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Charge-sensitive modelling of organic Rankine cycle power systems for off-design performance simulation

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HIGHLIGHTS

- True off-design models must be charge-sensitive to be fully deterministic.
- To account for the charge helps to identify the heat exchangers coefficients.
- Hugmark's void fraction model shows the best results to simulate two-phase flows.
- The presence of a liquid receiver arises numerical issues to model ORC systems.
- The charge-sensitive model is validated with experimental data.

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ABSTRACT

This paper focuses on a charge-sensitive model to characterize the off-design performance of low-capacity organic Rankine cycle (ORC) power systems. The goal is to develop a reliable steady-state model that only uses the system boundary conditions (i.e. the supply heat source/heat sink conditions, the mechanical components rotational speeds, the ambient temperature and the total charge of working fluid) in order to predict the ORC performance. To this end, sub-models are developed to simulate each component and they are assembled to model the entire closed-loop system. A dedicated solver architecture is proposed to ensure high-robustness for charge-sensitive simulations.

This work emphasizes the complexity of the heat exchangers modelling. It demonstrates how state-of-the-art correlations may be used to identify the convective heat transfer coefficients and how the modelling of the charge helps to assess their reliability. In order to compute the fluid density in two-phase conditions, five different void fraction models are investigated. A 2 kWe unit is used as case study and the charge-sensitive ORC model is validated by comparison to experimental measurements. Using this ORC model, the mean percent errors related to the thermal power predictions in the heat exchangers are lower than 2%. Regarding the mechanical powers in the pump/expander and the net thermal efficiency of the system, these errors are lower than 11.5% and 11.6%, respectively.

1. Introduction

Among the fields of research and development in the energy sector, power generation from low-grade heat sources is gaining interest because of its enormous worldwide potential [1]. For low-temperature (i.e. below 200 °C) or low-capacity applications (typically lower than 2 MWe), the use of conventional steam power plants is neither technically nor economically beneficial [2]. However, by substituting water with an organic compound as working fluid (WF), it is possible to efficiently convert low-grade heat into mechanical power by means of a closed-loop Rankine cycle. In such a case, the terminology *organic Rankine cycle* (ORC) is used to name the system [3]. A common aspect of most ORC power systems is the versatile nature of their operating conditions. Either for combined heat and power, waste heat recovery, geothermal or solar thermal applications, the heat source and the heat sink conditions often vary in time, which forces the ORC system to adapt its working regime for performance or safety reasons. Consequently, once sized and built, an ORC system often operates in conditions differing from its nominal design point.

The study of ORC systems in off-design conditions is not a new topic and numerous papers can be found in the scientific literature. Over the past years, both steady-state and dynamic models have been developed

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Nomenclature

Acronyms

BPHEX	Brazed Plate Heat Exchanger
CD	Condenser
EV	Evaporator
EXP	Expander
FCHEX	Fin Coil Heat Exchanger
HEX	Heat Exchanger
HP	High Pressure
HTF	Heat Transfer Fluid
LP	Low Pressure
LR	Liquid Receiver
MAPE	Mean Absolute Percent Error
NRMSE	Normalized Root Mean Square Error
PP	Pump
REC	Recuperator
WF	Working Fluid

Subscripts

amb	ambient
c	cold
cs	cross-section
ex	exhaust
exp	experimental
h	hot
i, j, k	index
l	saturated liquid
lam	laminar
lk	leakage
log	logarithmic
max	maximum
mec	mechanical
min	minimum
sc	subcooling
sim	simulation
sp	single-phase
su	supply
tot	total
tp	two-phase
turb	turbulent
v	saturated vapour

Variables

α	void fraction (–)
β	weighing factor (–)
Δ	difference (–)
$\dot{m}$	mass flow (kg/s)
$\dot{Q}$	heat power (W)
$\dot{V}$	volume flow (m^3/s)
$\dot{W}$	power (W)
η	efficiency (%)
μ	viscosity (kg/(s·m))
ω	spatial fraction of a zone (–)
ρ	density (kg/m^3)
θ	chevron angle (rad)
A	surface (m^2)
B	parameter (–)
Bd	bond number (–)
Bo	boiling number (–)
	correction factor (–)
D_h	hydraulic diameter (m)
G	mass flux (kg/(s·m^2))
H	convective heat transfer coefficient (W/(m^2·K))
h	enthalpy (J/kg)
it	iteration variable (–)
j	colburn factor (–)
K	parameter (–)
k	conductivity (W/(m·K))
L/l	length (m)
M	mass (kg)
m	Reynolds exponent (–)
MM	molecular weight (–)
Nu	Nusselt number (–)
P	pressure (Pa, bar)
Pr	Prandtl number (–)
Re	Reynolds number (–)
res	residuals (–)
rv	volume-ratio (–)
S	slip ratio (–)
T	temperature (K/°C)
U	global heat transfer coefficient (W/(m^2·K))
u	fluid velocity (m/s)
V	volume (m^3)
We	Weber number (–)
x	quality (–)

to simulate ORC units under various operations. To illustrate the current state-of-the-art, a non-exhaustive list of thirteen works is presented in Table 1. As highlighted in the last column, almost all the existing models rely on user-defined assumptions in the ORC state, e.g. an imposed fluid subcooling, superheating or condensing pressure. Such hypotheses make the off-design models not fully deterministic and can mislead the performance predictions. For instance, to assume a constant fluid subcooling in the ORC makes the simulations blind to important phenomena susceptible to occur in off-design operations, like the cavitation of the pump or the complete flooding of the liquid receiver. In practice, the state in an ORC system is unequivocally defined by its boundary conditions. All the pressures, temperatures and energy transfers *inside* the ORC unit are dictated by (i) the heat sink and the heat source supply conditions, (ii) the pump/expander rotational speeds, (iii) the ambient temperature, (iv) the components geometry and, finally, (v) the total mass of working fluid enclosed in the system. A true off-design model should account for this univocal relationship. In order to make the simulations free of such assumptions, the ORC model must implement both the energy *and* the mass balances in the system. Besides the energy transfers, the model must account for the total charge of fluid in the system and simulate its repartition through the components in function of the operating conditions. Such a model is known as *charge-sensitive*.

Charge-sensitive models are well known for refrigeration systems for which they have been extensively used for both design and performance analyses (e.g. see [18–21]). However, their use for ORC power systems is much less common. For steady-state simulations, a thorough search of the literature yielded only two articles dedicated to ORC charge-sensitive modelling. A first paper was proposed by Ziviani et al. [16] which described an ORC model developed in Python. The model could either use a specified subcooling or account for the total charge of working fluid. A simplified method to simulate the liquid receiver was introduced. Heat transfer coefficients in the various components were calculated with state-of-the-art correlations and Zivi's void fraction model characterized the two-phase flows. The overall cycle model was validated against two experimental setups featuring different cycle architectures. When the charge of fluid was specified as input, the overall cycle efficiency was estimated within a maximum