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Optimizing the performance of small-scale organic Rankine cycle that utilizes a single-screw expander

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HIGHLIGHTS

- A total of 102 steady-state points with R245fa and SES336 have been collected.
- R245fa led to 10% higher power output despite lower expander isentropic efficiency.
- The ORC running with SES36 presented a better matching between expander and cycle.
- The theoretical matching between expander volume ratio and cycle efficiency is determined.
- Steady-state performance maps are used to build a feed-forward controller.

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ABSTRACT

This paper deals with the operation and optimization of a down-scaled industrial organic Rankine cycle (ORC) for low-grade waste heat recovery. The system is a sub-critical regenerative ORC with a nominal power output of 11 kW. The ORC unit has been assembled using off-the-shelf components including three identical plate heat exchangers, a liquid receiver, a multi-stage centrifugal pump and a single-screw compressor adapted to operate as an expander. The experimental results are used to evaluate the influence of the expander performance on the behavior of the ORC system at nominal and part-load conditions. The matching between the volumetric expander and the system operating conditions is also analyzed. Results showed that in the case of SES36, both the expander efficiency and system performance were maximized for a pressure ratio between 7 and 9. In the case of R245fa, while the system efficiency achieved values similar to SES36, but the expander maximum isentropic efficiency was 17% lower. Two analyses are carried out to optimize the operation of the ORC unit with R245fa. At first, the insights gained by analyzing the experimental data are used to evaluate the theoretical matching between volumetric expander and the system maximum efficiency in terms of the Second Law of thermodynamics. Secondly, a control-oriented steady-state cycle model based on empirical correlations calibrated on the experimental results is developed. The model is used to implement a feed-forward control strategy based on predetermined steady-state points that allow to optimize the operation of the ORC unit. The frequency of the pump is used as controlled variable. The steady-state experimental data of both working fluids is provided in an electronic annex.

1. Introduction

In recent years, the organic Rankine cycle (ORC) technology is rapidly gaining maturity with an increasing number of applications [1]. Because of the adaptability of ORCs to different heat sources and cold sinks conditions, the number of theoretical analyses proposed in literature is also flourishing. As outlined by Maraver et al. [2], purely thermodynamic or theoretical analyses are useful as a screening method and to obtain an estimation of the expected performance, e.g., [3]. However, these analyses become useful only when design parameters and physical constraints are taken into account. There is still a limited number of studies that accounts for both aspects during the optimization that can provide a general

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Nomenclature

A	area (m^2)
BWR	Back Work Ratio (–)
c_p	specific heat at constant pressure (J/kg K)
D	diameter (m)
h	specific enthalpy (J/kg)
$\dot{m}$	mass flow rate (kg/s)
f_{pp}	pump frequency (Hz)
L	length (m)
N	rotational speed (rpm)
p	pressure (Pa)
$\dot{Q}$	heat rate (W)
r_p	pressure ratio (–)
r_v	specific volume ratio (–)
$r_{V,built-in}$	geometric volume ratio (–)
T	temperature (K, °C)
v	specific volume (m^3/kg)
V	volume (m^3)
$\dot{V}$	volume flow rate (m^3/s)
$\dot{W}$	power (W)
x	quality/fraction (–)
z_{sr}	number of starwheel tooth (–)
φ_{ff}	filling factor (–)
ε	effectiveness (–)
η	efficiency (–)
τ	torque (Nm)

Subscript

cd	condenser
cf	cold fluid
ex	exit
exp	expander
el	electric
eV	evaporator
gen	generator
hf	hot fluid
is	isentropic
in	inlet
inv	inverter
meas	measured
oa	overall
opt	optimum
pp	pump
r	refrigerant
sc	subcooling
sh	superheating shaft
sr	screw rotor
su	supply
sw	starwheel
th	theoretical
T66	Therminol66

perspective in the optimal design of ORCs. Maraver et al. [2] proposed a comprehensive framework to address several important aspects, existence of optimal evaporating temperature, effect of superheating, relationship between heat source temperature and working fluid temperature, range of usefulness of the recuperator among others. Additionally, cycle component requirements of expander, heat exchangers and pumps were included. A methodological approach to compare different cycle architectures (subcritical, transcritical and partial-evaporating cycles) under a large set of boundary conditions including thermo-physical and environmental constraints has been proposed by Lecompte et al. [4]. Starting from a large pool of working fluids, successive restrictions were applied to assess the applicability and effectiveness of each cycle architecture establishing a selection criteria based on applications. Pezzuolo et al. [5] developed a simulation tool that includes working fluids screening as well as technical and economical optimization routines. Four cycle configurations have been considered limited to subcritical conditions. The applicability of the tool is limited to dynamic expanders (both radial and axial turbines).

The research progresses on several aspects of the ORC such as environmentally-friendly working fluids, thermo-economic optimization, cycle and components modeling and control strategies. As highlighted by Lecompte et al. [6] in their comprehensive review, there is a general lack of experimental data from the open literature, especially regarding fluid comparison and novel cycle architectures. To be more precise, a number of experimental setups have been built and tested with emphasis, in many cases, on designing a small-scale, compact and relatively cost-effective systems [7,8]. For example, Jung et al. [9] conducted an experimental study on a lab-scale 1 kW ORC to demonstrate the feasibility of using a zeotropic mixture of R245fa and R365mfc (48.5%/51.5% on a mole basis) as working fluid for waste heat recovery. Little information was given about the operation of the ORC at different working conditions. Chang et al. [10] evaluated the performance of an open-drive scroll expander by using R245fa as working fluid and a heat source temperature below 100 °C. The influence of the superheating on the performance of both expander and cycle has been investigated. It is even more rare to find studies dealing with the optimization of real ORC installations at design and off-design conditions and providing methodologies to improve the operation of an ORC. Yang et al. [11] proposed an in-depth experimental analysis on the operation of an ORC with a scroll expander and R123 as working fluid by investigating the effect of pump frequency and expander generated torque. It was pointed out that the operation of the ORC strongly depends on the match between the heat source and the ORC as well as the match between pump and expander. The experimental results confirmed that the real behavior of the ORC can significantly deviate from the numerically predicted performance.

Analytic analyses of the heat source slope have been proposed for example by Chen et al. [12] and by Mikielewicz [13]. These methods are based on the analysis of the temperature-heat rate (T-Q) profiles of working fluid and heat source and on energy balance combined with a LMTD (log mean temperature difference) method, respectively. However, their results are not directly applicable to a real ORC unit installation because they do not account for the real geometry and performance of each cycle component, in particular the working fluid pump and expander.

Publications about practical use and behavior of different working fluids are still rare. Even more rare are experimental comparisons of working fluids performed on the same installation and the employment of zeotropic mixtures. Huck et al. [14] proposed a numerical comparison of different HCFOs as alternative for R245fa. A commercial ORC test unit has been used to perform a drop-in test. In particular, by maintaining all the components, including a radial expander, originally designed for R245fa, a second fluid, HCFO-1233zd(E), was tested. Regarding zeotropic mixtures, experimental studies on real ORC installations for waste heat recovery are almost absent. To the author's best knowledge, only Woodland [15] carried out a comprehensive experimental