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Review of Energy Balance and Efficiency Enhancement Options for Marine Diesel Engines

Nader R. Ammar[#,^,*] and Fathi A. Elwazzan[!]

[#]Department of Marine Engineering, Faculty of Maritime Studies, King Abdulaziz University, Jeddah, 21589 Saudi Arabia.
[^]Department of Naval Architecture and Marine Engineering, Faculty of Engineering, Alexandria University, 21544 Alexandria, Egypt
[!]Department of Nautical Science, Faculty of Maritime Studies, King Abdulaziz University, Jeddah, 21589 Saudi Arabia.

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Abstract

Most prime movers and auxiliary generators of ships are diesel engines. Owing to both the cheapest residual fuel oil and the maximum performance compared to all the other heat engines, high-pressure combustion engine is used as the main propulsion for the vessels. The present paper discusses the available literature on the energy balance and efficiency enhancement options for marine diesel engines. The analysis of the energy balance provides valuable information on the amount of the supplied fuel energy in the engine systems and defines the preventable losses of the actual engine cycle as regards the ideal cycle. Energy balance can be considered as a significant framework to lay out the components of the engine. The onboard diesel engines have an output of approximately 48–51 percent and the remainder of the input energy is emitted into the environment including exhaust gas, jacket cooling water, and other losses. The review extends to the options for improving diesel engine efficiency. These options include the use of steam turbine, exhaust gas boiler, and exhaust gas turbine.

Keywords: *Marine diesel engine, Heat balance, Engine efficiency, Efficiency enhancement options*

1. Introduction

The main goal of designing a marine power plant is to achieve the required power to run the ship and operate machinery, with high performance and minimal cost. One decisive measures of engines performance are the thermal efficiency defined as the amount of the combusted input fuel heat that is transformed into beneficial output work from the engine. Therefore, calculating thermal efficiency, heat losses must be accounted for throughout the entire engine cycle, this operation is referred to as “heat balance”[1, 2].

Heat balance is a procedure for determining the efficiency of a combustion process by applying the first law of thermodynamics which is simply a statement of the law of conservation of energy. The energy equation for a closed system is:

$$Q = W + \Delta E$$

Where Q is the net heat added to the system (input heat from fuel combustion), W is the output shaft work (work done by the working fluid) and ΔE is in the net change of the internal energy of the working fluid.

All heat losses (expressed as percentages) are added together; then their total is subtracted from 100%; the remaining figure represents the efficiency.

Hence the thermal efficiency is given by:

$$\eta_{th} = W/Q$$

In order to calculate the thermal efficiency knowledge of the cycle on which the engine operates is required.

The thermal efficiency at full load of combustion engines varies from around 20% for small petrol engines to more than 50% for large slow-speed diesel engines, which are the most effective means presently involved in transforming fuel combustion heat to useful mechanical output power [3, 4].

The aim of the current paper is to review the heat balance equations of marine diesel engines and enhancing their thermal efficiency, as well as briefly covering the available systems for recovering the heat energy lost in marine diesel engines’ exhaust gas.

2. Diesel engine energy balance

In the original patent of Rudolf Diesel, the diesel engine operated on a diesel cycle in which heat was added at

*Corresponding author’s ORCID ID: 0000-0002-1976-7274
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constant pressure. This was achieved by the principle of blast injection. Today, the term is universally used to describe any reciprocating engine in which the heat produced by compressing air in the cylinders produces a finely atomized spray of fuel. This means that the theoretical cycle on which the modern diesel engine operates is better represented by a dual or mixed cycle, as shown in Figure 1.[3, 5, 6].

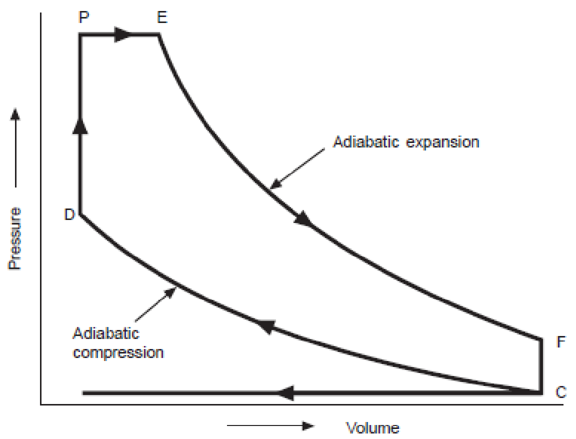

Figure 1 Typical cycle of diesel engine

From point C, the air is compressed adiabatically to point D. Fuel injection starts at D and heat is added to the cycle partly at constant volume as shown by the vertical line DP and partly at constant pressure as shown by the horizontal line PE. The expansion begins at point E. This proceeds adiabatically to point F when the heat is rejected for exhaustion at constant volume, as illustrated by the vertical line FC.

The ideal efficiency of this cycle is approximately 55–60 per cent: that is, about 40–45 per cent of the heat supplied is lost to the exhaust. Since compression and expansion strokes are assumed to be adiabatic and friction is ignored, there is no loss of coolant or ambient. For a four-stroke engine, the horizontal line at C shows the exhaust and suction strokes, and this has no effect on the cycle [3].

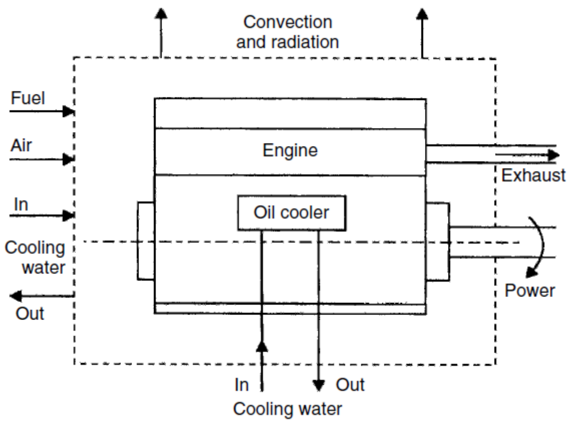

Figure 2 Control volume of a diesel engine showing energy flows

The energy distribution of an internal combustion engine is best measured in terms of the steady flow energy equation, combined with the concept of the control volume. In Figure 2 an engine is shown, surrounded by the control surface. The various flows of energy into and out of the control volume are shown [4, 7].

Applying the equation of the first law of thermodynamics, the steady flow equation will be [7, 8]:

$$Q_{add} = P_b + Q_{exh} + Q_{cw} + Q_{oil} + Q_{un} \tag{1}$$

The terms of the above equation are explained as follows. The total heat generated from fuel combustion (Q_{add}) in kW is calculated using Eq. 2.

$$Q_{add} = \dot{m}_f \times CV \tag{2}$$

where $\dot{m}_f$ is the mass flow rate of fuel in kg/s, and CV is the calorific value of the fuel in kJ/kg.

The Engine brake power (P_b) in kW can be calculated using the following two Equations.

$$P_b = 2 \times \pi \times N \times T \times 10^{-3} \tag{3}$$
$$P_b = P_{mb} \times L \times A \times N \times Z/i \tag{4}$$

Where N is the engine speed in rev/s, T is the output torque in N.m., P_{mb} is the brake mean effective pressure in kPa, L, A are the cylinder stroke and area, respectively, Z is the number of cylinders, i equals 1 for 2-stroke and 2 for 4-stroke engines. Note that it is not possible to show the indicated power directly in this energy balance since the difference between it and the power output P_b representing friction and other losses appears elsewhere as part of the heat to the cooling water Q_{cw} and other losses Q_l [4].

The amount of heat loss in exhaust gases (Q_{exh}) can be calculated using one of the following two equations.

$$Q_{exh} = (\dot{m}_f + \dot{m}_a) \times C_g \times (T_g - T_a) \tag{5}$$
$$Q_{exh} = \dot{m}_w \times C_w \times \Delta T_w + (\dot{m}_f + \dot{m}_a) \times C_p \times T_{cl} \tag{6}$$

where $\dot{m}_a$ is the mass flow rate of inlet air to the engine in kg/s, C_g is the average specific heat of the exhaust gases which can be assumed as the specific heat of air at mean exhaust temperature. Equation (5) is another approach for exhaust loss calculation is the use of exhaust calorimeter [9]. This is an air to water heat exchanger where the gas is cooled to a moderate temperature (not below 60 °C, because it's the dew point for the exhaust gas) and heat loss is calculated by observing the cool water flow and temperature rise.

The amount of heat, which is carried away by the cooling water (Q_{cw}) is calculated as follows:

$$Q_{cw} = \dot{m}_w \times C_w \times \Delta T_w \quad (7)$$

where $\dot{m}_w$ is the mass flow rate of cooling water in kg/s, C_w is the specific heat of the cooling water in kJ/kg.K

The amount of heat carried away by the lubricating oil (Q_{oil}) can be computed by using Eq. (8).

$$Q_{oil} = \dot{m}_{oil} \times C_{oil} \times \Delta T_{oil} \quad (8)$$

Finally, the unaccounted heat loss (Q_{un}) can be found by applying subtraction rule [10, 11].

$$Q_{un} = Q_{add} - (P_b + Q_{exh} + Q_{cw} + Q_{oil}) \quad (9)$$

A study for estimating a typical energy balance for a two-stroke diesel engine by MAN B&W has discovered that 24.6% of the released energy is wasted through the exhaust at ISO ambient reference conditions at 100% SMCR, and 16.5% and 5.6% in terms of the air cooler and jacket water respectively. Table (1) shows the balances of the energy fluxes of the MAN and Wärtsilä main propulsion low-speed Diesel engines corresponding to the maximum continuous rating value, MCR. These balances have been achieved based on the catalogue data of the engines. The table shows the maximum and minimum figures of the share in % of the waste power and waste heat flux contained in various carriers [12, 13].

There are three main heat sources with significant potential to be recovered for diesel engines as shown in Table (1), exhaust gas, air cooler and cylinder (jacket) cooler. The maximum exhaust temperature produced by two-stroke engine onboard ship is relatively low compared with four-stroke diesel engine, in the range of 250–500 °C. However, the quantity is in large amount. Therefore, significant amount of energy stored in exhaust gas is attractive to be recovered. Another promising character is that the limitation of the WHR systems' mass and volume are not as strict as that for vehicles. The scavenge air that enters the charger air cooler is between 130 and 150 °C, and between 70 and 120 °C for jacket cooling water at the engine outlet [14].

Table 1 Ranges of the energy balance percentages of marine diesel engine

Manufacturer	MAN		Wärtsilä	
Energy, %	max.	min.	max.	min.
Output power	50.8	47.1	50.9	48.5
Exhaust gases	24.6	21.5	25.5	23.7
Charge air cooling water	19.5	16.5	16.3	15.6
Lubricating oil	6.3	3.8	6.0	4.5
Cylinder cooling water	9.1	6.5	10.5	7.7
Radiation	0.9	0.5	0.6	0.5

3. Pressure charging of marine diesel engines

The naturally aspirated engine draws the same density of air as the ambient atmosphere. Since this air density determines the maximum fuel weight that can be effectively burned by working stroke in the cylinder, it also determines the maximum power that can be generated by the engine. Increasing the charge air density by applying an appropriate compressor between the air intake and the cylinder increases the weight of the air induced by the working stroke, allowing a higher fuel weight to be burned with a consequent increase in the specific power output. This increase in air density is achieved in most modern diesel engine types by exhaust gas turbocharging, in which the turbine wheel driven by exhaust gasses from the engine is rigidly coupled to a centrifugal air compressor. This is a self-government process that does not require an external governor [15, 16].

The power used to drive the compressor has an important influence on the operating efficiency of the engine. It is relatively uneconomical to drive the compressor directly from the engine by chain or gear, as some of the additional power is absorbed and the specific fuel consumption for the extra power is increased. Approximately 35% of the total thermal energy in the fuel is spent on the exhaust gasses so that, by using the energy in these gasses to drive the compressor, an increase in power is achieved in proportion to the increase in the air density of the charge [3, 17].

The turbocharger consists of a gas turbine driven by the exhaust gas of the engine mounted on the same spindle as the blower, with the turbine generating power equal to that required by the compressor. Figure 3 shows the full energy balances of several typical engines.

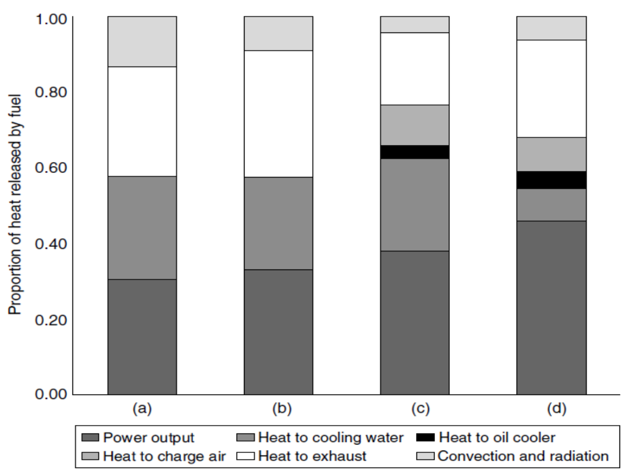

Figure 3 Representative of total power energy balances: (a) 1.71 gasoline engine (1998); (b) 2.51 naturally aspirated diesel engine; (c) 200kW medium speed turbocharged marine diesel; (d) 7.6MW combined heat and power unit [4]

There are several advantages of charging the pressure with an exhaust gas turbo blower system. A significant increase in engine power output for any given size and piston speed or, conversely, a substantial decrease in engine size and weight for any specified horsepower. An appreciable reduction in the specific fuel consumption rate for all engine loads. A reduction in the initial investment of the engine. Increased reliability and reduced maintenance costs, resulting from less demanding cylinder conditions. In the end, the turbocharger generates cleaner emissions and enhanced engine operating capability.

Figure 4b shows a supercharger powered by the engine and supplies the cylinders air with a pressure $p_2 = p_L$ identical to the cylinder pressure during the intake stroke so that compression starts at a higher pressure than in a naturally aspirated engine (1Z).

Once the expansion stroke (5Z) is completed, the exhaust valve is opened, and the cylinder charge is discharged against the ambient pressure (p1). This results in positive gas exchange work WLDW (areas 1Z, 6Z, 7Z, 8Z, 1Z) in the sense of work performed by the engine. [18].

The (isentropic) supercharger work WL the engine must produce is larger than its gas exchange work though. The perpendicularly hatched area corresponds to the loss of work resulting from the cylinder load being throttled from state 5Z to pressure p1 (after the exhaust valve) rather than being extended isentropically (loss due to incomplete expansion) [18].

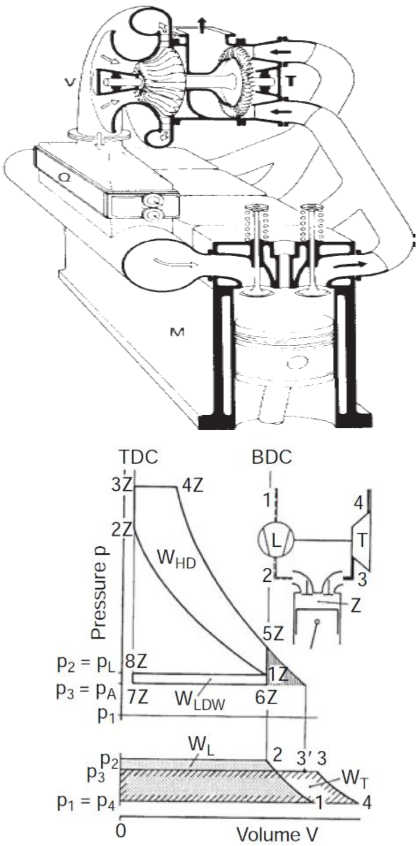

Figure 4 Turbocharged marine diesel engine [3, 18]

4. Waste heat recovery for marine Diesel engines

The ships are normally operating with engines that produce a significant amount of heat. Although modern diesel engines are very efficient, with more than 50% of the energy generated by fuel oil combustion being converted to mechanical energy, they still generate a large amount of waste heat when fully charged.

In many ways, the heat produced by the ship engines is removed from the engine. Approximately 5 percent of the engine 's total energy generation goes to the engine's cooling water system and about 25 percent to the exhaust gas. In both forms, heat is useful as a source of heat for other systems.

As far as the environment is concerned, the emission of exhaust gasses and particulate matter from seagoing vessels contributes significantly to the anthropogenic burden. With a view to protecting the Earth's climate and environment and alleviating the energy crisis, additional efforts are being made to design Green Ship in the future. Although clean combustion technology and post-treatment technology have developed [19, 20]. Waste heat recovery (WHR), alternative fuels will be an effective means of generating more energy based on the same emission quality [21-23]. Another reason why WHR technology attracts much more attention from energy and environmental researchers [24-26]. In addition, the International Maritime Organization (IMO) has introduced energy efficiency design and operational formulae to reduce greenhouse gas emissions [27].

The energy output of a large low-speed diesel engine with high-efficiency turbochargers can be increased by up to about 11 per cent by adding exhaust gas turbines and steam turbines. The system to do this typically consists of an exhaust gas boiler, a steam turbine (ST), an exhaust gas turbine (EGT) and a common electrical generator for both turbines. Some systems will not have an EGT and only a ST. Less power will be available from such a simple system, but it will require less alteration of the main engine. The exhaust gas for the turbine bypasses the turbocharger by means of a bypass valve. The exhaust bypass to the EGT is closed at engine loads below 50%. Figure (5) illustrates the arrangement of a slow-speed diesel engine with an EGT and ST with generator [13, 28].

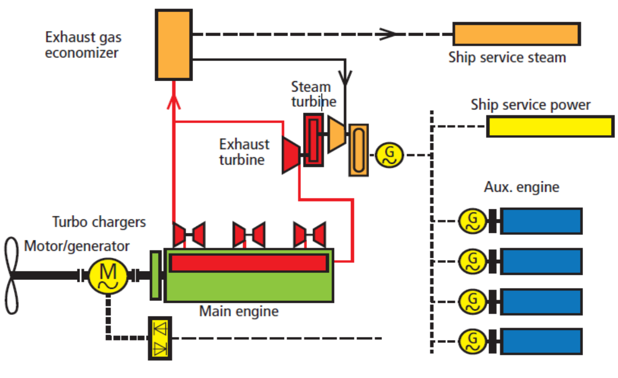

Figure 5 Arrangement of Slow-Speed Marine Diesel Engine with EGT and ST

If there is excess electrical power generation, the steam can be dumped to the condenser or the exhaust gas bypass can be closed. Usually, the added electrical generator can be worked in conjunction with the ship service diesel generators (SSDGs). In certain situations, all at-sea electrical power can be produced by the waste heat recovery generator, allowing the SSDG to be shut down, saving fuel and maintenance. In order to supply steam to the ST, the conventional exhaust gas boiler is replaced by an expanded unit with a super heater portion. Figure (6) illustrates a simple single-pressure steam system with saturated steam at an absolute 7 bar (6 bar g) at a vapor temperature of 165 °C. Superheated steam is produced at 270 °C in the lower part of the boiler [29-31].

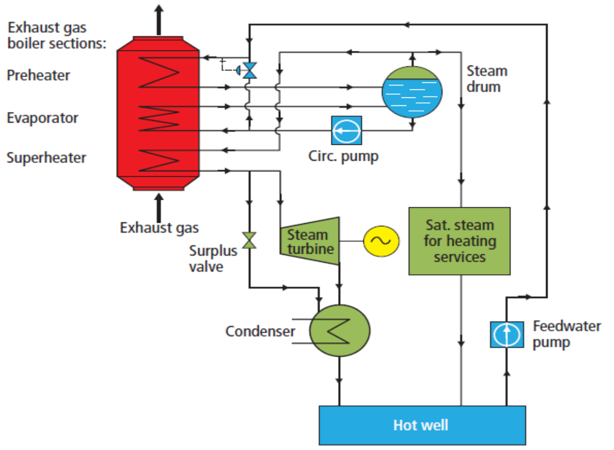

Figure 6 Waste heat recovery system based on simple steam cycle

Figure (7) illustrates a more complicated arrangement with two superheat vapor pressures and two turbine vapor inlets, high pressure (10 bar) and low pressure (4 bar). Adopting a more complex two-pressure system generates about 1% of the power output (MCR percentage), but it needs to be assessed if the extra complexity and cost is worth the power gain. [28, 32] .

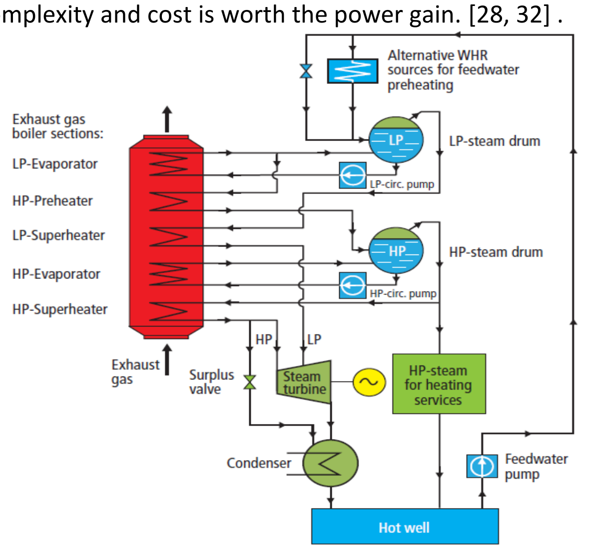

Figure 7 Two Pressure Steam System with Steam Turbine

Figure (8a) reveals the electrical power generation relative to the MCR that is possible with the installation of an exhaust turbine and a single or double pressure steam turbine. Up to a few MW of power can be produced for larger engines. This is more power than the typical ship's service electrical load, unless the vessel is a containership with many reefer containers on board. The alternative to using the generated power only for the ship's electrical power supply is to install a power supply (PTI) engine that will allow some of the generated power to be used for propulsion power. All the generated power can be used in this way. The scheme illustrated in Figure (8b) includes a PTI engine directly mounted on the shaft. [28, 30].

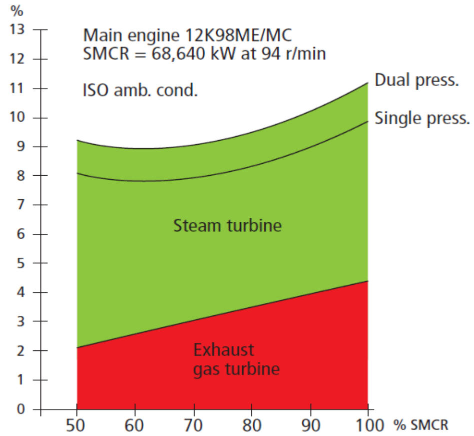

Figure 8a Percent of recovered electric power to the main engine MCR

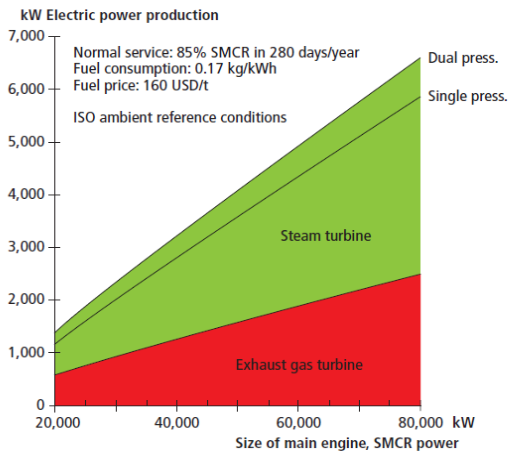

Figure 8b Recovered Electric Power using main engine waste heat

New advances in exhaust gas heat recovery are focused on Rankine Cycles using a different thermal medium, such as supercritical CO_2. Supercritical CO2 (sCO_2) operates in much the same way as traditional waste heat recovery but offers a much smaller footprint than traditional systems. These systems shown in Figure (9) are still in their initial phases of testing but may offer many benefits where enough thermal energy available in the exhaust gas. Such systems are anticipated to have lower costs for energy generation and low maintenance [28, 30, 33].

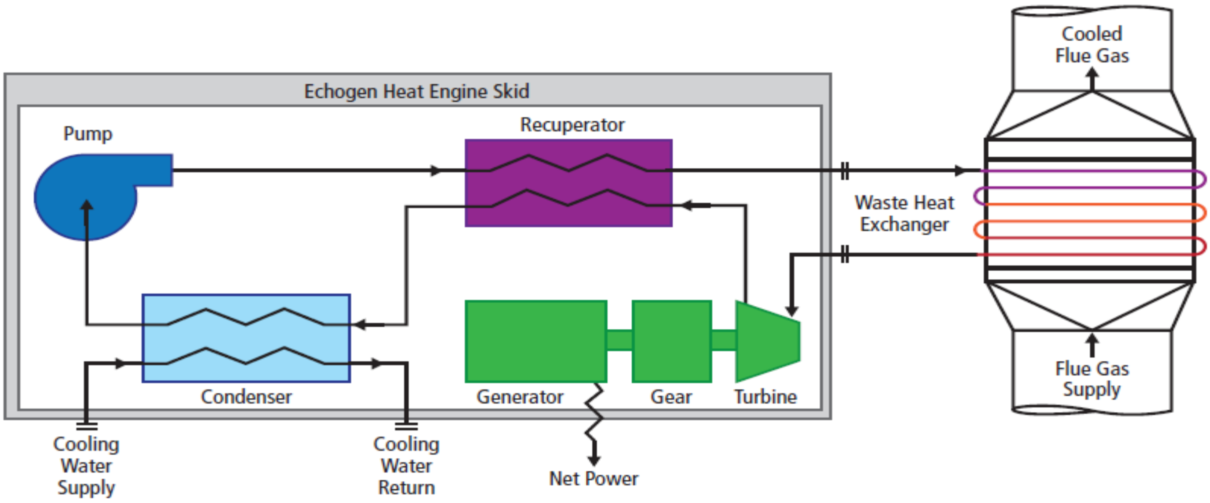

Figure 9 CO_2 Heat Recovery Cycle

Conclusions

A comprehensive energy balance survey of marine diesel engines and efficiency enhancement options is presented in this literature. The main findings from the presented literature review are:

- The energy balance analysis provides useful data on the prevalence of the fuel energy supplied in the engine systems and defines the potentially preventable losses of the actual engine cycle in relation to the ideal cycle. The new generations of marine diesel engines efficiently use almost 50% of the input combusted fuel energy. Regardless of this high efficiency, a significant ratio of the input energy is unused and lost to the environment as a waste energy.
- The main contributions of the energy lost in marine diesel engines are the exhaust gases and the cooling systems for the engine. The percent of the lost energy with the engine's exhaust gases is 25.1% of the input energy. In addition, the lost heat energy percentages in cooling lube oil, charge air, jacket water are 3.2%, 17.8%, and 4.8%, respectively. Moreover, 0.6% of the input energy is lost by radiation.
- There are different approaches for improving overall energy efficiency of marine diesel engines aim to reduce and make use of the wasted energy. Using the waste heat energy in the engine's exhaust gas and cooling waters will not only improves the thermal efficiency but also will reduce the harmful pollutant emissions. This will help to reduce the fuel consumption and the operating costs for the most commonly slow speed engine onboard large ships in case of making the best use of these lost energies.
- Finally, the proper evaluation of marine diesel engine power and its waste energy sources will be necessary in choosing the proper method for improving the engine efficiency. The assessment method must take into consideration the technical, environmental, and economic aspects of the different parameters for using the lost energy sources based on the engine output power and the remaining ship age.

References

[1]. Chakravarty, K. and S. Kumar, Increase in energy efficiency of a steel billet reheating furnace by heat balance study and process improvement. Energy Reports, 2020. 6: p. 343-349.

[2]. Sun, P., *et al.*, Experimental study on heat and exergy balance of a dual-fuel combined injection engine with hydrogen and gasoline. International Journal of Hydrogen Energy, 2019. 44(39): p. 22301-22315.

[3]. Woodyard, D., Pounder's Marine Diesel Engines and Gas Turbines Ninth Edition Preface. Pounder's Marine Diesel Engines and Gas Turbines, 9th Edition, 2009: p. 40-80.

[4]. Martyr, A.J. and M.A. Plint, Engine Testing: Theory and Practice, 3rd edition, Butterworth-Heinemann. 2007.

[5]. Zhu, D. and X. Zheng, Potential for energy and emissions of asymmetric twin-scroll turbocharged diesel engines combining inverse Brayton cycle system. Energy, 2019. 179: p. 581-592.

[6]. Zhao, R., *et al.*, Global optimization of the diesel engine–organic Rankine cycle (ORC) combined system based on particle swarm optimizer (PSO). Energy Conversion and Management, 2018. 174: p. 248-259

[7]. Abedin, M.J., *et al.*, Energy balance of internal combustion engines using alternative fuels. Renewable and Sustainable Energy Reviews, 2013. 26: p. 20-33

[8]. Hywood, J.B., Internal combustion engine fundamental, First edition Tata Mcgraw Hill Education. 2011.

[9]. Yüksel, F. and M.A. Ceviz, Thermal balance of a four stroke SI engine operating on hydrogen as a supplementary fuel. Energy, 2003. 28(11): p. 1069-1080.

[10]. Ajav, E.A., B. Singh, and T.K. Bhattacharya, Thermal balance of a single cylinder diesel engine operating on alternative fuels. Energy Conversion and Management, 2000. 41(14): p. 1533-1541.

[11]. Taymaz, I., An experimental study of energy balance in low heat rejection diesel engine. Energy, 2006. 31(2): p. 364-371.

[12]. Michalski, R., The Application of the Exergetic Analysis in Designing of Waste Energy Recovery Systems in Marine Diesel Power Plants. Journal of Polish CIMAC, 2012. 7: p. 110-125.

[13]. MAN B&W, Thermo Efficiency System (TES) for Reduction of Fuel Consumption and CO2 Emission. Copenhagen, Denmark: MAN B&W Diesel A/S. 2005.

[14]. Park, S., *et al*., Computational analysis of ship's exhaust-gas flow and its application for antenna location. Applied Thermal Engineering, 2011. 31(10): p. 1689-1702.

[15]. Yang, M., *et al*., Analysis on altitude adaptability of turbocharging systems for a heavy-duty diesel engine. Applied Thermal Engineering, 2018. 128: p. 1196-1207.

[16]. Sun, Y., *et al*., Development and validation of a marine sequential turbocharging diesel engine combustion model based on double Wiebe function and partial least squares method. Energy Conversion and Management, 2017. 151: p. 481-495.

[17]. Zhu, S., *et al*., Thermodynamic analysis of the turbocharged marine two-stroke engine cycle with different scavenging air control technologies. Energy, 2020. 191: p. 116533.

[18]. Mollenhauer, K., K.G.E. Johnson, and H. Tschöke, Handbook of diesel engines. Springer Science & Business Media. 2010.

[19]. Ammar, N.R. and I.S. Seddiek, Eco-environmental analysis of ship emission control methods: Case study RO-RO cargo vessel. Ocean Engineering, 2017. 137: p. 166 - 173. .

[20]. Ammar, N.R. and I.S. Seddiek, An environmental and economic analysis of emission reduction strategies for container ships with emphasis on the improved energy efficiency indexes. Environmental Science and Pollution Research, 2020.

[21]. Elgohary, M.M., I.S. Seddiek, and A.M. Salem, Overview of alternative fuels with emphasis on the potential of liquefied natural gas as future marine fuel. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 2014. 229(4): p. 365-375.

[22]. Ammar, N.R., Energy Efficiency and Environmental Analysis of the Green-Hydrogen Fueled Slow Speed Marine Diesel Engine. International Journal of Multidisciplinary and Current Research (IJMCR), 2018. 6: p. 1347-1356.

[23]. Ammar, N.R., An environmental and economic analysis of methanol fuel for a cellular container ship. Transportation Research Part D: Transport and Environment, 2019. 69: p. 66-76.

[24]. Ammar, N.R. and I.S. Seddiek, Thermodynamic, environmental and economic analysis of absorption air conditioning unit for emissions reduction onboard passenger ships. Transportation Research Part D: Transport and Environment, 2018. 62: p. 726-738.

[25]. Welaya, Y.M.A., M. Mosleh, and N.R. Ammar, Thermodynamic analysis of a combined gas turbine power plant with a solid oxide fuel cell for marine applications. International Journal of Naval Architecture and Ocean Engineering, 2013. 5(4)(4): p. 529-545.

[26]. Welaya, Y.M.A., M. Mosleh, and N.R. Ammar, Thermodynamic Analysis of a Combined Solid Oxide Fuel Cell with a Steam Turbine Power Plant for Marine Applications. Brodogradnja, 2014. 65(1): p. 97-116.

[27]. Ammar, N.R., Energy- and cost-efficiency analysis of greenhouse gas emission reduction using slow steaming of ships: case study RO-RO cargo vessel. Ships and Offshore Structures, 2018. 13(8): p. 868-876

[28]. MAN B&W, Exhaust Gas Emission Control Today and Tomorrow, Application on MAN B&W Two-stroke Marine Diesel Engines. MAN Diesel, Copenhagen, Denmark. 2010.

[29]. Jannatkhah, J., B. Najafi, and H. Ghaebi, Energy and exergy analysis of combined ORC – ERC system for biodiesel-fed diesel engine waste heat recovery. Energy Conversion and Management, 2020. 209: p. 112658.

[30]. MAN Diesel & Turbo, Waste Heat Recovery System (WHRS) for Reduction of Fuel Consumption, Emission and EEDI, Copenhagen SV, Denmark. 2012.

[31]. Theotokatos, G. and G. Livanos, Exhaust gas waste heat recovery in marine propulsion plants, in IMAM 2011. Proceedings of the 14th International Congress of the International Maritime Association of the Mediterranean, C. Guedes Soares and E. Rizzuto, Editors. 2011, International Maritime Association of Mediterranean: Genova (Italy).

[32]. MAN, MAN low speed diesel engines, in Pounder's Marine Diesel Engines (Eighth Edition), D. Woodyard, Editor. 2004, Butterworth-Heinemann: Oxford. p. 482-497.

[33]. Ouyang, T., *et al*., Design and modeling of marine diesel engine multistage waste heat recovery system integrated with flue-gas desulfurization. Energy Conversion and Management, 2019. 196: p. 1353-1368.