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Influence of Optimized Propulsive Efficiencies on De-carbonization of Ship Emission

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ABSTRACT

In this study, a detailed overview of carbon (IV) Oxide (CO_2) abatement potential through computer-based simulation of ship propulsive efficiencies and analyses with targets compatible with International Maritime Organization (IMO) long-term aim of keeping CO_2 emission low and contribute to maintaining the earth's surface temperature well below the catastrophic 2°C is presented. A tanker vessel-MT Diamond is selected as a case study. CO_2 emission reduction studies on propulsion systems conducted by several researchers are hinged on economic and efficiency factors,' route optimization, Engine-Propeller-Hull Matching (EPHM), trim, draft, and block coefficient optimization amongst others. As a result, credence in this direction of research is unavoidable and this research studied the correlation between ship CO_2 emission and ship propulsive efficiencies. The computational models and simulation for this work were brought to bear utilizing codes scripted in MATLAB. The models developed were implemented in MATLAB2018a to simulate the characteristics of some propulsion system efficiencies. Cumulatively, the study revealed that the optimal ship effective power is 8.20kW at a ship speed of 13knot coupled with a $0.049s^{-1}$ decay constant, the ship CO_2 emission level shows a commensurate improvement of 3.5% when the optimal overall ship propulsive efficiency is 50.7%*. Simulation conducted to reproduce the propulsion system characteristics and analyzed results to affirm the validity of the mathematical models. Also, the propulsion system parametric performance improvement shows a corresponding improvement in ship CO_2 emission level and specific fuel consumption (sfc).*

KEYWORDS: Simulation, Propulsive Efficiencies, CO_2 Emission, Modeling, Computational Analysis.

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1. INTRODUCTION

Many Countries has profited extensively from the use of fossil fuel energy for their unprecedented economic advancement. This has contributed to the rapid increase in carbon emissions. Even at lower CO_2 emission with respect to payload per unit mile, an estimated one billion tons of CO_2 per year and a total of 2.7% emission global CO_2 is attributed to commercial maritime fleet voyages and this is expected to increase in the future if concerted effort is not put in place to avert this catastrophic trend (Kadir *et al.*, 2019; Dey *et al.*, 2021). The concept of net zero emissions as envisioned, means striking a balance between greenhouse gases emitted and those extracted from the atmosphere. Under the Paris Agreement of 2015 and reiterated in Glasgow in 2022, approximately 197 countries have agreed to keep surface temperature rise "consciously below" 1.5°C to avoid severe consequences of climate change. Similarly, global net human-caused emissions of CO_2 would need to fall by approximately 45% by 2030 as against the 45% stipulated in 2010, reaching net zero around 2050. This therefore implies that any remaining emissions caused by human activity that cannot be abated, will need to be stabilized by removing from the atmosphere the CO_2 remnants.

Obviously, if there is no abetment to this trend, the world is predicted to be extremely hot in year 2100 (Kadir *et al.*, 2019). At a $+2.4°C$ rise in surface temperature, the world will experience acute water shortages, rise in sea levels, coral reefs will disappear, and natural disaster will be prevalent affecting shipping to a significant extent (Kadir *et al.*, 2019). Similarly, at $+6.4°C$ rise in earth's surface temperature, migrations will begin. Massive exodus of people will fall on migration routes hoping to avoid unfavourable climatic conditions (Kadir *et al.*, 2019). To rescind this track and avert global catastrophe, CO_2 emissions from maritime fleet must be reduced exigently.

Recently, to tread on this path of emission abatement, research on CO_2 emission from maritime transportation has been an extremely hot topic of interest. Most scholars have focused on the economic and efficiency factors' (Yu *et al.*, 2022). There are also suggestions for the control of peak energy consumption to balance cost and emissions, noting that peak shaving is one of the effective operations in daily port management (Zhu *et al.*, 2022). Some researchers have suggested the retrofitting of cranes and the deployment of a new liquefied natural gas tractor, which contributes to CO_2 emissions reduction (Martínez-Moya *et al.*, 2019). Several researchers have done work on port operation and route optimization, while some others focused on Engine-propeller-hull matching (EPHM) and optimization to reduce the load on the prime mover. This translates to reduced specific fuel consumption (sfc), improved ship Energy Efficiency Design Index (EEDI) and CO_2 emission reduction. The establishment of "Emission Control Areas (ECAs)" can also effectively reduce emissions from ships in port waters (Tan *et al.*, 2021).

The propulsion system helps them to move from one location to another. Higher requirements are placed on the propulsion system design to meet certain criteria such as: load on the engine, sfc and low emission regulations which is an indication of ship's energy efficiency (Odokwo, *et al.*, 2022). Since engine CO_2 emissions are related to the load on the engine and the engine power engaged for achieving the desired ship speed (Golam-Zakaria & Sohanur, 2017), to mitigate CO_2 emission from ships, the propulsion system performance and efficiency require greater attention. The findings of the present study revealed that there are still insufficient explorations of multi-level driving factors that potentially influence CO_2 emissions in the fields of economy and transportation. It therefore makes engineering sense to take advantage of the opening provided in this field to fill the research gap made available. Based on the above, this work proposed an analytical framework of propulsive efficiencies as a driving factor in CO_2 emission reduction in the marine environment. Attention in this regard will be given to performance parameters that influence the overall performance of the ship propulsion system.

2. MATERIALS AND METHODS

An optimized ship propulsion system is evaluated and its influence on ship emission is analyzed. This will provide a rational platform for a digital technology-based performance assessment of marine propulsion system and demonstrate marked advantage of software prowess in addressing propulsion system performance characteristics. The prime mover and transmission system will be modelled using Mean Value Engine Method (MVEM), thermodynamics and energy balance equations while the propeller will be modelled adopting the dimensionless coefficients based on the polynomial equations for Wageningen B propeller series. A detailed program code scripted in MATLAB was developed and implemented to simulate the behavior of the propulsion system to achieve the best performance scenario and understand its robustness on CO_2 emissions and sfc.

2.1 Modelling of the Propulsion System and Interaction

A schematic diagram of the propulsion system interaction as adopted for this research is shown in Fig. 1. The models of the ship propulsion system will be implemented via a computer-based program and simulated. Optimization is performed using Artificial Neural Network (ANN)

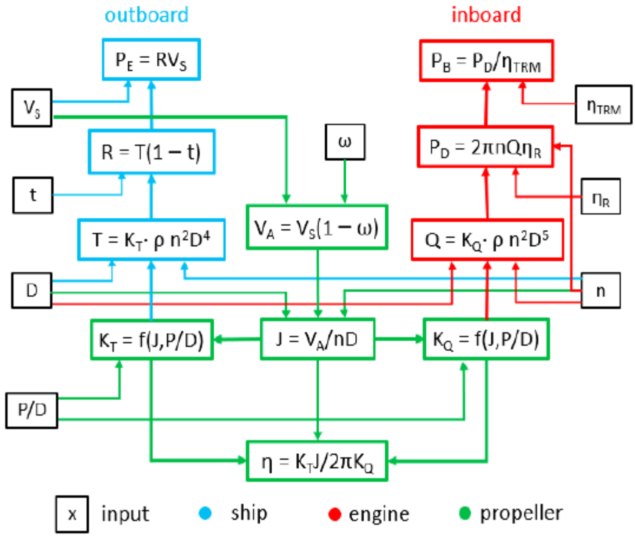

Fig. 1: Schematic Diagram of MT Diamond Propulsion System Interaction

For the purposes of this research, a schematic diagram of the prime mover shown in Fig. 1 is adopted for the modelling. The modelling will be carried out in segments for mathematical convenience and simplification to capture paramount performance parameters.

Important performance parameters of the diesel engine relevant to this work are captured in the modeling. The argument in favour of this approach is its ability to capture, predict and represent the engine parametric characteristics with sufficient accuracy and speed, while requiring limited amount of input data and quite a reasonable time of execution (Odokwo *et al.*, 2022).

2.1.1 Prime Mover Modelling

The overall turbocharger efficiency, η_{TC} is estimated from a relationship derived by the application of thermodynamic and energy balance as given by Vladimir *et al*. (2020) as shown in equation (1):

$$\eta_{TC} = \left(\frac{\dot{m}_a}{\dot{m}_g}\right)\left(\frac{C_{pa}}{C_{pg}}\right)\left(\frac{T_{c_1}}{T_{t_3}}\right)\left[\frac{\left(\frac{P_{c2}}{P_{c1}}\right)^{\left(\frac{\gamma_c-1}{\gamma_c}\right)}-1}{1-\left(\frac{P_{t_4}}{P_{t_3}}\right)^{\left(\frac{\gamma_g-1}{\gamma_g}\right)}}\right] \qquad (1)$$

Where: $\dot{m}_a = mass\ flow\ rate\ of\ air$,
$\dot{m}_g = mass\ flow\ rate\ of\ exhaust\ gas$
$C_{pa} = Specific\ heat\ capacity\ of\ air$
$C_{pg} = Specific\ heat\ capacity\ of\ exhaust\ gas$
$T_{c_2} = Compressor\ Temp.output$
$T_{c_1} = Compressor\ Temp\ input$
$\gamma_c = Compressor\ gas\ index\ of\ compression$
$\gamma_g = Exhaust\ gas\ index\ of\ expansion$

$P_{c1} = Compressor\ inlet\ pressure$
$P_{c2} = Compressor\ outlet\ pressure$
$P_{t3} = Turbine\ intlet\ pressure$
$P_{t4} = Turbine\ outlet\ pressure$

Similarly, the engine and propulsion shaft speed according to Guan *et al*. (2015) and Theotokatos, (2010) is obtained from the expression in equation (2):

$$\frac{dN_E}{dt} = \frac{30(\eta_s \eta_{GB} Q_E - Q_p)}{l_E + l_{GB} + l_s + l_p} \qquad (2)$$

For two stroke diesel engine, there are no installation of reduction gear box, then the respective terms in equation (2) are: $\eta_{GB} = 1 \; and \; I_{GB} = 0$ respectively

The engine volumetric efficiency which is an indication of the 'breathing' capability of the engine, is given by equation (3):

$$\eta_v = \frac{10 \dot{m}_a}{6 \rho_a N_E n \left(\frac{\pi D^2 L}{4} \right)} \qquad (3)$$

Kamal & Hui (2013) provides the relationship for obtaining the engine brake power, and it is given by:

$$B_p = \frac{5 P_b L \pi D^2 N_E K}{12} \qquad (4)$$

Brake-specific fuel consumption (*bsfc*) which is a measure of the fuel efficiency of any prime mover is given by:

$$bsfc = \frac{3.6 \times 10^6}{\eta_b \times Q_L} \qquad (5)$$

A relation for brake thermal efficiency of the prime mover is obtained as shown in equation (6):

$$\eta_b = \frac{3600 \times Brake\ Power}{Feul\ Energy} = \frac{3600 B_P}{\dot{m}_f Q_L} \qquad (6)$$

2.1.2 Hydrodynamic Modelling of the Propeller

Dimensionless coefficients based on the polynomial equations for Wageningen B propeller series will be applied in modeling the propeller. These non-dimensional parameters are propeller advance ratio (J), propeller thrust (K_T) and torque coefficient (K_Q) according to Odokwo *et al.* (2022) is defined by the expressions of equations (7), (8) and (9) respectively:

$$J = \frac{V_A}{n_P \times D_p} = \frac{V_s \cdot (1-\omega)}{n_P \times D_p} \qquad (7)$$

$$K_T = \frac{T_p}{\rho_{sw} \times n_p^2 \times D_p^4} \qquad (8)$$

$$K_Q = \frac{Q_p}{\rho_{sw} \times n_p^2 \times D_p^5} \qquad (9)$$

The propeller open water efficiency (η_0) which is imperative and regarded as the goal of matching is given by equation (10):

$$\eta_0 = \frac{K_T}{K_Q} \cdot \frac{J}{2\pi} \qquad (10)$$

Considering the mechanical efficiency of the shaft line, the ship propulsive efficiency (η_P) is obtained from the relationship given in equation (11):

$$\eta_P = \frac{P_E}{P_D} = \eta_D \times \eta_s = \eta_H \times \eta_o \times \eta_R \times \eta_s \qquad (11)$$

To estimate the total ship propulsion system efficiency, the quotient of ship effective power and the engine fuel power given by equation (12):

$$\eta_{sp} = \eta_b \eta_P = \eta_b \times \eta_H \times \eta_o \times \eta_R \times \eta_s \qquad (12)$$

2.2 Propulsive Efficiencies and Ship Emission Modelling

Legislation introduced by IMO for calculating energy efficiency of vessels is hinged on the mitigation of CO_2 through EEDI which estimates the amount of CO_2 emitted. Therefore, the lower a vessel's EEDI, the lower the emitted CO_2. This translates to minimal ship emission level. Therefore, ship emission (i.e., CO_2 emission) is synonymous to EEDI. The CO_2 emitted from the ship, have its source from the prime movers with the rate of emission varying as the load on the prime mover also varies. Reduced load on the engine certainly curtails the emission level of the ship. Improving the propulsive efficiencies helps in achieving this aim. In its simplest form ship emission is represented by the quotient of emitted CO_2 to the transport work shown in equation (13):

$$Ship\ CO_2 Emission = \frac{(f_j \times P_{ME} \times SFC_{ME} \times C_{f_{ME}}) + (P_{AE} \times SFC_{AE} \times C_{f_{AE}})}{f_i \times f_c \times f_w \times Dwt \times V_s} \qquad (13)$$

Where: Dwt = ship Capacity

2.2.1 Modelling ship CO₂ Emission and Propeller Open Water Efficiency

In studying and understanding the relationship between ship CO₂ emission and propeller open water efficiency η_0, the sfc is usually assumed as a constant. Taking this into consideration, the EEDI formula can be represented by equation (14):

$$Ship\ CO_2 Emission = \frac{K_1 \times P_{ME} \times K_2}{K_3 \times Dwt \times V_s} \tag{14}$$

Where: $K_1 = f_j \times SFC_{ME} \times C_{f_{ME}}$

$K_2 = P_{AE} \times SFC_{AE} \times C_{f_{AE}}$ and

$K_3 = f_i \times f_c \times f_w$

Specifically, from the propulsion energy chain, power from the main engine, P_{ME} can be calculated from the vessel's effective power and certain related efficiencies according to Huilin *et al.* (2019) as given in equation (15):

$$P_{ME} = \frac{P_E}{\eta_s \times \eta_D} = \frac{P_E}{\eta_s \times \eta_H \times \eta_O \times \eta_R} \tag{15}$$

With appropriate substitution and evaluation, the EEDI will be given by equation (16):

$$Ship\ CO_2\ \text{emission} = \frac{K_6}{\eta_O} + K_7 \tag{16}$$

Where: $K_6 = \frac{K_4 \times P_E}{V_s \times capacity \times \eta_O}$ and $K_7 = \frac{K_5}{capacity \times V_s}$

Equation (16) provides an inversely relationship between open water efficiency, η_O of a propeller ship emission. Meaning that the process to achieve the maximum open water efficiency translates to obtaining a minimum emission level from the ship.

2.2.2 Modelling Ship CO₂ Emission and Propulsive Efficiency

According to Inegiyemiema & Odokwo (2018), the power developed by the main engine is given by the expression in equation (17)

$$P_{ME} = \frac{P_E}{\eta_s \times \eta_D} \tag{17}$$

With appropriate substitution, the power developed by the main engine is related to the propulsive efficiency as given by equation (18):

$$P_{ME} = \frac{P_E}{\eta_s \times \eta_D} = \frac{P_E}{\eta_s \times \eta_H \times \eta_R \times \eta_O} = \frac{P_E}{\eta_p} \tag{18}$$

Simplifying further, equation (18) will yield equation (19):

$$Ship\ CO_2\ \text{emission} = \frac{K_8 \times P_E}{\eta_p} + K_9 \tag{19}$$

Where: $K_8 = \frac{f_j \times SFC_{ME} \times C_{f_{ME}}}{f_i \times f_c \times f_w \times \eta_p \times V_s \times Capacity}$ and

$K_9 = \frac{P_{AE} \times SFC_{AE} \times C_{f_{AE}}}{f_i \times f_c \times f_w \times V_s \times Capacity}$

Equation (19) shows that EEDI is inversely proportional to the vessel's propulsive efficiency as expressed in equation (20):

$$Ship\ CO_2\ \text{emission}\ \alpha\ \frac{1}{\eta_p} \tag{20}$$

2.2.3 Modelling Ship CO₂ Emission and Overall Ship Propulsive Efficiency

The overall efficiency of a ship (η_{ship}) is the ratio of the work output to the work input or energy input expressed mathematically by equation (21):

$$\eta_{ship} = \frac{P_E}{\dot{m}_f \times LCV} = \frac{P_E}{Q_f} \tag{21}$$

Substituting appropriately and according to Gerasimos & Vasileios (2016), the overall efficiency of a vessel is given by the relationship of equations (22):

$$P_{ME} = \frac{P_E}{\eta_s \times \eta_H \times \eta_R \times \frac{\eta_{ship}}{\eta_b \times \eta_H \times \eta_R \times \eta_s}} = \frac{\eta_b \times P_E}{\eta_{ship}} \tag{22}$$

Keeping other parameters and terms constant and simplifying equation (22) further yields the expression relating $Ship\ CO_2\ \text{emission}$ and overall ship efficiency as given by equation (23):

$$Ship\ CO_2\ \text{emission} = \frac{K_{10} \times P_E}{\eta_{ship}} + K_{11} \tag{23}$$

This shows that $Ship\ CO_2\ \text{emission}$ is inversely proportional to the overall vessel's efficiency as expressed in equation (24):

$$Ship\ CO_2\ \text{emission}\ \alpha\ \frac{1}{\eta_{ship}} \tag{24}$$

Where: $K_{10} = \frac{f_j \times \eta_b \times SFC_{ME} \times C_{fME}}{f_i \times f_c \times f_w \times V_s \times Capacity}$ and

$$K_{11} = \frac{P_{AE} \times SFC_{AE} \times C_{fAE}}{f_i \times f_c \times f_w \times V_s \times Capacity}$$

3. RESULTS AND DISCUSSION

A dominant factor in ship propulsion system formulation is the installed power of the vessel. This parameter is determined by the design speed, the efficiency of the hull and propulsion system which undoubtedly impact relatively on the sfc and EEDI. To achieve low sfc and an improved ship CO_2 emission at the designed speed of a vessel, it requires certain critical performance parameters of the propulsion system to be numerically analyzed and simulated. It is on this premise, that a thorough investigation of the robustness and effect of propulsive parametric series of a ship propulsion system using script coded in MATLAB was evaluated and analyzed. To keep the scope of this research within reasonable limits, attention is given to performance parameters that influence the overall performance of the propulsion system. In analyzing the propulsion system model with respect to performance parameters of interest and to ascertain the suitability of the models for engineering application, a computer-based simulation was conducted. This gives the basis for computation, data generation and assessment of the characteristics of the propulsion system parametric performance with CO_2 emission in view.

Hence, performance characteristics of the brake specific fuel consumption (bsfc), brake thermal efficiency (η_b), propulsive efficiency (η_P), overall ship efficiency (η_{ship}) and ship CO_2 emission which constitutes the fundamentals of this work is presented. Fig. 2 shows a computational framework for the propulsion system analysis and simulation. Results from the simulation show that the model predicts the performance output of the system with a high degree of accuracy. Also, improvement in the propulsion system performance parameters gives a commensurate improvement in the ship emission level and sfc of the vessel.

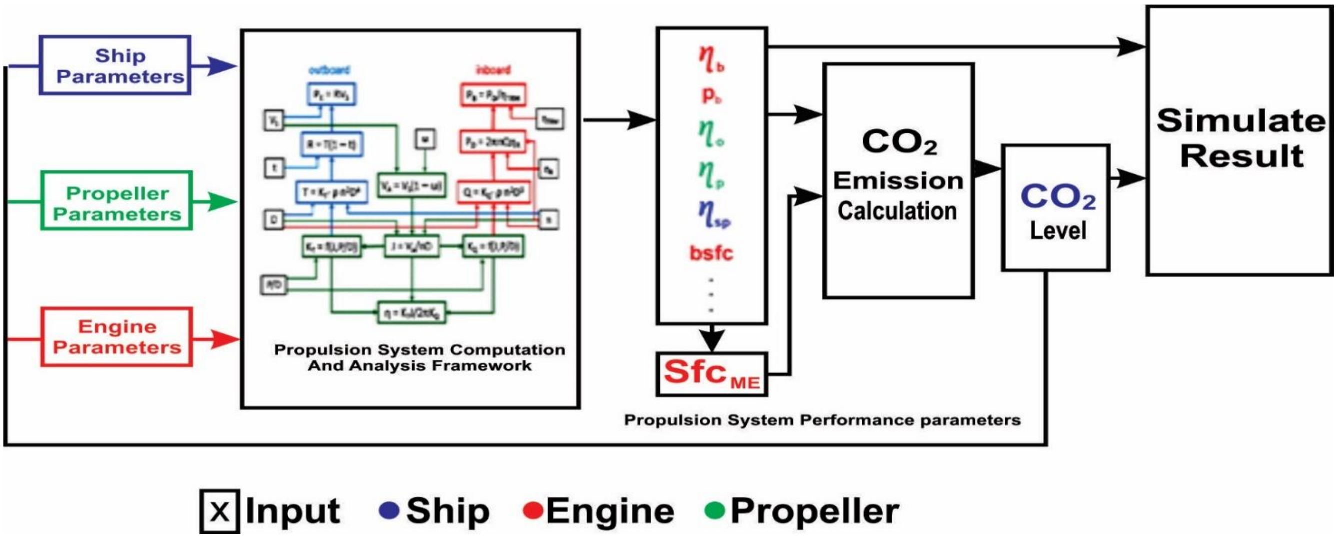

Fig. 2: Propulsion System Study Framework with Ship CO_2 Emission Analysis

Some data generated using MATLAB code for some performance parameter of the propulsion system is shown in Table 1.

Table 1: Extract of Data Generated for Some Performance Parameter of the Propulsion System

PE (Kw)	η_P	η_{sh}	P_{ME}(Kw)	CO_2(g/tm)	η_O	bsfc	η_b
2.5625	0.035412	0.013662	72.36289	43.39334	0.170483	0.222177	0.385793
10.81149	0.077062	0.027717	140.2954	18.25987	0.371	0.238314	0.359669
26.41458	0.126854	0.042777	208.2279	11.64682	0.610712	0.254186	0.337211
51.03095	0.184787	0.058707	276.1604	8.596281	0.889619	0.269797	0.317699
86.31978	0.250862	0.075406	344.0929	6.841005	1.207721	0.285155	0.300589
133.9403	0.325078	0.092797	412.0254	5.7008	1.565017	0.300265	0.285462

Series of plots of important performance parameters were simulated and generated. The plots showed similar trends and profiles as captured in the literatures, giving an indication of the models' accuracy and applicability. Figure 3 shows a graph of engine speed against engine power. The power developed by the engine from the plot is directly proportional to the speed of the engine. As the engine power increases, the engine speed increases linearly. This increase in engine speed does not necessarily translate to an increase in vessel speed, because the vessel will have to deal with and overcome several external factors during voyage.

A graph of bsfc against ship CO_2 emission is presented in Fig. 4. bsfc gives an indication of the measure of the fuel efficiency of the prime mover. From the diagram, the bsfc improves as the ship CO_2 emission improves. The bsfc improves rapidly from 0.25% to 0.7% as the ship CO_2 emission level also drops having a decay constant of 0.027s^{-1}.

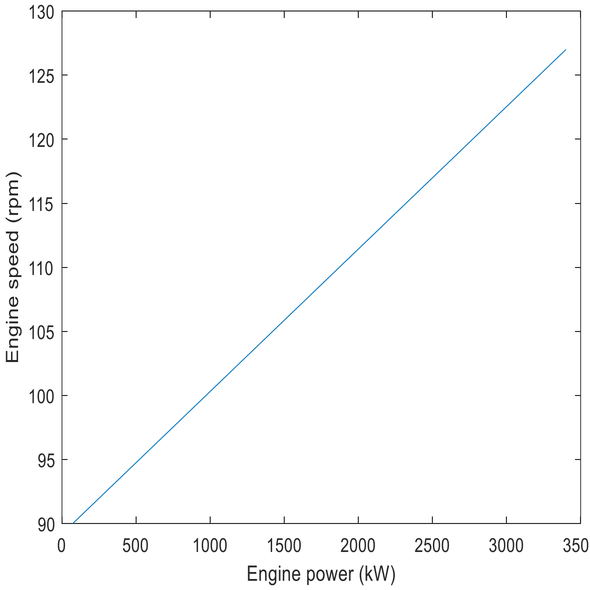

Fig. 3: Engine Power Versus Engine Speed

This can be accounted for by the fuel conversion efficiency following an optimal performance of bsfc as one of the propulsive efficiencies and this impact positively on the ship emission level as less fuel will be consumed for a given power output from the marine prime mover. Fig. 4 lucidly expresses the impact of bsfc on ship emission status and its attendant influence on the vessel's emission level.

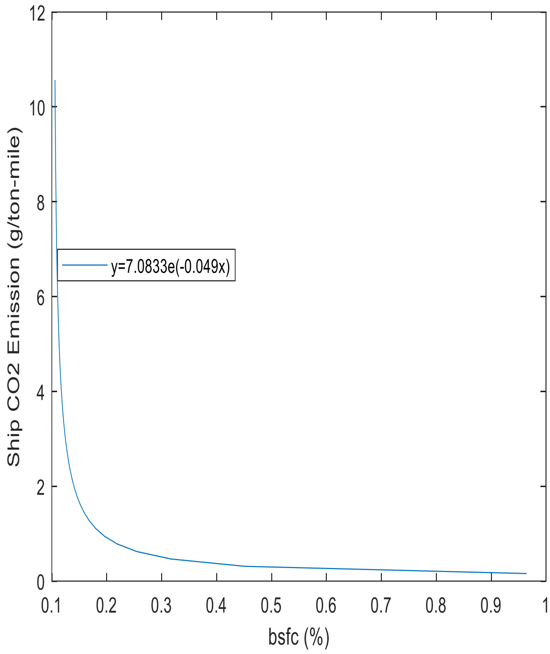

Fig. 4: Ship CO_2 Emission Versus bsfc

Fig. 5 present a plot of η_b and ship CO_2 emission. This parameter is a single variable that describes the performance characteristics of a marine prime mover. It is indicated from Fig. 5 that as the ship CO_2 emission decay constantly at $0.049s^{-1}$, the η_b increases steadily to 85% and above. Therefore, optimizing the vessels η_b as a propulsion system performance parameter of interest in this work, can significantly reduce sfc and reduce ship CO_2 emission. From Fig. 4, the ship CO_2 emission reduces gradually as the η_b increases rapidly to 0.2, but gradually to about 0.85 and attains stable value thereafter. Beyond this point, any further improvement of the η_b can reduce the ship CO_2 emission to net zero, considered impossible in engineering.

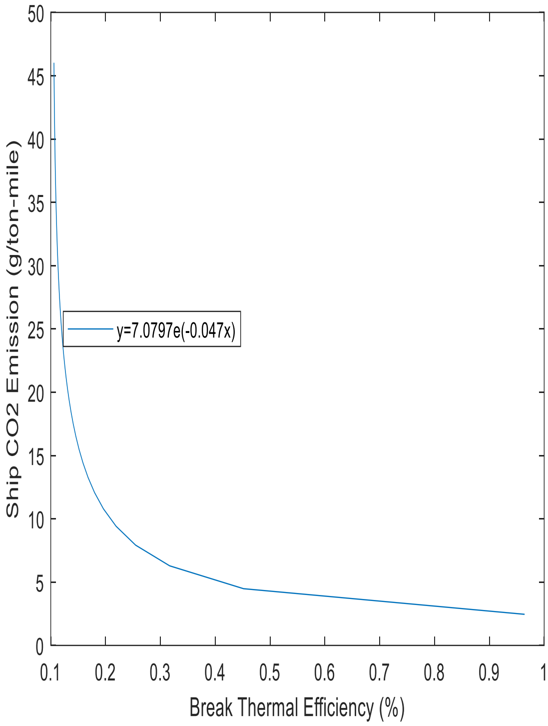

Fig. 5: ship CO_2 Emission Against Brake Thermal Efficiency

Fig. 6 shows a graph of ship CO_2 emission against ship η_P. The η_P considers the propeller open water efficiency which is critical and considered as the main aim of EPHM. Maximizing the propulsive efficiency matches up as an integral measure that decreases the load on the engine glossing into improved sfc and CO_2 emission. The curve indicates that the relationship between η_P and ship CO_2 emission is inverse as given in equation (20). This implies that with an improvement in the η_P, the ship CO_2 emission reduces likewise the sfc. With a decay constant of about $0.039s^{-1}$, ship CO_2 emission improves swiftly from 11g of /ton m to 4.5g of CO_2/ton m before decreasing gradually following a corresponding improvement in the vessel's η_P from 0.12% to about 0.75%. This can be accounted for by engine load reduction and precise EPHM.

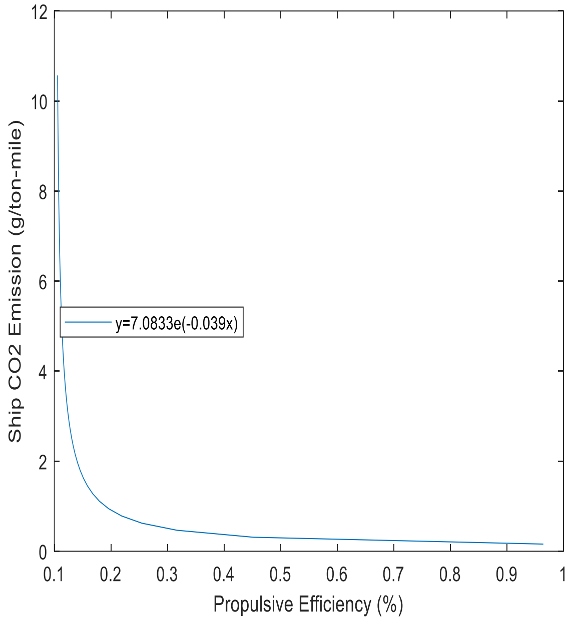

Fig. 6: Graph of ship CO_2 Emission **Against Propulsive Efficiency.**

Presented in Fig. 7 is a plot of ship CO_2 emission against η_{ship}. This propulsive parameter integrates η_b and η_p which take care of all the propulsive efficiencies of interest with respect to a vessel. Improving the η_{ship} directly translates effective measure that optimize the entire efficiencies of the ship altogether. From the curve an inverse relationship between the η_{ship} and ship CO_2 emission is visible and validate equation (24). By implication, as the η_{ship} increases, there is an improvement of sfc and ship CO_2 emission. Obviously, at a decay constant of $0.049s^{-1}$, the ship CO_2 emission improves rapidly before decreasing gradually accordingly with improvement in the vessel's η_{ship} from 0.11 to about 0.8. The consequence of this plot gives a true delineation of an optimized propulsive parametric characteristic of a vessel that magnifies improvement in operational cost and environmental impact vis-a-vis ship CO_2 emission.

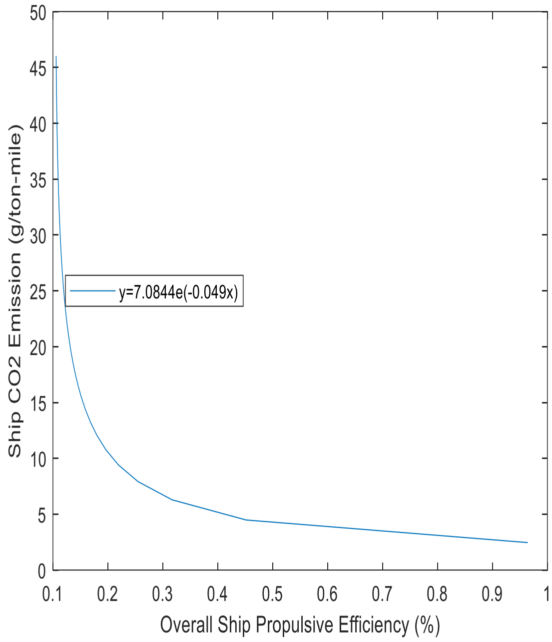

Fig. 7: Graph of ship CO_2 emission **against Overall Ship Propulsive Efficiency**

Fig. 8 presents a plot of sfc and ship CO_2 emission. This parameter is one variable amongst others that describes the performance characteristics of a vessel emission level. It is shown from Fig. 8 that as the ship CO_2 emission decay at $0.036s^{-1}$, the sfc of the ship improves steadily from 20% to 80%. Therefore, optimizing the vessels sfc will reduce ship CO_2 emission.

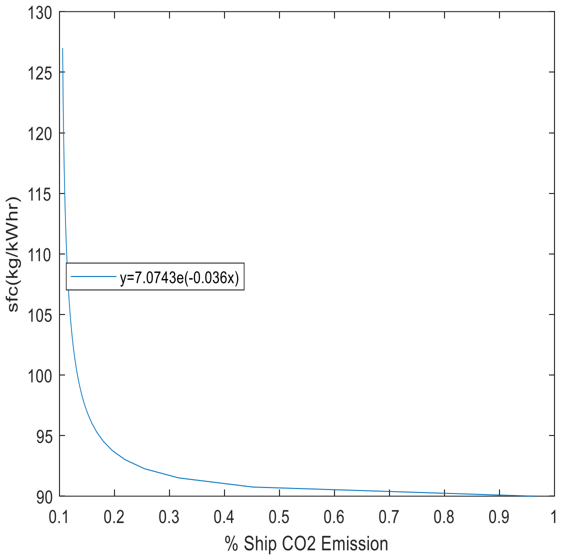

Fig. 8: Graph of ship CO_2 Emission **against sfc**

4. CONCLUSION

The modeling and simulation of a ship propulsion system is presented in this research. Program code scripted MATLAB2019a utilizing data of MT Diamond propulsion system. A computer-based simulation followed that helped in the authentication and validation of the models developed. This in furtherance enhance the comprehension of the behaviour of several performance parameters of the propulsion system and its relationship with $Ship\ CO_2$ emission. Results from the simulation analysis conducted indicate the validity of the mathematical models. Also, with an overall ship efficiency 50.7% at a speed of 13 knots, the vessel's propulsion system experiences an improvement of about 3.5% of the $Ship\ CO_2$ emission which also translates to improvement of ship operational cost via lower sfc. It is worthy to note that optimized propulsive efficiencies have positive correlation with CO_2 emissions.

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