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THE ANALYSIS OF THERMODYNAMIC PARAMETERS AND ENERGY EFFICIENCY IN A NAVAL SHIP'S ENGINE POWERED BY VLSFO AND MGO

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Abstract: Presentation of the current state of regulations on energy efficiency on board of sea-going ships and the issue of air pollution in the maritime domain, where the nominative energy efficiency index (EEDI), the vessel's energy efficiency management plan (SEEMP) and the operational efficiency indicator (EEOI) were scored. Analysis of thermodynamic parameters and energy efficiency in a marine engine powered dual by MGO and VLSFO. The case study is carried out on a container ship in the category of large ships with slow two-stroke engines MAN B&W 12K98 ME Engines.
The thermal calculation attached to the paper shows the following values of the thermodynamic parameters and energy efficiency for both fuel supply regimes VLSFO and MGO of the propulsion engine for the study vessel as presented
All calculations are done using the Main Engine's software and the PMI EDS Computer – PMI- Pressure monitoring Indicator and COCOS – Computer controlled Surveillance, EDS – Engine Diagnose System.
The purpose of these determinations was to highlight the differences of the two types of fuel under study by comparative analysis of thermodynamic parameters and energy efficiency, while following the effect of CO2 emissions in the gases of the engine.
The results obtained after analyzing all the factors in the study, the calculation of the thermodynamic parameters, of the operational energy efficiency indicator (EEOI) on the route presented, highlight the differences in the two types of fuels under analysis, such as the variation of exhaust gas temperatures for MGO and VLSFO depending on the load, the figures showing that with the increase in engine load, the exhaust gas temperatures for both fuels also increase used in the study, for MGO the lowest temperature values are recorded, the variation of the specific fuel consumption for MGO and VLSFO depending on the load and it is observed that with the increase of the engine load between 50-75%, the specific fuel consumption decreases for both fuels used in the study, moreover, when fueling the engine with MGO, the specific fuel consumption has the lowest values**.**

Key words: EEDI, EEOI, MGO, SEEMP, VLSFO.

1. INTRODUCTION

The current climatic conditions, which are constantly changing, worry the world. International entities have created various regulations, guidelines, recommendations and standards designed to guide, influence and encourage organizations in taking measures to reduce the amount of air pathogens in the form of greenhouse gases, especially from the combustion of the fuel in industries.

Seagoing vessels offer a significantly lower greenhouse gas and air pollution intensity than any other types of transport. However, it has been observed that there is a lot of progress to be made in reducing emissions by achieving a higher level of efficiency for each type of vessel. For example, in the container ships segment, the top 5% energy-efficient ships are 38% more carbon intensive than the industry average, while the bottom 5% emit 48% more carbon dioxide to move a unit of cargo over a certain distance.

The maritime industry is making great efforts to increase energy efficiency and reduce carbon emissions from new ships, and these efforts can extend to practical methods of improving fuel consumption. Shipping activities continue to grow at a rate that can outpace overall economic growth, placing great importance on energy improvements.

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At a global level, a combination of efficiency standards EEDIs and high technological penetration and operational practices should reduce carbon emissions by 2035-2040.

Mitigating the climate impact of the industry can be fully compatible with the basic purpose of business if properly addressed. As fuel costs erode the profitability of the maritime industry, increasing efficiency will become an important method of preserving profits.

2. ACTUAL STATE ON INCREASING ENERGY EFFICIENCY IN SHIPS

The climate changes that have occurred over the last few decades have drawn the attention to the importance of greenhouse gas emissions, with their reduction being a global priority. Since 1997, based on the Kyoto Protocol, UN member states have imposed, the reduction of greenhouse gas emissions by 5.2% between 2008 and 2012 compared to 1990. In 2012, this Protocol was extended until 2020 by the Doha Amendment. [1] The last UN climate conference was held in Paris in 2015, where an agreement was reached on keeping the increase in the global average temperature below 2°C, further limiting it to 1.5°C.[1].

This agreement will fundamentally change the way unsustainable economies act in terms of fossil fuel consumption over the coming decades. In this context, CO2 will become the target strategic priority, given the emissions from diesel engines that contribute significantly to the greenhouse effect. [2]

The transport services sector is one of the main producers of greenhouse gas emissions, which come from the exhaust gases of propulsion engines and diesel generators. Following evidence of CO2 emissions in 2013, it was estimated that shipping is responsible for 3.1% of total CO2 emissions worldwide. In addition, scenarios for future seagoing vessels show that by 2050 CO2 emissions could increase by 50% to 250% due to economic growth and the evolution of the global energy market. [6],[7]

In order to reduce greenhouse gas emissions from ships, the International Maritime Organisation IMO, as the body responsible for the international maritime transport regulations, imposed certain energy efficiency standards by Resolution MEPC.203 (62) of 2011.Thus, the energy efficiency standard imposed by the IMO is the Energy Efficiency Design Index EEDI, which is determined for each category of ship according to its type and tonnage. EEDI is expressed in grams of carbon dioxide gCO2 per ship capacity (DWT) and transport distance in Nautical miles. [3]

2.1 Energy Efficiency Index (EEDI)

EEDI is one of the technical measures on newer ships and aims to promote the use of engines and equipment that are much more energy-efficient and consequently less polluting. EEDI requires a minimum level of energy efficiency per mile capacity for different types of ships and size segments. From 1 January 2013, following a 2-year 0 phase, the design of new ships must meet the reference level for their type of ships. The level must be strengthened every 5 years, in this way EEDI is expected to stimulate continuous innovation and technological development of all components that contribute to the energy efficiency of a ship from the design phase. EEDI is a non-prescriptive, performance-based mechanism that allows technology to choose to use an industry-specific ship design. As long as the required level of efficiency is achieved, ship designers and builders are free to use the most cost-effective ship solutions in compliance with these standards. EEDI provides a specific figure for a specific ship design, expressed in grams of carbon dioxide per ship's capacity-mile (the lower the EEDI, the more efficient the ship design) and is calculated according to a formula based on the technical design parameters of that ship.

The CO2 reduction level grams of CO2 per tonne mile, for the first phase is set at 10% and will be lowered every 5 years to keep pace with the technological development of new efficiency and reduction measures. The reduction rate has been set until the period of 2025, and starting with, when a 30% reduction for the applicable ship types calculated from a baseline representing the average efficiency of ships built between 2000 and 2010 will be mandated. EEDI is developed for the largest and most energy-intensive segments of the world's merchant fleet and will encompass emissions from new ships, including the following ship types: oil tankers, bulk carriers, gas tankers, general cargo ships, container ships, refrigerated cargo carriers and combined cargo. In 2014, the MEPC adopted amendments to the EEDI regulations to extend it to natural gas, RO-RO, RO-RO passenger and cruise ships with unconventional propulsion [5]. These amendments meant that the ship types responsible for around 85% of CO2 emissions from international shipping are incorporated under the regulatory regime [6].

Also ship owners and other entities are studying the use of alternative fuels in present and future such as LNG, Methanol, Ethanol and Ammonia.

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2.2 Ship Energy Efficiency Management Plan SEEMP and Energy Efficiency Operational Indicator EEOI

SEEMP is an operational parameter that establishes a mechanism to improve the energy efficiency of a ship in a cost-saving manner. SEEMP also provides an approach for shipping companies to manage the efficiency performance of the vessel and fleet using, for example, the EEOI as a monitoring tool. The guidelines for the development of SEEMP for new and existing ships incorporate best practices for operating the ship in a fuel-efficient manner, as well as guidelines for the voluntary use of EEOI for new and existing ships. (MEPC 1/Circ.684). The EEOI allows operators to measure the fuel efficiency of a ship in operation and measure any changes in operation: better voyage planning, or more frequent propeller cleaning, or the introduction of technical measures such as wasted heat recovery systems or a new propeller. SEEMP urges ship-owners and operators at every stage of the plan to consider new technologies and practices when seeking to optimize the vessel's performance. [5]

3 PRESENTATION OF THE MODEL AND THE PROPULSION ENGINE UNDER STUDY

The study of this work is done on a container ship. Below are the main characteristics of the vessel, including technical data and main ship's particulars:

- Loading capacity: 11,384 TEU;
- Gross tonnage (GT): 131,332 t;
- Deadweight (DWT) (summer): 128.550 t;
- Overall Length (LOA): 363 m;
- Length between perpendiculars (LBP): 348 m;
- Maximum width: 45.6 m;
- Draft (DFT): 15.5 m;
- Depth (DPH): 29.74 m;
- Maximum speed (MAX Spd): 24.7 kts;
- Main engine: MAN B&W 12K98ME-C, 12-cylinder, slow, reversable,2 stroke with an output of 72,400 kW/ 98200 Bhp at 104 rpm. at 100% MCR; [3]
- Diesel generators: HYUNDAI-MAN B&W L27/38, 5 generators of: 2 sets of 2970 kW HYUNDAI-MAN B&W 9L27/38, 3 sets of 2200 KW HYUNDAI-MAN B&W 9L27/38;[4]
- Boiler: MISSION OS with a combustion capacity of 500 kg/h of fuel.

The engine is designed by MAN B&W, it's a crosshead engine, electronically controlled, two-stroke, directly reversible, turbocharged at constant pressure [3]. It is a slow revving 12-cylinder engine with a bore of 980 mm and a stroke of 2400 mm, reaching an output of 72,400 kW at 104 rpm. The engine is optimized at 85% SMCR so the specific fuel consumption at 90% SMCR when the engine operates in economy mode is 178.7 g/kWh. The ME engine concept consists of a mechanical hydraulic system for activating fuel injection and exhaust valves. The engine has individual units called HCU – Hydraulic Cylinder Units having Fuel Oil Boosters, Exhaust Valve Actuators, and FIVA - Fuel Injection Valve Actuator – a valve which controls the combustion process, nitrogen accumulators and the cylinder lubricator. The actuators are electronically controlled by a number of electronic units called MPC's (Multi-Purpose Controller) that form the complete engine control system ECS. MAN Diesel & Turbo specially developed both the hardware and the internal software to achieve an integrated solution for the ECS engine control system. The fuel pressure booster consists of a simple piston powered by a hydraulic piston activated by oil pressure. [3] The oil pressure is controlled by an electronically controlled proportional valve. The exhaust valve is hydraulically opened by a two-stage valve actuator activated by the control oil through an electronically controlled proportional valve. The exhaust valves are closed by the "air spring". In the hydraulic system, normal lubrication oil is used as medium. It is filtered by a fine filter with automatic discharge and pressurized by the hydraulic unit consisting of piston axial pumps - squash plate pumps mounted on the engine or placed in the machine room. The main start valves are pneumatically opened by electronically controlled "On/Off" valves, which make possible to dispense with the mechanically activated starting air distributor. Through the above electronic valve control, according to the measured instantaneous position of the crankshaft by angle encoders/crank angle sensors, the motor control system completely controls the combustion process [3].

4. THEORETICAL DETERMINATION OF THERMODYNAMIC PARAMETERS AND CO2 EMISSIONS OF THE ENGINE POWERED BY MGO AND VLSFO

Table 1. Chemical Proprieties of the Fuels

Fuel Type/Chemical Proprieties	VLSFO	MGO
Density at 15°C (ISO 3675) [kg/m3]	955	890
Viscosity at 50°C (ISO 3104) [mm2/s]	380	2
Cetane number	51,5	60
Carbon concentration	84	86

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[%]		
Hydrogen concentration [%]	12,4	12
Oxygen concentration [%]	0,6	1
Sulphur concentration (ISO 8754) [%]	0,5	0,05

It can be observed from the table of chemical characteristics of the fuels used the superiority of MGO in terms of fuel qualities, with low density and viscosity values compared to VLSFO compared to ISO standards.

For the thermal calculation, the initial parameters will be used as follows:

- Effective power: P ef = 72240 kW;
- strokes: $\tau = 2$;
- nominal speed: n = 104 rpm.;
- number of cylinders: I = 12;
- boost pressure: P b = 4·105 Pa;
- Stroke/bore ratio: $\psi_D = 1$.

Given that it's a naval propulsion engine, the engine's operation will be at atmospheric pressure at sea level: P0 = 1.01325·105 Pa.

As the temperature of the environment depends on a combination of factors, will adopt: T0 = 290 K.

The ratio of the 2 pressures (at the cylinder inlet and the initial pressure) represents the coefficient of decrease of the inlet pressure ζ_a. The adopted value is: $\zeta_a = 0.88$.

The residual flue gas temperature will be adopted in the range of T_r = 600... 900 K. The used value is: Tr = 900 K.

Upon contact with the hotter parts of the engine, the air blown by the turbocharger increases it's temperature by ΔT = 10... 20 K, will adopt ΔT = 10 K.

Inside the intermediate air cooler, a reduction in the temperature of the fresh fluid is ensured. This temperature drop can be ΔShot = 20... 100 K will adopt: ΔShot = 50 K.

The value of the excess air coefficient can be

$\alpha = 1.7...\ 2.2$.

For the supercharged engine, will adopt: $\alpha = 2$.

In the case of supercharged engines, the residual flue gas coefficient has the following values:

$\gamma_r = 0.01...\ 0,04$, will adopt: $\gamma_r = 0.02$.

The coefficients of the heat use in the two phases of combustion record the usual values:

$\xi_v = 0.75...\ 0.85$ and $\xi_p = 0.65...\ 0.75$.

Will use $\xi_v = 0.8$ and $\xi_p = 0.8$.

The rounding coefficient of the indicated diagram is the parameter that takes into account the differences between the actual and theoretical indicated diagrams of the operating cycle. Its usual values are: $\varphi_r = 0.96...\ 0.99$. Will be adopted: $\varphi_r = 0.98$; $\varphi_r = 0.98$

The mechanical efficiency of a marine diesel engine depends, first of all, on its type and construction. It is also influenced by other factors, such as: engine speed and load; the quality of the lubrication oil and the lubrication process. For supercharged, four-stroke engines, the experimental values of this parameter are: $\eta_m = 0.75...\ 0.92$. The value will be estimated: $\eta_m = 0.85$.

The ratio between the maximum volume of the combustion chamber V_a and its minimum volume Va is called the compression ratio:

$$\varepsilon = \frac{V_a}{V_c} . \quad (1)$$

The choice of value ε depends on the type of engine, its speed, the type of formation of the fuel mixture, the construction features, as well as a number of other factors. The adopted value is: ε = 12.

The ratio of crank radius to connecting rod λ_d = R / Lb takes values between 1/5.5 and 1/3. In our case, this ratio has the value: $\lambda_d = 0.25$.

The optimal injection feed is established experimentally when the prototype engine is on the test bench. For naval engines, β = 6... 40 °RAC, at nominal load. The value will be: β = 20 °RAC.

The total duration of combustion is considered as the algebraic sum of the injection feed, the fuel self-ignition delay angle and a correction angle with values of: ξ_θ = -3… +3 °RAC. Will use:

$$\xi_\theta = +\ 3\ °\text{RAC}. \quad (2)$$

The compression of the fresh charge in the supercharger/turbocharger is a polytrophic process whose exponent ns, for centrifugal blowers, takes values of 1.4... 1,8; it will be used: ns = 1.5.

The following values of the thermodynamic parameters and energy efficiency for both fuel supply regimes of the propulsion engine for the study vessel show the thermal calculation, as in the below table.

Table 2: Calculated thermodynamic parameters

Calculated parameters / Fuel type	**VLSFO**	**MGO**
Exhaust gas temperature [K]	671,571	670,214
Indicated yield	0,492810933	0,5053418
Effective Yield	0,41888	0,42954
Specific consumption indicated	0,18974111	0,1889

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[kg/kWh]		
Actual specific consumption [kg/kWh]	0,2232245	0,222238
Indicated power [kW]	84988.23 kW	78019.30 kW
Effective power [kW]	65327.85 kW	66316.26 kW
Engine load [N/ms]	1,4434612·104	1,4653006·104
Energy balance [kJ/h]	134337451	149109525
Mass of CO2 emissions [tonnes/h]	23,718	23,079

The results presented in Table 2 are subject to comparative analysis in graphical form as follows: The figures show that as the engine load increases, the exhaust gas temperatures for both fuels used in the study also increase. Moreover, when the engine is supplied with MGO, the lowest temperature values are recorded.

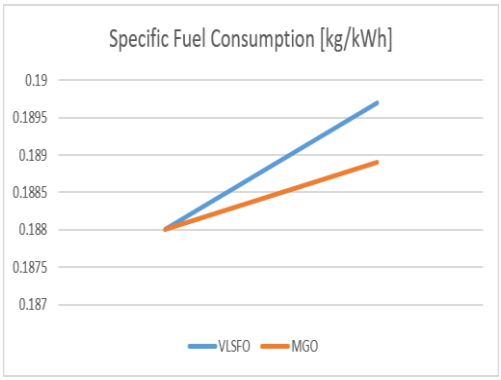


Figure 1 Analysis of the specific consumption indicated

In the case of powering the main propulsion engine ME with VLSO, an increase of the indicated specific fuel consumption SFOC can be observed.

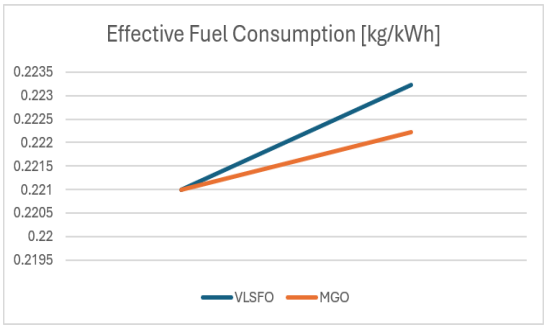


Figure 2. Analysis of actual specific consumption

In the case of powering the main propulsion engine with VLSO, an increase of the indicated specific fuel consumption can be observed.

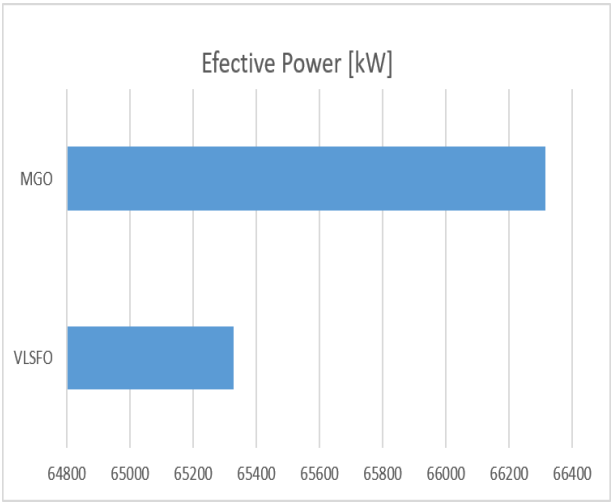


Figure 3. Sympathetic Effective Power Analysis

When the engine is powered by VLSFO, an increase in the Effective power may occur.

Although an increase in the indicated power is observed in the case of the indicated power when the engine is powered by VLSFO, the effective power is lower than that developed in the case of MGO power.

The variation in specific fuel consumption SFOC for MGO and VLSFO IS dependent on the load. We find out that with the increase in engine load between 50-75%, the specific fuel consumption decreases for both fuels used in the study. Moreover, when fuelling the engine with MGO, the specific fuel consumption SFOC has the lowest values. The increase in fuel consumption, with the increase in load, is due to the decrease in oxygen supply in the combustion process and therefore to the air/fuel ratio.

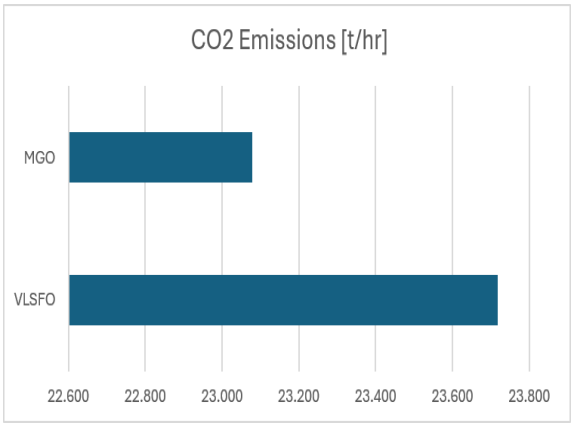


Figure 4. CO2 Emissions[t/hr]

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In view of the problem of air pollution in the maritime sector, the mass of CO_2 emissions resulting from the combustion of a fuel is an important factor in choosing the right engine fuel regime. As can be seen from the graph, the choice of MGO over VLSFO can decrease the impact that the same ship can bring to the environment by almost 20 tons of CO2 per day.[8]

5. CONCLUSIONS

The purpose of these determinations was to highlight the differences of the two types of fuel under study by comparative analysis of thermodynamic parameters and energy efficiency, while following the effect of CO2 emissions in the gases of the engine.

The calculations and analyses resulted in the following conclusions, further confirmed by previous researches:

CO_2 emissions increase with increasing load, both for MGO and VLSFO; CO2 emissions are lower than those used up in the case of diesel for the full range of loads; With the increase in engine load, the specific fuel consumption became lower for all fuels used in the study.

Moreover, for engine loads in the range of 50-75%, the specific consumption recorded the lowest values for both types of fuels used in the study. The lowest specific consumption was obtained for MGO.

In conclusion, it can be stated that the results obtained from the calculations are consistent with the results presented in the scientific literature. In addition, the use of MGO instead of VLSFO is a viable method of reducing emissions from exhaust gases belonging to marine engines.

6. CREdit authors statement

Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision;Validation; Visualization; Writing – original draft; Writing – review & editing: E.Z; L.C.S.

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