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Thermoeconomic analysis and off-design performance of an organic Rankine cycle powered by medium-temperature heat sources ☆

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Abstract

This paper presents the performance of an organic Rankine cycle (ORC) powered by medium-temperature heat sources. A simulation model, developed by the authors, has been improved to this scope. The model is based on zero-dimensional energy and mass balances for all the components of the system. It is also strictly related to the geometrical and design parameters of its components, especially in case of heat exchangers. The model evaluates the energetic and economic performance of the system, for different operating conditions and design criteria. In particular, the model allows one to set the geometrical parameters of heat exchanger and evaluate the off-design performance of the system. Hence, it could be an useful tool in the preliminary design of the plant. The *n*-butane has been used as working fluid according to results of the previous authors' work.

Two types of simulations have been performed. The first simulation aims at selecting a design optimization criterion of some geometrical parameters of the shell and tube heat exchangers. The total cost of ORC plant has been selected as objective function. The parametrical analysis has been performed in steady-state regime.

The second simulation evaluates the off-design performance of the ORC power plant. The thermal input of the cycle, i.e. diathermic oil coming from the heat source, has been varied in terms of mass flow rate and temperature to analyze the plant response to variations of boundary conditions starting from the design point.

With respect to the total cost minimization, as objective function, the simulation results show that for all heat exchangers the higher the heat transfer area, the higher the net power generated and income. Instead, the evaporator shows different trends, hence it represents a key element in ORC design. The geometric optimization of heat exchangers allows the ORC to increase the economic benefit, the net power generated and the global efficiency of about 21.06%, 20.01% and 33.60% respectively.

The results of the off-design analysis show that the heat source mass flow rate is a key parameter in net power generation. Fixed the heat source temperature on the upper bound of its variation range (185 °C), the net power generation shows both the maximum and minimum value, 335.4 kW and 269.3 kW, in correspondence of the lowest and the highest value of heat source mass flow rate respectively. Moreover, the results show that the plant efficiency decreases as both heat source mass flow rate and temperature increase. Its maximum value, 14.7%, is achieved for heat source temperature and mass flow rate equal to 155 °C and 18 kg/s, while its minimum value, 9.54%, is reached for heat source temperature and mass flow rate equal to 185 °C and 24 kg/s.

Keywords: ORC; Thermo-economic optimization; Heat exchanger; Off-design

1. Introduction

In the last decades, the global energy crisis and the higher environmental awareness have been pushing Developed Countries to promote renewable energy

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Nomenclature

AF	annuity factor
c	heat capacity rate (kJ kg^{-1} K^{-1})
d	diameter (m)
e	electricity price (c€/kW h)
f	friction factor
G	corrected mass flow rate
g	gravitational acceleration (m s^{-2})
I	income ($ year^{-1})
i_{lv}	latent heat of evaporation (kJ kg^{-1} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
$\dot{m}$	mass flow rate (kg/s)
N	number of tube
n_{row}	row number
NTU	number of thermal unit
Pr	Prandtl number
$\dot{Q}$	heat power (kW)
Re	Reynolds number
T	temperature (°C)
$\dot{W}$	Power (kW)

Greek symbols

ε	heat exchanger efficiency
η	efficiency
ρ	density (kg m^{-3})
μ	dynamic viscosity (Pa s)

Subscripts

c	convective
des	design
ex	expander
fluid	organic fluid
fp	feedpump
hex	heat exchanger
id	ideal
in	inlet
Inc.	incentives
l	liquid
o	outer
oil	diathermic oil
off	off design
ORC	organic fluid
out	exit end
p	primary circuit
PP	power plant
pump	pump
s	isentropic
sat	saturated
T	iso-thermal wall
tariff	tariff
TP	two-phase
v	vapor
w	wall

Symbols

€	cost or het gain (€) or (€/year)

sources. Furthermore, in many countries, liberal policies determined the electric market deregulation, with the scope to reduce prices, support customers and promote distributed power generation. As a consequence, the technologies dedicated to the exploitation of low–medium temperature heat sources have been strongly developing and widely increasing. In this framework, the organic Rankine cycles (ORC) is commonly considered one of the most promising technologies (Bertrand et al., 2011).

The steam/water Rankine cycle is one of the most common thermodynamic cycle used in power plants.

However, when the temperature of the heat source is low, the use of water as working fluids may be unfeasible, due to the specific trend of its saturation curve. In such case, an organic fluid shows a significantly better performance with respect to the water thanks to the higher molecular weight, the lower evaporation heat, the positive slope of the saturated vapor curve in the *T–s* diagram and the lower critical and boiling temperatures.

These features make the ORC technology very attractive in applications where low and medium temperature sources are considered as solar energy, geothermal energy, biomass products, waste heat, etc. This is shown by several papers available in literature, investigating potential and existing applications of ORC power plants, as reviewed in reference (Bertrand et al., 2011). The selection of the working fluid plays a key role in ORC design. Many studies on the organic fluid selection criteria are available in the scientific literature (Golubovic et al., 2007; Wang et al., 2009, 2010; Hsu et al., 2011; Furuhata et al., 2001; Tao and Rayegan, 2011; Koglbauer et al., 2007; Li et al., 2013). Capuozzo et al. (2013) investigated on the performance of the ORC system object of this work by using different working fluids and varying the heat source temperature level from 120 °C to 300 °C. The authors stated that two organic mediums are suitable for the exploitation from low to high temperature heat sources, namely, *n*-butane and Isobutane, while the R245fa can be used when the heat source temperature is up to 170 °C.

The selection of the appropriate organic fluid is the very first step in the ORC optimization process that is strictly related to the type of heat source. Zhao et al. (2010) designed, built and tested a low-temperature solar ORC cycle using R245fa as working fluid and a tailor made