Investigation of ship electric propulsion system performance from environmental and energy efficiency perspective

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Research Article

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Abstract

The maritime industry faces many challenges regarding the adverse environmental impact, whether at the level of legislation set by the International Maritime Organization (IMO) or the economic crises that arising from the Covid-19 pandemic. IMO has found that the highest percentage of ship emission is mainly coming from the ship propulsion systems. Therefore, the current research proposes an electric propulsion system to drive the ship instead of the conventional one to reduce ship emissions and enhance energy efficiency. As a case study, a passenger ship is investigated. The results showed that the proposed electric propulsion system has lower emission rates than the conventional one by 10%, 21%, and 88% for CO₂, NO_x, and SO_x emission, respectively. From an energy efficiency point of view, the diesel-electric propulsion system enhances the energy efficiency and complies with the required IMO values as actual energy efficiency is about 66%, 70%, 83%, and 95% of the required IMO values at baseline, phase 1, phase 2 and phase 3, respectively.

1. Introduction

Recent regulations set by the International Maritime Organization (IMO) and financial challenges that arising from the Covid-19 pandemic made the shipping industry faces numerous difficulties (Lee et al. 2014; Ammar and Seddiek 2020). Latest measurements from IMO shows that ships emitted 2.6% of the total worldwide Carbon dioxide (CO₂) emissions (El-Gohary 2012; Ammar and Seddiek 2021). Therefore, IMO has given a few enactments to lessen the unfriendly ecological effect (Halff et al. 2019). Mohseni et al (Mohseni et al. 2019) pointed that the most elevated level of ship outflow is fundamentally comes from the propulsion system. The solution is to propose a more efficient system than conventional propulsion system (Elgohary 2009; Geertsma et al. 2017). The most efficient solution is electric propulsion system as it can be adopted to different vessel types at different speeds (Nuchturee et al. 2020).

Lim et al (Lim et al. 2019) presented an application of electric system in a ship to reduce nitrogen oxides (NO_x) to be accepted with the regulations released from IMO. Offshore supply vessels and Liquefied Natural gas ships can use the electric propulsion system incorporated with Azipod propeller as shown in (Bassam et al. 2016). Another research investigated the evaluation of power and other dynamic specifications for electric propulsion system (Prempraneerach et al. 2009). Zahedi & Norum (Zahedi and Norum 2013) Validate the electric propulsion system components and its design through a simulation software. Moreover, Bassam et al (Bassam et al. 2017) investigated the hybrid system included electric system and found that an environmental and economic benefits from the application. Therefore, the application of electric propulsion system onboard ship is very hot research issue because of its economic and environmental benefits resulted from the previous literature survey.

The aim of the research is to propose an electric propulsion system to drive the ship instead of the conventional system to reduce ship emissions and enhance energy efficiency. The environmental assessment will be based on a comparative analysis between the proposed electric propulsion system

and the conventional system through evaluation of greenhouse gas emissions. As a case study, a passenger ship will be investigated.

2. Case Study Description

The case study for the assessment process of energy efficiency and environmental impacts is selected to be a passenger ship. The ship is operated by Holland America line passenger vessels under name (MS Westerdam) with a capacity of 2366 passengers and 820 crew members. The ship was built in 2004 and sailing under the flag of the Netherlands. Principal specifications of the ship are shown in Table 1 (Hollandamerica 2021). The ship is suggested to be operated by a diesel-electric propulsion system as shown in Fig. 1 with a total power of 51,840 kW covers both the electric propulsion and auxiliary/hotel power requirements for the ship.

Table 1
Main specifications of the studied passenger ship

Ship Name	MS Westerdam
IMO number	9226891
Length overall, [m]	285
Beam, [m]	32
Draft, [m]	7.8
Service speed, [knots]	22
Number of passengers	2366
Gross tonnage, [ton]	82,897
Electric power, [kW]	51840

The propulsion system can be provided with the required electric power from 6 generators (G) through transformers. Cyclone convertor (C.C) regulates the frequency according to the required propulsion motor speed (P.M). The diesel generator will be operated by ultra-low sulfur heavy fuel oil (ULSHFO) with 0.1 sulfur and a specific fuel consumption of 155.6 g/kWh with load factor of 90% and efficiency equals to 41.3 %.

The ship is sailing from Canada (Vancouver port) to Japan (Tokyo port) to attract more passengers to increase the financial benefit of the ship. This sailing route is 10,560 nautical miles (NM) and takes 20 days in one trip the average number of trips per year is five.

3. Performance Evaluation Methodology

The environmental performance can be assessed by evaluating the exhaust emissions from ships. The energy efficiency can be assessed by using the procedure recommended from IMO by using Energy Efficiency Design Index (EEDI) procedure (Elkafas et al. 2021b).

Firstly, the total emissions during ship cruise can be evaluated by using Eq. (1) which depending also on the type of engine (Eng) like main engine and auxiliary engine.

$$M_{trip,n} = \sum [T * \sum_{Eng} (P \times L \times F_n)] \quad (1)$$

Where (P) is the power of engine in [kW], L is the load factor of engine, T is the operating time of ship in [hour], (n) is the type of pollutant, and (F) is the fuel emission factor in [g/kWh]. The emission factors for NO_x, Sulfur oxide (SO_x) and CO₂ are 13, 0.4, and 485 [g/kWh], respectively for diesel electric engine operated with ULSHFO 0.1%S (Ammar and Seddiek 2020). On the other hand, the emission factors are 539 g/kWh, 16.4 g/kWh and 3.29 [g/kWh] for CO₂, NO_x and SO_x respectively for conventional diesel engine operated with MDO (1%S) (Elkafas et al. 2021a).

Furthermore, the energy efficiency of the case study can be assessed by using the EEDI procedure (Ammar and Seddiek 2021). EEDI can be assessed by calculated the reference value through Eq. (2) and the attained value set by IMO through Eq. (3) and measured in [gCO₂/GT-NM] (Ammar and Seddiek 2021; Elkafas et al. 2021a).

$$EEDI_{ref} = \left(\frac{170.84}{GT^{0.214}} \right) \left(1 - \frac{X}{100} \right) \quad (2)$$

Where, (GT) is the gross tonnage of passenger ship, (X) is the reduction rate set by IMO as follow; 5% in phase 1 (2015-2019), 20% in phase 2 (2020-2024) and 30% in phase 3 (2025-onwards) (El Gohary and Ammar 2016; Elkafas et al. 2019).

$$EEDI_{att} = \frac{\left(\frac{HL_{max}}{\eta_{gen.}} + \frac{\sum_{i=1}^n (0.75 \cdot MPP(i))}{\eta_{PTI} \cdot \eta_{gen.}} \right) \cdot (C_F \cdot SFC_{AE})}{GT \cdot v_{ref.}} \quad (3)$$

The previous equation depends on the electric power during ship cruise in kW (HL_{max}), the efficiency of generator (η_{gen}), the electric propulsion motor power in kW (MPP), the electric propulsion systems efficiencies at 75% of the electric motor output rated power η_{PTI}, the fuel conversion factors of the consumed fuel to CO₂ (C_F), the average specific fuel consumption for all engines (SFC_{AE}) at 75% of the maximum continuous rating (MCR) power in [g/kWh] and (V_{ref.}) which is the operational vessel speed in knots.

4. Results And Discussions

The environmental performance can be assessed by evaluating the exhaust emission rates per trip. The examined emission types are NO_x, SO_x, and CO₂ as these types are related with IMO regulations. The assessment process depends on the comparative study between the proposed diesel electric propulsion system operated with ULSHFO (0.1% S) and the conventional one operated with MDO (1%S), therefore, the different emissions rates can be compared in Fig. 2. The emissions rates are in ton/trip as discussed in Eq. (1). As shown in Fig. 2, the conventional diesel engine emitted more NO_x emission rates than the diesel electric engine as NO_x emission have a solid relation with the combustion temperature inside the engine and the combustion of MDO (1%S) will produce higher NO_x rates than ULSHFO (Mrzljak and Mrakovčić 2016). The conventional diesel engine will produce higher SO_x emission than the diesel electric as SO_x emission depends on the sulfur content of the combustion fuel. On the other hand, the CO₂ emission rates in two options are very closely as it depends on the carbon content of the fuel, but the diesel electric will produce fewer CO₂ emission than the conventional one.

NO_x and SO_x emission rates have been compared with the IMO 2016 and 2020 emission-limit rates, respectively. The IMO 2020 SO_x and tier III 2016 NO_x limits are 1.555 kg/min and 2.008 kg/min, respectively. Figure 3 shows a comparative diagram between IMO limit and the SO_x and NO_x emission rates for diesel electric propulsion system. It can be noticed that SO_x emissions rates for the diesel electric engine comply with the IMO 2020 limits because of it use ULSHFO with a little amount of sulfur. On the other hand, it can be noticed that NO_x emissions from diesel electric engine isn't comply with IMO 2016 limits, therefore, it is recommended to use selective catalytic reduction (SCR) technique which can reduce NO_x emission rate from the proposed diesel electric engine by up to 90% (Ammar and Seddiek 2020).

Finally, the energy efficiency can be assessed by the calculation of EEDI for electric propulsion system as recommended from IMO. By conducting the procedure in Sect. 3 to the case study, it is shown that the reference EEDI and its value in the three phases can be calculated based on the gross tonnage of passenger ship as investigated in Fig. 4.

This reference value will be compared with the actual attained EEDI which can be calculated by using Eq. (3) based on 22 knots service speed, 3.114 ton-CO₂/ton-fuel conversion factor of fuel to CO₂ and 82,897 gross tonnages. The attained EEDI will be 10.03 g CO₂/GT-NM. The relative attained EEDI value to the reference value at different phases for the proposed diesel electric propulsion system can be described in Fig. 5.

It is shown that, the proposed diesel electric propulsion system will comply with the required IMO phases now and in the future as the attained EEDI is about 66%, 70%, 83%, and 95% of the reference EEDI value at baseline, phase 1, phase 2 and phase 3, respectively.

5. Conclusions

The present research discusses the electric propulsion system for a passenger ship from environmental and energy efficiency point of view. The diesel electric propulsion system operated by ULSHFO (0.1% S) is proposed to propel the ship instead of the conventional diesel engine which operated by MDO (1% S). The main conclusions from the current paper are:

- From environmental point of view, diesel electric engine operated by ULSHFO (0.1%S) comply with IMO SO_x and not comply with NO_x emission. Be comparing the exhaust emissions rates between diesel electric and conventional engine, it is shown that diesel electric has lower emission rates than the conventional one by 10%, 21% and 88% for CO₂, NO_x, and SO_x emission, respectively.
- From energy efficiency point of view, the diesel electric propulsion system enhances the attained EEDI and complies with the required IMO values as it is about 66%, 70%, 83%, and 95% of the reference EEDI values at baseline, phase 1, phase 2 and phase 3, respectively.

Declarations

Consent to Participate

Not applicable

Conflict of interest

The authors declare that they have no conflict of interest.

Ethics approval

Not applicable

Consent for publication

Not applicable

Data availability

The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

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Not applicable

Authors' contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Ahmed G. Elkafas. The first draft of the manuscript was written by Ahmed G.

Elkafas. Mohamed R. Shouman is commented and reviewed the final draft of the manuscript.
Supervision of the research: Mohamed R. Shouman. All authors read and approved the final manuscript.

References

- Ammar NR, Seddiek IS (2020) Enhancing energy efficiency for new generations of containerized shipping. *Ocean Eng* 215:107887. <https://doi.org/10.1016/j.oceaneng.2020.107887>
- Ammar NR, Seddiek IS (2021) Evaluation of the environmental and economic impacts of electric propulsion systems onboard ships: case study passenger vessel. *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-021-13271-4>
- Bassam AM, Phillips AB, Turnock SR, Wilson PA (2016) An improved energy management strategy for a hybrid fuel cell/battery passenger vessel. *Int J Hydrogen Energy* 41:22453–22464. <https://doi.org/https://doi.org/10.1016/j.ijhydene.2016.08.049>
- Bassam AM, Phillips AB, Turnock SR, Wilson PA (2017) Development of a multi-scheme energy management strategy for a hybrid fuel cell driven passenger ship. *Int J Hydrogen Energy* 42:623–635. <https://doi.org/https://doi.org/10.1016/j.ijhydene.2016.08.209>
- El-Gohary MM (2012) The future of natural gas as a fuel in marine gas turbine for LNG carriers. *Proc Inst Mech Eng Part M J Eng Marit Environ* 226:371–377. <https://doi.org/10.1177/1475090212441444>
- El Gohary MM, Ammar NR (2016) Thermodynamic analysis of alternative marine fuels for marine gas turbine power plants. *J Mar Sci Appl* 15:95–103. <https://doi.org/10.1007/s11804-016-1346-x>
- Elgohary MM (2009) Energy Conservation: passenger and container ships case studies. *Alexandria Eng J* 48:151–159
- Elkafas AG, Elgohary MM, Shouman MR (2021a) Numerical analysis of economic and environmental benefits of marine fuel conversion from diesel oil to natural gas for container ships. *Environ Sci Pollut Res* 28:15210–15222. <https://doi.org/10.1007/s11356-020-11639-6>
- Elkafas AG, Elgohary MM, Zeid AE (2019) Numerical study on the hydrodynamic drag force of a container ship model. *Alexandria Eng J* 58:849–859. <https://doi.org/10.1016/j.aej.2019.07.004>
- Elkafas AG, Khalil M, Shouman MR, Elgohary MM (2021b) Environmental Protection and Energy Efficiency Improvement by using natural gas fuel in Maritime Transportation. *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-021-14859-6>
- Geertsma RD, Negenborn RR, Visser K, Hopman JJ (2017) Design and control of hybrid power and propulsion systems for smart ships: A review of developments. *Appl Energy* 194:30–54. <https://doi.org/https://doi.org/10.1016/j.apenergy.2017.02.060>

- Halff A, Younes L, Boersma T (2019) The likely implications of the new IMO standards on the shipping industry. *Energy Policy* 126:277–286. <https://doi.org/https://doi.org/10.1016/j.enpol.2018.11.033>
- Hollandamerica (2021) MS Westerdam. In: cruise ships. https://www.hollandamerica.com/en_US/cruise-ships/ms-westerdam/5.html. Accessed 1 Jun 2021
- Lee DK, Jeong YK, Shin JG, Oh DK (2014) Optimized design of electric propulsion system for small crafts using the differential evolution algorithm. *Int J Precis Eng Manuf - Green Technol* 1:229–240. <https://doi.org/10.1007/s40684-014-0029-9>
- Lim C og, Park B cheol, Lee J chul, et al (2019) Electric power consumption predictive modeling of an electric propulsion ship considering the marine environment. *Int J Nav Archit Ocean Eng* 11:765–781. <https://doi.org/10.1016/j.ijnaoe.2019.02.011>
- Mohseni SA, van Hassel E, Sys C, Vanelslander T (2019) Economic evaluation of alternative technologies to mitigate Sulphur emissions in maritime container transport from both the vessel owner and shipper perspective. *J Shipp Trade* 4:. <https://doi.org/10.1186/s41072-019-0051-8>
- Mrzljak V, Mrakovčić T (2016) Comparison of COGES and Diesel-Electric Ship Propulsion Systems. *J Marit Transp Sci Special ed*:131–148. <https://doi.org/10.18048/2016-00.131>
- Nuchturee C, Li T, Xia H (2020) Energy efficiency of integrated electric propulsion for ships – A review. *Renew Sustain Energy Rev* 134:110145. <https://doi.org/https://doi.org/10.1016/j.rser.2020.110145>
- Prempraneerach P, Kirtley J, Chryssostomidis C, et al (2009) Design of the All-Electric Ship: Focus on Integrated Power System coupled to Hydrodynamics. In: *Proceedings of the American Society of Naval Engineers and the Society of Naval Architects and Marine Engineers Electric Ship Design Symposium*. pp 563–568
- Zahedi B, Norum LE (2013) Modeling and Simulation of All-Electric Ships With Low-Voltage DC Hybrid Power Systems. *IEEE Trans Power Electron* 28:4525–4537. <https://doi.org/10.1109/TPEL.2012.2231884>

Figures

Figure 1

Proposed electric propulsion system arrangements for the case study

Figure 2

Exhaust emission rates for diesel electric engine compared with conventional one

Figure 3

IMO NOx and SOx emissions for the DE and COGES propulsion options

Figure 4

Reference EEDI values for passenger ship

Figure 5

Relative attained to the reference EEDI and the average EEOI values for the case study