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Numerical investigation of a premixed combustion large marine two-stroke dual fuel engine for optimising engine settings via parametric runs

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ABSTRACT

As the environmental regulations have become more stringent, the shipping industry has been focusing on more efficient and environmentally friendly means of propulsion and electric power generation. In this respect, dual fuel engines, which operate either in diesel mode or dual fuel (DF) mode by burning diesel fuel or natural gas and pilot diesel fuel to initiate ignition respectively, has become one of the most promising solutions as their dual fuel operation leads to reduced nitrogen oxide (NOx), carbon dioxide (CO_2), as well as almost elimination of particulate matter (PM) and sulphur oxide (SOx) emissions. The present study focuses on the comprehensive investigation of a large marine two-stroke dual fuel engine of the low gas pressure concept by using the GT-Power software. Appropriate combustion, scavenging, heat transfer and friction models were used to fully represent the engine performance and emissions characteristics, whereas a knocking model was employed to characterise the engine abnormal combustion. The simulation results were initially validated against the manufacturer data and subsequently, the entire engine envelope in both operating modes was simulated. The derived results were used for analysing and discussing the engine operation, performance and emissions as well as for comparing the two operating modes in terms of the turbocharger matching. In addition, a parametric investigation was performed in the dual fuel mode and the results were used for identifying the settings that can further optimise the engine operation in terms of CO_2 and NOx emissions trade-off. The results indicate that the CO_2 and NOx emissions can be simultaneously reduced; however, the engine optimisation in the high load region is challenging due to the permissible cylinder pressure constraint.

1. Introduction

Stringent environmental regulations have been implemented in the last decade by the involved international and national regulatory bodies to control the shipping NOx and CO_2 emissions as well as the fuel sulphur content and consequently, the related SOx emissions. Following the examples of the automotive and power generation industries, there is a strong indication that the future regulations will adopt stricter limits and will include additional pollutants (CO and PM). In this respect, Liquefied Natural Gas (LNG) that is considered a clean fuel compared to the conventional liquid fossil fuels, has been attracting the interest of the maritime industry as its use leads to the reduction of the greenhouse and non-greenhouse gaseous emissions [1]. With the fuel sulphur global limit of 0.5% (on mass basis) coming into effect on 1st January 2020 [2], the LNG fuel seems to be a viable solution for vessels sailing both inside and outside Sulphur Emission Control Areas (SECAs). At the same time the continuous rapid expansion of the global LNG infrastructure along with the lower LNG fuel price levels, is advantageous and renders LNG as an attractive green fuel alternative [3]. To address this and considering that marine two-stroke engines are the most commonly used solution for large merchant ships [4,5], the marine engine manufacturers have developed dual fuel (DF) versions of their engines which can operate either in diesel or dual fuel mode.

Two different pathways have been followed by the major two-stroke engine manufacturers. These include: (a) the high-pressure direct injection of natural gas within the engine cylinders leading to the

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Abbreviations: 0D, zero-dimensional; 1D, one-dimensional; 3D, three-dimensional; BMEP, brake mean effective pressure; BSEC, brake specific energy consumption; BSFC, brake specific fuel consumption; CA, crank angle; CFD, computational fluid dynamics; CO, carbon monoxide; CO_2, carbon dioxide; DF, dual fuel; EGR, exhaust gas recirculation; EV, exhaust valve; EVP, exhaust vale profile; FI, fuel injector; GI, gas fuel injector; IMEP, indicated mean effective pressure; IMO, international maritime organisation; LNG, liquefied natural gas; MCR, maximum continuous rating; MVEM, mean value engine model; NO, nitric oxide; NOx, nitrogen oxides; PI, pilot fuel injector, proportional-integral; PM, particulate mater; SECA, sulphur emission control area; SOx, sulphur oxides; SP, scavenging ports; TC, turbocharger; WG, waste gate

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Nomenclature

a_{kp}	model parameter [-]
b_{kp}	model parameter [-]
b	model parameter [-]
b_k	model parameter [-]
c	model parameter [-]
c_k	model parameter [-]
exh	exhaust gas
FF	fraction of fuel per Wiebe curve [-]
I_K	induction time integral [-]
k	model constant [-]
K	model constant [-]
mfr	mass flow rate [kg/s]
n	engine speed [r/min]
N_2	nitrogen concentration [mol/cm^3]
NO	nitric oxide concentration [mol/cm^3]
O_2	oxygen concentration [mol/cm^3]
p	pressure [bar]
P	power [kW]
P(k)	probability of knocking [%]
T	temperature [K]
TEbT	temperature of exhaust gas before turbine [-]
x_b	burned fuel rate [-]

Subscript

1	Zone 1
2	Zone 2
50 mfb	50% mass fraction burned fuel
75 mfb	75% mass fraction burned fuel
b	brake
comp	compression
i	index number of each Wiebe curve
max	maximum
ref	reference
scav	scavenging

Greek symbols

α	model constant [-]
α_k	model constant [-]
β	model constant [-]
γ	model constant [-]
Δ	change [-]
$\Delta\theta_{CD}$	combustion duration [degrees]
ε	compression ratio [-]
θ	crank angle [degrees]
θ_{CS}	crank angle at calculation start [degrees]
θ_{SOC}	crank angle at start of combustion [degrees]
θ_K	crank angle at which 'the critical pre-reaction level is reached [degrees]
λ	air-fuel equivalence ratio [-]

diffusive gas fuel combustion concept [6] and, (b) the low-pressure injection of the natural gas during the compression process resulting in a premixed combustion process [7,8]. Compared to each other, the former requires the use of exhaust gas after-treatment systems in order to fully comply with the environmental regulations for NOx emissions, whilst the low-pressure lean burn technology is sensitive to problems such as knocking and methane slip [9]. In both cases, the computational investigation of the engine operation in both modes is expected to provide insights for the engine characteristics, performance and emissions as well as the turbocharger (TC) matching, which has to accommodate the two different modes of operation.

Various modelling approaches have been extensively used for analysing the marine engines and ship propulsion systems. Generally, and depending on the type of application, the most common ones include: the cycle mean value engine models (MVEM), the zero- or one-dimensional models (0D/1D) and the three-dimensional models (3D). Each of these approaches vary in terms of complexity, computational time, expected accuracy, input data requirements and capabilities. Previous investigations using MVEMs for marine engines are reported in [10–12]. Various versions of combined zero/one-dimensional, and mean value/zero- dimensional engine models have been extensively used to investigate the performance and emission characteristics of marine engines as reported in [13–18]. Such approaches are usually preferred due to their trade-off between the needed model complexity, required input and computational time. The one-dimensional models are mainly used to represent the flow inside intake and exhaust pipes, pipe junctions and manifolds [19,20]. Three-dimensional (3D) computational fluid dynamics (CFD) modelling is also a more detailed method for simulating the engine operation typically used for the engine components design as it focuses in greater detail on the in-cylinder processes, where other approaches have limited applications. Examples of pertinent investigations that have developed 3D CFD models to examine the effects of combustion on the engine performance and its emissions are reported in [21–23].

With regard to the development of mathematical models for marine diesel engines, Theotokatos [11] reported the development of an in-house MVEM in the MATLAB/Simulink environment and its usage for studying the operation of a large marine two-stroke diesel engine. For the prediction of the steady-state performance and transient response of various engine configurations including four-stroke, two-stroke, Diesel, natural gas, turbocompound engines, etc., a detailed zero-dimensional code has been developed and used for a number of years in [24,25]. Scappin et al. [14] developed a zero-dimensional model of a marine two-stroke low speed diesel engine to predict its performance and NOx emissions. Savva and Hountalas [26] developed a pseudo-multi-zone model applied on large-scale two and four-stroke diesel engines for the prediction of NOx emissions at various operating conditions. Guan et al. [27] have developed a two-stroke engine model using a modular zero-dimensional simulation tool. Raptotasios et al. [28] applied a phenomenological multi-zone combustion model on a marine two-stroke diesel engine with the aim of predicting the exhaust gas recirculation (EGR) effect on NOx emissions and engine performance and investigating the in-cylinder combustion and NOx formation mechanisms. Wang et al. [29], developed a 0D/1D model of a marine two-stroke diesel engine in the GT-Power software and examined the effect of exhaust gas recirculation (EGR) combined with cylinder bypass (CB) and exhaust gas bypass (EGB) on NOx emissions. Cordtz et al. [30], developed a zero-dimensional multi-zone combustion model, based on experimental pressure traces, of a large low speed two-stroke diesel engine, to investigate the in-cylinder formation of gaseous sulphur trioxide (SO_3) by means of a detailed reaction mechanism. The same model was used by Cordtz et al. [31] to simulate the in-cylinder condensation of sulphuric acid and water vapour. Feng et al. [32], investigated the effect of EGR combined with Miller-cycle methods on NOx emissions by developing a combined 1D/3D model of a two-stroke marine diesel engine, using the AVL Boost and AVL FIRE simulation tools. In this investigation the output of the one-dimensional model was used to determine the initial conditions for the 3D CFD calculations. Moreover, Wei et al. [33], investigated the influence of the swirl flow and oxygen concentration on spray, combustion and emissions of a two-