ISSN 0554-6397
Izvorni znanstveni članak
(*Original scientific paper*)

Vladimir Pelić
E-mail: vladimir.pelic@pfri.uniri.hr
University of Rijeka, Faculty of Maritime Studies, Studentska 2, Rijeka, Croatia
Tomislav Mrakovčić
E-mail: tomislav.mrakovcic@riteh.hr
University of Rijeka, Faculty of Engineering, Vukovarska 58, Rijeka, Croatia
Radoslav Radonja
E-mail: radoslav.radonja@pfri.uniri.hr
University of Rijeka, Faculty of Maritime Studies, Studentska 2, Rijeka, Croatia
Ozren Bukovac
E-mail: ozren.bukovac@riteh.hr
University of Rijeka, Faculty of Engineering, Vukovarska 58, Rijeka, Croatia

The Influence of Reduction in Sailing Speed on the Efficiency and Energy Potential of the Waste Heat of the Marine Diesel Engine

Abstract

One of the essential conditions for the sustainable development of maritime transport is the increase of energy efficiency, which contributes not only to economic efficiency but also to the reduction of pollutant emissions. Reduction of pollutant emissions can be achieved by adjusting the combustion process in the engine cylinder, after-treatment of exhaust gases, use of alternative fuels or reduction of sailing speed. Reduction of sailing speed is widely used in container ships, as it does not require additional investment and, if applied reasonably, has a positive effect on reducing fuel consumption and pollutant emissions. However, it leads to an increase in sailing time, and a greater reduction in sailing speed leads to a reduction in main engine efficiency and a reduction in the energy potential of the waste heat. In this paper, the effects of reducing the sailing speed on the efficiency and energy potential of the waste heat of a low-speed marine engine are investigated. The waste heat from the exhaust gases and the engine cooling system is used to generate steam and electricity and for desalination. In the examples studied, a 30.4% reduction in sailing speed from the planned speed results in a 53.1% reduction in fuel consumption and a 43.8% increase in sailing time. When determining the optimal sailing speed, it is also important to consider the specific fuel consumption data, which shows that an engine load of 60% to 80% is optimal for efficiency. Data from the manufacturer WinGD on fuel consumption and available waste heat for various engine loads as a function of the container ship's sailing speed were used for the study.

Keywords: reduction of sailing speed, energy efficiency, waste heat

1. Introduction

Maritime transport is an important factor in the global exchange of goods, as it is the most efficient way of transporting large quantities of goods over long distances. United Nations Conference on Trade and Development (UNCTAD) estimates that more than 80% of global trade in goods by volume and more than 70% by value is carried by sea [1]. According to UNCTAD's projections, maritime trade is expected to grow at an average rate of 1.4% to 2.3% per year between 2022 and 2027, and container traffic is expected to grow by 1.2% to 3.8% over the same period [2].

Considering the amount of goods, distance travelled and energy requirements, maritime transport is very energy efficient. Compared to other modes of transport and other sources of pollutant emissions, maritime transport has a relatively low negative impact on the environment. It is responsible for about 30% of total global emissions of NO_X, 20% of SO_X, 6% of CO_2 and 1.75% of greenhouse gases [3]. Energy efficiency and environmental friendliness are essential requirements to achieve economic sustainability. Shipping companies, motivated by legal regulations and complex conditions for survival in the market, are taking various measures with the aim of further improving efficiency and reducing the negative impact on the environment. To achieve the set goals, great efforts are made, and resources are invested to improve existing technical and technological solutions in maritime transport and to develop new ones.

The requirements to increase energy efficiency, rationalise energy consumption and reduce emissions in maritime transport stem from the Kyoto Protocol and IMO (International Maritime Organisation) regulations. To achieve the set goals of rational energy use and reduction of negative impact on the environment, the Energy Efficiency Design Index (EEDI) has been introduced, which applies to newly built ships, while the Energy Efficiency Existing Ship Index (EEXI) applies to ships in service from November 1, 2022. The same method for calculating a ship's energy efficiency is used to determine the EEDI and the EEXI. For all existing ships, the EEXI will be calculated in accordance with MARPOL Annex VI. After compliance testing, an IEEC (International Energy Efficiency Certificate) is issued to all ships that meet the requirements. According to Bureau Veritas, it is estimated that 70% of ships that meet the EEDI requirements also meet the EEXI requirements [4]. For ships that do not meet the EEXI requirements, harmonisation is required through the application of various measures to achieve the required EEXI value. These measures include limiting engine power, installing energy-efficient equipment, replacing the ship's propeller, and other measures to rationalise energy consumption. The paper [5] provides an overview of various technologies and measures to reduce greenhouse gas emissions and includes the results of about 150 studies.

Sailing at reduced speed (slow steaming) is a simple and effective measure that leads to a reduction in fuel consumption and CO_2 emissions. Since it does not require additional investment, reduced speed steaming is well accepted by ship owners. The impact of reduced sailing speed on fuel consumption and CO_2 emissions largely depends on the intended sailing speed of the vessel. According to [6], the positive effect of reduced speed is particularly emphasised for large vessels designed for relatively high speeds. The possibilities of applying slow steaming are particularly pronounced for large container ships, which are usually designed for a sailing speed of 23 to 25 knots. Reducing the sailing speed of container ships by only 5% can achieve fuel savings of 16% to 19%, while the fuel consumption of bulk carriers and tankers drops by about 13% for the same speed reduction [7].

The positive effect of sailing at reduced speed on reducing fuel consumption and thus on reducing pollutant emissions is generally greater when the reduction of the sailing speed is greater than the designed sailing speed [8]. Various aspects and the effects of a reducing sailing speed on fuel consumption reduction are analysed in a large number of publications, e.g. in [9] [10]. Studies on the effects of reducing the sailing speed of a container ship from 24 to 19 knots in three different sea conditions from 4 to 6 on the Beaufort scale have shown that a reduction in fuel consumption of about 53% is possible regardless of the sea conditions [11]. Publication [12] also indicates a 55% reduction in fuel consumption when the container ship speed is reduced from 24 to 17 knots. However, the authors point out that the overall economic effect of a reduction in sailing speed depends heavily on fuel prices and freight rates. Using a simple model, the authors in [13] analyse the impact of a reduction in sailing speed on delivery times, fuel costs and service quality. The analysis shows that by adjusting the sailing speed to the ship's operating conditions, significant fuel savings can be achieved while improving service quality.

A moderate reduction in sailing speed results in a 20% to 40% reduction in fuel consumption per nautical mile travelled. Extreme reductions in sailing speed can reduce fuel consumption, and therefore CO_2 emissions by more than 60% [14]. A study of the effects of reducing sailing speed on the fuel consumption of a post-Panamax container ship found that the propulsion system with two slow-speed diesel engines allowed the sailing speed to be reduced to 13 knots. At the same time, the reduction in fuel consumption per nautical mile travelled is 71.79% compared to sailing at a speed of 23 knots [15]. According to [16], depending on the operating conditions of the container ship, a reduction in fuel consumption of about 70% can be achieved if the planned speed is reduced to about half the designed speed.

The power of the propulsion engine required for sailing in calm seas depends on the third power of the ship's speed, so that even a relatively small reduction in sailing speed leads to a significant reduction in the power required for sailing. The specific fuel consumption of marine diesel engines is usually lowest at an engine load of 85% MCR (Maximum Continuous Rating) according to the manufacturer. At this load, the efficiency of conversion of chemical fuel energy into mechanical energy is highest and ranges from 50% to 53% for low-speed two-stroke diesel engines, while it is slightly lower at 46.3% to 47.6% for medium-speed diesel engines [17] [18] [19]. It should be noted that a load change in the range of 75% to 100% MCR has a relatively small effect on the efficiency, while at a load of 50% MCR the reduction can be 3% to 5% [20]. In addition, operating the propulsion engine at reduced load leads to a reduction in the mass flow and temperature of scavenging air and exhaust gases.

With the available technologies for utilising waste heat of marine diesel engines, the overall efficiency can be increased from 56% to 58% [21]. On ships, waste heat from diesel engines is mainly used to generate low-pressure saturated steam for fuel heating. To a lesser extent, systems with superheated steam and a turbogenerator are also used to generate electricity. Systems with a gas turbine, which uses exhaust gases to generate electricity, in combination with a steam turbine are used much less. In seawater desalination, the use of fresh water generators is widespread, where the evaporator is heated with water from the High Temperature Fresh Water (HTFW) engine cooling system. To further improve energy efficiency, waste heat recovery systems use the heat from the scavenging air after the turbocharger to heat fuel and liquid charge using thermal oil. In this way, it is possible to use more of the waste heat from the exhaust gases to generate electricity. Organic fluids can be used to further improve the efficiency of converting waste heat from marine diesel engines into mechanical energy.

In the paper [22], an energy and exergy analysis of the ORC (Organic Rankine Cycle) was carried out using the energy of the exhaust gases and the HTFW system of a two-stroke marine diesel engine. The study was conducted at a load of 60% to 100% MCR on the propulsion diesel engine. The analysis showed that R113 is the best organic fluid in terms of energy and exergy efficiency. According to the research results published in [23], it is possible to reduce the specific fuel consumption of diesel engines by up to 20% in a combined diesel-gas turbine propulsion system with a thermochemical reactor for waste heat recovery. When a diesel engine and a natural gas turbine are operated simultaneously, the efficiency of the system can be increased from 4% to 5%.

In addition to the methods mentioned above, waste heat can also be used in onboard absorption cooling systems. The research presented in [24] showed that the exhaust gases from auxiliary diesel engines are a suitable source of thermal energy for the onboard absorption refrigeration system. The analysis carried out shows that the absorption chiller operates at a significantly higher efficiency than the compressor chiller under tropical conditions.

Sailing at reduced speed leads to a significant reduction of the energy potential of waste heat due to a lower mass flow of the medium (exhaust gases, cooling water, thermal oil) and a lower temperature of the medium. In this paper, the propulsion system of a container ship is analysed to evaluate the effects of reducing the driving speed on the efficiency and energy potential of the waste heat. The propulsion engine is a low speed two-stroke diesel engine X82-2.0 with the highest continuous power of 5.5 MW /cylinder at 84.0 rpm, manufactured by WinGD. All engine operating data required for the analysis at a load of 25% to 100% MCR were obtained from the manufacturer via the application GTD (General Technical Data for WinGD two-stroke engines).

2. Data on the ship and the propulsion engine

The paper examines the effects of a post-Panamax container ship sailing at reduced speed on the energy conversion efficiency of the fuel used by a two-stroke diesel engine. The required power of the propulsion engine to operate the ship at the intended speed was determined based on the ship model test data. The tests of the ship model were carried out at the Brodarski Institut in Zagreb. The basic characteristics of the ship and the model are listed in Table 1.

Table 1. Main characteristics of the model and full-size ship (full-scale ship)

Characteristics	**Ship**	**Model**
Length between perpendiculars (Lpp)	286.58 m	8.1460 m
Length on waterline (Lwl)	292.37 m	8.3107 m
Beam (B)	40.03 m	1.1378 m
Draught forward (TF)	11.98 m	0.3405 m
Draught aft (T_A)	11.98 m	0.3405 m
Wetted surface (S)	9173.2 m^2	10.7668 m^2
Displacement volume (∇)	85556 m^3	1.9650 m^3

In testing a model with a constant-pitch propeller, the power required at the propeller shaft was determined for different sailing speeds. The diagram in Figure 1 shows the relationship between sailing speed and engine power. In determining the power required for propulsion, it was assumed that the losses in the shaft line bearings are approximately 2%. The engine power required for navigation is determined assuming that the ship is sailing in calm seas (without the influence of wind, waves and currents). The dependence between the sailing speed and the engine power is shown in Figure 1. For the selection of the engine, the power determined during the testing of the model is increased by 10% engine margin and another 10% sea margin. The fact that the required power increases exponentially becomes clear if, for example, the power for a speed of 19 knots is taken, which is about half the power required for a design speed of 23 knots.

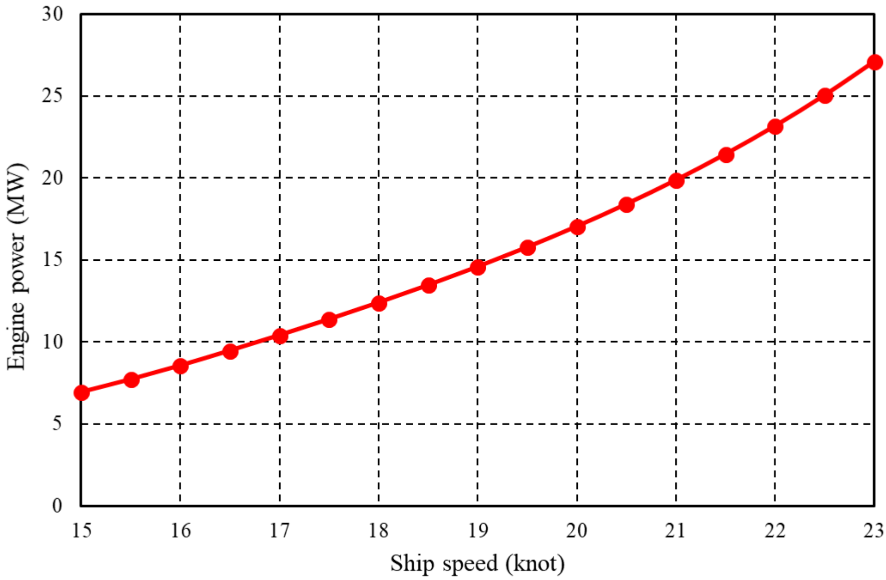

Figure 1: Dependence of sailing speed and engine power (source: Authors)

Considering the power required for sailing at the intended speed, a 2-stroke diesel engine of the manufacturer X82-2.0 WinGD with the basic characteristics given in Table 2 was selected.

Table 2. Basic characteristics of a low-speed diesel engine WinGD X82-2.0 (Source: [25])

Characteristics	**Value**
Bore	820 mm
Stroke	3375 mm
Number of cylinders	6
Power (MCR)	5500 kW/cyl.
Speed (MCR)	84 rpm
Mean effective pressure	22.0 bar

3. Influence of load on diesel engine efficiency

To determine the efficiency of the diesel engine at various loads, the engine manufacturer's break specific fuel consumption BSFC data listed in Table 3 were used.

Table 3. BSFC data of the diesel engine WinGD X82-2.0 (Source: [26])

Power [%]	100.0	90.0	80.0	70.0	60.0	50.0	40.0	30.0
Power [MW]	33.00	29.70	26.40	23.10	19.80	16.50	13.20	9.90
BSFC[1] [g/kWh]	168.5	162.8	160.4	160.0	160.7	162,4	163,8	164,9

[1] Tolerances: + 5% at 100 - 85% power, +6% at < 85 - 65% power, + 7% < 65 - 50% power

BSFC data is given for: air temperature before compressor is 45°C, coolant temperature before SAC (Scavenge Air Cooler) is 36°C, relative humidity is 60%, exhaust gas back pressure is 300 mm WC and LHV = 42700 kJ/kg (Lower Heating Value) of MDO (Marine Diesel Oil).

The change in BSFC as a function of engine load according to the data in Table 3 is shown in Figure 2.

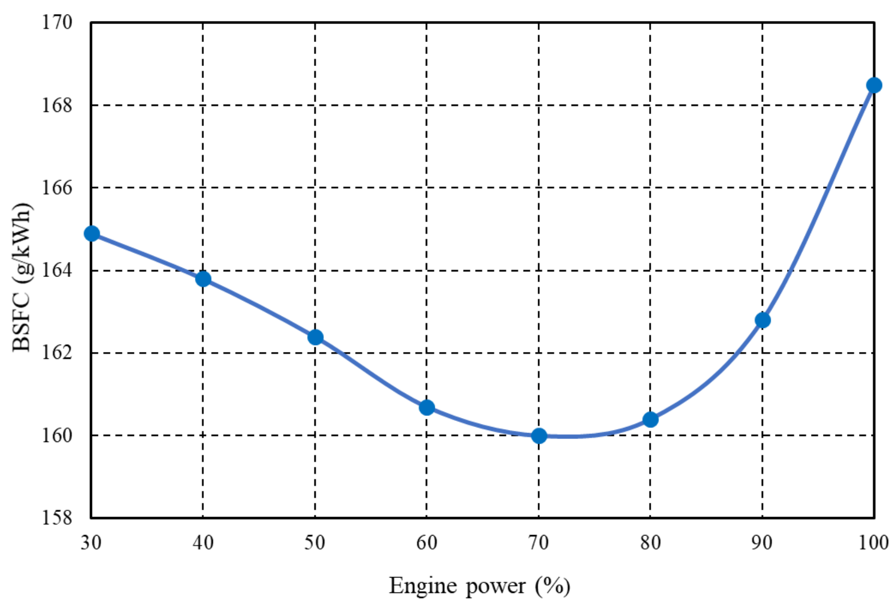

Figure 2: Dependence of BSFC on engine load (source: Authors)

The efficiency at different engine loads is calculated using the specific consumption and the lower heating value for MDO (Marine Diesel Oil) according to Equations 1.

$$\eta_{DE} = \left(1 / \left(\frac{LHV}{3600} \cdot \frac{BSFC}{1000}\right)\right) \cdot 100 \quad (\%) \tag{1}$$

where it is:

LHV – Lower Calorific Value of fuel (kJ/kg),

BSFC – Brake Specific Fuel Consumption (g/kWh)

The change in efficiency when converting the chemical energy of the fuel into mechanical energy at different engine loads is shown in Figure 3.

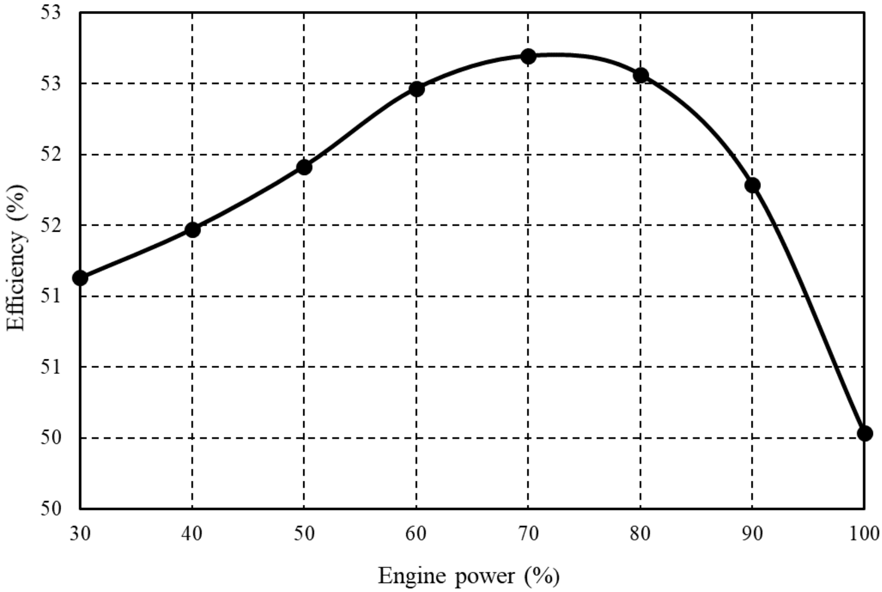

Figure 3: Efficiency at different engine loads (source: Authors)

From the diagrams in Figures 2 and 3, the engine with the highest efficiency operates in the range of 60% to 80% MCR. The selected diesel engine achieves the highest efficiency at a sailing speed of about 22 knots, when the engine load is about 70% MCR. In determining the required power, it was assumed that the vessel sails under ideal conditions and that no shaft generator is used. Considering the size and purpose of the ship and the number of refrigerated containers, the required power of the shaft generator is about 5000 to 6000 kW. If the sailing speed is to be maintained in bad weather, the power provided by the engine also depends on the strength and direction of the wind, the sea state and the ocean currents. As mentioned above, only navigation under ideal conditions without the use of a shaft generator is considered in this paper.

4. The effects of reducing sailing speed

The effects of reducing sailing speed on fuel consumption per nautical mile travelled and the increased cruising time compared to the designed sailing speed of 23 knots are shown in Figure 4. A reduction in speed to 30.4% (16 knots) results in a 53.1% reduction in fuel consumption and a 43.8% increase in travel time. If the speed is reduced by 8.7% from 23 to 21 knots, the fuel consumption is reduced by 19.02% and the travel time is increased by 9.52%. The above examples show that the relationship between the reduction in fuel consumption and the increase in travel time is significantly more favourable at lower speeds.

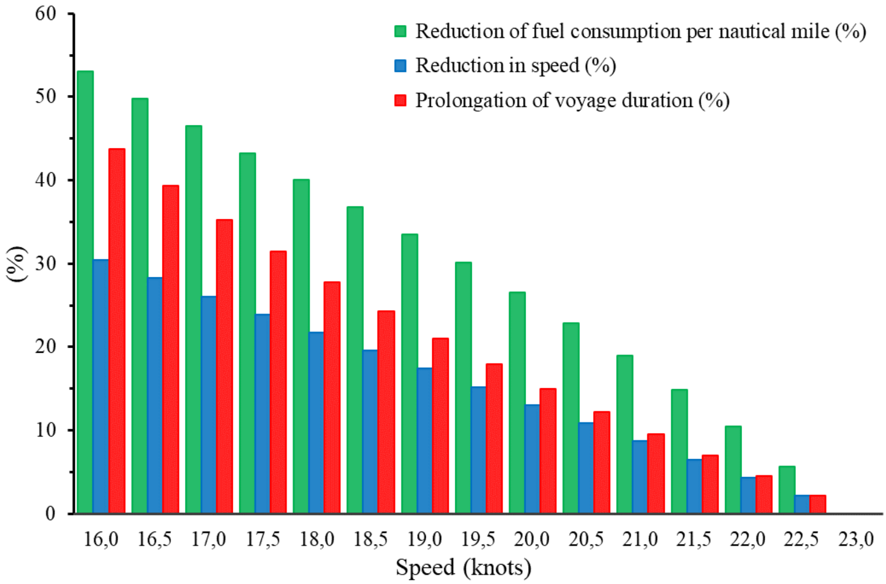

Figure 4: The impact of reducing the speed of navigation (source: Authors)

Reducing the sailing speed to less than 15 knots requires engine operation with a load of less than 25%. Continuous operation of the engine at a load of less than 25% is not recommended because of the increased build-up of deposits in the combustion area, the need for continuous operation of the auxiliary blowers, and the significantly lower efficiency of the engine.

5. Analysis of the influence of navigation at reduced speed on the exergy of waste heat

Part of the waste heat generated by diesel engine operation on ships is mainly used to recover water vapour and produce fresh water by distilling seawater. The remaining thermal energy of the exhaust gases after the turbocharger is used to generate saturated and superheated water vapor. The thermal energy from the HTFW cooling system can be used to heat the feed water and for desalination. The scavenging air required to operate the two-stroke diesel engine is provided by a turbocharger. Depending on the load, up to 50% of the available exhaust gas energy is used for turbocharger operation. During air compression in the turbocharger, the temperature of the scavenging air rises (up to approx. 245°C at 100% MCR), and it is necessary to cool it to approx. 45°C by removing heat in the scavenging air cooler. In most cases, the heat of the scavenging air is removed only by the cooling water of the LT circuit, wasting a large part of the exergy. It is much more advantageous if the temperature of the scavenging air is removed with two heat exchangers. In this case, the scavenge air in the first stage transfers the heat to the HTFW cooling system or the thermal oil, which is heated to a higher temperature, and in this way a much larger part of the available exergy is saved. In determining the available energy potential (exergy) of the heat, the equation according to [27] [28] was used:

$$\dot{E}_{e} = \dot{Q} \cdot \left(1 - \frac{T_{O}}{T}\right) \quad (\mathrm{kJ/s}) \tag{2}$$

where it is:

$\dot{Q}_i$ – energy transfer by heat (kJ/s = kW),

T_O – temperature of the environment (K)

T – temperature of the working medium (K)

In determining the exergy, the data on the available heat flow of the waste heat, the temperature of the exhaust gases and the temperature of the scavenging air after the turbocharger from the Excel spreadsheet created with the application GTD for the slow-running diesel engine 6X82-2.0 of the company WinGD were used. In all calculations, the temperature of the LTFW (Low Temperature Fresh Water) system is 36°C regardless of the load and that of the HTFW system is 90°C under steady-state engine operating conditions. In determining the exergy of the heat, a value of 25°C was assumed as the ambient temperature. Two cases are considered in this paper:

Case – 1: All the heat extracted from the scavenging air is transferred to the HTFW system,

Case – 2: Part of the heat extracted from the scavenging air is transferred to the thermal oil.

In determining the exergy in both cases, the exergy of the thermal energy of the lubricating oil is relatively small and can be neglected. For the same reason, the remaining exergy of the LTFW system in the second case was not considered.

From the diagrams in Figure 5 and Figure 6, it can be seen that a reduction in the engine load leads to a reduction in the exergy of the total waste heat flux. The reduction in available exergy is much less pronounced for LTFW and HTFW systems (*E*e HT and *E*e LT) because the temperature is approximately constant.

The exergy of exhaust gases after turbocharger (*E*e EGaTC) and the exergy of the scavenging air (*E*e SA) are significantly reduced not only by reducing the exhaust and air flow rate, but also by lowering their temperature at low engine load.

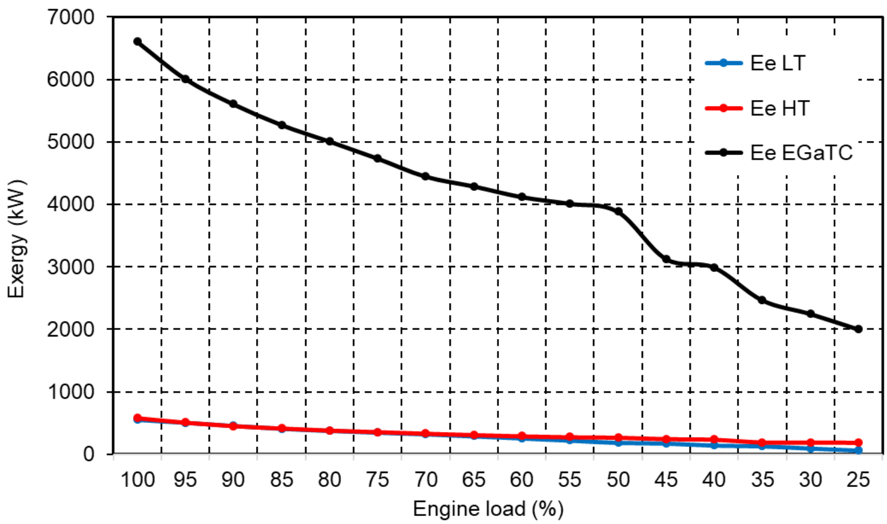

Figure 5: Effect of reduction of sailing speed on available exergy, Case 1

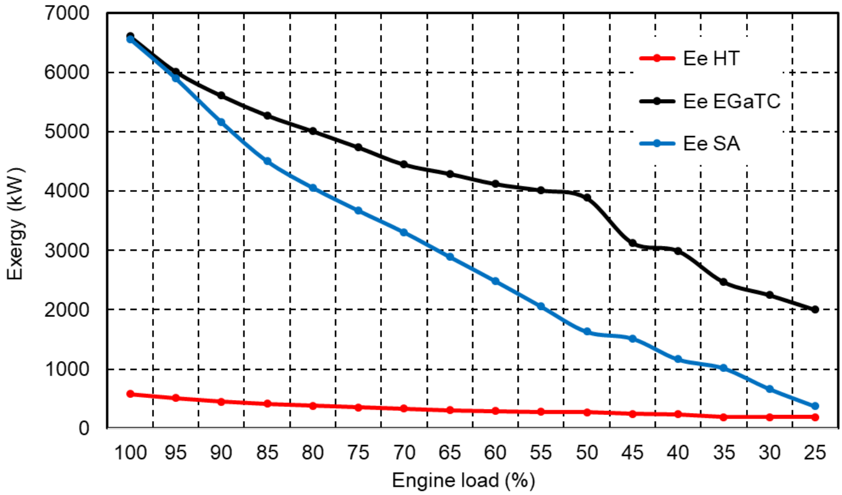

Figure 6: Effect of reduction of sailing speed on available exergy, Case 2

The exergy of exhaust gases in the range from 100% to 50% MCR decreases significantly less than the exergy of the scavenging air. If the engine power is reduced to 50%, the exergy of the exhaust gases decreases by 41.2% and the exergy of the scavenging air by 75.1%. At the same power reduction, the exergy of the HTFW and LTFW systems decreases by about 53.4 %.

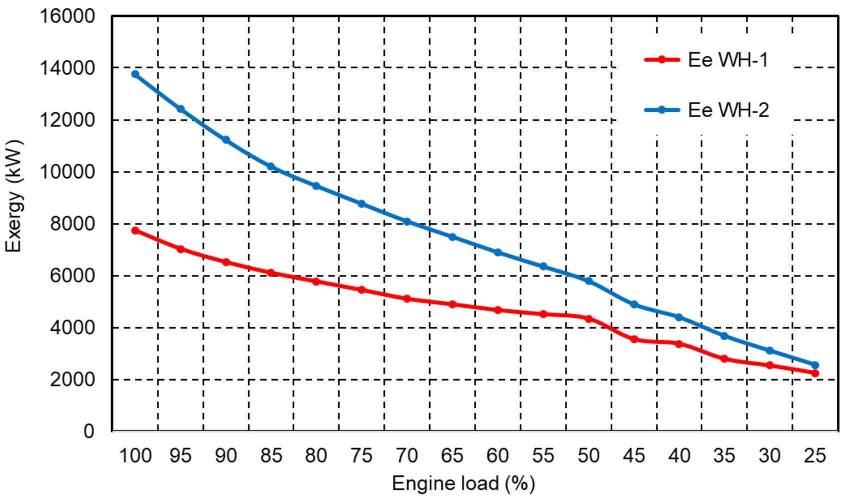

Figure 7: Effect of reduction of sailing speed on total available exergy

The total available exergy for both cases as a function of engine load is shown in the diagram in Figure 7. Here, the total exergy for case 2 at 100% MCR is almost twice that of case 1. As the load decreases, the difference decreases continuously and is 24.9% at 50% MCR, and there is almost no difference at 25% MCR. The main reason for the significant decrease in exergy of scavenge air is the decrease in temperature, as shown in Figure 8, where temperature of exhaust gases after turbocharger is marked with *T*_EGaTC and temperature od scavenge air after turbocharger is marked with *T*_SAaTC.

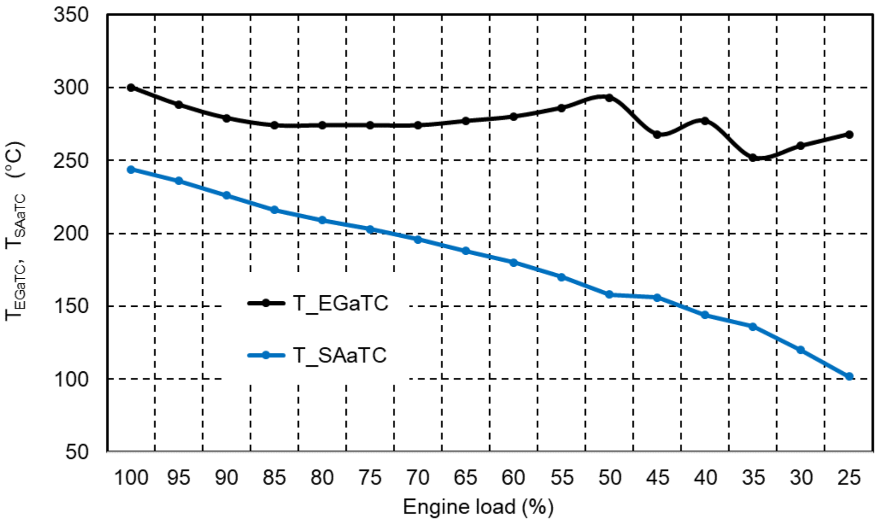

Figure 8: Impact of reduction of sailing speed on temperature of exhaust gas and scavenge air

If the overall efficiency of the system for generating electricity from waste heat is about 60% at an engine load of 85%, about 6000 kW of electricity can be generated in Case 2, but only 3600 kW in Case 1. Load reduction leads to a reduction in the energy potential of waste heat and the possibility of covering the entire electricity demand of the ship with waste heat. The difference has to be compensated by operating the shaft generator or the diesel generator, which leads to an increase in fuel consumption.

6. Conclusion

Maritime transport is very energy efficient, considering the amount of goods carried, the distance travelled, and the energy required. Compared to other modes of transport and other sources of pollutant emissions, maritime transport has a relatively low negative impact on the environment. However, increasing energy efficiency, rationalising energy use and reducing emissions resulting from the Kyoto Protocol and IMO regulations are the basic guidelines for the further development of maritime transport. To achieve the set goals, various technical and technological solutions are used. Reducing sailing speed is one of the most popular measures to reduce fuel consumption and CO_2, NO_X and SO_X emissions generated by the operation of marine diesel engines.

In the examples studied, a 30.4% reduction in sailing speed from the planned speed results in a 53.1% reduction in fuel consumption and a 43.8% increase in sailing time. With a smaller reduction in speed of 8.7%, fuel consumption is 19.02% lower and sailing time is 9.52% longer. It can be concluded that the relationship between the reduction in fuel consumption and the increase in travel time is much more favourable at lower reduced sailing speeds. When determining the optimal sailing speed, it is also important to consider the BSFC data, which shows that an engine load of 60% to 80% is optimal for efficiency. In this load range, the exergy of the waste heat is sufficient to cover all or at least most of the ship's electrical and thermal energy requirements.

The efficiency of waste heat utilisation depends on the available heat flow, but to a much greater extent on the temperature of the medium. In terms of energy potential, the exhaust gases come first and scavenge air second. The cooling water of the HT circuit, which is mainly used in fresh water generators, has a much lower exergy. Analysis of the available energy potential and the possibility of using it with the aim of increasing energy efficiency has shown that a reduction in engine load leads to an almost exponential decrease in the exergy of waste heat. This has a negative effect on the overall efficiency of the marine power plant. The exergy in Case 2 is almost twice as high as in Case 1 at 100% MCR. If the engine load is reduced, the difference decreases continuously and is 24.9% at 50% MCR. The decrease in exergy is due to the decrease in mass flow and temperature of the scavenge air and exhaust gases.

The decision on the strategy of applying slow steaming is made by the ship owner depending on the conditions of the maritime market, the size, purpose and speed of the ship, and the characteristics of the propulsion engine and waste heat recovery system. The rational application of slow steaming can improve EEXI. For the application of slow steaming to provide optimal results when planning each voyage of a container ship, the weather conditions, the amount of cargo and the number of reefer containers must be considered.

7. Acknowledgements

This work was fully supported by the Croatian Science Foundation within the projects:

IP-2020-02-6249 and **IP-2020-02-8568**.

8. References

1. *UNCTAD: Trade and Environment Review 2023*, United Nations: Geneva, Switzerland, 2023, https://unctad.org/system/files/official-document/ditcted 2023d1_en.pdf (12.09.2023.)
2. *UNCTAD: Review of Maritime Transport 2022*, United Nations: Geneva, Switzerland, 2022, https://unctad.org/system/files/official-document/ditcted2023d1_en.pdf (12.09.2023.)
3. CHING-JIN, CHEN; CHUN-LIEN, SU; JEN-HAO, TENG; ELSISI, MAHMOUD: *Feeder Losses Analysis of Marine Vessel Power Systems: A Case Study of Container Ship Power Loss Analysis Using Newton–Raphson Method,* Energies 2022, 15(23), 9175.
4. *Bureau Veritas Marine and Offshore*, https://marine-offshore.bureauveritas.com/ shipping-decarbonization/carbon-index/eexi, (12.09.2023.)
5. BOUMAN, EVERT; LINDSTAD, ELIZABETH; RIALLAND, AGATHE; HAMMER STRØMMAN, ANDERS: *State of the art technologies, measures, and potential for reducing GHG emissions from shipping - A review,* Transportation Research Part D Transport and Environment, 2017, 52(2), 408–421.
6. CHANG, CHING-CHIH; WANG, CHIH-MIN: *Evaluating the effects of speed reduce for shipping costs and CO2 emissions,* Transportation Research Part D Transport and Environment, 2014, 31, 110–115.
7. BARREIRO, JULIO; ZARAGOZA, SONIA; DIAZ-CASAS, VICENTE: *Review of ship energy efficiency*, Ocean Engineering 257, 2022, 111594.
8. HALIM, RONALD; KIRSTEIN, LUCIE ; MERK, OLAF; MARTINEZ, LUIS: *Decarbonization Pathways for International Maritime Transport: A Model-Based Policy Impact Assessment*, Sustainability, 2018, 10(7), 2243.
9. FARKAS, ANDREA; DEGIULI, NASTIA; MARTIĆ, IVANA; GRLJ, CARLO GIORGIO: *Is slow steaming a viable option to meet the novel energy efficiency requirements for containerships?,* Journal of Cleaner Production, 2022, 374(8), 133915.
10. GOSPIĆ, IVAN; MARTIĆ, IVANA; DEGIULI, NASTIA; FARKAS, ANDREA: *Energetic and Ecological Effects of the Slow Steaming Application and Gasification of Container Ships*, Journal of Marine Science and Engineering, 2022, 10(5), 703.
11. TEZDOGAN, TASCHIN; INCECIK, ATILLA; TURAN, OSMAN; KELLETT, PAULA: *Assessing the Impact of a Slow Steaming Approach on Reducing the Fuel Consumption of a Containership Advancing in Head Seas*, Transportation Research Procedia, 2016, 14(7), 1659–1668.
12. CARIOU, PIERRE: *Is slow steaming a sustainable means of reducing CO2 emissions from container shipping?,* Transportation Research Part D Transport and Environment, 2011, 16(3), 260–264.
13. LEE, CHUNG-YEE; LEE, HAU L.; ZHANG, JIHENG: *The impact of slow ocean steaming on delivery reliability and fuel consumption*, Transportation Research Part E, 2015, 76, 176–190.
14. HUI, XING; STEPHEN, SPENCE; HUA, CHEN: *A comprehensive review on countermeasures for CO2 emissions from ships*, Renewable and Sustainable Energy Reviews, 2020, 134(C), 110222.
15. PELIĆ, VLADIMIR; BUKOVAC, OZREN; RADONJA, RADOSLAV; DEGIULI, NASTIA: *The Impact of Slow Steaming on Fuel Consumption and CO2 Emissions of a Container Ship*, Journal of Marine Science and Engineering, 2023, 11, 675.
16. CORBETT, JAMES J.; WANG, HAIFENG; WINEBRAKE, JAMES J.: *The effectiveness and costs of speed reductions on emissions from international shipping*, Transportation Research Part D: Transport and Environment, 2009, 14(8), 593–598.
17. *MAN 48/60B Project Guide - Marine, Four-stroke diesel engine compilant with IMO Tier II, MAN Energy Solutions SE*, Augsburg, Germany (wwww.man-es.com).
18. *MAN 51/60DF Project Guide - Marine, Four-stroke diesel engine compilant with IMO Tier II, MAN Energy Solutions SE*, Augsburg, Germany (wwww.man-es.com).
19. *WARTSILA 32/40, Wärtsilä 32 Product Guide*, Wärtsilä, Marine Solutions, Vaasa, September 2016.
20. PELIĆ, VLADIMIR; RADONJA, RADOSLAV; MRAKOVČIĆ, TOMISLAV; BRATIĆ, KARLO: *Natural gas as fuel for the COGES ship propulsion system*, Proceedings, 37th International Scientific & Expert Meeting of Gas Professionals, Opatija, Croatia, May 11-13, 2022.

21. *Study on the optimization of energy consumption as part of implementation of a Ship Energy Efficiency Management Plan (SEEMP)*, International Maritime Organization, 2016, https://glomeep.imo.org/wp-content/uploads/2016/06/E-book_web.pdf (14.09.2023.).
22. KOROGLU, TURGAY; SOGUT, OGUZ SALIM: *Advanced Exergy Analysis of an Organic Rankine Cycle Waste Heat Recovery System of a Marine Power Plant*, Journal of Thermal Engineering, 2017, 3(2), 1136-1148.
23. CHEREDNICHENKO, OLEKSANDR; SERBIN, SERHIY: *Analysis of Efficiency of the Ship Propulsion System with Thermochemical Recuperation of Waste Heat*, Journal of Marine Science and Application, 2018 17:122–130.
24. CHABOKI, YADOLLAH AGHDOUD; KHOSHGARD, AHMAD; FAZELPOUR, FARIVAR; SALEHI, GHOLAM REZA: *Energy, exergy, and environmental analysis of meeting cooling demand of a ship with waste heat recovery*, Energy Efficiency , 2021, 14(2).
25. *Marine Installation Manual X82-2.0*, Issue 2023-03, 2023, Winterthur Gas & Diesel Ltd., www.wingd.com (18.09.2023.)
26. *General Technical Data, GTD 2.19.0.1*, Winterthur Gas & Diesel Ltd., Winterthur Switzerland (29.07.2023).
27. PRELEC, ZMAGOSLAV: *Energetika u procesnoj industriji*, Školska knjiga, Zagreb, Zagreb - Rijeka, 1994.
28. MRZLJAK, VEDRAN, ANĐELIĆ, NIKOLA, LORENCIN, IVAN, BARESSI ŠEGOTA, SANDI: *The influence of various optimization algorithms on nuclear power plant steam turbine exergy efficiency and destruction*, Scientific Journal of Maritime Research, 2021, 35(1), 69-86.