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Thermodynamic analysis of a Rankine dual loop waste thermal energy recovery system

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ABSTRACT

Waste thermal energy recovery systems have assumed an important role in the last decade as an effective way to improve fuel utilization in thermal engines, since they provide an opportunity to produce eco-friendly electrical power from an otherwise wasted energy source, leading to a reduction of the pollution and an increase of the overall system efficiency.

In this scenario, the Rankine cycle technology based on simple or Organic Rankine cycle, earned a promising market position, since it allows for the production of additional electric power from relatively low-temperature heat sources (350–650 K); this feature makes these cycles a very suitable solution to recover thermal energy from Internal Combustion Engines, geothermal sources, solar thermal modules and micro-gas turbines.

This paper presents the comparison between a single loop and a dual loop waste energy recovery system specifically designed as a bottomer to marine engines of different power range. The particular application considered shows several advantages for the installation of a waste energy recovery system; in particular, the basically infinite availability of the cooling medium represented by the seawater substantially facilitates the condenser design. R 245fa and R600 have been implemented in the second recovery loop and their performance has been addressed. The paper shows how adding a second recovery loop based on organic Rankine cycle to the steam Rankine cycle loop improves the system performance both in terms of recovered electric power (up to 8.11% and 2.67% respectively in small and large application size) and heat source utilization rate, since the heat source temperature could reach values as low as 343.15 K when considering a sulfur free fuel. In addition, R 245fa is to be preferred over the R 600 since it allows for the production of the same power considering lower values for the cycle top pressures.

1. Introduction

Waste thermal energy recovery (WER) is a practice commonly used in energy conversion plants that allows to partially or completely convert the heat discharge of a primary cycle -that would otherwise leave the process as a "waste" and be released into the environment- into useful energy, either thermal or electrical.

Such a system increases the overall efficiency, defined as the amount of useful final specific work produced per fuel unit mass, introducing several thermodynamic and economic advantages. Higher efficiency leads to the reduction of the increasingly regulated carbon dioxide emissions and fuel savings, since using otherwise discharged heat to produce additional work leads to a decrease of the fuel consumption. On the other hand, the heat recovery system presents a monetary additional installation cost that needs to be considered in the overall engineering feasibility analysis.

According to Tchanche et al. [1], WER systems can be classified into 3 different groups depending on their top temperature level: low (<500 K) [2], medium (500–900 K) [3] and high (>900 K) [4]. Internal Combustion Engines (ICEs), because of the relatively high temperature of the exhausts (approximately 973 K for atmospheric intake ICE and 573–673 K for turbocharged Diesel), can be placed on the medium–high side, offering a great potential for thermal energy recovery [5].

Aim of this work is to recover heat from marine ICE exhaust gas. A yacht non-supercharged Diesel engine (300 kW) and a ship turbocharged one (3 × 12.6 MW) have been investigated. The recovered

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Nomenclature

Acronyms
HRSG heat recovery steam generator
HT high temperature
ICE internal combustion engine
LMTD logarithmic mean temperature difference
LT low temperature
ORC Organic Rankine Cycle
RbORC Rankine bottoming Organic Rankine cycle
RbORCr Rankine bottoming Organic Rankine cycle regenerated
RbORCri Rankine bottoming Organic Rankine cycle regenerated and integrated
WER waste energy recovery

Symbols
h specific enthalpy [kJ/kg]
LHV lower heating value [kJ/kg]
$\dot{m}$ mass flow rate [kg/s]
p pressure [bar]
P power [kW]
Q_{lost} heat loss [kW]
sfc specific fuel consumption [kg/s]
T temperature [K]
U heat transfer coefficient [kW/m^2 K]
η_I 1st law efficiency [–]
ρ density [kg/m^3]

Subscripts
c cold
c_1 cooling fluid when working fluid is at saturated liquid state
c_2 cooling fluid when working fluid is at saturated vapor state
ph pre-heating
h hot
h_1 hot fluid when working fluid is at saturated vapor state
h_2 hot fluid when working fluid is at saturated liquid state
in inlet
L liquid
out outlet
p pump
sh super-heating
T turbine
V vapor
vap vaporization
w water

electric energy produced by the WER system is intended for on board use, replacing a 15 kW electric generator currently installed on the yacht and exploiting part of the 10 MW hotel loads of the ship. The WER system proposed is Rankine cycle based, considering different working fluids, depending on the thermodynamic conditions of the waste heat. Several studies [6–8] have been published on the selection of the proper fluid for each application, and all results demonstrate that simple Rankine cycles, using water as the operating fluid, work well when the heat source temperature is high (673–873 K) while the use of organic fluids such as R245fa or R 600 is more suitable when heat source temperature is low (353–423 K).

Vankeirsbilck et al. [9], in his study on the comparison between Steam and organic Rankine cycle (ORC) for small scale power generation, underlines how, for a low temperature heat source, the LMTD between hot and cold fluid is lower when using ORC, implying higher efficiency; in addition, the opportunity ORC offers to expand the fluid avoiding superheating increases the power density.

Yu and Shu [8] analyzed a bottoming organic Rankine cycle applied to a 300 HP Diesel engine, considering as waste heat both the exhaust gas and the jacket water for different engine work conditions; their results show that it is possible to increase thermal efficiency up to 6.1% and produce power up to 15.5 kW.

Vaja and Gambarotta [10] compare ORC-WER systems to exploit ICEs wasted thermal energy. They claim it is possible to improve the engine efficiency up to 12.5% with respect to engine with no bottoming, when considering Benzene as the ORC working fluid.

Zhang et al. [11] studied a dual loop bottoming Organic Rankine Cycle applied to a 4 cylinders ICE; the high temperature (HT) loop recovers heat using R245fa as operating fluid, while the low temperature (LT) loop uses R134a. The cycle performance has been calculated for several engine operational conditions, the conclusions being that the net power of the LT loop is higher than that of the HT and the efficiency increases of about 14–16% in the peak effective thermal efficiency region but up to 38–43% at part load and in the high speed region. According to the author, such a cycle constitutes a promising scheme to recover heat from light-duty diesel engines.

The ICE operating conditions constitute an important aspect that needs to be considered in the installation of a waste energy recovery system to produce electric power; in fact, while this cycle perfectly matches engines that work mainly at steady conditions, it suffers substantial performance derangements when installed on engines in which the operating conditions vary considerably over time. One of the reasons for the present work emphasis on WER for marine applications is that usually both ships and yachts travel at fixed speed, resulting in steady conditions ideal for the operation of the heat recovery steam generator (HRSG).

The relatively high power/volume density of these installations makes them suitable for many on board applications in which the plant weight and size have a fundamental role, such as marine applications.

When the heat rejection from the primary cycle is energetically rich, as it is for ships, it is also possible to consider the application of a double loop heat recovery system, in which at first high temperature fluid is converted into power in a Rankine cycle followed by an ORC in which the residual thermal energy is used to produce additional electric power, increasing the overall recovery system efficiency. In order to reach this goal, two different fluids have been studied to investigate their characteristics in terms of thermodynamic properties and toxicity, to find out the most convenient ones for the applications object of this work.

This study combines the comparison of two different organic fluids and the analysis of a dual loop recovery system, able to recover a substantial portion of the available waste thermal energy. In addition, the influence of the cycle top pressure has been investigated over a wide range, providing a better understanding of the most convenient cycle thermodynamic condition. Marine application represents a scarcely investigated field for what concern waste energy recovery; the main advantage with respect to other applications is represented by the condensing pressure of the working fluid that can reach low values because of the presence of the unlimited sink of relatively cold sea water to be used