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# Quasi-steady state simulation of an organic Rankine cycle for waste heat recovery in a passenger vessel

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## HIGHLIGHTS

- A regenerative ORC integrated for waste heat recovery of the exhaust gases in a ship was performed.
- A quasi-steady state simulation was carried out to estimate the ORC power production in a round trip.
- The estimated ORC power production could cover 22% of the power demand on board.

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## ABSTRACT

In this work we present the quasi-steady state simulation of a regenerative organic Rankine cycle (ORC) integrated in a passenger vessel, over a standard round trip. The study case is the M/S Birka Stockholm cruise ship, which covers a daily route between Stockholm (Sweden) and Mariehamn (Finland). Experimental data of the exhaust gas temperatures, engine loads, and electricity demand on board were logged over a period of four weeks. These data where used as inputs for a simulation model of an ORC for waste heat recovery of the exhaust gases. A quasi-steady state simulation was carried out on an off-design model, based on optimized design conditions, to estimate the average net power production of the ship over a round trip. The maximum net power production of the ORC during the round trip was estimated to supply approximately 22% of the total power demand on board. The results showed a potential for ORC as a solution for the maritime transport sector to accomplish the new and more restrictive regulations on emissions, and to reduce the total fuel consumption.



## 1. Introduction

The international maritime transport was responsible in 2012 for 602 million tonnes of $CO_2$ emissions, accounting for about 1.90% of the total worldwide $CO_2$ emissions produced from fossil fuels combustion. Although this contribution could initially be considered negligible, it must be remarked that the total $CO_2$ emissions from the international shipping sector have experienced a 28% rise during the period from 1990 to 2012, and data show the trend is on the rise [1]. Moreover, the increasing rate in the $CO_2$ emissions is higher for the shipping industry than for the total world $CO_2$ emissions, which shows the growing importance of this sector in a foreseeable future from the environmental point of view [2]. Besides the contribution to the global warming effect, there is also a direct negative effect of ship emissions on the coastal population health, as shipping stands for a large fraction of sulfur dioxides ($SO_x$) and nitrogen oxides ($NO_x$) in these areas. This is due to the majoritary use of high sulfur residual fuels because of their low price and the lack of regulated emissions in the open seas [3]. However, it is estimated that about 70% of the ships routes are within 400 km from the coast, which means that a great amount of the emissions are displaced to densely populated areas. This has negative repercussions on the humans health in those areas [4], making it obvious the urgent need of reducing ship emissions.

In this sense the International Maritime Organization (IMO) stipulated several emission control areas (ECA), where $SO_x$ and $NO_x$ emissions are under control [5]. In addition, since 1st January 2015, the Baltic Sea is considered as a sulfur emission control area (SECA), which implies that the sulfur mass content of the fuel used by the ships in that area should not exceed 0.1%. In order to comply with this new regulation, sulfur emissions must be reduced by either using a fuel with a lower content in sulfur, or by cleaning the exhaust gases. These two alternative methods imply an extra cost for the ship-owner [6], as the price of distillate fuels is higher

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**Nomenclature**

| | |
|---|---|
| $h$ | specific enthalpy, kW/kg |
| $k$ | calibration constant |
| $m$ | mass flow rate, kg/s |
| $p$ | pressure, bar |
| $Q$ | heat flow rate, kW |
| $\rho$ | density, kg/m$^3$ |
| $T$ | temperature, K |
| $W$ | power, kW |
| $\eta$ | energy efficiency |
| AE | auxiliary engine (for power) |
| EL | engine load, % |
| FRP | fuel rack position |
| ME | main engine (for propulsion) |
| GWP | global warming potential over 100 years relative to $CO_2$ |
| ODP | ozone depletion potential relative to CFC-11 |
| ORC | organic Rankine cycle |

*Subscripts*

| | |
|---|---|
| $e$ | electrical |
| evap | evaporator |
| exhaust | exhaust gases |
| in | inlet |
| loop | intermediate loop |
| $m$ | mechanical |
| net | net |
| out | outlet |
| $p$ | pump |
| pre | preheater |
| sink | sink fluid property |
| super | superheater |
| $t$ | turbine |
| AE | auxiliary engine |
| CAC | charge air cooler |
| FO | fuel oil |
| ME | main engine |
| ORC | working fluid property |

and scrubbers capital cost is important. As a consequence, there is a necessity of reducing the fuel consumption, in order to reduce both the operational costs and emissions.

About 98% of the ships use diesel engines as the main propulsion, which have a thermal efficiency of approximately (49–51)%. This means that a great part of the fuel energy is dissipated through both the exhaust gases and the engine cooling circuits. Today a fraction of the heat from the exhaust gases is recovered to preheat the heavy fuel oil (HFO) to (65–75) °C before it is combusted in the engine. However, if, in the near future, the fuel is shifted to a distillate fuel instead of a high viscosity fuel, this demand for low temperature heat would be lower, and therefore the total system efficiency would be reduced, thus increasing the heat wasted through the exhaust gases.

Organic Rankine cycles (ORC) have recently gained interest for their use in waste heat recovery systems from industrial exhaust gases. In this sense, a number of the on-going research works on ORC are focusing on the use of ORC for waste heat recovery on ships. The main reasons for this arise from the necessary adaption of the ships to the new regulations mentioned above, as well as the lower payback periods expected in off-shore applications. Although the integration of this technology on ships is still at a very early stage, it has been suggested that ORC could have a great potential to reduce the ships fuel consumption and, therefore, the $CO_2$ emissions. In this regard, a number of recent publications evaluate the suitability of the use of ORC for waste heat recovery from different heat sources from marine Diesel engines. Concerning the research on the integration of ORC on ships, the majority of the works deal with the optimization of the working fluid and cycle parameters for different heat sources. For instance, Soffiato et al. [7] studied three configurations of an ORC to recover the waste heat from the lubricating oil and the jacket cooling water of the engines of an electrically driven LNG carrier, and found that the two-stage ORC configuration yielded the maximum net power output. Yang and Yeh [8,9] carried out a working fluid and cycle parameters optimization for an ORC for waste heat recovery from the exhaust gases of a marine Diesel engine, and estimated the payback period of the installation. Also, Yang and Yeh [10] evaluated a regenerated ORC which used the jacket cooling water of large marine Diesel engines as the heat source. Larsen et al. [11] performed a working fluid and cycle parameters optimization for subcritical and transcritical ORC intended for waste heat recovery on ships by using the principles of natural selection. Additionally, in Ref. [12] Larsen et al. focused on the evaluation of the environmental and safety aspects of the integration of ORC on ships. The authors concluded that ORC had a great potential for increasing the energy efficiency of ships and reducing the fuel consumption, although also pointed out as a major inconvenient the high global warming potential and safety of the used working fluids. More recently de la Fuente et al. [13] compared the performance of several hydrocarbons to that of R245fa, when used as working fluids in an ORC for waste heat recovery of the exhaust gases of the main engines of merchant ships. The authors concluded that, although hydrocarbons have a high flammability risk, they can offer a great potential when used for high temperature applications if all safety are sufficiently addressed, given the lack of working fluids in that temperature range and the environmentally-friendly characteristics of hydrocarbons. In a deeper study of the integration of ORC, Nielsen et al. [14] proposed a system for cleaning the exhaust gases sulfur from a ship combined cycle, in which the heat resulting from condensing the exhaust gases was used as a heat source for an ORC. The authors concluded that this technology had potential for marine applications as it could increase by 2.6% the thermal efficiency of the combined cycle. Also, Yuksek and Mirmobin [15] presented a new efficient, non-regenerated and compact ORC design, developed by Calnetix Technologies, especially designed for the waste heat recovery of the jacket cooling water from the main propulsion engine of large ships. Grljušić et al. [16] evaluated a combined and heat plant which used the waste heat from the propulsion engines of an oil tanker. The system consisted of a supercritical ORC which could satisfy all the electricity demand on board when the engines were operating at full load.

In our previous work we carried out a working fluid and cycle parameter optimization of an ORC integrated on a passenger vessel [17]. The ORC performance was then evaluated at six selected off-design conditions, based on the vessel speed, for the working fluids with better performance. In this work we aim at evaluating the off-design performance of the optimized ORC with time over an average round trip of the vessel, and how the ORC power production would meet the electricity demand on board along the route.