integrated numerical approach. Preliminary, the authors implemented a 0-D model in Matlab-Simulink® environment able to reproduce the behavior of the engine in several operating conditions. An additional 1-D model, with a more complete description of the engine system, was used to accurately describe the entire engine and to provide initial input values for a single cylinder for subsequent CFD calculation.

The description of the combustion phenomenon with both methane and methanol was possible by a 3-D model by implementing appropriate chemical kinetic mechanisms and LFS correlations for the two fuels. The results obtained from the CFD model show how the different characteristics of methanol cause combustion to develop with higher pressure and rate of heat release peak and reduced combustion duration, maintaining in all cases a lean mixture. For methanol, an equivalence ratio sensitivity analysis was carried out (from 0.35 to 0.46) and as it increases, the pressure peak rises and the performance too, in accordance with what is reported in the literature. In terms of pollutant results, CO_2 emissions increase compared to the methane case, while for both fuels CO and HC present very low values, demonstrating a high combustion efficiency.

The positive response of methanol as pure fuel in this preliminary numerical study leads to refine the design of the complete pre-chamber cylinder system, to get closer to the real geometry, while also experimenting with other propeller conditions for the real application.

ACKNOWLEDGMENT

This research of University of Naples Federico II was supported by EU funding within PNRR project 'Centro Nazionale per la Mobilità Sostenibile' (CUP E63C22000930007), Mission 4, Component 2.

REFERENCES

[1] International Maritime Organization; 2023, MEPC 80/17/Add.1 report of the marine environment protection committee on its eightieth session.

[2] Karvounis, P., Theotokatos, G., Vlaskos, I., & Hatziapostolou, A. (2023). Methanol combustion characteristics in compression ignition engines: a critical review. Energies, 16(24), 8069.

[3] Fridell, E., Salberg, H., & Salo, K. (2021). Measurements of emissions to air from a marine engine fueled by methanol. Journal of Marine Science and Application, 20, 138-143.

[4] MAN Energy Solutions: The Methanol fuelled MAN B&W LGIM Engine, 2021.

[5] Verhelst, S., Turner, J. W., Sileghem, L., & Vancoillie, J. (2019). Methanol as a fuel for internal combustion engines. Progress in Energy and Combustion Science, 70, 43-88.

[6] Geng, P., Zhang, H., & Yang, S. (2015). Experimental investigation on the combustion and particulate matter (PM) emissions from a port-fuel injection (PFI) gasoline engine fueled with methanol–ultralow sulfur gasoline blends. Fuel, 145, 221-227.

[7] Zhang, Z., Wen, M., Cui, Y., Ming, Z., Wang, T., Zhang, C., ... & Liu, H. (2022). Effects of methanol application on carbon emissions and pollutant emissions using a passenger vehicle. Processes, 10(3), 525.

[8] Vancoillie, J., Demuynck, J., Sileghem, L., Van De Ginste, M., Verhelst, S., Brabant, L. V. H. L., & Van Hoorebeke, L. (2013). The potential of methanol as a fuel for flex-fuel and dedicated spark-ignition engines. Applied Energy, 102, 140-149.

[9] Gong, C. M., Huang, K., Jia, J. L., Su, Y., Gao, Q., & Liu, X. J. (2011). Regulated emissions from a direct-injection spark-ignition methanol engine. Energy, 36(5), 3379-3387.

[10] Güdden, A., Pischinger, S., Geiger, J., Heuser, B., & Müther, M. (2021). An experimental study on methanol as a fuel in large bore high speed engine applications–Port fuel injected spark ignited combustion. Fuel, 303, 121292.

[11] Leng, X., Deng, Y., He, D., Wei, S., He, Z., Wang, Q., & Zhu, S. (2022). A preliminary numerical study on the use of methanol as a Mono-Fuel for a large bore marine engine. Fuel, 310, 122309.

[12] Maria Cristina Cameretti, Roberta De Robbio, and Raffaele Tuccillo, Performance Improvement and Emission Control of a Dual Fuel Operated Diesel Engine, SAE paper 2017-24-0066.

[13] RollsRoyce, Project Guide C2633L BERGEN Gas ENGINE

[14] Altosole, M., Benvenuto, G., Campora, U., Laviola, M., & Zaccone, R. (2017). Simulation and performance comparison between diesel and natural gas engines for marine applications. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 231(2), 690-704.

[15] Acanfora, M., Altosole, M., Balsamo, F., Campora, U., Scamardella, F. A Methanol Fueled Marine Engine Simulator for Fast Craft Applications. In HSMV 2023: Proceedings of the 13th Symposium on High-Speed Marine Vehicles; IOS Press: Amsterdam, The Netherlands, 2023.

[16] Cuper-Przybylska, D., Nguyen V. N., Nam C. D., Kowalski, G. (2023). High Quality Multi-Zone and 3D CFD Model of Combustion in Marine Diesel Engine Cylinder. Polish Maritime Research, 30, 61-67. 10.2478/pomr-2023-0021.

[17] Cameretti MC, De Robbio R, Palomba M. (2023). Numerical Analysis of Dual Fuel Combustion in a Medium Speed Marine Engine Supplied with Methane/Hydrogen Blends. Energies (Basel). 16, 6651. 10.3390/en16186651.

[18] Pichler C, Nilsson EJK. Reduced kinetic mechanism for methanol combustion in spark-ignition engines. Energy Fuels 2018;32(12):12805–13.

[19] Xiaoyan Li, Xudong Zhen, Yang Wang, Zhi Tian, Numerical comparative study on performance and emissions characteristics fueled with methanol, ethanol and methane in high compression spark ignition engine, Energy 254 (2022) 12437, https://doi.org/10.1016/j.energy