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A review of the use of organic Rankine cycle power systems for maritime applications

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ABSTRACT

Diesel engines are by far the most common means of propulsion aboard ships. It is estimated that around half of their fuel energy consumption is dissipated as low-grade heat. The organic Rankine cycle technology is a well-established solution for the energy conversion of thermal power from biomass combustion, geothermal reservoirs, and waste heat from industrial processes. However, its economic feasibility has not yet been demonstrated for marine applications. This paper aims at evaluating the potential of using organic Rankine cycle systems for waste heat recovery aboard ships. The suitable vessels and engine heat sources are identified by estimating the total recoverable energy. Different cycle architectures, working fluids, components, and control strategies are analyzed. The economic feasibility and integration on board are also evaluated. A number of research and development areas are identified in order to tackle the challenges limiting a widespread use of this technology in currently operating vessels and new-buildings. The results indicate that organic Rankine cycle units recovering heat from the exhaust gases of engines using low-sulfur fuels could yield fuel savings between 10% and 15%.

1. Introduction

Shipping is the primary means of transport worldwide. About 90% of the world trade is carried by sea [1]. The volume of seaborne trading is progressively growing, following the increment of the world population and economy. Besides its cost effectiveness, shipping is at present the most environmentally friendly and carbon efficient mode of transport, as it presents the lowest CO_2 emissions per metric ton of freight and per km of transportation [2]. Considering a medium-size cargo vessel, the carbon dioxide (CO_2) emissions per kilometer to transport one tonne of goods are two times lower compared to a heavy-duty truck with trailer and twenty times lower compared to a cargo aircraft [1]. However, shipping is still responsible for an estimated 2.4% of the total global CO_2 emissions [3]. The shares of nitrogen oxides (NO_x) and sulfur oxides (SO_x) are about 15% and 13%, respectively, of the global emissions from anthropogenic sources [4].

More than 90% of large operating vessels use diesel engines fueled by heavy fuel oil (HFO) as prime movers [5]. A significant potential to abate fuel consumption and pollutants still exists, considering that around 50% of the fuel energy content is dissipated as waste heat at various temperature levels. The International Maritime Organization (IMO) has recently enacted regulations to force the shipping industry to reduce emissions. Moreover, these regulations require the use of several performance indicators, such as the energy efficiency design index (EEDI), in order to enhance the energy conversion efficiency of new ships.

The most common approaches to reduce the fuel consumption in 2014 were slow steaming, optimization of the voyage, and cleaning of the hub and propeller [6]. The major criteria leading to a decision on which measure to adopt are the payback period, vessel age, and investment cost [6]. A complementary solution is the use of a waste heat recovery system (WHRS), i.e., a unit capable of converting the thermal energy discharged by the diesel engine into (electric or mechanical) power. The use of the steam Rankine cycle (SRC) technology for waste

Abbreviations: AIS, automatic identification system; CFC, chlorofluorocarbons; DME, dimethyl ether; DWT, deadweight tonnage; ECA, emission control area; EEDI, energy efficiency design index; EGR, exhaust gas recirculation; EU, European Union; GEN, generator; GWP, global warming potential; HCFC, hydrochlorofluorocarbons; HFO, heavy fuel oil, or hydrofluoroolefins; HEX, heat exchanger; IMO, International Maritime Organization; ISO, International Organization for Standardization; KC, Kalina cycle; LNG, liquefied natural gas; MCR, maximum continuous rating; MDO, marine diesel oil; MGO, marine gas oil; MM, hexamethyldisiloxane; NO_x, nitrogen oxides; NPV, net present value; ODP, ozone depletion potential; ORC, organic Rankine cycle; PT, power turbine; R&D, research and development; SMCR, specified maximum continuous rating; SOLAS, safety of life at sea; SO_x, sulfur oxides; SP, Technical Research Institute of Sweden; SRC, steam Rankine cycle; TEU, twenty foot equivalent unit; TUR, turbine; WHR, waste heat recovery; WHRS, waste heat recovery system

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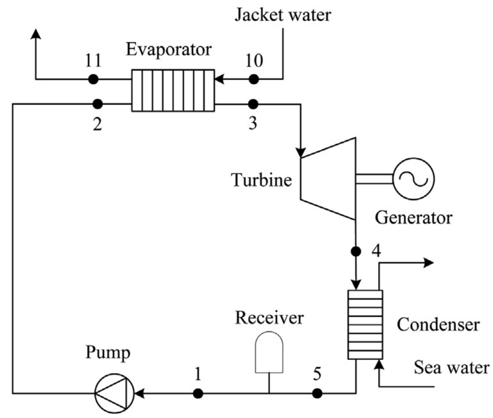

Fig. 1. Block diagram of an organic Rankine cycle power system recovering the heat from hot jacket water [9].

heat recovery (WHR) is well-established; however, its use for maritime applications is mostly limited to the utilization of heat sources of fairly high temperatures (> 250 °C).

A possible alternative is the use of organic Rankine cycle (ORC) systems. These units operate as a Rankine heat engine using an organic compound as the working fluid. This adds a degree of freedom (i.e., the working fluid) in the design phase which can be used to tailor the plant to the power capacity and temperature difference between the heat source and heat sink [7]. Furthermore, the thermophysical properties of organic fluids allow for manufacturing efficient expanders, especially at power capacities lower than a few megawatts [8]. Fig. 1 shows the diagram of an exemplary ORC power system harvesting the heat from the jacket cooling water of the main engine aboard a container ship (see Ref. [9]). The simplest layout of an ORC unit comprises the following components: evaporator, expander, condenser, liquid receiver and pump. A recuperator placed after the turbine may be added to preheat the fluid and thereby increase the energy conversion efficiency.

Today, the ORC technology is mainly used for the conversion of thermal power from biomass combustion, liquid-dominated geothermal reservoirs, and waste heat from industrial processes [8]. For the time being, only three ORC units have been tested aboard three ships, namely, an ORC unit on the merchant ship M V Figaro, an ORC unit on the container ship Arnold Mærsk, and a third unit installed on board the coal carrier Asahi Maru. A number of challenges, e.g., the high purchase cost, the flammability and toxicity of the working fluid, and the integration on board, exist before economy of production and standardization can be achieved.

In 1984, Angelino et al. [10] presented a first review on the design, construction, and testing of ORC power systems, from the perspective of the Italian activity. Since then, a number of review works on topics related to the ORC technology have been published. While some reviews provide a general overview of the technology [7,8,11–16], others focus on specific aspects such as the heat source characteristics [17] or the applications [18–22]. Other reviews analyze the details of components design for ORC units, presenting the advances on expanders design [23–28] or the selection criteria of working fluids [28–30].

Regarding the application of ORC units for WHR, Lecompte et al. [31] presented recently a general review. Earlier, Ziviani et al. [32] analyzed the challenges of ORC systems used for low-grade thermal energy recovery. Rahbar et al. [33] presented a review of ORC power systems for small-scale applications, including WHR of internal combustion engines. Tocci et al. [34] also presented a review of small-scale ORC power systems, with a special focus on the specific cost of these systems. Liang et al. [35] and Saidur et al. [36] reviewed different technologies, including ORC power systems, for WHR from exhaust gas heat. The economic and technical feasibility of different power cycles were presented and discussed. The application of ORC units for WHR of internal combustion engines was expanded by Sprouse and Depcik [37] in their review, which focused on the exhaust gases of vehicle engines. Concerning the WHR from diesel engines, Wang et al. [38] presented a survey on the use of SRC and ORC power systems. The main topics were the effect of the expander performance on the plant efficiency and the selection of the working fluid. Shu et al. [39] and Singh and Pedersen [40] reviewed different WHR technologies for two-stroke marine diesel engines. In the review by Shu et al. [39] ORC power systems were suggested as promising technologies for WHR on ships. Moreover, Bouman et al. [41] reviewed the state-of-the-art technologies for reducing the greenhouse gases emissions from shipping, including a review of WHRS for power and propulsion. Pili et al. [42] presented a study evaluating the economic feasibility of integrating ORC power systems in different transportation sectors, including maritime transport. The authors concluded that the low weight ratio of ORC units to ships payload, and the high share of fuel costs of the total cost of shipping, result in a very profitable use of ORC power systems.

In the above-mentioned works, there is no comprehensive review of the use of ORC power systems for maritime applications addressing the design and operational features of ORC units relevant for this particular application. A survey is lacking on the actual potential of this technology, based on the availability of heat sources on the shipping fleet worldwide. Furthermore, no previous study has addressed the challenges nor provided directions for future research for the integration of ORC power systems in marine applications. This paper aims at determining the most relevant vessel types and heat sources for the implementation of the ORC technology on large ships. The analysis presented here is not only based on published scientific literature, but is also supported by a detailed analysis of data for the design and operational profiles of existing ships. Guidelines on the integration on board, cycle layout, and the working fluid and components selection are given considering environmental, technical, and economic criteria. Challenges and limitations are outlined accounting for operational and technical constraints. The fuel-saving potential of the implementation of ORC power systems aboard is estimated for different ship types. The ORC technology is compared with other available WHRSs, e.g., the SRC unit and the Kalina cycle (KC) plant, and future R&D areas are identified. Data for the review were retrieved from open literature, private communications with ship owners and an engine manufacturer, and the Clarksons Research World Fleet Register [43].

First, the paper introduces (Section 2) the current legislation regulating the emissions in the marine sector. Section 3 ranks the ship types by number of units, main engine power, and CO_2 emissions. Here, the available heat sources are screened and the WHR potential is quantified. Section 4 is dedicated to the design of the ORC unit and its integration on board. Section 5 describes other alternative WHR technologies. Limitations, challenges and possible R&D areas are outlined in Section 6. Concluding remarks are given in Section 7.

2. Legislation

Most merchant ships operate across country borders and in international waters. Therefore, the IMO issues regulations on ship emissions under the umbrella of the United Nations. Until now, the IMO has set limits on CO_2, NO_x and fuel sulfur content, the latter being related to SO_x emissions and, to some extent, particle emissions.

The first binding agreement on emissions since the Kyoto Protocol, was the establishment of the energy efficiency design index (EEDI) for ships [44]. The EEDI is the ratio of CO_2 emissions associated with the main and auxiliary engines of a ship to the product of its capacity and speed, expressed in grams of CO_2 per tonne nautical mile ($g\ t^{-1}\ M^{-1}$). The method for calculating the index accounts for factors such as the type of fuel, machinery system layout, and the use of green technologies, e.g., renewable energy sources [45]. The reference EEDI is a line relating the average energy efficiency versus the deadweight of ships built between 2000 and 2010. Based on this reference, the required