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Review Article

# A literature survey on exergy analyses of marine diesel engine and power systems

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## ABSTRACT

The oil crisis in the world has led countries to seek an alternative fuel that can replace fossil fuels. In addition, the fact that global warming, which is one of the most important problems for the world, has reached significant levels, has led to an increase in studies on greenhouse gas emissions and the efficient use of energy. Every effort to increase efficiency contributes to both environmental and economic improvements. Considering this situation, the study was compiled by examining the studies on energy and exergy analysis related to diesel engines and marine diesel power systems in the literature. As a result of the study, it has been seen that the use of different fuel types contributes significantly to the decrease in environmental emissions as well as the increase in efficiency in diesel engines. In addition, it is thought that there are few studies in the literature on ship diesel engines, and with the increase in the studies to be done on this subject, there may be important references to both companies engaged in maritime transport and studies that will conduct research on this subject.

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## 1. INTRODUCTION

Technological developments made progress with the impetus of the developing world order and have a significant impact on the development and growth of international trade, but in addition to the positive effects of this growth in trade volume, negative effects have also begun to emerge. As a result of the oil crisis that emerged in the 1970s, many countries around the world have started to search for alternative fuels that can be used instead of fossil fuels (Costa & Sodré, 2011). At this point, the fact that the danger of climate change, which occurs with global warming, has reached serious extents, reveals the need to reduce the greenhouse gas emission effects on the world (Baldi, Ahlgren, Nguyen, Thern, & Andersson, 2018). On the other hand, along with the increase in fuel prices, the economic problems that arise due to fuel consumption are results as negative effects (Johnson, 2013). Related to mentioned problems, the International Maritime Organization (IMO) has published and put into action the Energy Efficiency Design Index (EEDI) in order to reduce greenhouse gas emissions and increase energy efficiency in maritime transport (Zhu, Ma, Zhang, & Deng, 2020a). Researchers and international organizations are conducting important

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studies on improving energy efficiency, reducing greenhouse gas emissions, and using different fuel alternatives (Sanli & Uludamar, 2020; Wu, Xie, Wang, & Roskilly, 2018).

Every step to be taken to increase efficiency directly contributes to the improvement of both economic and environmental impacts. Accordingly, the detection of losses in any energy system actively provides the greatest benefit. While energy analysis creates the energy balance of the systems and enables the detection of energy leaks and losses, exergy analyzes are used to determine how much usable energy the systems and their components have lost, in other words, the exergy destruction. (Z. Liu, Liu, Guo, Xin, & Yang, 2019).

Considering the aforementioned important problems, in this study, the literature investigation on diesel engines and power systems, on which energy- and exergy-based analyses were performed, was carried out. Due to the insufficient number of studies on marine diesel engines in the literature and the fact that the working principles of diesel engines and ship diesel engines are the same, a conceptual framework has been created based on studies that have examined ship diesel engines and conventional diesel engines. This study aims to create a starting point for the studies to be performed in this field as well as to shed light on the previous studies to extend the investigations through the state of the art.

## 2. MATERIALS AND METHODS

In this section, diesel engines, diesel power systems, and waste heat recovery systems are introduced and explained.

### 2.1. Diesel engine

In 1982, the concept of the diesel engine was introduced into the literature with the work of Rudolf Diesel entitled "Working Method Design for Combustion Engines" (Mollenhauer & Tschoeke, 2010). With the construction of a diesel engine onboard a river boat named Vandal in 1903, diesel engines began to be used onboard ships, to the present, diesel engines are used in the vast majority of ships navigating the world (Morsy El-Gohary, 2013).

The operating principles of diesel engines, which are a type of internal combustion engine (Taylor, 1996) in general, are summarized as follows:

i. The air is compressed by pistons and its pressure and temperature are increased.

ii. A combustion event occurs as a result of spraying fuel through injectors into the compressed air whose temperature and pressure are increased.

iii. Gases formed as a result of combustion with high temperature and pressure push the piston located in the cylinder, allowing it to expand. As a result of this expansion, power is produced.

iv. Finally, the combustion gases inside the piston cylinder mechanism are discharged from the system as exhaust. (Kucuksahin, 2011).

The diesel power system is a system to produce power not only through the usage of the diesel engine on its own but also through the support of auxiliary systems to continue power production as well as new opportunities to produce more power. Hence, the diesel engine must be assisted by the auxiliary systems for continuous performance. The basic systems that help a diesel engine to operate are namely turbocharger, fuel, cooling water, and lubrication systems. The compressor of the turbocharger increases the pressure and temperature by compressing the air, after the air whose pressure and temperature rise exits the compressor, it is cooled in the intercooler which is a part of the cooling system, and sent to the diesel engine. The main task of cooling water systems is to prevent temperature increases that occur as a result of combustion in diesel engines and to ensure that the engine operates within a certain temperature interval. The main function of the turbine of the turbocharger system is to expand the exhaust gases to produce shaft power and transfer the power to the compressor. The main function of the lubrication systems is to lubricate the pistons, cylinders, and other moving parts of the engine to reduce the friction that may occur in the system, and to help cooling as a secondary task. (Koroglu, 2018).

### 2.2. Waste heat recovery systems

Waste heat recovery systems are used to reuse the thermal energy thrown into the environment, to use fuel energy more effectively, and/or to produce power (Singh & Pedersen, 2016). The first use of waste heat recovery systems in ship diesel engines appeared in Europe and the United States due to the oil crisis in the 1970s (Platell & B, 1976). By developing a heat recovery system consisting of a heat recovery boiler (economizer), steam turbine, and generator, MAN increased engine efficiency by 10%; Wärtsilä determined that engine efficiency could be increased by 11.4% by designing a recovery system consisting of a turbine and a double pressure boiler. (Jing & Fan, 2010). Rankine cycle, Organic Rankine Cycle, and Brayton Cycle are generally used as waste recovery systems onboard.

#### *2.2.1. Rankine cycle*

The Rankine cycle is named after William John Macquorn Rankine and is a cycle that converts thermal energy into mechanical energy and is used to recover waste heat (Rankine & Tait, 1881). The Rankine cycle is the most used cycle in marine diesel engine systems to generate additional power and utilize waste heat. A simple Rankine cycle consists of a boiler, pump, turbine, and condenser. The water used as the working fluid in the Rankine cycle is pressurized by the pump, evaporates, and is superheated with the heat given in the boiler, then expands in the turbine to produce work. Finally, the exhaust steam passes through the condenser and condenses.

#### *2.2.2. Organic rankine cycle*

The Organic Rankine system is a thermodynamic cycle consisting of an expander or a turbine, a condenser, a pump, and an evaporator. The principle of operation is the same as the conventional Rankine cycle. However, organic fluids are used instead of water as a working fluid (Andreasen, Meroni, & Haglind, 2017; Kaya, Ust, & Karakurt, 2020). In the organic Rankine cycle, the vapor is produced in the boiler and expands in the turbine, and the work resulting from the expansion is made available. The working fluid at the turbine outlet is completely condensed in the condenser and then the fluid is brought to the required pressure with the help of the pump (Verschoor & Brouwer, 1995).

#### *2.2.3. Brayton cycle*

The Brayton cycle occurs as a result of the use of gas as a fluid, and the processes in the Rankine cycle are adapted to gas fluid. The gas, which takes the heat in a heat exchanger, expands in the turbine at high temperature and pressure and provides power production (Karakurt, Ozel, & İskenderli, 2021). Since the gas fluid does not go into a condensation state, excess heat is thrown away employing a heat exchanger instead of a condenser, and since it does not become liquid, it is compressed until it reaches the required high pressure with the compressor instead of the pump (Çengel et al., 2019). Studies on these cycles, which are not yet as popular as the Rankine cycle related to their application on ships, have also been increasing recently (Du, Hu, Yang, Wang, & Dong, 2022; Feng et al., 2020; Pan et al., 2020). The reason for the lack of studies is that the temperature interval of the exhaust of the ship's diesel engines is not efficient for operating using such a system.

Similar to the Brayton cycle, an extra power turbine separated by a valve from the part of the exhaust gases going to the turbocharger is used to generate extra power by expanding the part of the exhaust gas that is left over from the compressor drive and disposed of as a bypass (Qu, Feng, Zhu, Zhou, & Zhang, 2021). On this occasion, in ships with space problems, additional power is provided to the shaft or used by adding only one turbine.

### 2.3. Methods

In this section, after monitoring the literature, the common methods used in scientific research are discussed for examination; energy and exergy analysis methods are briefly mentioned.

#### *2.3.1. Energy and energy analysis*

Energy is the ability of a system or object to do useful work. Energy exists in nature in different forms as nuclear, chemical, mechanical, electrical, or thermal energy. (Arshad et al., 2019). The energy balance in continuous flow systems is expressed as (Cengel & Boles, 2013; Cengel, Boles, & Kanoğlu, 2019).

$$E_g - E_c = \Delta E_{system} \quad (1)$$

Here E is the energy; subscripts g, c, and system represent the inlet, outlet, and system, respectively. In a system, the difference between the energies entering and leaving the system is said to be equal to the change in energy in the system. Since the engineering devices are designed as open systems with a continuous flow since they reach the regime, the given equation is updated according to unit time to match this. (Cengel & Boles, 2013; Cengel et al., 2019):

$$\dot{E}_g - \dot{E}_c = \frac{dE_{system}}{dt} = 0 \quad (2)$$

#### *2.3.2. Exergy and exergy analysis*

Exergy is defined as the maximum work potential that a system can produce by interacting with its environment in a dead state, that is, when it is in a balanced state with its environment (Bejan, 2006; Cengel & Boles, 2013; Cengel et al., 2019; Sonntag & Borgnakke, 2013; Szargut, 1980). The concept of exergy is also generally referred to as "useful work" or "usable energy". Exergy analysis, on the other hand, provides the establishment of a state of equilibrium between the exergy entering and exiting a system, and the determination of the exergy destruction in the system as a result of this established equilibrium state. Exergy destruction also gives information on how the system should be improved so that the system can work more efficiently with the improvements that can be made. All of these processes are defined as exergy analysis. The exergy balance for continuous flow systems is expressed as follows (Cengel & Boles, 2013).

$$\dot{E}x_D = \sum \dot{E}x_g - \sum \dot{E}x_c \quad (3)$$

Here, $\dot{E}x$ represents exergy and subscript D represents destruction. Based on Bejan's fuel (subscript F) – product (subscript P) approach, the exergy balance can be expressed as follows (Bejan, Tsatsaronis, & Moran, 1996).

$$\dot{E}x_D = \dot{E}x_F - \dot{E}x_P \quad (4)$$

Exergy analysis, in contrast with the energy analysis, explains what the irreversibility is caused by, what the causes are, which component in the system originates from, or which component has the greatest effect, and the magnitude of the irreversibility that causes the effect. This is the main difference between exergy and energy analysis.

## 3. STUDIES IN THE LITERATURE

In addition to providing information about the general condition of a system, exergy analyses are also used to evaluate the aspects of the system that can be developed and improved regarding the components or fluids in the system, such as which type of fuel would lead to better performance effects. The studies carried out in the literature have been examined here first as diesel engines, then as ship diesel engines, and ship diesel waste heat recovery systems in separate subsections.

### 3.1. Exergy based studies on diesel engines

Sarikoc et al. investigated the energetic, exergetic performance and sustainability of diesel-biodiesel-butanol fuel mixtures on a direct injection (DI) diesel engine. As a result of the study, they stated that the increase in engine speed increases the fuel energy, and the exhaust gas components and temperature are the main causes of exhaust gas energy losses. They said that while the use of biodiesel fuel provides a significant reduction in CO emissions, it causes an increase in $CO_2$ emissions. They also added that the energy efficiency of the system is higher than the exergy efficiency due to some thermodynamic irreversibility and the energy-exergy efficiency of the triple fuel mixture (diesel-biodiesel-butanol) is a type of fuel that can be used in diesel engines because its sustainability is almost the same as euro diesel fuel. (Sarıkoç, Örs, & Ünalan, 2020). Atelge has examined the performance of diesel engines under full load and partial load conditions using energy and exergy analyses by using biogas in diesel engines. As a result of the study, it was found that the increase in engine load increases energy efficiency and energy conversion. As a result of exergy analysis, it was found that the increase in engine loads reduces exergy destruction and increases exergy efficiency (Atelge, 2021). Jafarmadar Lister examined the combustion processes in the pre- and main combustion chambers of the 8.1 Indirect Injection (IDI) diesel engine in terms of the second law of thermodynamics under conditions of 2.96 bar and 5.96 bar brake mean effective pressure (BMEP) with 50% load and full load operations. As a result of the study, it was determined that 77% of the total exergy destruction in the system in half-load operation and 55% in full-load operation was caused by combustion in the main chamber. It is also stated that 65% of the total thermal exergy loss of the system in half-load operation and 55% in full-load operation is due to the heat loss in the main chamber (Jafarmadar, 2013). Odibi et al. studied the effects of oxygen-containing fuels on energy and exergy parameters using the first and second laws of thermodynamics for a diesel engine using triacetin and biodiesel fuel with oxygen content. As a result of the study, they stated that the decrease in engine load and the increase in engine speed increase the oxygen ratio, the increase in this ratio reduces the fuel and exhaust exergy and exergy efficiency, and the exergy destruction increases. It was determined that the increase in the amount of oxygen with the addition of triacetin decreased the irreversibility and therefore better combustion occurred as a result of the losses in the heating value. (Odibi et al., 2019). Şanlı and Uludamar investigated a four-stroke diesel engine, using diesel, hazelnut biodiesel (HB), and canola biodiesel (CB) fuel types, by applying energy and exergy analysis methods at various speeds. As a result of the study, they determined that the engine speed significantly affects energy and exergy efficiency. They stated that the highest irreversibility and thus the highest entropy production rate for all fuel types occur at 2400 rpm engine speed and diesel-fueled engines are more sustainable than engines using other fuel types at all engine speeds (Sanli & Uludamar, 2020). In another study, the energetic and exergetic performance of a dual-fuel diesel engine in which a liquid diesel and natural gas fuel mixture is used at ambient intake temperature, are theoretically and empirically investigated. It was found that the changes in engine power between 10 and 150 kW increased the energy and exergy efficiencies with the increase in engine speed for both diesel fuel and diesel-natural gas fuel mixture types compared, and higher engine efficiency was obtained by using diesel-natural gas fuel mixture from high engine powers. They noted that the increase in engine power for the two different fuel types compared increased the exergy of fuel products. (Ramos Da Costa, Barbosa De Lima, Bezerra Filho, & De Araujo Lima, 2012). Çanakçı and Hoşoz investigated a turbocharged diesel engine operating with different biodiesel and diesel fuel types by using the energy and exergy analysis method. They stated that the use of soybean oil methyl ester (SME) and yellow grease oil methyl ester (YGME) biodiesel fuels have a higher fuel consumption than the use of diesel fuel, and the thermal efficiency of biodiesel fuels is slightly higher than diesel fuel. They have seen that diesel fuel causes more exhaust energy loss than other fuel types and the exhaust exergy loss of all fuels gives similar results. Lastly, it is found that diesel fuel has lower exergetic efficiency than biodiesel fuels (Canakci & Hosoz, 2006). The effect of using pomegranate seed oil biodiesel fuel in a direct injection diesel engine, whose combustion chamber components are coated with ceramics, was investigated using the first and second laws of thermodynamics by Karthickeyan et al.. In the study, 20% pomegranate seed oil biodiesel and 80% diesel fuel mixture (B20) were used and the conventional engine and the ceramic-coated engine were compared. It was determined that the thermal efficiency was high with respect to the compression ratio (CR), injection pressure (IP), and injection time (IT) variation processes in both the conventional engine and the ceramic coated engine. Due to the presence of oxygen and high combustion temperature in biodiesel under all load conditions, high NOx emissions were observed when B20 fuel was used. They found 45.95%, 46.07% and 46.19% exergy destruction in IP4, CR4 and IT4, respectively. (Karthickeyan, Thiyagarajan, Ashok, Edwin Geo, & Azad, 2020). Bharathiraja et al. experimentally investigated the effects of gasoline fumigation on the engine performance of a single-cylinder diesel engine with direct injection in terms of emissions, energy, and exergy analyses have been studied. As a result of the study, they found that the use of gasoline fumigation under 3.5 kW load conditions resulted in a reduction in diesel consumption. They also found that while diesel-gasoline fumigation decreased the brake thermal efficiency in low engine power conditions, it increased the brake thermal efficiency in medium and high engine load conditions. Moreover, it is stated that fumigation increases carbon monoxide and unburned hydrocarbon emissions compared to diesel fuel, while carbon dioxide emissions are significantly reduced. Furthermore, the energy and exergy efficiencies showed a similar trend in all fuel tests performed, and since the fuel exergy was higher than the fuel energy, the brake thermal efficiency was higher than the exergy efficiency under the same operating conditions (Bharathiraja, Venkatachalam, & Senthilmurugan, 2019). Mina et al. examined a diesel engine converted to spark plug ignition using ethanol and gasoline-ethanol mixtures using the exergy analysis method. They determined the maximum fuel exergy rate at 2100 rpm in ethanol fuel and 3200 rpm in diesel fuel. The highest Exergy destruction for all fuels at 3200 rpm while achieving the results, the highest exergy efficiency of %16,46 occurred for the ethanol fuel at a 9:1 compression ratio and pm 2100 rpm, and the lowest exergy efficiency of %9.6 occurred for diesel fuel at 3200 rpm in (Zapata-Mina, Restrepo, Romero, & Quintero, 2020). Yamin et al. examined a four-stroke direct injection diesel engine using biodiesel fuel obtained from petro-diesel and waste cooking oil from the point of view of the first and second laws of thermodynamics. They stated that the use of biodiesel fuel leads to more specific fuel consumption than the use of petro-diesel fuel, and the reason for this is the high amount of oxygen in biodiesel fuel and the higher energy content of the fuel. They found that petro-diesel fuel produces 7%-15% more energy at high speeds compared to biodiesel fuel, and petrol-diesel engines utilize energy potential more usefully than biodiesel-fueled engines (Yamin, Sheet, & Hdaib, 2018). Liu et al. investigated the effects of injection parameters of a turbocharged diesel engine on the exergy terms at different engine loads using experimental data and theoretical calculations. They determined that there is a positive relationship between injection pressure and exergy terms, and the reason for this is the general progress in the combustion phase. In addition, there is a negative relationship between exergy destruction and exhaust gas exergy as well as injection pressure. When they compared the injection timing with the injection pressure, they stated that the injection timing had a greater effect on the exergy than the injection pressure, and the changes in the exergy values were generally seen in the combustion processes of the injection parameters (C. Liu et al., 2019). Jafarmadar and Amini Niaki experimentally investigated the use of fuel obtained by mixing $TiO_2$ nanoparticles with diesel fuel in a four-stroke direct injection diesel engine using energy and exergy analysis methods. They stated that fuel energy and exergy showed similar values due to small nanoparticles and that the increase in engine revolutions increased the fuel energy and exergy. It was determined that the addition of 2.5 ppm $TiO_2$ into diesel fuel increased the energy and exergy efficiency, and the increase in engine speed for both conventional diesel and diesel $TiO_2$ added fuel mixture decreased the exergy efficiency (Jafarmadar & Amini Niaki, 2022). Unlike the studies in the literature, Ozsari and Ust examined the combustion process in the combustion chamber using the method of exergy analysis. They found that the traditional combustion process has higher exergy destruction than the oxygenated combustion process. The increase in oxygen fraction from 0.21 to 0.30 also increases chemical exergy. Moreover, it is stated that the combustion chamber inlet temperature has no effect on chemical exergy. When they compare gasoline, diesel and natural gas fuel types; they concluded that diesel fuel is the more advantageous type of fuel in terms of exergy and temperature ratio, while diesel fuel is the most advantageous fuel in terms of exergy destruction (Ozsari & Ust, 2019).

#### *3.1.1. Exergy based studies on marine diesel engines*

Yao et al. examined the energy efficiency of a ship diesel engine with high power and medium speed using the energy balance and exergy analysis method. They determined that the energy loss from the exhaust is the highest in the system and that the increase in the exhaust temperature also increases the heat loss from the exhaust. They stated that the increase in the temperature and pressure of the gas in the cylinder increases the work exergy and the heat dissipation exergy in the cylinder wall, and the highest exergy loss is the irreversible exergy loss, and the decrease in the combustion quality index increases the energy efficiency (Yao, Qian, Li, & Hu, 2019). Gökalp investigated a tugboat's diesel generator using kerosene fuel mixed with safflower oil methyl ester (AME) by applying energy and exergy analyses. They said that the inefficiency and exergy destruction in the system are caused by irreversible processes such as combustion, and the exergy destruction caused by the heat flows in the exhaust gas and engine affects the inefficiency in the system. It has been determined that AME mixed with kerosene provides an improvement in light absorption coefficient emissions, which is a significant disadvantage for diesel engines, particularly in regions such as ports and shores. It is also noted that decreases in CO emissions are revealed with AME and its mixtures (Gokalp, 2018). The effects of diesel-hydrogen dual fuel use on the environmental, energetic, and exergetic performance of low-speed ship diesel engine were examined by Ammar. It is revealed that the increase in hydrogen substitution percentages not only increases the exergy efficiency of the engine in comparison with conventional diesel engines but also decreases CO and $CO_2$ emissions. It has been determined that if a selective catalytic reduction (SCR) system is applied to the engine, NOx emissions will also comply with the emission standards set by IMO (Ammar, 2018). Cavalcanti developed a gas-diesel fueled version of the engine and investigated a trigeneration system driven by a ship diesel engine with energy, exergy, and exergo-environmental analysis methods. As a result of the study, he stated that the energy efficiency of the system was 58%, and the efficiencies of pump 1, the Natural Gas (NG) compressor, and the low-temperature cooler are low. He also concluded that the gas-diesel fuel mixture reduces the exergy efficiency of the system, while the environmental impact of the products per exergy unit is 17.27 mPt/MJ for electricity and 31.27 mPt/MJ for cooling water (Cavalcanti, 2021). Manavalla et al. investigated a direct injection diesel engine running on triple diesel fuel by exergy analysis method. Their results yielded that three different biodiesel mixtures showed almost similar exergy destruction at 20 nM load and that the increase in the amount of biodiesel in the mixtures did not cause great differences in exergy destruction. They observed that when diesel fuel is used, exergy destruction is less at low loads and 2nd law efficiency is higher for diesel fuel at all load conditions (Manavalla et al., 2022).

### 3.2. Exergy-based studies with WHR systems added to marine diesel and diesel engines

One of the well-known methods of increasing energy efficiency and generating more power with the same amount of fuel is the recovery of heat discharged from any part of the system as waste heat to the environment (Alvik, Eide, Endresen, Hoffmann, & Longva, 2009; Turgay Koroglu, 2021). Generally, in marine diesel energy systems, waste heat is mostly discharged from the exhaust, but the heat discharged to the cooling water and lubricating oil can be evaluated due to the relatively high energy content they carry (MAN Diesel&Turbo, 2014). In this way, producing more power by utilizing the same amount of fuel, not only increases efficiency but also reduces specific fuel consumption and fewer greenhouse gases are released into the environment thanks to less specific fuel consumption. Steam systems are one of the important systems used onboard ships and are also used in the recovery of waste heat (Gonca & Ozsari, 2016).

Zhu et al. carried out a comprehensive thermodynamic analysis of a double-pressure steam Rankine cycle with a system that provides waste heat recovery (WHR) from a two-stroke marine diesel engine. Their results showed that exergy destruction is caused by the irreversibility of the combustion process, which accounted for 70%-80% of the total destruction in the system. They stated that reductions in engine loads would also reduce the exergy destruction of sweeping air. It is found that the largest exergy destruction in the double-pressure steam Rankine cycle system also occurs in the low-pressure steam turbine, while the smallest destruction occurs in the preheater. They noted that under normal conditions, fuel economy improved by up to 7.3%, while at 40% load this improvement was reduced to 3.2%. (Zhu, Ma, Zhang, & Deng, 2020b). Mito et al. stated that in a diesel engine, to increase the power production efficiency of the system by using sweeping air as hot fluid in the waste heat recovery system, the overall efficiency of the conventional system increased by 2.3% with a power output of 1210 kW. They found that if the sweeping air system was used, the exergy efficiency increased by 6.6% and the fuel consumption decreased by 9.7% (Mito, Teamah, El-Maghlany, & Shehata, 2018). Rangasamy et al. conducted a comprehensive experimental study using energy and exergy analysis methods to examine the effects of biodiesel fuel on the diesel engine. They stated that the increase in methanol energy ratio reduced the combustion time and in this case, the brake thermal efficiency increased. Dual-fuel reagent controlled compression ignition (DFRCCI) combustion mode compared to conventional diesel combustion (CDC) mode; they observed that the brake thermal efficiency was less. They also concluded that the energy lost in the exhaust and coolant was higher in the CDC mode than in the DFRCCI combustion mode, and as a result of their exergy analysis, almost 26% of the lower quality energy could be recovered from the exhaust and coolant by using the waste heat recovery method (Rangasamy, Duraisamy, & Govindan, 2020). Baldi et al. carried out an examination on a chemical tanker with measurement and technical information of the ship system by energy and exergy analysis. As a result of the study, a large part of the energy consumption onboard was consumed in the propulsion power systems. They stated that since the exergy values of the exhaust gases represent 18% of the engine power outputs, the potential for waste heat recovery is important for exhaust gases (Baldi, Johnson, Gabrielii, & Andersson, 2015). Abdu et al. conducted an exergy analysis on the exhaust gases of a marine diesel engine in three case scenarios to determine a waste heat recovery system (WHRS) with the highest second law efficiency for a marine diesel engine. Their results showed that most of the exergy destruction in the system was caused by the boiler in all cases. They stated that the system in case 1 had the highest efficiency at the ambient temperature, Moreover, the system in case 2 was less efficient than the system in case 1 due to exergy destruction in the Organic Rankine Cycle (ORC) turbine. Furthermore, the system in case 3 was the least efficient than the systems in the other two cases. The reason why the system in case 3 was the least efficient was the high level of exergy destruction in the steam turbine (Abdu, Zhou, & Orji, 2016). Wang et al. investigated the effects of the Miller cycle, in which they redesigned the camshaft, combined with the exhaust gas recycle (EGR) system, on marine diesel engine performance, energy and exergy analyses results. They found out that combining the Miller cycle with EGR increased the rate of heat release in the premix (pre-mixing of reactants) combustion process while decreasing the heat release rate in the main combustion process. They concluded the study by determining that the recovery potential of the heat energy transferred to the refrigerant is much lower than the exhaust energy (Wang et al., 2021).

## 4. DISCUSSIONS

Table 1 shows the selected studies with their application, system, and key findings. Among the scientific publications examined under the title of exergy-based studies on ship diesel engines, in the study of Yao et al. with respect to the other three studies, it was seen that the exergy losses and exergy destructions in the system were on which components they occur and the causes of exergy destruction in a general perspective. In the studies conducted by Gökalp and Ammar in this section, it has been demonstrated that the exergy efficiency of the engines has increased as a result of the use of different fuel types in marine diesel engines, while it has been revealed that the greenhouse gas emissions from ships have decreased. It is considered to be a remarkable result of these two similar studies, especially as a result of Ammar's study, that NOx emissions can be reduced to the dimensions set by IMO with the addition of the SCR system to the ship diesel engine. The study by Ammar can be a reference for shipping companies with similar types of machinery to both increase efficiency and reduce emissions through the use of the SCR system. Cavalcanti's study showed that the different types of fuel use showed that the efficiency of the components was low compared to the study conducted on the other two different fuel types in this section. In addition, the energy efficiency of the system decreased. It is thought that the reason for this may be due to the type of fuel used.

When the exergy-based studies in diesel engines are examined based on the literature and their general context is taken into consideration, it is seen that they carried out investigations on engines with energy and exergy methods using different types of fuel. Of the studies examined, four studies revealed that the increase in engine speeds affected exergy efficiency. For example, Odibi et al., Jafardamar, and Amini Niaki found that the increase in engine speeds reduced the efficiency of the exergy, while Costa determined in his study that the increase in engine speed increased the efficiency of the exergy. Apart from this, it is also stated that the main effect of reducing the exergy efficiency is the increase in the amount of oxygen in the fuel types used and the addition of titanium oxide to diesel fuel. (Jafarmadar & Amini Niaki, 2022; Odibi et al., 2019). In the other studies examined, exergy analyzes were evaluated with different parameters. At this point, while there are studies examining diesel engines using the exergy analysis method by taking into account combustion chambers and combustion processes, (Jafarmadar, 2013; Karthickeyan et al., 2020), using a different types of fuel in the diesel engine, there are also studies comparing the type of fuel used with the use of diesel fuel in terms of exergy (Canakci & Hosoz, 2006). Unlike these, Lui et al. examined diesel engines using the method of exergy analysis by taking into account the injection parameters.

Considering the studies examined under the title of ship diesel engines and WHR systems, it is seen that the studies in this section mainly evaluate the effects of waste heat recovery on diesel engines through different parameters. While Zhu et al. and Mito et al. found that waste heat recovery reduced fuel consumption in diesel engines, Mito et al. stated that in addition to fuel consumption, the exergy efficiency of the waste heat recovery system also increased (Mito et al., 2018; Zhu et al., 2020b, 2020a). In their study, Rangasamy et al. examined waste heat recovery and also examined the effects of biodiesel fuel on diesel engines. As a result of the study, it was determined that the use of biodiesel fuel increased the brake thermal efficiency and that the low energy of 26% could be recovered by using the WHR system (Rangasamy et al., 2020). Baldi et al. took into account the common topic of waste heat recovery, as in the studies in this chapter, and revealed that there is a significant potential for waste heat recovery for exhaust gases (Baldi et al., 2018, 2015). Abdu et al. evaluated the waste heat recovery with 3 different scenarios and examined the cases comparatively (Abdu et al., 2016). Unlike other studies in this section, In the study where Wang et al. examined the effects of the miller cycle on the performance of the ship diesel engine, it was determined that the speed of the heat release decreased as a result of the combination of the miller cycle with the EGR system, and the recovery of the exhaust energies was more likely to recover the heat energies (Wang et al., 2021).

## 5. CONCLUSION

The main purpose of the study is to carry out a literature survey on the energy and exergy analysis of marine diesel engines. The reason for considering the two methods is that the systems examined with energy and exergy analysis play an important role in increasing the efficiency and in the recovery of the waste heat thrown out of the system. The most striking point in the investigation of exergy analysis is that it is important to determine the exergy destruction occurring in the systems, to determine which component has the most exergy destruction in the components, and to increase the exergy efficiency by improving the destructions and contribute to the more efficient operation of the systems. In the preference of diesel engines and marine diesel engines as a system, the use of diesel power

**Table 1.** Key findings of selected literature

| Reference | System | Analysis | Key findings |
|---|---|---|---|
| (Sarıkoç et al., 2020) | DI diesel engine | The performance of the system was examined by the energy and exergy analysis method. | Due to some irreversibilities, the energy efficiency of the system is higher than the exergy efficiency.<br>As a result of the use of biodiesel fuel, it has been found that CO emissions have decreased significantly and $CO_2$ emissions have increased. |
| (Ammar, 2018) | Low speed marine diesel engine | Using exergy and energy analysis methods, he examined the environmental, energy, and exergy performance of the marine diesel engine. | The increase in the amount of hydrogen in the fuel has enabled conventional diesel machines to increase their exergy efficiency and reduce the number of harmful emissions released to the environment.<br>With the use of the SCR system for diesel engine, NOx emissions can be reduced up to the standards set by IMO. |
| (Zhu et al., 2020b) | Two-stroke marine diesel engine, WHR system, and steam Rankine system | They examined the systems with comprehensive thermodynamic analyses. | The vast majority of the total destruction in the system is due to irreversibilities in the combustion process.<br>While an improvement of up to 7.3% is achieved in fuel consumption under normal conditions, this improvement decreases up to 3.2% under 40% load conditions.<br>The highest exergy destruction in the system occurred in the low-pressure steam turbine. |
| (Baldi et al., 2015) | Chemical tanker ship | He analyzed the systems of a chemical tanker ship using energy and exergy analysis methods. | The potential of waste heat recovery is especially important for exhaust gases.<br>Most of the energy consumption in the system is consumed by propulsion power systems. |
| (Mito et al., 2018) | Marine diesel engine, waste heat recovery system | The use of sweeping air as a hot fluid has been studied from a thermodynamic point of view. | With the use of sweeping air in the system, exergy efficiency increased by 6.6% on average, fuel consumption decreased by 9.7%. |
| (Rangasamy et al., 2020) | Diesel engine | The effect of biodiesel fuel use on diesel fuel was investigated using the exergy analysis method. | The increase in the methanol ratio has reduced the burning time.<br>The increase in the methanol ratio has increased the brake thermal efficiency. |
| (Manavalla et al., 2022) | DI diesel engine | The effects of three different fuel usage on diesel engine were examined by the exergy analysis method. | The increase in the amount of biodiesel in fuel mixtures did not lead to major differences in exergy destruction<br>Three different biodiesel fuel mixtures gave similar results in terms of exergy destruction at a load of 20 nM. |
| (Cavalcanti, 2021) | Marine diesel engine | They evaluated the effects of the developed gas-diesel fuel mixture from the point of view of a marine diesel engine in terms of energy and exergy. | The energy efficiency of the NG compressor and low-temperature chiller is low.<br>The gas-diesel fuel mixture has reduced the exergy efficiency of the system. |
| (Yao et al., 2019) | A marine diesel engine with high power and medium speed | They evaluated the energy efficiency of the system using thermodynamic methods. | It has been determined that the energy loss caused by the exhaust is the highest in the system.<br>The increase in exhaust temperature also increases the heat loss caused by the exhaust. |
| (Sanli & Uludamar, 2020) | Four-stroke diesel engine | A four-stroke diesel engine, using (HB) (CB) fuel types, was examined the diesel engine with energy and exergy analysis methods at various revolutions. | It significantly affects the energy and exergy efficiency of the engine speed.<br>The highest irreversibility and, accordingly, the highest entropy production rate for all fuel types is realized at 2400 rpm engine speed. |

DI: Direct injection; SCR: Selective catalytic reduction; NOx: Nitrous Oxide; IMO: International Maritime Organization; WHR: Waste heat recovery; HB: Hazelnut biodiesel; CB: Canola biodiesel systems in the world fleet is excessive, and since maritime trade is the most widely used transportation method in international trade, the studies on marine diesel engines have been selected because it is thought that the results to be obtained will assist the researchers and institutions studying, operating and working in this field.

The studies in the literature were examined under three main sections namely, diesel engines, marine diesel, and WHR systems added after diesel engines. In studies on diesel engines, it has been observed that the effect of different fuel mixtures on the performance of diesel engines has been examined. In these studies, it has been determined that the fuel types used in general have positive effects in terms of energy and exergy efficiency. In addition, the effects on environmental outcomes were also examined in the studies. Considering the studies on diesel engines, it has been determined that there are not many studies in the literature on the comparative analysis of different engine types. When the studies on marine diesel engines are surveyed, it is seen that the evaluation of the use of alternative fuels in marine diesel engines by using the exergy analysis method enables the effects of alternative fuels on the inefficiency of the systems to be examined more clearly. Moreover, it has been observed that the determination of the exergy destructions and inefficiencies in the systems is important both economically and environmentally. As a result, the improvements to be made in the system or the components make the systems work more efficiently and reduce the emissions that harm the environment. It has been determined that exergy analysis is an important method for marine diesel engines because of the increase that can be achieved in energy and exergy efficiency, both in terms of costs and enabling the systems to work better. It has been observed that studies on these subjects have been carried out in the literature, taking into account the problems such as environmental effects of harmful emissions, exergy destruction in systems and components, efficient operation of systems, and alternative fuel use due to harmful emissions. The fact that there are few researches based on marine diesel engines is a matter that should be paid attention to in terms of literature. Moreover, the increase of conducted studies in this field can be a reference to maritime transport, which undertakes a large part of international trade while maritime companies experience economic or environmental issues. Considering that, it can offer solutions to the mentioned problems, it is thought that an increase in studies on the field is an important issue. On the other hand, when the studies on the systems appended to conventional diesel engines and marine diesel engines are examined, it has been found that it provides an increase in exergy efficiency due to the recovery of waste heat. In the studies reviewed, it was found that different types of fuel and systems added after the main engines have more positive results on the performance and efficiency of engines, while the negative results obtained are among the points that need to be paid attention to. In terms of future studies, it is thought that there is an important gap in the literature, especially on marine diesel engines, in which the effects of different ship types and shiploads on the performance of diesel engines should be examined and compared.

The main purpose of the roadmap drawn for the study is to review and evaluate the existing literature on diesel and marine diesel engines and to be a reference for the studies to be conducted in this field. However, according to the information obtained as a result of the study; marine diesel engines do not yet have a wide literature and it is thought that it is an important point to draw attention to in the name of current field studies. At this point, another issue to be pointed out is that the increase in the number of studies that will contribute to the field will be important for researchers who study in the field of maritime transport and maritime business. To conclude this study, it is recommended that researchers should be encouraged to study in a way that closes the gaps in the literature on the topics that are open and mentioned above.

Considering global warming and environmental problems, which are among the most important problems in the world, it is recommended that researchers lead studies towards reducing harmful emissions and increasing the number of studies using renewable and carbon-free fuels as an alternative that will help to solve both environmental as well as economic problems. Since the waste heat recovery in diesel engines is thought to have positive effects in environmental and economic terms, it is thought that increasing thermodynamic-based studies on these areas will provide significant benefits. In the field of ship diesel engines, since the studies examining the effects of ship sizes and cargo amounts on energy efficiency and exergy destruction are very few in the literature, it is recommended that future studies should also be directed to this topic.

## DATA AVAILABILITY STATEMENT

The published publication includes all graphics and data collected or developed during the study.

## CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## ETHICS

There are no ethical issues with the publication of this manuscript.

## FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

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