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A brief technical review of emerging waste heat recovery solutions for marine diesel engines

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ABSTRACT

Diesel engines remain the most widely used option to power a wide variety of transport ships. In terms of the maximum installed volume of all shipping vessels, 96% of this energy is generated from diesel engines. Due to the lack of alternative propulsion systems with the same energy density, cost, and fuel efficiency as diesel engines, it is not expected that marine diesel engines will be replaced within an expected 100 years. Modern large diesel engines are about 50% efficient in using the burning thermal energy of the fuel and the rest is lost to the environment as waste heat. The efficient use of waste heat energy can enhance the power system efficiency and reduce emissions, by using a dedicated waste heat recovery system for power generation or heating needs. Technologies that recover waste heat from engines have been around for 30 years, but recovery efficiency, cost of installation, and the ability to take up space in engine room space have caused certain obstacles. This paper conducts a brief review of the techniques and prospects of emerging waste heat recovery technologies from marine diesel engines. The results achieved would be useful suggestions for ship managers and owners in equipping marine fleets with waste heat recovery systems to meet the increasingly stringent IMO requirements for energy efficiency and environmental protection.

KEYWORDS

Waste heat recovery, emerging technologies, IMO, energy efficiency, environmental protection.

INTRODUCTION

Today, diesel engines are still the most widely used option to power a wide variety of ships. In terms of maximum installed volume of all civilian ships over 100 tons (GT), 96% of this energy is generated from diesel engines [1][2][3]. Due to the lack of alternative propulsion systems with the same energy density, cost, and fuel efficiency as diesel engines, it is not expected that marine diesel engines will be replaced within an expected 100 years [4] due to their high pollutant emissions such as PM and NOx [5][6][7]. Therefore, the use of biofuels or renewable energy [8-22], or advanced injection technologies [23-26] are considered as the useful solution to reduce the pollutant emissions from diesel engines. However, modern large diesel engines are about 50% efficient in using the burning thermal energy of the fuel and the rest is lost to the environment as waste heat [27]. Efficient use of waste heat energy can improve the efficiency of the driving system and reduce emissions, by using the dedicated Waste Heat Recovery System (WHRS) to generate electricity or use it for warming and drying needs [28][29].

For a conventional vessel, the heat load is negligible compared to the available waste heat, leaving a large volume of thermal energy unused [30]. WHRS can use the residual waste heat to convert heat energy into mechanical/electrical energy, which can then meet the needs for propulsion equipment and auxiliary engines without additional fuel costs and no CO_2 emissions [31]. MAN Diesel sees a potential total efficiency of 60% for fuel energy used on onboard diesel main engine uses. Other studies, mostly forecasts based on energy analysis, can achieve 4-16% fuel savings for a mid-range tanker using WHRS [32][33]. Waste heat on ships is mainly fuel energy that is released into the environment by various processes going on during normal operations, e.g. heat transfer. For a diesel train, the diesel engine is the largest source of waste heat [34]. Figure 1 depicts the energy balance of a 2-stroke large ship diesel engine and shows that about 50% of the total thermal energy fuel is emitted around the surrounding in different ways without doing any useful work. Each waste heat stream is different and the amount of energy taken away differs both in quantity and quality [35][36].

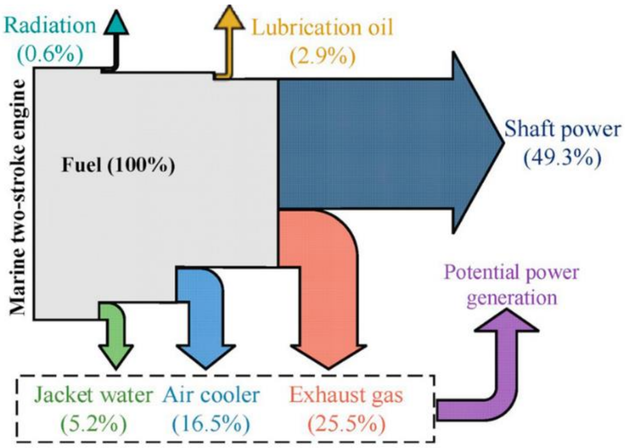

Figure 1. Scheme of thermal balance for a marine diesel engine by MAN 12K98ME / MC [37]

The heating quality of the waste is determined by the temperature of the exhaust gas. Thermal energy is classified as low, medium, and high quality depending on its temperature range as shown in Table 1. WHR's effectiveness is directly dependent on heat quality with its higher performance potential over the high-temperature range. From marine engine sources, most of the waste heat falls between low and medium quality. Table 2 provides a list of the main sources of waste heat along with their typical temperature ranges for a cruise ship.

Table 1. Thermal energy quality classification depending on the temperature range

Thermal energy quality	High	Medium	Low
Temperature range (ºC)	≥ 650	232 - 649	≤ 232

Table 2. Temperature ranges of major waste heat sources from vessels

Heat source	Temperature range (ºC)
Incinerators	850 – 1200
Exhaust emission	200 – 500
Intake air with Turbocharger	100 – 160
Cooling water	70 – 125

The exhaust temperature range varies with the type of two-stroke or four-stroke engine, the four-stroke engine having the higher exhaust temperature. Although the exhaust gas temperature varies depending on the load and ambient conditions, for nominal loads, the range is between 325 - 345ºC for two-stroke engines and 400 - 500ºC for four-stroke engines. Meanwhile, the exhaust gas temperature is higher for dual-fuel engines when operating on gas fuel. Engine coolant temperature ranges from 80 to 90ºC for most engines. However, for some gas-fueled dual-fuel engines, the cylinder cap coolant temperature can reach 125ºC, at a coolant pressure of 3-4 bar [38]. Among the listed waste heat streams, the highest quality is provided by the incinerator flue gas and has the highest potential for use by the WHRS. On the other hand, the operation of the incinerator is not continuous and the amount of heat provided is quite small compared to other flows.

However, the incinerator heat can be used to operate the dedicated WHRS or to supplement the WHRS designed for other flows for better efficiency in incinerator operations. Along with high mass retention rates and high temperatures, the self-sufficient exhaust gas is the best source of waste heat, both in quantity and in quality [39]. The use of the exhaust gas energy depends on the lowest temperature at which it can be cooled in the heat exchanger. In the case of fuel oil-burning engines, there is a risk of corrosion due to the condensation of sulfuric acid in the exhaust gas stream [40][41]. Therefore, WHRS uses flue gas should be designed to ensure that the flue gas is not cooled below the acid dew point. This factor restricts the heat recovery from the exhaust gas [22][42]. MAN Diesel recommends an outlet temperature of no less than 165 ° C to avoid acid corrosion and soot accumulation in exhaust heat exchangers. Future use of cleaner fuels may reduce the risk of acid formation at lower temperatures and possibly increase energy recovery from the exhaust gas.

The high-temperature sweep gas at the output of the turbocharger turbine (T / C) is cooled to increase density before being fed to the engine. Traditionally, the sweep gas is cooled by transferring heat to the cooling water in the air cooler. The scanning gas thermal range makes it a potential candidate for use in WHR. The constant supply of this waste heat during engine operation makes it more attractive for salvage operations. The heat that carries the cylinder coolant of a diesel engine is either used in a freshwater generator to produce pure water from seawater for serving on board or released into the atmosphere through heat exchangers [43]. Despite being a low-quality source of heat, cylinder coolers are available in large quantities and continuously during engine operation. With WHRS suitably selected, it makes a good candidate for WHR applications [44][45]. WHRS can be designed to operate on one or a combination of different heat sources. Depending on the source of waste heat, WHRS has three alternatives; (i) only flue gas is the easy standard solution, (ii) HT high-temperature air emissions and coolant represent modern state and waste heat sources for the highest possible recovery. This paper presents an evaluation of emerging heat recovery solutions including thermal oil systems, waste heat recovery by Kalina Cycle, waste heat recovery by Organic Rankin Cycle.

TECHNOLOGY TO RECOVER WASTE HEAT BY THERMAL OIL SYSTEM

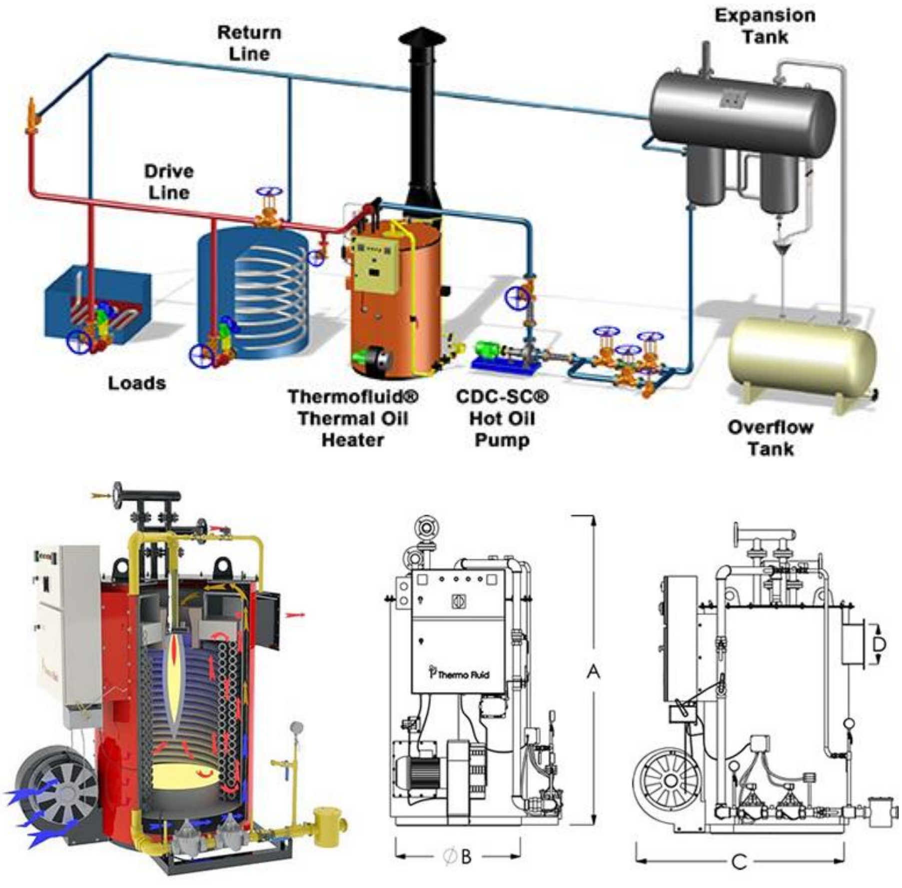

Figure 2. A typical thermal oil system is fitted on the tanker to heat cargo oil

Thermal oil or heat transfer fluids are widely used to carry thermal energy in process heating, metalworking and machine cooling applications. They are mainly used in high temperature process applications where the optimal bulk liquid operating temperature between 150ºC and 400ºC is safer and more efficient than steam heating methods, direct fire or electricity. Use of thermal oil systems first began in the late 1930s. They are used due to their high energy efficiency and the rate of heat transfer. However, the oils used are unstable if the temperature rises above the rated stable temperature set point during regular service periods, resulting in oil failure and partially oxidized and thermally unstable. As a result, a number of thermal oil system failures have occurred, prompting companies to go back to a safer option, rather than a steam system. In practice, however, the thermal oil system is less complex, easier to design, and safer than the steam system, provided that the right application, maintenance, and fluid are suitable for the application [46][47].

Since the introduction of thermal oil systems, significant advances have been made in technology and today thermal oil is much more stable in terms of heat, non-toxic, and can generate higher temperatures at atmospheric pressure than their previous oils. As a result, many companies are researching the use of this technology in their heat transfer (Figure 2). The decision to use thermal oil as a heat transfer medium can be based on many reasons, but one of the main incentives is to use it on a non-pressurized system [48]. The steam system operates under pressure and is subject to statutory and regulatory requirements due to inherent risks from pressure and increased installation costs and the requirement for periodic insurance testing. Thermal oil is usually only suitable for vessels with narrow spaces but is required to heat oil for main engines, because the thermal oil heating system is very compact, with a small capacity. The temperature of the thermal oil coming out of the “pot of oil” can be up to 300ºC. However, it is necessary to slowly raise the temperature of the pipe to avoid heat "shock" for the pipes that can lead to bolt and weld breakage, so bringing the oil temperature up to 300ºC takes a long time [49]. Therefore, analysis of the thermal oil systems in the study suggests that they could be a good alternative to today's steam systems commonly used on the majority of ships.

WASTE HEAT RECOVERY TECHNOLOGY BY KALINA CYCLE

The thermodynamic energy cycle is based on a mixture of water and ammonia, proposed by Dr. Alexander Kalina in 1983 and since then the cycle has been named after him as the Kalina cycle (KC). It is a modified form of RC that works better for some applications. The most promising uses and significant increases in efficiency are carried out in heat sources at low temperatures, making it a suitable option for waste heat recovery [4]. KC uses a mixture of ammonia and water as a liquid to operate in variable combinations with varying boiling and condensing temperatures between bubbles and dew points. Figure 3 shows that, for a given part of pressure and mass of ammonia, the liquid begins to boil at the bubble point and continues until the dew point where all the liquid turns into a vapor. During boiling/condensation variable temperature results in a better thermal match with the right heat source and coolant during a phase change. This contributes to improving the thermodynamic efficiency of the boiler and lowering the minimum temperature in the condenser. By varying the volume of ammonia, the bubbles and dew point of the liquid can also be changed to match the source and the sink temperature in the boiler and condenser, respectively. In terms of layout, the KC system is quite similar to the RC system with a few additional components. A basic KC system will have a collector, separator, mixer, and flow control valve in addition to the standard components of the RC system shown in Figure 3 [50].

Operationally, the flow control valve acts as a regulator that controls the total ratio of the feed pump to the separative device. Precise control of the flow is essential to maintain different ammonia concentrations inside the boiler-turbine and the condensate portion of the reagent stream. The Recuperator recovers some of the heat from the liquid at the turbine outlet to heat the flowing liquid to the separative device. It mainly reduces the amount of heat removed in the condenser. It also controls the temperature of the liquid going to the separative device, an important factor in determining the mass fraction of the poor and rich mixture flowing out of the separative device. A separator is used to separate the liquid coming from the collector into a rich and poor mixture. The flow rate of the rich and poor mixture depends on the separation efficiency, the temperature, the composition of the inlet mixture, and the pressure inside the separative device. There are two mixers used in the system to achieve the required component currents in the system circuit. The mixer is first placed at the inlet of the condenser, where the poor mixture from the separative device is mixed with the exhaust gas from the turbine after passing through the collector. Here, turbine exhaust and mixed liquid separator to deliver low concentration liquid to condenser. The second mixer is located on the inlet side of the boiler, where the residual flow from the flow control valve and the rich mixture from the separative device is mixed to supply the boiler with high concentrated working [51].

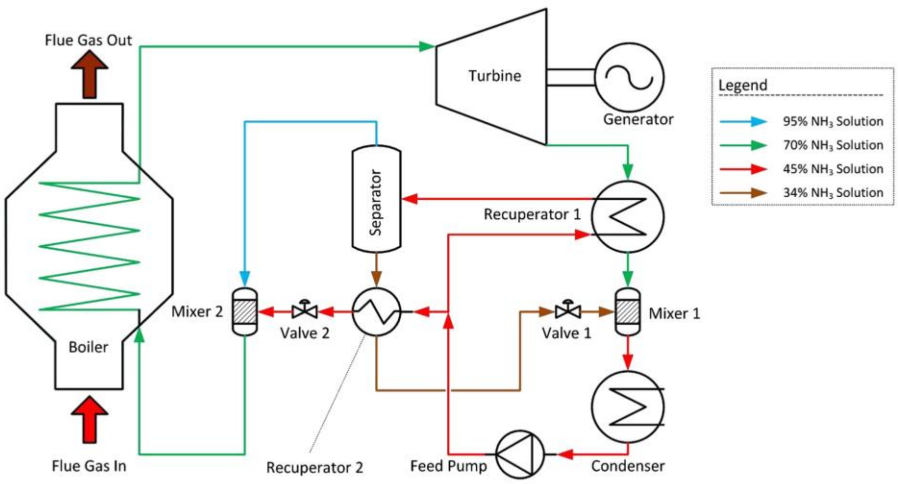

Figure 3. Configuration of a basic KC system for WHRS on vessel

When first introduced, efficiency was 5% and 15% according to the first and second law of thermodynamics for the KC system compared to the steam-based SRC. Studies with bottom-bottom KC systems have better thermodynamic performance than SRCs for diesel-gas dual-fuel engines. Bottoming cycles using the best water-ammonia mixtures can produce 40% -50% more power than single-pressure steam SRCs and 20% -24% higher than double-pressure steam cycles. In the 200 - 400 ° C exhaust gas temperature ranges of a ship's diesel engine, KC is 20% -40% more efficient than the RC. The Kalina separation cycle with reheating increases efficiency by 2% compared to the same cycle without reheating [52].

Another advantage of the KC system is that it is able to operate under freezing temperatures compared to RC when using water. Water - ammonia has reduced freezing temperatures and as a result condensation temperature can be reduced to accommodate transport routes in the arctic region. KC can use traditional axial steam turbines because the molecular weights are roughly equal to 17 for ammonia and 18 for water. Compared to RC, KC systems are smaller and cheaper thanks to back-pressure turbines instead of vacuum condensation, thereby reducing the density of the liquid at the turbine outlet. This is a positive feature for ships with limited space. In terms of material technology, KC has no special requirements and carbon steel is perfectly acceptable for low-temperature applications like WHR [53]. Some stainless steel also does not corrode in ammonia water mixtures.

With regard to the safety concerns associated with ammonia use, it is a chemical that is widely used and handled both ashore and safely transported on ships. It is ecologically safe and harmless when diluted. With its pungent odor automatically alarms in case of a leak. With wide industrial use, proven safety standards for consideration of water-ammonia mixtures, are environmentally friendly and safe for engineering applications [24]. With these outstanding advantages and strong recent developments, the safe adoption of the KC cycle for ship WHRs is very promising. It is perfectly suited for waste heat source applications with low temperature and higher cycle efficiency than RC and ORC. Therefore, applying the KC cycle will be an effective solution to better save fuel and reduce emissions.

TECHNOLOGY TO RECOVER WASTE HEAT BY ORGANIC RANKINE CYCLE

The Organic Rankine Cycle (ORC) is a modified form of RC; where the system working fluids are converted from water/steam to other organic liquids such as hydrocarbon gas, refrigerants such as hydrochloro-fluorocarbons (HCFC), etc. system uses Rankine cycle and has the same basic ingredients. At moderate heat source temperatures, best efficiency and highest power output are usually achieved by using a suitable organic liquid in place of the water /vapor in the RC [54][55]. This is mainly because the specific heat vaporization of organic fluids is much lower than that of water. Therefore, the 'after' organic liquid is better than the heat source fluid that is cooled. An ORC system can be arranged in many different configurations to achieve optimum cycle efficiency and reduce heat loss [4][56].

The different energy utilization technologies for WHR and ORC currently achieve conversion efficiency of 8-12% corresponding to the temperature range of the waste heat source from 95 - 260ºC [57]. When the exhaust gas temperature of the engine is 470ºC and the fluid capacity is benzene, the overall efficiency of the system can be increased by about 12% [58]. An 18-21% ORC system efficiency for marine diesel engine translates into a 10% increase in overall plant efficiency. With the power system of ships using a gas turbine, when equipped with an ORC system, the efficiency can be up to 20-30% [50][59]. Top optimum ORC system efficiency, ranging from 20% to 30% for heat source temperatures between 180°C and 360°C for marine applications [60][61]. With the configuration of ORC using waste heat from the engine coolant, the lubricating oil cooler and the sweep gas cooler have the ability to recover heat with an efficiency of 8% [36][62].

For low and medium temperatures, the WHR wet-liquid application is not particularly desirable due to the lack of potential for overheating and can cause condensation resulting in turbine blade erosion [63]. Wet, isotropic, and dry liquid formulas are promising for ORC applications, and the ideal fluid work is typically determined based on the source temperature range. Zeotropic binary blends have also been suggested for ORCs due to the better thermal combination with the heat source and an improved system performance up to 15% compared to pure liquid work [64].

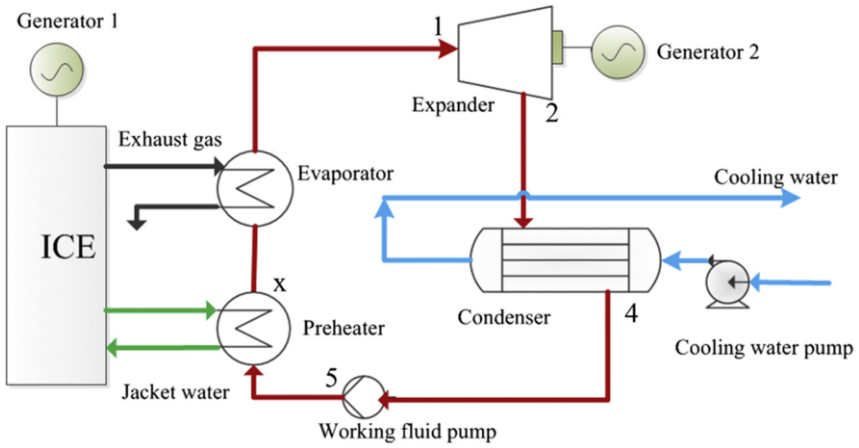

Figure 4. Configuration of ORC waste heat recovery system from exhaust gas cooled water

CONCLUSION

A waste heat recovery system produces power by utilizing the heat energy lost to the surroundings from thermal processes, at no additional fuel input. For marine vessels, about 50 percent of the total fuel energy supplied to diesel power-plant aboard is lost to the surroundings. While the total amount of wasted energy is considerable, the quality of this energy is quite low due to its low temperature and has limited potential for power production. Effective waste heat recovery systems use the available low temperature waste heat to produce mechanical/electrical power with high efficiency value. This paper outlines the main technologies for WHR for marine applications. The WHR technologies discussed here are organic Rankine cycle, Kalinacycle, and thermal oil system. A comprehensive review of these technologies has been carried out based on the waste heat sources available on marine vessels. This work helps in identifying the most suitable heat recovery technologies for maritime use depending on the properties of shipboard waste heat and achievable recovery efficiencies, whilst discussing the features of each type of system.

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