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Review

A review of waste heat recovery technologies for maritime applications

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ABSTRACT

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. In this study a review of different waste heat recovery systems has been conducted, to lay out the potential recovery efficiencies and suitability for marine applications. 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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Contents

1. Introduction

With the growing environmental concerns and the emission regulations, already in place and the upcoming ones in future, there arises a need to reduce emissions from marine vessels. As per the third IMO GHG study 2014, maritime shipping from the year 2007–2012, both domestic and international, accounted on an average for about 2.8% of global Green House Gases (GHG) emissions amounting to about 1 billion tons annually, along with 15% and 13% of NO_X and SO_X global emissions, respectively, from anthropogenic sources annually. Most of the shipping emissions

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Nomenclature

Hy-T/C	hybrid turbocharger	TC	turbocharger
KC	Kalina cycle	TCS	turbo compound system
ORC	organic Rankine cycle	TEG	thermo-electric generator
PT	power turbine	THS	turbo-hydraulic system
RC	Rankine cycle	WHR	waste heat recovery
SCRC	super-critical Rankine cycle	WHRS	waste heat recovery system
SMCR	specified maximum continuous rating		
SRC	steam Rankine cycle		

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are a result of fossil fuel consumption aboard to produce power for propulsion and auxiliary services [1]. The shipping fleet is dominated mainly by three types of ships namely, bulk carriers, tankers and container carriers, accounting for about 84% of the total tonnage [2]. These vessels also contribute the most in terms of the total fuel consumed and consistently for all ship types, the main engines are the dominant fuel consumers [1]. Table 1 gives the breakup of fleet share and fuel consumption of each individual category.

To meet the power requirements for operations and due to their mobility and location, most of the vessels have a dedicated onboard power plant commonly using diesel engines, steam turbines and gas turbines. These systems burn fossil fuels to convert the combustion heat energy, into the mechanical power which is further converted to other forms as required by the consumers. The byproducts of fuel combustion are the main source of emissions and consequently most of the shipboard emissions increase in parallel with the fuel consumption. Therefore, in order to reduce maritime emissions, the fuel consumption needs to be reduced from the current levels. This can be achieved by improving the overall power-plant efficiency, as one of the options.

Diesel engine is by far the most widely used option for power production on a wide range of vessel types. In terms of the maximum installed output of all the civilian ships above 100 gross tons (GT), 96% of this energy is produced by diesel plants. Because of the missing alternative propulsion systems available with similar power density, cost and fuel efficiency, it is expected that diesel engines are not replaced in a foreseeable period of time [4]. Modern large diesel engines are about 50% efficient in utilizing the fuel heat energy and the remainder is lost to the environment as waste heat [5]. Effective utilization of wasted thermal energy can enhance the plant efficiency and reduce emissions, either by using a dedicated waste heat recovery system (WHRS) for power production or by using it for heating services. For a conventional vessel the heating loads are marginal in comparison to the available waste heat, leaving a large chunk of heat energy unused. A WHRS can utilize the remaining wasted heat for producing mechanical-/electrical power which can then feed the demand for propulsion and auxiliary services at no additional fuel costs and zero associated CO_2 emissions. MAN Diesel [6] sees possibilities of achieving a total efficiency of 60% for the utilized fuel energy onboard diesel propelled vessels while Baldi and Gabrielli [7] predicted, based on

exergy analysis, an achievable fuel savings of 4–16% for a medium range tanker by the use of WHRS.

Much work has been done in the field of industrial waste heat recovery. Bonilla et al. [8] discussed the potential of different WHR technologies for using the waste heat from the industry located in the Basque country in Spain. Nguyen et al. [9] discussed power generation using steam Rankine cycle (SRC), organic Rankine cycle (ORC) and Kalina cycle (KC) for low temperature waste heat sources up to 225 °C. Al-Rabghi et al. [10] reviewed industrial WHRS for power production and process heating purposes. Within the oil and gas sector Khatita et al. [11] analyzed ORC for WHR from gas turbine exhaust for an upstream natural gas treatment facility. Jung et al. [12] analyzed the use of ORC for waste heat from a stream of liquid kerosene which need to be cooled for vacuum distillation in petroleum refineries. Kalinowski et al. [13] discussed the improvement in WHR using absorption refrigeration for LNG recovery process. Bai and Zhang [14] proposed the use of LNG cold energy for better WHR. For cement industry Karellas et al. [15] analyzed and compared SRC and ORC for WHR applications. Relevant to the metal manufacturing industry, Barati et al. [16] discussed the methods of energy recovery from high temperature slags. Zhang et al. [17] reviewed WHR technologies for heat recovery from molten slags in the steel manufacturing industry. Kaska [18] proposed ORC for WHR from blast furnaces in steel industry.

Geothermal power generation is another area utilizing low/medium temperature waste heat recovery technologies. Zare [19] in his work compared the different configurations of ORC for geothermal power plants. Walraven et al. [20] in their work analyzed and compared subcritical and trans-critical ORC and KC for 100–150 °C source temperatures. Yang and Yeh [21] analyzed trans-critical ORC using refrigerants and CO_2 as working fluids. Coskun et al. [22] analyzed and compared flash cycle, binary cycle (flash cycle in combination with RC/ORC) and KC for geothermal applications.

Work on WHRS applicable for internal combustion engines and in particular on diesel power plants is of special relevance to marine WHR. Significant to WHR from internal combustion engines, Bombarda et al. [23] analyzed and compared ORC and KC for diesel WHR. Song et al. [24] analyzed ORC WHRS for marine diesel engines. Zhang et al. [25] studied the combined use of thermo-electric generator (TEG) and ORC for diesel WHR. Yang et al. [26] analyzed a dual loop ORC for diesel WHR under varying operating

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Table 1
Individual fleet contribution and fuel consumption of main ship types (ships above 100 GT) [2].

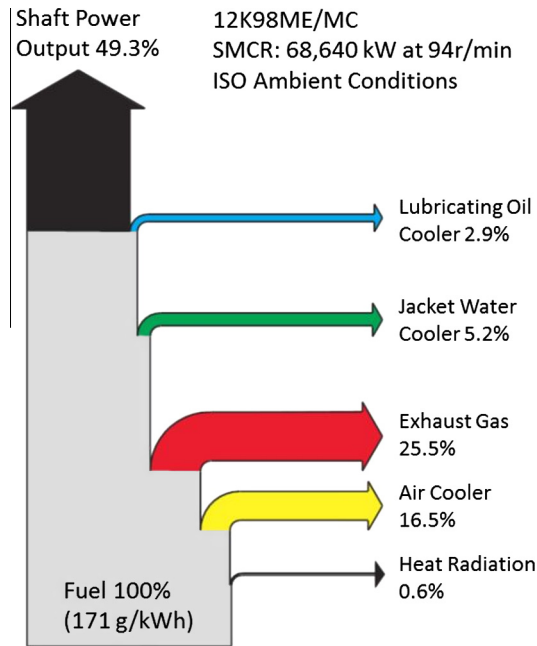| Ship type	Tonnage (million DWT)	Percentage of total tonnage (%)	Number of ships [3][a]	Fuel consumption (M tons/Year) [1]
Bulk carriers	726	42.9	10,018	53.4
Oil tankers	482	28.5	9317	39.7
Container ships	216	12.8	5077	66

[a] Based on figures for 2014.

Fig. 1. Heat balance diagram for MAN 12K98ME/MC marine diesel engine operating at 100 SMCR under ISO conditions [5].

Table 2
Classification of the quality of heat energy depending on the temperature range [41].

Quality	Temperature range (°C)
High	650 and higher
Medium	232–649
Low	232 and lower

Table 3
Temperature range of main waste heat sources [40,42,45,46].

Source	Temperature range
Waste incinerator	850–1200 °C [45]
Engine exhaust gas	200–500 °C [46]
Scavenge air (compressor outlet)	100–160 °C [40,42]
Engine cooling water	70–125 °C [40,42]

conditions. MAN Diesel and Turbo [5,27] has discussed the use of SRC and power turbine for shipboard WHR. Most of the studies available in the field of WHR discuss and analyze selected few WHR technologies in detail and studies reviewing individual technologies are available. For instance, Lecompte et al. [28], reviewed the advanced configurations of ORC for WHR applications. Sprouse et al. [29] reviewed ORC for WHR from diesel engine exhaust gases with a focus on vehicle installations. Hung et al. [30] reviewed and analyzed a simple ORC system for low grade WHR. Wang et al. [31] conducted a review of WHR using different RC configurations for diesel exhaust gases. In the work of Zhang et al. [32] research conducted on KC has been reviewed. Riffat and Ma [33] reviewed the use of thermoelectrics for WHRS.

For maritime applications, Larsen and Haglind [34] compared the SRC, ORC and KC for marine WHR. Similarly, the works of Theotokatos and Livanos [35,36], analyzed a single pressure SRC for marine WHR. Altosole et al. [37] compared SRC-WHRS for new design and retrofitting onboard maritime vessels. Benvenuto et al. [38] analyzed a dual pressure SRC as a WHRS for marine diesel waste heat. In spite of numerous studies on individual WHR

technologies for marine diesel engines, hardly any comprehensive review studies covering most relevant WHR technologies together are available. The work of Siadur et al. [39] reviews four type of WHRS namely ORC, TEG, 6-stroke cycle and developments in turbocharger technology but failed to include other available high potential technologies. To the knowledge of the authors, only one study by Shu et al. [40] is available which reviews marine WHRSs. Comparatively, this work reviews marine WHRSs for power production in a greater detail and discusses their recovery potential and expected gains.

2. Marine waste heat

The wasted heat on a marine vessel is primarily the fuel energy which is lost to the environment from various ongoing processes during normal operations, e.g. thermodynamic heat transfer. For a diesel powered vessel, the diesel engine is the largest source of wasted heat. Fig. 1 depicts the energy balance of a 2-stroke large marine diesel engine and shows that about 50% of the total fuel heat energy is rejected to the surroundings via different streams without doing any useful work [5]. Each waste heat stream is distinct and the amount of energy carried away varies both in terms of quantity and quality.

The utility or the 'quality' of waste heat is determined by the temperature at which it is available. Heat energy is categorized as low, medium and high quality depending on its temperature range as given in Table 2 [41]. WHR opportunities are directly dependent on heat quality with higher efficiency potentials in the high temperature range. From marine sources most of the wasted heat lies between low and medium quality. Table 3 gives the list of major waste heat sources along with their typical temperature range for an ocean going vessel.

The temperature range of exhaust gas varies for two-stroke and four-stroke engines, with the latter having higher exhaust temperatures. While the exhaust temperatures vary depending on load and ambient conditions, for nominal loads the range lies between 325–345 °C for two-stroke and 400–500 °C for four-stroke engines [42]. Project guides [43,44] from engine manufacturers suggest even higher exhaust temperatures for dual fuel engines when operating on gas fuel. Engine cooling water temperatures of 80–90 °C are fairly standard for most engines; nevertheless for some dual-fuel and gas engines the cylinder head cooling water temperature can reach 125 °C, at cooling water pressure of 3–4 bars [42].

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 be cooled in a heat exchanger. In the case of engines burning fuel oil, there exists a risk of corrosion due to sulfuric 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. MAN Diesel and Turbo recommends exhaust outlet temperature of not less than 165 °C to avoid acid corrosion and soot buildup in the exhaust gas heat exchangers [47]. 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.

High temperature scavenge air at the outlet of the turbocharger (T/C) turbine is cooled to increase its density before being supplied to the engine. Traditionally, the scavenge air is cooled by rejecting heat to the cooling water in a scavenge air cooler. The temperature range (see Table 3) of the scavenge air makes it a potential contender for use in WHR. The continuous supply of this form of waste heat during engine operation makes it more attractive.

The heat carried away by the jacket cooling water of diesel is either used in the fresh water generator to produce pure water from seawater for onboard consumption or lost to the atmosphere via heat-exchangers. Despite being a low quality heat source, the jacket water heat is large in quantity and continuously available during engine operation. With suitably chosen WHRS it makes a good candidate for WHR applications.

A WHRS can be designed to operate either on a single or a combination of different heat sources. Depending on the waste heat source, a WHRS has three alternative options; (i) exhaust gas only which is standard easy to retrofit solution, (ii) exhaust gas and HT cooling water representing the state of the art and finally (iii) all the waste heat sources for highest possible recovery [7].

3. Main WHR technologies

As discussed in the previous section, the available marine waste heat lies in the region of low and medium quality. Systems and technologies capable of utilizing low and medium quality heat for power production qualify for WHR. Such options have been in use and development within industrial WHR and power generation, e.g. geothermal power generation. More specifically for marine use, the WHRS should have the following features:

1. High efficiency in utilizing the waste heat.
2. High power density to supply large power demands.
3. Able to handle transient heat source and sink properties.
4. Adaptable to the changing vessel operational profile, e.g. slow steaming.
5. Easy to integrate with other power systems aboard.
6. Reliable in operation.
7. Smaller footprint due to space and weight limitations.
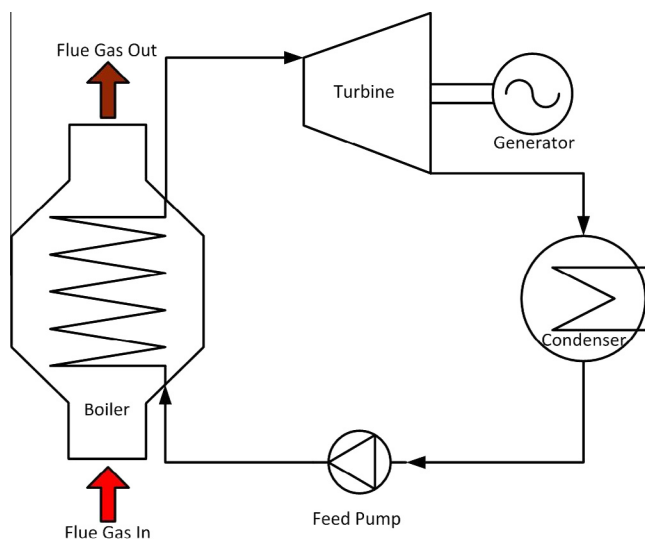8. Safe in operation and handling aboard.

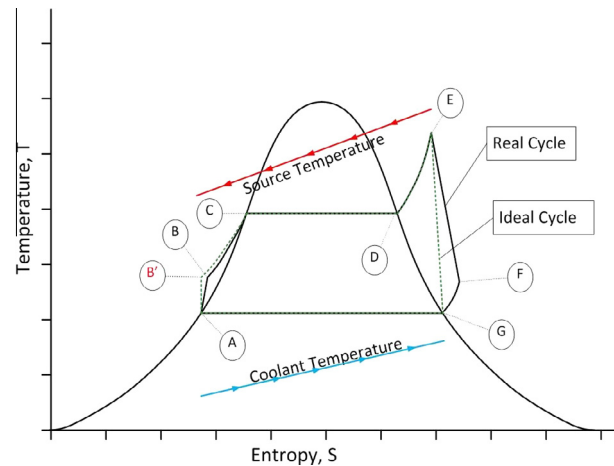**Fig. 2.** Schematic of a simple Rankine cycle plant.

Fig. 3. Temperature–entropy (*T*–*s*) diagram for a Rankine cycle.

While many technical solutions for WHR are available for medium and low quality heat sources, which otherwise may prove satisfactory for specific industrial applications, their use for marine WHR comes with additional challenges. Due to the nature of operations the quality and quantity of the marine diesel waste heat varies and so are the ambient conditions, e.g. sea-water temperature, changing with the vessel location and seasonal changes. A WHRS operating within such dynamic boundaries should be able to adjust and adapt to the external changes in order to deliver optimal performance. Every additional system installed aboard a vessel brings in added complexity to the overall system and a WHRS needs to be integrated with the existing power systems thus facilitating a smooth power sharing. The installation of WHRS is much suitable for new-build vessels but solutions for retrofitting existing vessels with minimum intervention need to be explored achieving higher WHR efficiencies. From an economic point of view, WHRS should not only be technically feasible but also economically viable so as to have a shorter payback period.

In the following parts of this section, most suitable WHRS for marine application are presented. The first part discusses closed loop thermodynamic power cycles using different working fluids. Technologies discussed here are namely the Rankine cycle, organic Rankine cycle, supercritical Rankine cycle, and the Kalina cycle. In the second part exhaust-gas turbine system is presented. Different turbine system configurations suitable for marine diesel engines are given, listing their applicability and operational features. The potential of the thermoelectric generation using 'Seebeck effect' has been discussed in the last part of this section.

Although this is not an exhaustive list of all the technologies available for WHR, nevertheless it discusses the most important ones with higher potentials and relative applicability aboard marine vessels, contributing toward the improvement of overall plant efficiency, reduced emission and better financial gains.

3.1. Rankine cycle

Rankine cycle (RC) is a thermodynamic cycle which converts heat energy into mechanical work. A circulating working fluid is continuously evaporated and condensed during the operation. A simple power plant operating on RC essentially comprises of four main components namely, vapor-generator (boiler + superheater), expansion device (turbine), condenser and feed-pump. The ordered layout of the system components is given in Fig. 2 and a typical temperature–entropy diagram for an ideal and real RC is shown in Fig. 3.

In its definition the RC does not restrict the use of any particular working fluid or a temperature range but different variants have been given specific names in the field of research and industrial applications. Given below are the most common variants of a RC plant.

3.1.1. Steam/conventional Rankine cycle (SRC)

A SRC is a water based system using water/steam as the working fluid. Steam based thermodynamic systems have been used for power production for over a century. Steam turbine saw its first use in maritime industry with the launch of SS Turbinia in 1894 [48]. Steam turbines have been used both for main propulsion as well as auxiliary power production. With the diesel as the preferred main power plant option in current times, SRC still offers a good solution to WHR.

Medium quality waste heat, e.g. the exhaust heat could be used to generate steam to operate a SRC system. Combining other available low and medium quality sources for feed-water preheating and steam generation, overall heat utilization of a SRC plant could be improved.

Theotokatos et al. [49] predicted an increase in plant efficiency from 3.2% to 3.5% for dual fuel engines running on LNG and 2.5–3.5% while operating in diesel mode, by using a simpler single steam pressure WHR system. Theotokatos and Livanos [35,36] investigated a single pressure steam based WHRS for handymax bulk carrier using 2 stroke and 4 stroke main propulsion engines operating between 50% and 100% MCR. Steam cycle efficiencies ranging between 6–14% for 2-stroke and 12.5–18% for 4-stroke engines were reported with a corresponding increase in overall plant efficiency of 0.5–1.3% and 2–3% respectively. Dolz et al. [50] carried out a parametric study on heat recovery from heavy duty truck engines and found an increase of 5% plant efficiency for a given exhaust temperature of 509 °C while utilizing all waste heat sources from the engine. This may not be the best case for marine applications where the exhaust temperatures range is lower. In their study on WHR for large containerships, Ma et al. [51] found that a 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. [52] 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 °C, while at lower temperatures steam system becomes less cost effective and requires bulkier equipment. Also the waste heat at 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 [41].

SRC is a time tested technology both for onshore and maritime use. It is well adapted for onboard use and offers substantial savings by WHR from medium temperature sources. It is safe in operation owing to the use of water and cheaper due to off the shelf availability of components. Steam systems do not require special training requirements for the ship crew as most marine engineers are quite familiar with these systems. Despite a lower efficiency due to low source temperatures, steam system certainly qualify for certain ship types given their merits and recovery potential.

3.1.2. Organic Rankine cycle (ORC)

An ORC is a modified form of SRC; wherein the working fluid of the system is switched from water/steam to other organic fluids like hydrocarbon gases, refrigerants like hydrochlorofluorocarbons (HCFCs), etc. An ORC plant layout is similar to that of a Rankine plant and has the same basic components.

At moderate heat source temperatures, the best efficiency and highest power output is 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 [53]. 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 Lecompte et al. [28].

Thekdi et al. [54] compared various power generation technologies for WHR and suggested ORC for the source temperature range of 95–260 °C and stated conversion efficiency of 8–12% for the given temperature range. Vaja et al. [55] also calculated an increase of about 12% overall plant efficiency using a bottoming ORC with select working fluids (e.g. Benzene) and an engine exhaust gas temperature of 470 °C. Song et al. [24] concluded ORC system efficiency of 18–21% for marine diesel engine translating into about 10% increment in overall plant efficiency. Pierobon et al. [56] stated ORC efficiency of 20–30% for offshore applications using gas turbine exhaust heat. Larsen et al. [57] states the highest optimum ORC system efficiencies ranging from 20% to 30% for heat source temperature ranging from 180 °C to 360 °C, 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 [29]. Soffiato et al. [58] analyzed different configurations of ORC using waste heat from engine cooling water, lubrication oil cooler and scavenge cooler demonstration the feasibility of low quality WHR with recovery efficiency up to 8%.

For ORC applications a range of working fluids are available and the efficiency of the system varies considerably with the properties
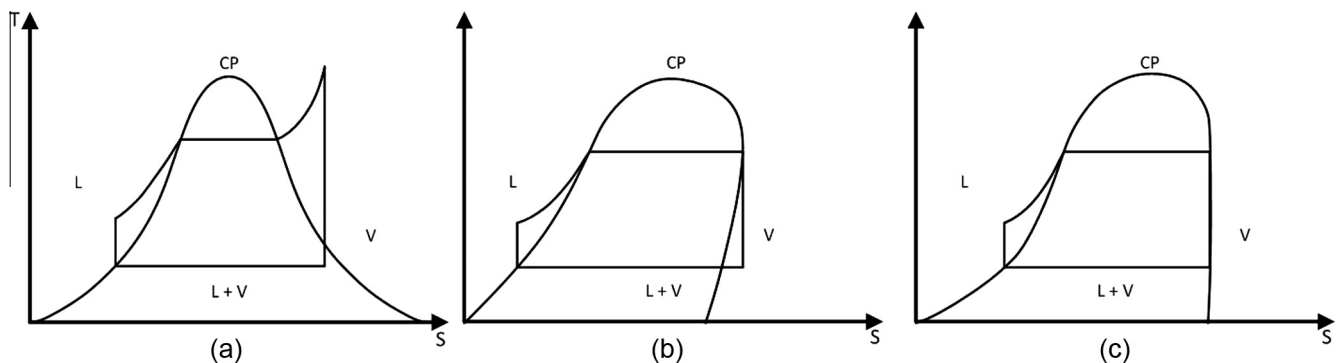

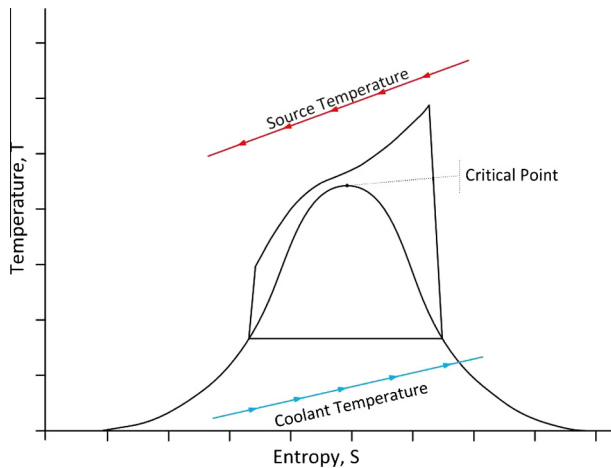**Fig. 4.** Fluid types: (a) wet fluid; (b) dry fluid; (c) isentropic fluid.

Fig. 5. Temperature–entropy (*T–s*) diagram for a typical supercritical cycle.

of the fluid in use. Depending on the slope of the saturated vapor-line in the temperature–entropy (*T–s*) diagram, organic fluids are classified as wet, dry and isentropic fluids as shown in Fig. 4.

For low and medium temperature WHR wet fluids are not particularly desirable due to the lack of superheating capability of the source and can cause condensation leading to turbine erosion. Dry, isentropic and slightly wet fluids are the promising candidates for ORC applications and an ideal working fluid should be determined on the basis of temperature range of the source. Zeotropic binary mixtures have also 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 [59,60]. Selection of working fluid has been studied in various works [59,61–66] suggesting optimal fluids for different applications and heat properties.

OPCON Marine [67] 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 1.5 MW capacity demonstrating the potential capabilities [68]. Turboden SRL of Italy, claims an efficiency figure of 19% for heat source temperature of 250–300 °C and projects efficiencies of around 25% for hotter sources [69,70]. A list of commercial ORC plant manufacturers can be found in the work of Schuster et al. [56,71]. An ORC has several advantages over a SRC plant for low temperature heat sources. Organic fluids have 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 [72].

ORC offers great 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 a good solution.

3.1.3. Super-critical Rankine cycle (SCRC)

In SRC and ORC plants the working fluid is heated in the evaporator at a pressure lower than its critical pressure and passes from liquid phase to wet vapor and finally to a vapor phase. In contrast to the SRC and ORC plants, in the case of SCRC 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 [73]. A typical temperature–entropy diagram of a SCRC is shown in Fig. 5 where the vapor generation phase tries to follow the heating medium.

Mikielewicz [74] claimed relative improvements of about 5% in comparison to subcritical cycles for a selection of organic fluids. Schuster et al. [75] compared subcritical and supercritical cycles under same parameters and found supercritical cycles to be more efficient by around 8% relative efficiency gain which is due to lesser exergy destruction. Karellas [76] found a gain of about 13% relative efficiency for SCRC than subcritical cycles. Chen et al. [73] investigated a SCRC using zeotropic mixtures as working fluid and obtained efficiency in range of 10–13%, higher by 3% compared to an ORC with similar conditions and source temperature range of 393–453 K. The exergy efficiency was also shown to be comparatively higher in their work.

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, CO_2 has a critical temperature of 31 °C making it difficult to condense with seawater cooling especially in warm areas where seawater temperature is higher than 25 °C, 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.

The findings of the research work carried out on WHRS using different configurations of Rankine cycle discussed above are given in Table 4.

3.2. Kalina cycle (KC)

Thermodynamic power cycle based on ammonia–water mixture was proposed by Dr. Alexander Kalina in 1983 and cycle has since been named after him as Kalina cycle (KC) [77]. It is a modified form of RC and has a better operating efficiency for several applications. The most promising utilization and significant efficiency gains are realized in the low temperature heat sources, making it a suitable option for waste heat recovery.

Table 4
Studies on Rankine cycle configurations.

Cycle configuration	Reference	Efficiency (%)
SRC	[49]	2.5–3.5[*]
SRC	[35,36]	0.5–3[*], 6–18[**]
SRC	[50]	5[*]
SRC	[51]	3–3.5[*]
SRC	[52]	4.5–7.5[*]
ORC	[54]	8–12[**]
ORC	[55]	12[*]
ORC	[24]	10[*], 18–21[**]
ORC	[56]	20–30[**]
ORC	[57]	10–15[*], 20–30[**]
ORC	[29]	15–20[*]
ORC	[67]	5–10[*]
ORC	[69,70]	19–25[**]
SCRC	[74]	+5[***] over SRC
SCRC	[75]	+8[***] over SRC
SCRC	[76]	+13[***] over SRC
SCRC	[73]	+3[***] over ORC

[*] Gain, overall plant.
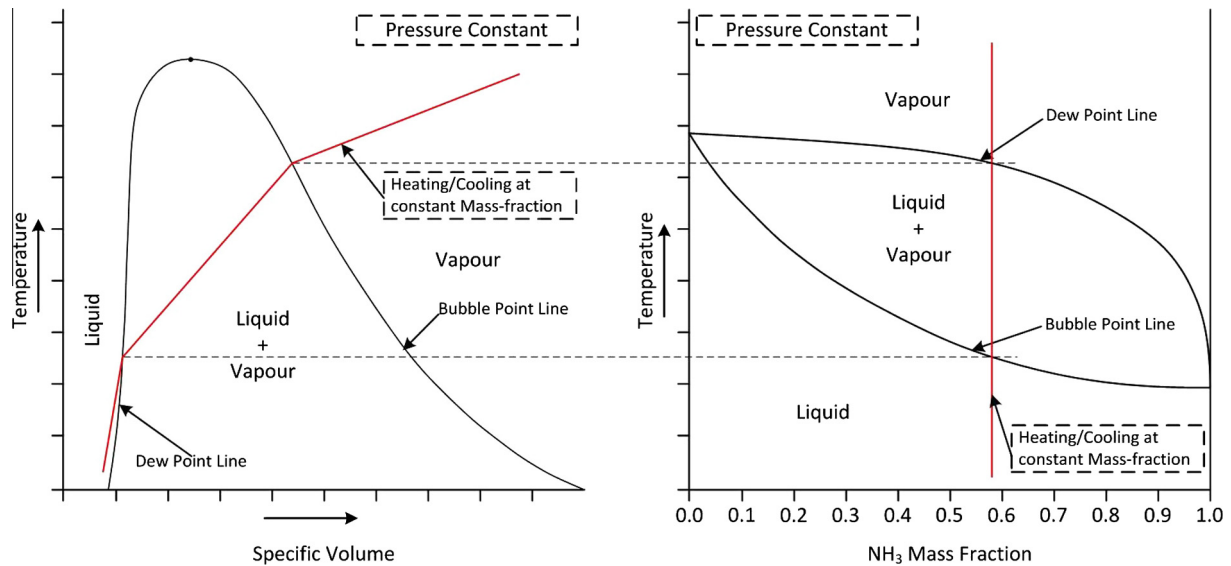[**] WHRS system.
[***] Comparing other WHRS.

Fig. 6. Variable boiling and condensation of ammonia water mixture at different compositions.
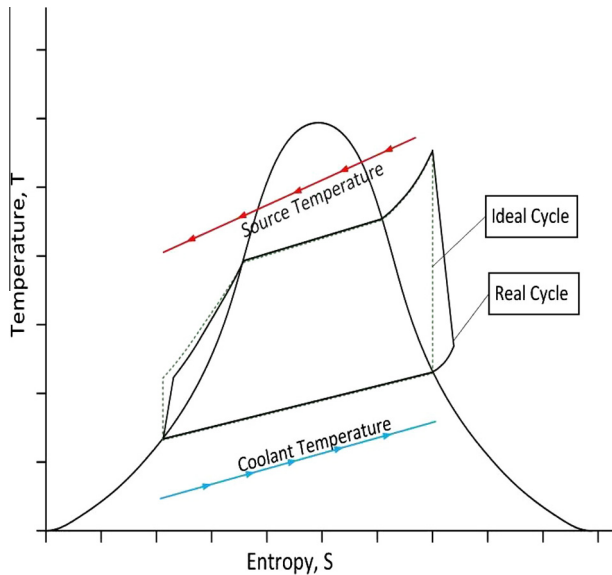

Fig. 7. Variable boiling and condensation following the heating and cooling medium, respectively.

KC uses ammonia and water mixture as the working fluid to operate in variable compositions with variable boiling and condensation temperature ranging between the bubble and dew points. Fig. 6 shows, for a given pressure and ammonia mass fraction, the liquid starts boiling at the bubble-point and continues until the dew-point where all of the fluid turns into vapor. The variable temperature boiling/condensation process has another advantage that it yields a better thermal match with the sensible heat source and the coolant during the phase change process, as shown in Fig. 7. This contributes to improvement of thermodynamic efficiency of the boiler and brings down the minimum temperature of the condensate outlet. By changing the ammonia mass-fraction, the bubble and dew point of the fluid can also be varied to suit the source and the sink temperature in the boiler and the condenser, respectively.

In terms of layout, KC plant is quite similar to a RC plant with a few additional components. A simple KC plant shall have a recuperator, separator, couple of mixers and flow control valves in addition to the standard components of a RC plant as shown in Fig. 8.

In terms of their working, the flow control valve acts as a regulator which controls the total fraction of feed pump flow to the separator. Precise control of the flow is essential for maintaining different concentrations of ammonia inside boiler-turbine and condenser section of the circuit. Recuperator recovers a part of the heat from the fluid at the turbine outlet to heat up the fluid flowing to the separator. It essentially reduces the amount of heat rejected in the condenser. It also controls the temperature of the fluid going to the separator which is a crucial factor in determining the mass fraction of the lean and rich mixture flowing out of the separator. The separator is used to separate the incoming fluid from the recuperator into rich and lean mixtures. The mass flow rate of the rich and lean mixtures depends on the separation efficiency, temperature, composition of the inlet mixture and the pressure inside the separator. A set of two mixers is used in the system to achieve the required composition flows in the system circuit. First mixer is located at the inlet of the condenser where a lean mixture from the separator is mixed with the exhaust from the turbine after passing through the recuperator. Here the turbine exhaust and separator lean fluid mix to feed a low concentration fluid to the condenser. The second mixer is located at the inlet side of the boiler where the remaining flow from the flow control valve and rich mixture from the separator are mixed to feed the boiler with high concentration working fluid.

In the early stages of its development Park and Sonntag [78] concluded a an advantage of about 5% and 15% in terms of first and second law efficiency for KC over a steam based SRC. Jonsson [79] in her doctoral thesis found that the bottoming KC has better thermodynamic efficiency than the SRC for gas–diesel engines. The best ammonia–water bottoming cycle could generate 40–50% more power than a single-pressure SRC and 20–24% more power than a dual-pressure steam cycle. Mirolli [80,81] supported the use of KC for cement plants WHRS, where the temperatures of the waste heat are in the range of 200–400 °C which coincides with the waste heat from marine diesel engines. Within this temperature range KC is 20–40% more efficient than RC. Larsen et al. [82] in their study on Kalina split-cycle for large marine diesel applications found optimized cycle efficiencies of around 23%. Nguyen et al. [83] analyzed Kalina split-cycle with reheat
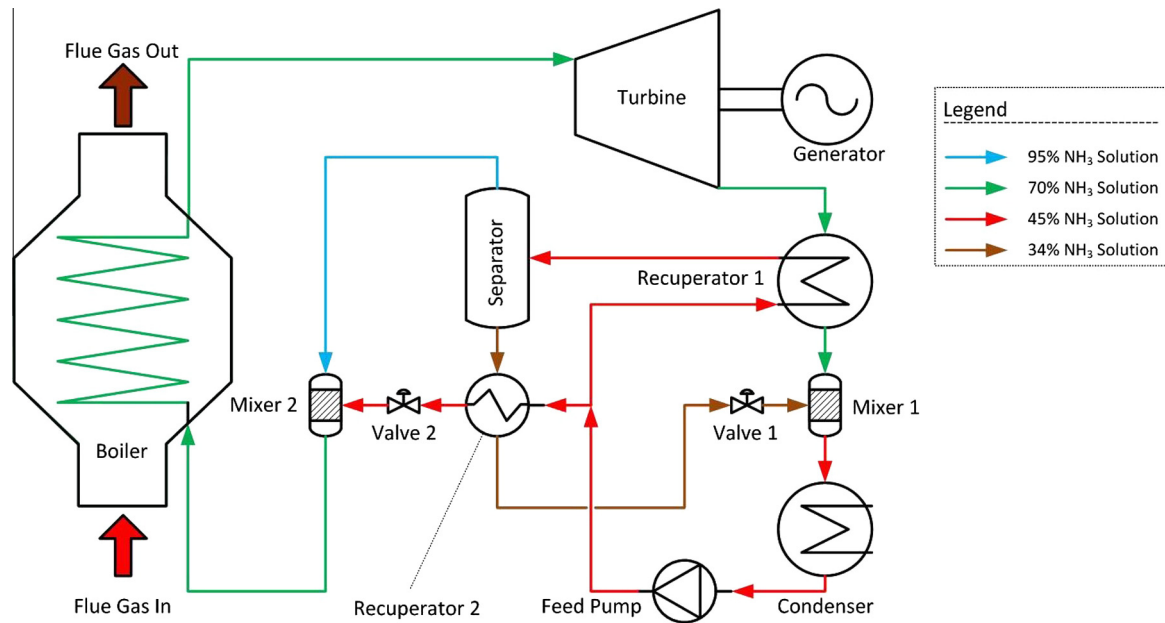
Fig. 8. Schematic of a simple Kalina cycle plant.

concluding a gain of 2% efficiency compared to a similar cycle without reheat. Zhang et al. [32] concluded in their work that KC had a better thermodynamic performance than the RC and ORC both in terms of energy and exergy efficiency. Similar results were obtained by other comparative studies conducted by Junye et al. [84], Valdimarsson and Eliasson [85], Fu et al. [86] and Zhang et al. [87].

The operational success of a KC power plant has been shown at a demonstration plant at Department of Energy's Energy Technology Engineering Center near Canoga Park in California, USA [88]. Another plant has been successfully operating using geothermal fluid as source at Husavik, Iceland. In this case the KC had a performance advantage of about 20–25% compared to that of an ORC [89].

Among other advantages, KC plant offers its ability to operate below freezing temperatures as compared to water based RC. Ammonia–water fluids have a reduced freezing temperature and as a result the condensation temperatures can go down to suit arctic shipping routes. KC can use conventional axial flow steam turbines owing to nearly similar molecular weight of 17 and 18 for ammonia and water, respectively. In comparison to RC, KC plants are smaller and cheaper owing to back pressure turbines instead of vacuum condensers, thereby reducing the specific volume of the fluid at turbine exhaust [90]. This is positive feature for ships with limited space. In terms of materials technology, KC has no special requirements and carbon steels are quite acceptable for low temperature applications like WHR. Several stainless steels also do not appear to suffer corrosion due to ammonia–water mixtures [32,90].

With reference to the safety issues concerning the use of ammonia, it is a widely used and handled chemical both ashore and has been transported safely via marine vessels. It is ecologically safe and harmless when diluted sufficiently. With its pungent smell its self-alarming in case of leakages. With its extensive use within industry the safety standards have matured enough to consider ammonia–water mixtures environmentally friendly and safe for engineering applications [32,90].

With its merits and recent developments, one could safely argue in favor of KC for marine WHR. Being suitable for low temperature waste heat source applications and with higher cycle

efficiencies than RC and ORC, KC offers better savings and reduced emissions, comparatively.

3.3. Exhaust gas turbine system

The energy content (enthalpy) of the exhaust gases from an engine depends on its static pressure and the temperature at the exhaust valve outlet. The pressure difference in the exhaust gas receiver from that of the ambient conditions can be utilized to produce work by expanding the exhaust gases in an expander. Traditionally, the turbocharger (T/C) of an engine extracts a part of this energy in a turbine to run the compressor to feed compressed scavenge air to the engine.

Continuous improvements in the T/C efficiencies over the past decades have made it possible for the exhaust stream to have surplus energy than required for supercharging process during normal engine load conditions. The trends in the T/C efficiency improvements over the past few decades have been shown in Fig. 9 [91].

The excess energy can be harvested by the expanding the exhaust gas either in the turbine side of a T/C itself or in a separately installed dedicated power turbine. For an optimally designed high efficiency T/C, it does not need all the exhaust gas to flow
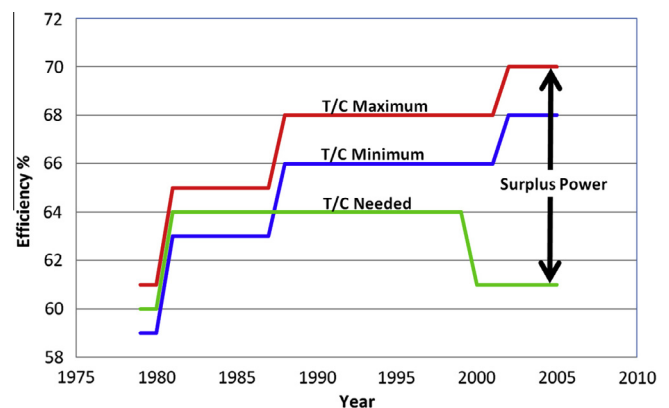

Fig. 9. Turbocharger efficiency improvement trends. Shows surplus efficiency for new generation turbochargers.

through it during nominal engine loads. The excess gas from the exhaust gas receiver is lead to the power turbine (PT) where it expands to the stack pressure producing work output. For currently available high-efficiency T/C matched for ambient air intake, about 10–12% of the exhaust gas flow can be branched off at upper engine load range to drive a power turbine [5,92]. The use of a separate PT for WHR is called turbo-compounding and such a system is referred to as Turbo-Compound System (TCS). In the case of a TCS both the T/C and the PT can be designed for best performance based on the optimum exhaust gas mass flow rate thorough each turbine. Research studies analysing WHR using TCS have been conducted to find the potential gains and technological trends. Hopmann and Algrain [93] analyzed TCS for truck engine and found fuel savings in the range of 5–10%. Kishishita et al. [94] calculated a maximum of about 15% fuel saving potential with TCS for automotive engines using power turbines with 80–85% efficiency and heat insulation. Brands et al. [95] tested heavy duty truck engines and found the best case improvement of around 16% in fuel consumption using TCS. Teo et al. [96] concluded an addition of 1.2% of engine power output using mechanical TCS. Weerasinghe et al. [97] concluded an increase of 4.1% in total power output using TCS for truck engines. Kee and Lee [98] discussed technology trends in the TCS for WHR. TCS has shown potential for around 5% BSFC improvement for marine propulsion engines [99].

The power produced by the turbine is available at the turbine shaft as rotational mechanical energy delivered at a very high shaft speed. At this speed the power available is of not much use by the consumers which may either need a slower rotational speed or a different form of energy other than the mechanical power. Thus turbine shaft power needs to be converted, transformed or conditioned to suitable forms as desired by the consumers. Different technological configurations for treating the turbine mechanical power are available and are discussed in the following sections.

3.3.1. Hybrid turbocharger

A hybrid turbocharger (Hy-T/C) is a modified form of conventional T/C wherein a high speed motor-generator set is mounted on its shaft. A Hy-T/C serves two purposes, firstly to assist the T/C at low engine loads when the exhaust gas energy is insufficient, thereby improving the transient response and secondly to recover excess exhaust gas energy at high engine loads when the exhaust gas energy is more than the requirement of the T/C compressor, to supplement the bus-bar with the additional electrical power.

ClassNK [100] projects on the development of Hy-T/C for marine use has shown actual savings of 1.8% form onboard tests and aims to achieve about 3% savings with further developments. Mitsubishi Heavy Industries (MHI), Japan, started developing a large Hy-T/C in 2008 for marine applications. In 2011 this Hy-T/C was tested and installed aboard bulk carrier M/V Shin Koho. The test results showed that the Hy-T/C could supply stable and continuous power to all the ship's electrical demand at engine load of 75% or more. Among the advantages MHI states that only a few modifications to the engine are required to install the Hy-T/C and retrofitting is relatively easy with a slight increase in external dimensions. They also claim that the system is free from thermal and piping losses and the turbine provides high efficiency [101].

3.3.2. Mechanical turbo-compound system

The mechanical power obtained from the turbine can be fed back to the engine shaft thereby increasing the total power output from the system. In a mechanical TCS the power supply to the engine shaft from the turbine is done via a reduction gearbox. The gearbox steps down the turbine shaft speed to that of the engine speed serving as a coupler between the two shaft systems.

Normally the turbine rotational speed is at a few thousand revolutions per minute (rpm) while the engine shaft runs very slow comparatively, of the magnitude of a few hundred rpm only. This large difference in speed calls for a gearbox of a very high gear ratio. The fixed gearing ratio makes the system unsuitable for varying speed of the engine and the turbine over their operational range. This is overcome by the use of speed regulating mechanism, e.g. fluid coupling, etc. Moreover there has to be mechanical linkages between the turbine and the engine shaft for power transfer which can make the system bulky and requires additional space.

3.3.3. Hydraulic turbo-compound system

A hydraulic TCS transfer the turbine power to the engine shaft or the generator at the desired speed by means of a hydraulic system. The main components of the hydraulic system are a high speed hydraulic pump, low-speed hydraulic motor and a speed controller. The turbine drives the hydraulic pump and circulates the fluid at a high pressure inside the hydraulic circuit. The high pressure fluid drives the hydraulic motor which is connected to the engine shaft/generator at a desired speed. The speed control of the hydraulic motor is achieved by the controller which regulates the motor speed equal to that of the consumer shaft.

Mitsui Engineering and Shipbuilding of Japan, has developed a hydraulic system for marine 2-stroke engines, named as turbo-hydraulic system (THS). A basic schematic of the THS is shown in Fig. 10 along with its layout on an actual engine in Fig. 11. THS reduces the fuel consumption by supplementing the engines normal torque production with the hydraulic energy recovered. THS has shown reduction in fuel consumption by 3% & 4% at 85% and 100% engine load, respectively [102].

3.3.4. Electrical turbo-compound system

Electrical power is a versatile form of energy. It can be generated, transmitted, transformed and converted to other forms with high efficiency and is easy to control electrical machines. The virtues of electrical power are utilized in an electrical TCS where an electrical system acts as an interface between the turbine and the consumers. The main components of electrical system are a high speed alternator, rectifier and inverter. The turbine runs a high speed alternator which converts mechanical power into electrical. The electrical power output from the generator is an alternating current (AC) at a very high frequency and cannot be fed to the power distribution system of the vessel directly unless it
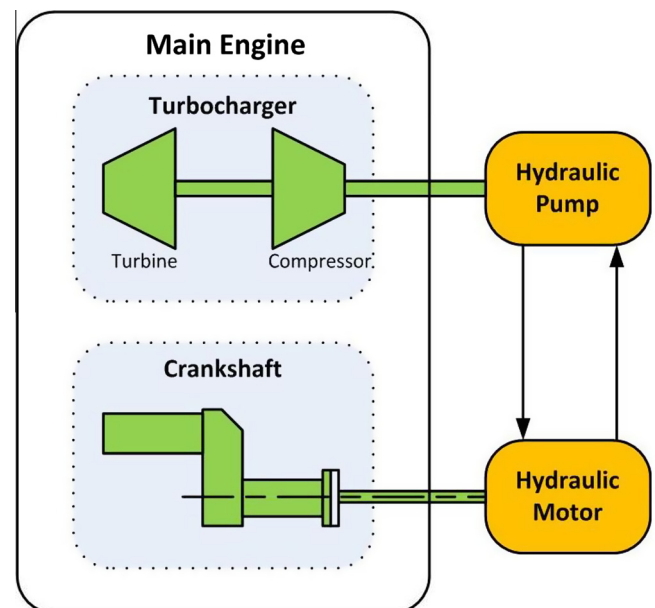

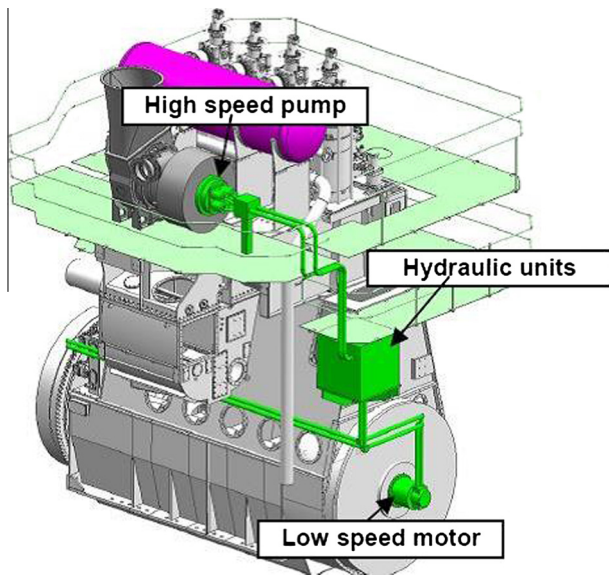**Fig. 10.** Turbo hydraulic system (THS) schematic layout [102].

Fig. 11. Turbo hydraulic system (THS) installation layout for a two stroke engine [102].

matches the voltage and frequency of the main switchboard. For a Direct Current (DC) main distribution system, the high frequency AC power from the generator is converted to DC using rectifier and then fed to the switchboard. In the case of an AC main distribution system the high frequency AC power is first rectified to DC in a rectifier and then converted back to AC in an inverter with a frequency matching that of the main distribution system. A basic schematic of electrical TCS is shown in Fig. 12.

Electrical TCS power output would be slightly less than the turbine power due to the efficiency of the generator and transmission losses [5] but can have higher efficiency than mechanical TCS [103].

3.4. Thermoelectric generation systems

Thermoelectric generation (TEG) is based on the 'Seebeck Effect' discovered by T.J. Seebeck in 1821, where a temperature difference between two dissimilar conductors or semiconductors in contact with each other produces a voltage difference between the two substances. Thermoelectric modules, like thermocouples, are solid state devices that convert thermal energy directly into electrical energy. In its simpler form a thermocouple consists of n-type

(material with excess electrons) and p-type (material deficit in electrons) elements connected electrically in series and thermally in parallel. Heat from the source is supplied to the hot junction of the module at a higher temperature and rejected via cold junction to a lower temperature sink. A temperature gradient across the thermoelectric material drives electron charge carriers from the hot to the cold junction side and produces a voltage [40]. The magnitude of the thermoelectric voltage and the power produced depends on the temperature difference between the hot and cold junctions, the properties of the semi-conductor materials and the external load resistance (or electric current) [104,105]. Each thermocouple acts like a battery cell and can be arranged in series or parallel to give the desired amount of voltage or current depending upon the generation requirements. A simple TEG module is shown in Fig. 13.

The performance of TEG device depends on the thermoelectric figure-of-merit (ZT) of the thermocouple material as $ZT = S^2\sigma T/k$, where S, σ, k and T are the Seebeck coefficient, electrical conductivity, thermal conductivity and absolute temperature, respectively. For a better electricity generation the material should have a high thermoelectric figure-of-merit [106].

The recent developments in the thermoelectric materials have achieved higher ZT values over an increased temperature range [107,108]. Rowe [109] states typical efficiencies of around 5% for TEG in specialized use within medical military and space applications. Crane et al. [107] states optimal ZT values of 0.8 for both p-type and n-type Bi_2Te_3 (Bismuth Telluride) at a lower temperature range (<200 °C), 1.2 for n-type Te–Ag–Ge–Sb (TAGS) alloys
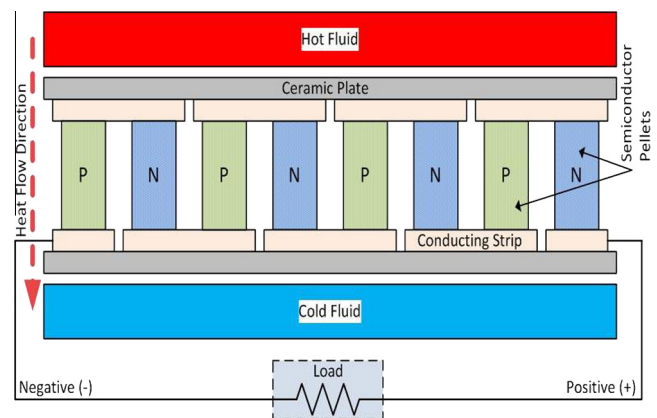

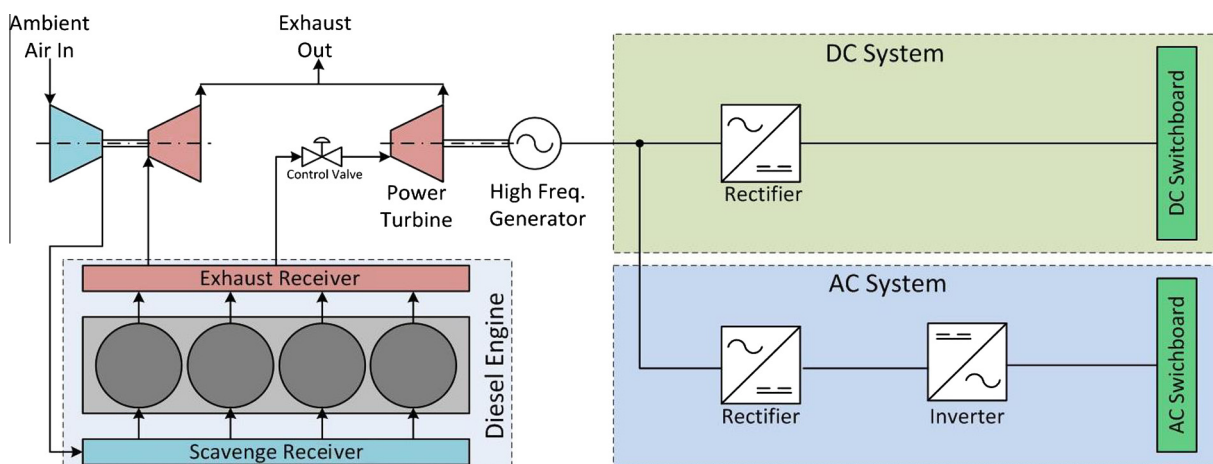**Fig. 13.** A simple thermo-electric generator (TEG) module.

Fig. 12. Electrical TCS line diagram both for AC and DC main distribution system.

and 0.8 for n-type PbTe at a medium temperature range (200–500 °C) which seem to be the temperature ranges of the marine waste heat sources. Bell [110] states a ZT of 1.0 for the best commercially available TE modules in present times. For effective WHR form exhaust gas with about 350 °C temperature differential and 10% TEG efficiency the corresponding value of ZT should be around 1.25. In his work, Bell also reviewed the latest development of TE materials using nanotechnology and has listed high ZT values of up to 3.2 for laboratory demonstrations. Despite the promising results, efficiency gains at device levels have yet to be demonstrated. The U.S. Department of Energy has a target of 10% reduction in vehicular fuel consumption using higher ZT levels while gains of 5–10% would be possible for diesel power plants with future development in TEG materials [110]. Zhang et al. [111] states TEG efficiency of 2.9% for automotive exhaust. Barma et al. [112] in their work estimated the maximum electrical output of 4.4 W for a TEG module (n-type Bi_2Te_3 and p-type $(Bi,Sb)_2Te_3$) operating at a temperature difference of 235 K with a recovery efficiency of about 8%. Kristiansen et al. [113] evaluated using TEG for marine incinerators and found recovery efficiency of 6.8%.

An experimental setup for marine TEG WHR has been prepared within ECOMARINE project and the initial calculations have suggested a conversion efficiency of 6.4% for a temperature difference of 220 °C between the source and the sink [114].

TEG has no moving parts, silent operation, totally scalable and offers a very reliable system [40,108,109]. TEG systems are known for their durability and maintenance free operations (often for 20-years) with negligible performance degradation over their operational life span [110].

TEG can offer a suitable solution for clean energy from waste heat for shipboard operations. Technological developments in future leading to improvements in the recovery efficiency, makes it a potential candidate for marine applications and use.

4. Standalone or combination of technologies

In the previous sections, individual technologies have been elaborated with their potentials for recovering waste heat and improving the overall plant efficiency. Each system discussed has an optimum heat source temperature range for efficient operation and is distinct depending on the system design, properties of the working fluids, etc. As a result different systems could be used to recover waste heat from different sources for best possible WHR.

It is worth noting that each of the technologies could be implemented as a sole WHRS or as a combination of different technologies together depending on the respective vessel specifications, recovery potential and efficiency targets. The combination of various systems gives flexibility in terms of best efficiency output from various sources depending upon the waste heat quantity and quality. The combination of systems needs to be chosen to give the least complexity in the overall plant layout.

Fig. 14 shows a combination system ST–PT (steam turbine–power turbine) developed by MAN Diesel Turbo. It combines energy recovery by using an exhaust gas driven power turbine and a steam turbine operating on Rankine cycle to drive a generator. The combined system has better recovery potentials than any one of the systems operating as a standalone WHR unit. For a large container ship this system could produce up to 9% of the total engine output [27]. Benvenuto et al. [38] proposed an improved variant of ST–PT system with gains of about 2.5% overall plant efficiency as compared to the previous system. Wartsila [115] claims for a similar system, fuel savings of 10% with an increase of 5.5% plant efficiency.

Nielsen et al. [116] proposed an advanced WHRS arrangement comprising of power turbine, steam turbine and ORC using the waste heat from exhaust gas, jacket water and scavenge air yielding about 2.5% of additional power compared to a reference system without ORC. Another combination of WHR from a diesel engine is shown in Fig. 15 where power turbine, Kalina cycle and ORC/SCRC operate together. In this case the PT extracts the pressure energy while the KC plant recovers the thermal energy from the exhaust gas. The low quality energy in the cooling water circuits is recovered by the ORC/SCRC plant. In the same way, different technological combinations can be explored to get the best efficiency of the overall plant, e.g. depending on the power requirements, KC plant could be replaced by a TEG module, etc. Each system could be selected to achieve the best possible heat recovery for different
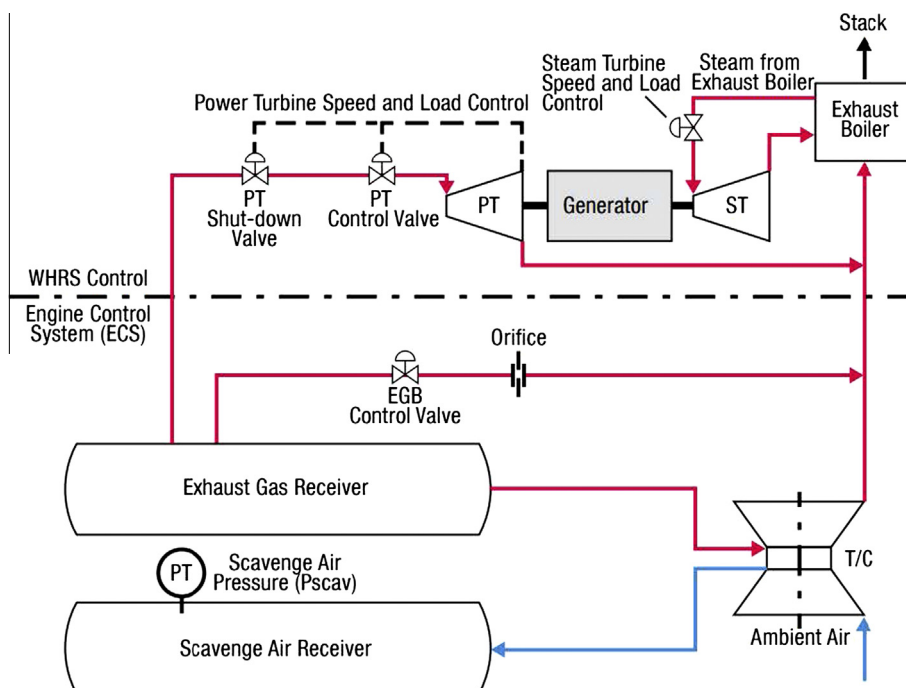

Fig. 14. Combination WHR system with steam turbine and power turbine [27].
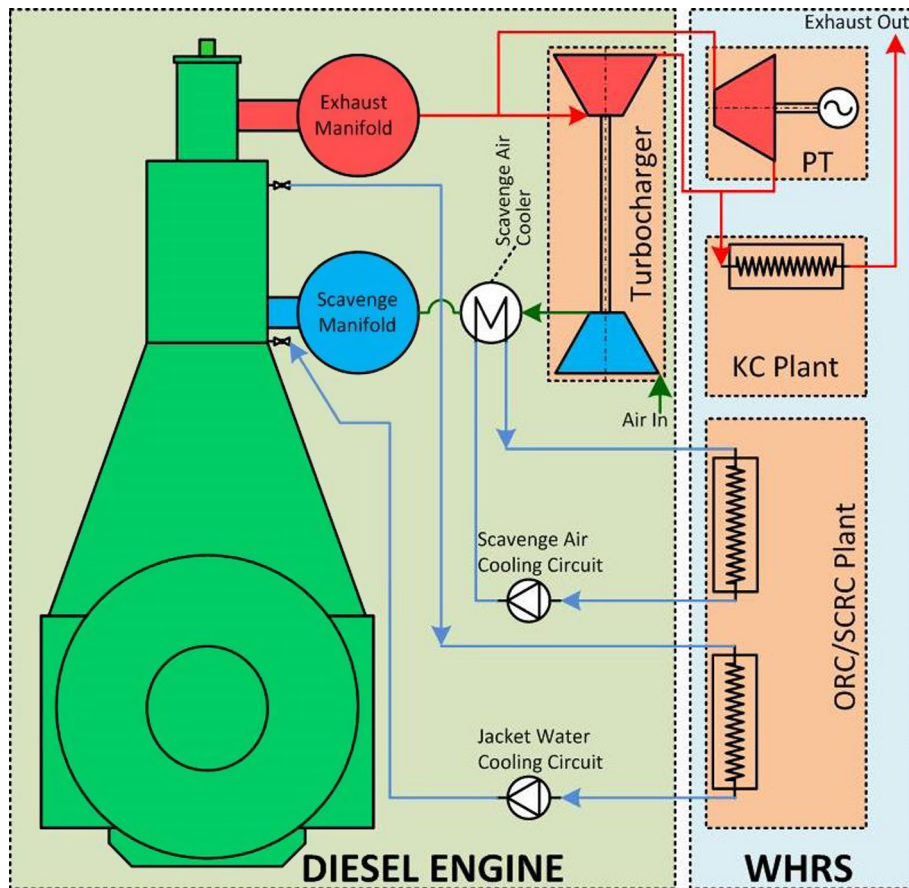
Fig. 15. Diesel WHR with ORC/SCRC, Kalina cycle (KC) and power turbine (PT) in combination.

heat sources and optimized to work together. The choice of a technologies suitable for a given vessel case could be very case specific depending on the machinery systems installed aboard, along with the quality and quantity of the waste heat energy available. Other factors like size and space limitations, added system complexity, sailing routes and trading pattern of the vessel can affect the decision in selection.

Suitable options could also vary for new-building projects and retrofitting existing vessels with WHRS later during service life. Altosole et al. [37] carried out a comparison of WHRS installation for new-build and retrofitting projects with former capable of delivering more than double the amount of power production and fuel savings as compared to the latter. In the case of new-build a wider optimization of complete WHRS can be carried out at the early design stages while a retrofit project would demand minimum intervention. In addition to all the technical aspects pertaining to the selection, factors like capital expenditure, life cycle costs and payback period for each technology would play an important role.

5. Conclusions

This paper outlines the main technologies for WHR for marine applications. The WHR technologies discussed here are Rankine cycle, organic Rankine cycle, supercritical Rankine cycle, Kalina cycle, exhaust gas turbine systems and thermos-electric generators. A comprehensive review of these technologies has been carried out based on the waste heat sources available on marine vessels. The range of source temperatures for each type of WHRS

is shown in Figs. 16 and 17 summarizes the efficiency range of WHRS for different waste heat sources.

Engine exhaust gas has the highest WHR potential in terms of heat quality and quantity while the KC offers a promising WHRS for medium quality sources with highest recovery efficiency. KC is adaptable and flexible for WHR both for full-load and part-load engine operations. On the other hand, technologies like ORC and SCRC also offer greater recovery efficiency values while RC is a safe and reliable technology. TCS offers substantial savings whereas TEG has a huge potential with future development. On systems
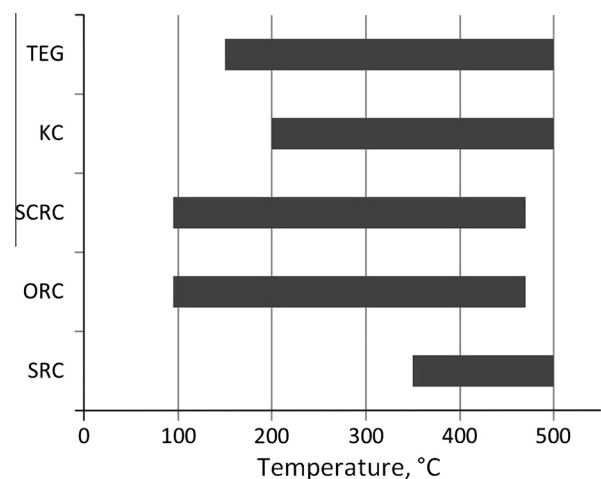

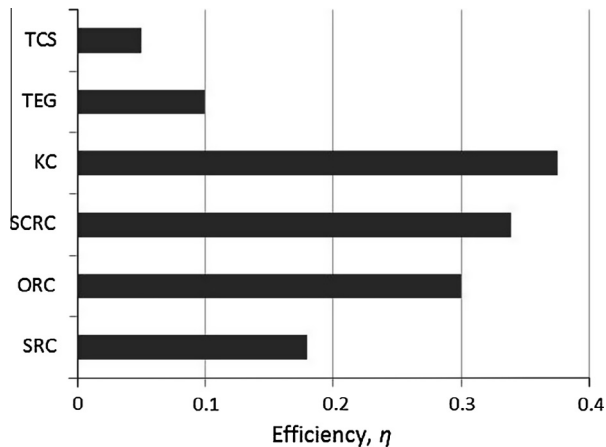**Fig. 16.** Suitable waste heat temperature ranges for each technology.

Fig. 17. Possible efficiency ranges for different WHRS.

level, a single WHRS can provide simpler solutions while a combination of systems can offer greater recovery efficiency with added complexity.

To sum up, properly selected WHRS can improve overall plant efficiency, reduce the operations cost and cut down maritime emissions enhancing the eco-friendly performance of ships.

Acknowledgements

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