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A REVIEW OF THE DEVELOPMENTS OF ORC AND ABSORPTION REFRIGERATION WASTE HEAT RECOVERY SYSTEMS FOR MARINE APPLICATIONS

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ABSTRACT

The utilization of the heat energy lost during combustion process is a critical problem for energy conversion for marine application. In the maritime shipping sector, around 50% of the energy supplied by the fuel is lost to the surroundings. Practical methods to save the energy lost have been investigated extensively to use the low-grade energy for power production, heat generation, and water desalination. In this paper, a review of the available waste heat recovery systems is presented, highlighting the common methods having higher energy utilization potential for marine applications. This study helps to outline the suitable waste heat recovery technologies that are suitable to use for each desired outcome onboard of naval ships, and achieve higher efficiencies.

KEYWORDS*: Absorption, Development, Maritime, ORC,Waste Heat Recovery*

INTRODUCTION

In the past few years, growing concerns were expressed about the impact of maritime emissions on the environment and marine life. Additionally, with the rising emission levels from the maritime shipping, some regulations were set to limit the emission levels and ensure the safety of the environment. With these concerns in mind, several technologies were introduced to reduce the emissions and maintain an efficient energy conversion. One of the most prominent technologies is the Rankine cycle that has been explored extensively by researchers over the past decade. Shu et al. [1] provided a reliable evaluation of an organic Rankine cycle for a marine WHRS. The model is used to propose an ORC system to analyze the thermodynamic performance of different working fluids. The results indicated that an increase in electricity production by 36-41% when the operational profile is included. A state of the art review of thermodynamic cycles for heat recovery was given by Iglesias Garcia et al. [2]. The survey highlighted the characteristics of ORC and advantage over the other Rankine Cycles with their modifications. It was shown that closed processes are more efficient than others, while still, the low efficiencies are a drawback. Chintala et al. [3]reviewed the potential of waste heat recovery from the exhaust gas, water jackets and intake charge air of CI engines. The study stated that engine-ORC system could operate with the maximum thermal efficiency range about 10–25% and R245fa is a better organic working fluid for engine-ORC application based on better performance, availability, economic and environmental aspects.

The power generation efficiency improvement was investigated by Mito et al. [4] through a proposed novel technique. The technique aimed to integrate the heat rejected from the scavenge air cooling process and the exhaust gas in operating a single and dual pressure steam power generation cycles. The results showed a 2.3% increase in the cycle efficiency, the power output by 9.7% of the engine's rated power, an exergy efficiency increase by 6.6% and a reduction of both fuel consumption and carbon dioxide emission. Andreasen et al. [5]compared between dual pressure SRC and ORC for low and high sulfur fuel cases. The comparison shows that at high loads the net output power is higher for SRC and the ORC performance is higher at lower loads. Regarding turbine efficiency, the ORC turbine can achieve higher efficiency than SRC using c-pentane giving 10% increase in values. Rech et al. [6] tried to exploit the heat from four different dual fuel diesel engines by investigating three ORC systems configurations onboard an LNGC. The results indicated an optimum speed of 16.5 knots on a loaded voyage for better performance of a single stage system with 1.67 GWh at a peak efficiency of 6.5%. Moreover, using the supercritical configuration leads to the optimum performance of the two-stage ORC giving a 2.3 GWh work and a thermal efficiency of 12.6% at 15.5 knots.

Many researchers have investigated a different kind of waste heat recovery systems that are used for diverse applications. Chen et al. [7] proposed an ammonia-water combined power and cooling system, in which the waste heat contained in the jacket water and exhaust gas of an internal combustion engine can be recovered efficiently to generate power and cooling energy simultaneously. The results of an economic analysis indicate that the proposed system has a good economic benefit. A novel NH3-H2O-LiBr absorption cycle was investigated, Liang et al. [8] proposed a system that uses an electrodialysis device to separate the LiBr from the solution stream entering the absorber so that the LiBr is retained in the generator as much as possible. Results indicated that, due to the integration of electrodialysis process, the operating temperature in the generator is significantly reduced and the COP of the proposed system is improved compared to the regular NH3-H2O-LiBr absorption refrigeration cycle when LiBr mass fraction varies from 0% to 50%. For optimum energy utilization, a hybrid system can be used to utilize the energy from different heat sources. Su and Zhang[9] studied a hybrid compression-absorption refrigeration air-conditioning (AC) system combined with liquid desiccant dehumidification. The PEE of the proposed system is 34.97% higher than that of traditional absorption refrigeration AC system at the same operating condition. Moreover, compared with the traditional absorption refrigeration AC system, the generation temperature of the proposed system can decrease from 100 °C to 60 °C due to the existence of the compressor. Although there have been many studies on the Rankine cycle, there is still hardly any comprehensive review of the recent developments in waste heat recovery technologies in marine applications. To the knowledge of the authors, there is a lack of literature on hybrid waste heat recovery systems that focus on the generation of both power and heat. In this context, this review aims to highlight the current technologies of WHRS and the trends of hybrid systems that utilize the low and medium grade temperatures.

WASTE HEAT RECOVERY FOR MARINE APPLICATIONS

The fuel used in combustion engines is not utilised entirely due to the heat energy that is lost to the environment through the combustion process. The largest portion of the lost heat is from the exhaust gases, and it can be seen from the Sankey diagram shown in Fig.1, there is about 25.5% of the fuel’s energy that is lost to the surroundings [10] through the exhaust gases and others. The available temperature of the waste heat is the primary factor to be considered when determining the quality of the heat. There are three main categories of waste quality such as low, medium, and high quality and it depends on a range of temperature as shown in Table 1. The higher efficiencies are achieved with higher heat quality for the waste heat recovery systems, but for marine, the usual quality is either low or medium.

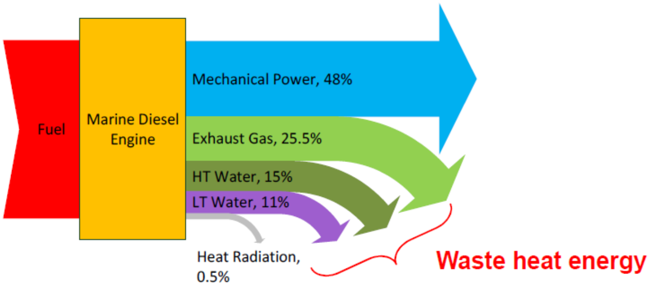

Figure 1: Sankey's Diagram of a Typical Marine Diesel Engine

The major contributors to waste heat in a marine engine are exhaust gas, scavenge air and engine cooling water. The range of exhaust gas temperature varies from 2 to 4 stroke engines, but four-stroke engines have higher temperatures. Although the exhaust temperature is dependent on several factors including ambient conditions and the engine's load, a general range for the two-stroke engine is 325–345℃,and for four-stroke-engines, it is 400–500℃[11]

Even higher exhaust temperatures are attained in dual fuel engines when operating on gas fuel. Engine cooling water temperatures of 80–90 ℃ are relatively standard for most engines; nevertheless, for some dual-fuel and gas engines, the cylinder head cooling water temperature can reach 125℃, at cooling water pressure of 3–4 bars. Out of the listed waste heat streams, the highest quality is supplied by the exhaust from the waste incinerator and has the highest potential in terms of utilization by a WHRS. While on the other hand the incinerator operation is intermittent and the quantity of the heat supplied is quite small as compared to other streams. Nevertheless, incinerator heat could be used to operate a dedicated WHRS or to supplement WHRS designed for other streams for better efficiency during incineration activities. Together with a high mass flow rate and a reasonably high temperature the exhaust gas offers itself as the best waste heat source, both in terms of quantity and quality. The utilization of exhaust gas-energy depends on the lowest temperature to which it could becooled in a heat exchanger. In the case of engines burning fuel oil, there exists a risk of corrosion due to sulphuric acid condensation in the exhaust stream. Therefore, WHRS utilizing the exhaust gas should be designed to ensure that the exhaust gas is not cooled below the acid dew point. This factor limits the heat recovery from the exhaust gas. Many suppliers recommend that an exhaust outlet temperature of not less than 165℃ to avoid acid corrosion and soot build-up in the exhaust gas heat exchangers. The use of cleaner fuels in future can reduce the risk of acid formation at lower temperatures and can increase energy recovery from the exhaust gases.

Table 1: Waste Heat Quality Classification and Its Range of Temperature

Waste Heat Quality	Range of Temperature
Low	≤ 232
Medium	$233 - 650$
High	≥ 650

Current Waste Heat Recovery Technologies

Different technologies can utilize the waste heat from the marine engine, and they are categorized based on the waste heat grade. These technologies have been used and continuously developed to ensure efficient and optimum energy conversion. These systems are extensively used because of their advantages including utilization of energy with high efficiency, easily integrated into the system, can be used on different types of vessels, and safe in operation.

The Ideal Rankine Cycle

This thermodynamic cycle is commonly used for heat energy conversion into mechanical work in the marine application. A working fluid is used for heating and evaporation throughout the operation of the cycle, which is normally water and turned into steam. The cycle consists of four main components namely, turbine, pump, condenser, and boiler. The layout of the cycle with its components are shown in Fig. 2 along with the ideal temperature-entropy diagram for the steam Rankine cycle. There are no restrictions on the use of different working fluids or temperature ranges, but the performance of the cycle is variable depending on several factors including the field of application and the utilization of energy.

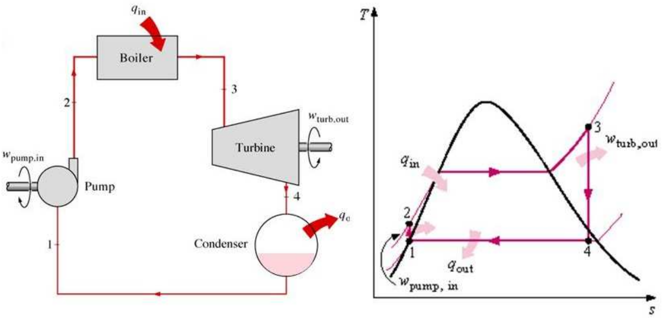

Figure 2: Ideal Rankine Cycle with a Typical T-S Diagram

Rankine Cycle with Water as the Working Fluid

The most common type which has been used for years is the steam Rankine cycle that uses water as the working fluid. This thermodynamic cycle was used extensively over the past century for power generation and it was first found in a maritime application with the launch of SS Turbinia in 1894 [12]. In terms of the main propulsion and auxiliary power, the steam turbines have been used in both for power production. However, the diesel propulsion system was the preferred choice for power generation, but the Rankine cycle can still offer an optimum utilization of power as a waste heat recovery system. The steam Rankine cycle can utilize medium quality waste heat i.e. exhaust gases to heat the working fluid in the boiler. In addition to the combination of other low or medium quality heat sources for feed water heating, the overall efficiency of the cycle could be improved. A prediction of an increase in the cycle efficiency by 8.5% through the use of SRC WHRS was shown by Theotokatos et al. [13] for LNG powered dual fuel diesel engines, and 28% while operating in diesel mode. In their study on WHR for large containerships, Ma et al. [14] found that an SRC could contribute to about 3–3.5% overall plant efficiency within the engine operating range from 50% to 100% of engine SMCR, while working together with an exhaust gas driven power turbine. Liang et al. [15] analyzed SRC for marine 2-stroke exhaust heat with varying degree of superheating and condensing temperatures, gaining overall plant efficiency of 4.5– 7.5% with an exergy efficiency of 45–55%. Traditionally, SRC is an efficient WHR option for source temperatures above 350–370 ℃, while at lower temperatures steam system becomes less cost-effective and requires bulkier equipment. Also, the waste heat at the lower temperature is unable to provide sufficient energy to superheat the steam, which is a requirement to prevent condensation and subsequent erosion of turbine blading [16].

Hence, this technology is used for both offshore and onshore application for power generation and waste heat recovery. It has been proven that it offered several benefits as a waste heat recovery system from medium quality waste heat sources. The operation of this technology is considered safe because of the water usage and also cheaper to operate the components. The cycle doesn't require any special training for the crew as most of the crew is already familiar with this basic cycle and its operation procedures. However, the efficiency of the cycle is low when operating with low-grade waste heat source, but the operation of this cycle given it merits and operation makes it an asset.

ORGANIC RANKINE CYCLE (ORC)

When dealing with the Rankine cycle, it is usually described by the operation of the steam and the effects on the turbine's blades. There have been many efforts to improve the overall efficiency of the cycle by using alternative fluids. The organic Rankine cycle is a modified cycle from the ideal Rankine cycle that uses organic fluid instead of the regular water/steam working fluid to operate the system. There are different kinds of fluids that can be used such as hydrocarbon gases, refrigerants like hydrochlorofluorocarbons (HCFCs), and using the regular water working fluid. The cycle components are similar to those of the steam cycle and operate in similar way. At moderate heat source temperatures, the best efficiency and highest power output are usually obtained by using a suitable organic fluid instead of water in the RC. This is mainly because the specific vaporization heat of organic fluids is much lower than that of water. Thus the organic working fluid ''follows" better the heat source fluid to be cooled [17]. An ORC plant can be arranged in many different configurations to achieve the optimal cycle efficiency and reduced heat losses. A detailed review of different advanced ORC configurations and layout stating the possible applications is available in the work of Pierobon et al. [18] stated ORC efficiency of 20–30% for offshore applications using gas turbine exhaust heat. Larsen et al. [19] state the highest optimum ORC system efficiencies ranging from 20% to 30% for heat source temperature ranging from 180 ℃ to 360 ℃, respectively, for marine applications. This could translate into an improvement of the overall plant efficiency between 10% and 15% approximately. On average, optimistic simulations forecast overall plant efficiency improvements between 15% and 20%, while realistic expectations lie well in the range of 7–10% improvement with ORC [20]. Soffiato et al.

For ideal working fluid, Zeotropic binary mixtures have been suggested for ORC due to better thermal match with the heat source and improved system efficiencies of up to 15% as compared to pure working fluids. Selection of working fluid has been studied in various works suggesting optimal fluids for different applications and heat properties. OPCON Marine has commissioned the first ORC-WHR plant aboard M/V Figaro and expects fuel savings around 4–5% for the case while expecting a savings potential of 5–10% for other installations. On the other hand, OPCON has developed ORC-WHRS for shore industry for up to 1.5MWcapacity demonstrating the potential capabilities [21]. Turboden SRL of Italy, claims an efficiency figure of 19% for heat source temperature of 250–300 ℃ and projects efficiencies of around 25% for hotter sources [22]. A list of commercial ORC plant manufacturers can be found in the work of Schuster et al. [23]. An ORC has several advantages over an SRC plant for low-temperature heat sources. Organic fluids have the lower specific heat of vaporization and require less amount of heat for evaporation. The evaporation process takes place at lower pressure and temperature. The expansion process ends in the vapor region, and hence the superheating is not required avoiding the risk of blades erosion. The smaller temperature difference between evaporation and condensation also means that the pressure-drop ratio will be much smaller and thus simple single stage turbines can be used [24]. ORC offers excellent potential for WHR and improving the overall plant efficiency. ORC system can be designed to utilize both low quality and medium quality heat energy. With a carefully selected working fluid which offers higher system efficiency, is chemically stable and safe in handling and storage, ORC offers an excellent solution

SUPER-CRITICAL RANKINE CYCLE (SCRC)

In the previous two modifications of the ideal Rankine cycle, the working fluid is heated in the evaporator at a pressure lower than the critical pressure allowing it to pass from liquid phase to wet phase and finally to the vapor phase. However, in the Super-critical Rankine cycle the working fluid is fed to the boiler at a pressure higher than its critical pressure and then it is directly heated from the liquid state into the supercritical state, bypassing the two-phase region, which allows it to have a better thermal match with the heat source, resulting in less exergy destruction .Mikielewicz [25] claimed relative improvements of about 5% in comparison to subcritical cycles for a selection of organic fluids. Schuster et al. [26] compared subcritical and supercritical cycles under the same parameters and found supercritical cycles to be more efficient by around 8% relative efficiency gain which is due to lesser exergy destruction. Karellas [27] found a gain of about 13% relative efficiency for SCRC than subcritical cycles.

The properties of the fluid for SCRC are crucial for marine application and needs to be selected carefully. The critical point of the fluid has to be lower than the outlet temperature of the boiler so that the fluid comes out in a superheated state. For marine WHR it is difficult to heat water to its critical point and can be excluded leaving only organic fluids for SCRC applications. Also, the critical temperature should be higher than the seawater temperature so that the fluid could be condensed in a condenser. For example, CO2 has a critical temperature of 31 ℃ making it difficult to condense with seawater cooling especially in warm areas where seawater temperature is higher than 25 ℃, making it unsuitable for marine applications. With proper fluid selection and carefully developed SCRC system can provide better gains over RC and ORC plants by offering better efficiency and lower emissions.

Absorption Refrigeration

To improve fuel economy and environmental compliance, many studies focused on the available waste heat recovery technology. There are current efforts to utilize the different types of waste heat for onboard ships for refrigeration. There are several types of refrigeration technology being used for marine applications.

Sorption refrigeration systems as shown in Fig.3 and its p-T plot is given in Fig.4 are driven by thermal energy and requires less electricity, and it can utilize the waste heat of the engine and improve the energy conversion efficiency. Therefore, fuel can be saved considerably. Both absorption and adsorption refrigeration are sorption refrigeration technologies [28].

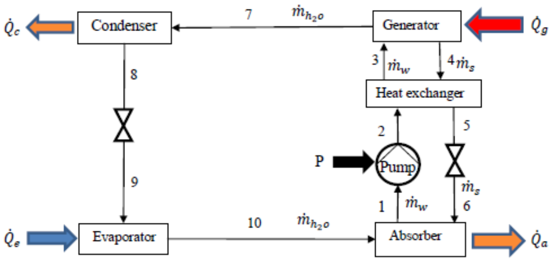

Figure 3 - A Schematic of A Single Effect Water-Libr Absorption Refrigeration Cycle

Challenges to the absorption cooling system on shipboard applications were also addressed by suggesting potential solutions. Fernandez-Seara et al. [29] designed, modeled and analyzed a gas-to-thermal fluid WHR system for a trawler chiller fishing vessel. An ammonia-water absorption refrigeration plant was used for onboard cooling. Synthetic oil was used as a heat transfer fluid. The influence of geometric design parameters and thermal operating conditions were studied on heat exchangers and system thermal performance.

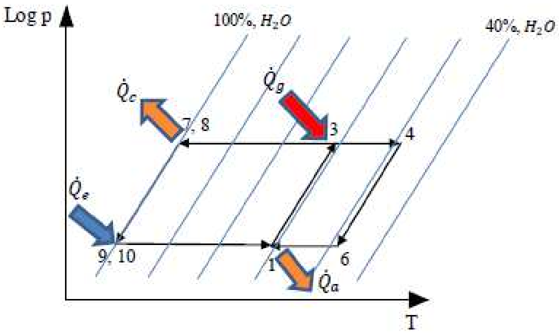

Figure 4 - Log p-T of a Single-Effect Water-LiBr Refrigeration Cycle

Menzel et al. [30] presented an experimental study of an ammonia-water absorption refrigeration system using the exhaust gas of an internal combustion engine as an energy source. The exhaust gas energy availability and the impact of the absorption refrigeration cycle on engine performance, exhaust emissions, and power economy were evaluated. Kaita [31] developed equations for calculating the vapor pressure, enthalpy, and entropy of LiBr solutions at high temperatures using measured data of vapor pressure and heat capacity which are very helpful for the modeling and design of triple-effect water-LiBr absorption chillers; these temperatures and pressures are higher than those used in traditional double-effect chillers. The developed equations were valid for concentrations between 40 and 65% and also for temperatures of 40–210˚C. Lansing [32] described and analyzed the dynamic simulation and the computer modeling procedure of a water-LiBr absorption refrigeration system. The concentration of refrigerant and solution in the range of interest was from 0.50 to 0.65 kg LiBr/kg solution. The results from this simulation were heat rates, line concentrations, pressures, and the overall COP. Kim et al. [33] carried out an experimental study on a vertical countercurrent slug flow absorber working with the ammonia-water mixture at low solution flow rates. To predict precise absorption performance in the real absorption heat pump system, they developed a data reduction model to obtain local heat and mass transfer characteristics.

A different solution was presented by Garimella et al. [34] for a single-effect water-LiBr absorption and supercritical CO2 vapor compression coupled cycle. The system was modeled for application on a naval ship. The exhaust heat (175–275˚C) of the onboard gas turbine power plant was used as the power source for the generator of the absorption heat pump. Megawatt-scale cooling loads are required for advanced naval electronics. In order to reach 1 kW/cm2 cooling fluxes with plausible technical advances while operating on large surface areas, it is necessary to have, for example, a coolant available at -40˚C. This is why vapor compression with a liquid CO2 tank is needed. Additionally, most naval ships require medium-temperature cooling (5˚C) for electronics and the AC. The evaporation of the absorption refrigeration system was divided into two different stages. The first stage was used to chill the liquid CO2 vapor compression cycle in order to meet the cooling storage needs on demand. This arrangement improves the efficiency of the vapor compression cycle. The second stage is used for the steady-state cooling of electronics and used in the AC.

Recuperative and solution heat exchangers were added to the system to improve its efficiency. The COP of the individual absorption cycle was estimated to be 0.7803 and for the combined total-energy-input based COP, it was estimated to be 0.594, which means that all the cooling power produced is divided by all the energy needed in the cascade system. The electrical COP was also defined as the total cooling power divided by the system's electricity power (compression and pumping) requirements; it was estimated to be 5.685. The cascaded absorption/vapor compression cycle was estimated to save up to 31% of the electricity consumption in the case ship studied when compared to an equivalent two-stage vapor-compression system.

Typically, refrigeration is produced using vapor compression, which consumes considerably more electricity compared to an absorption refrigeration system. This electricity is produced at a rather low efficiency using diesel engine combustion. The chilling process is necessary for different requirements in maritime transport. For example, the AC, ice-making, and medical or food preservation all need refrigeration [35]. First, state-of-art and fundamentals of absorption refrigeration are introduced. Two of the most conventional absorption refrigeration systems are explored with a steady-state thermodynamic model. These systems use water (as a refrigerant) and lithium bromide (as absorbent), and ammonia (as a refrigerant) and water (as absorbent) as working pairs [36]. Equations suitable for higher temperatures of LiBr solutions are selected [37] in the ammonia-water case the model takes the operation of the rectifier into account. The process data of the exhaust gases and cooling water flows in different climate conditions and operation profiles for a B. Delta37 bulk carrier is studied to estimate the refrigeration potential for ships in general. Energy production by WHR, cooling power possibilities, and annual fuel savings are evaluated in ISO and tropical conditions.

CONCLUSIONS

This paper highlighted the key technologies of the Rankine cycle and Absorption refrigeration for marine applications. There were several modifications of the original Rankine cycle that were discussed such as the organic and the supercritical cycles. An extensive review of both technologies has been carried out based on the current trends and available waste heat energy resources on a marine vessel. In terms of heat recovery potential, it is found that the exhaust gases are the primary contributor that offers a higher temperature for heat recovery. In addition, the fluid selection of the working fluid inside an ORC is considered an essential part of the primary design process and can differ significantly in terms of performance. The supercritical cycle is another promising technology that deals with medium quality heat sources with high energy recovery ratio. On the one hand, the ideal Rankine cycle has been used for years and proved itself as a reliable source. However, on the other hand, there is a continuous search to improve the energy efficiency of the vessels and provide optimum solutions. While the Rankine cycle is safe, the organic and supercritical cycles offer higher efficiencies. Moreover, the application of refrigeration onboard of marine ships was studied by many researchers especially focusing on thermodynamic analysis. The carried out investigations used different operation conditions by varying the temperatures of generator, condenser, absorber, and evaporator. The performance of the cycle was increased when improving the effectiveness of the heat exchanger and did not affect the circulation ratio. To conclude, the proper selection of waste heat recovery systems could increase the overall efficiency reduce operational costs and emissions by following the IMO regulations.

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