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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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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		

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

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.