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Improving the semi-empirical modelling of a single-screw expander for small organic Rankine cycles

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HIGHLIGHTS

- The common semi-empirical modelling for positive-displacement expanders is revised.
- A more physically sound modelling is adopted for mechanical and ambient heat losses.
- The proposed procedure is calibrated and validated for a single-screw expander.
- Mass flow rate, electric power and exhaust fluid temperature are appreciably simulated.
- The expander performance is analyzed based on variations of the operating conditions.

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ABSTRACT

The common semi-empirical modelling adopted for positive-displacement rotary expanders is revised in this paper. Paying particular attention to the leakage flow rates, the mechanical losses at the shaft and the ambient heat losses by the proposal of a more physically sound modelling, this paper aims at improving the performance simulation of a single-screw expander for which there exists a wide experimental campaign in literature. In detail, the mechanical losses are modelled with an approach consistent with the Stribeck's theory, whereas the contributions of both natural convection and radiation are taken into account for a proper modelling of the ambient heat losses.

After calibration and validation of the modelling procedure, based on experimental data of the expander operation with R245fa, mean absolute percentage errors of 0.69%, 1.77% and 0.33% as regards mass flow rate, electric power output and exhaust fluid temperature, respectively, are calculated. These errors are lower than the ones reported by other researchers, so the current simulations are more consistent with the experimental data.

Considering the higher reliability for a better performance simulation by the new modelling procedure, the model is finally used to study the behavior of the expander. In particular, attention is paid to the mass flow rate, the shaft and the electric power outputs, the expander efficiency, as well as the ambient heat losses, and to their relations with the operation parameters such as the degree of fluid superheat at the expander inlet, the fluid pressure at the expander inlet, the pressure ratio and the rotational speed.

1. Introduction

The organic Rankine cycle (ORC) is a well proven technology used to produce useful work or electricity from heat at low temperature from renewable energy sources, such as solar or geothermal, and from low-grade heat produced in an industrial process which cannot be recovered [1,2].

The performance of an organic Rankine cycle is strictly dependent on the conditions of the heat source and cold sink, on the proper selection of the working fluid to exploit the heat source and on the selection of the expander [3]. The production of useful work from an ORC system relies on the expander behavior. However, it is challenging to find a device with efficient performance, especially at lower capacity ranges. Several researchers have suggested positive-displacement expanders as a suitable solution [4]. Although they are not a commercially ready technology, lots of prototypes are available as developed for the purpose of laboratory experiments by modifying a commercial machine for air compression or HVAC applications to make it run in reverse mode. In this field, significant researches have been conducted on scroll-type expanders, as detailed in a number of papers [5–12]. More recent

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Nomenclature

$a_{leak,0}$	coefficient for leakage area, m^2
$a_{leak,1}$	coefficient for leakage area, $m^2\ bar^{-1}$
A	area, m^2
AU	heat transfer coefficient, $W\ K^{-1}$
b_{nc}	coefficient of heat losses for natural convection, $W\ K^{-1.25}$
b_{ra}	coefficient of heat losses for radiation, $W\ K^{-4}$
BVR	built-in volume ratio
c_{ht}	convection coefficient, $W\ m^{-2}\ K^{-1}$
c_p	specific heat at constant pressure, $J\ kg^{-1}\ K^{-1}$
D	hydraulic diameter, m
err	error
e_m, e_P, e_T	weights
f	friction coefficient
FF	filling factor
$f_{loss,0}$	coefficient for mechanical losses, m^3
$f_{loss,1}$	coefficient for mechanical losses, m^3 s bar
h	specific enthalpy, $J\ kg^{-1}$
HVAC	heating, ventilation, and air conditioning
K	geometric coefficient, $m^{1.8}$
L	length, m
mep	mean effective pressure, Pa
$\dot{m}$	mass flow rate, $kg\ s^{-1}$
MAPE	mean absolute percentage error
n_g	number of grooves in the screw rotor
N	rotational speed, rpm
Nu	Nusselt number
ORC	organic Rankine cycle
p	pressure, Pa
P	power, W
Pr	Prandtl number
PR	pressure ratio
$\dot{Q}$	heat transfer rate, W
Re	Reynolds number
s	specific entropy, $J\ kg^{-1}\ K^{-1}$
T	temperature, K
U	thermal transmittance, $W\ m^{-2}\ K^{-1}$
v	specific volume, $m^3\ kg^{-1}$
V	volume, m^3
$V_{g,max}$	volume of the groove at the end of the adapted expansion process, m^3
w	velocity, $m\ s^{-1}$
z	number of points for model calibration
α	dimensionless coefficient
γ	isentropic exponent
η	efficiency
λ	thermal conductivity, $W\ m^{-1}\ K^{-1}$
μ	dynamic viscosity, Pa s
ρ	density, $kg\ m^{-3}$
τ	torque, N m

Subscripts

amb	ambient
crit	critical
el	electric
exp	experimental
gen	generator
grid	grid
in	inlet
inv	inverter
int	internal
is	isentropic
leak	leakage
load	load
loss	loss
mech	mechanical
oa	overall
out	outlet
sh	shaft
sim	simulated
sse	single-screw expander
sw	swept
vol	volumetric
w	envelope

is the interest in another positive-displacement expander, namely the single-screw machine [13–18], even though the initial concept goes back to 1960 [18]. As a matter of fact, its configuration has some advantages over the twin-screw architecture [19–22] such as balanced loading of the main screw rotor, higher volumetric efficiency, long working life, low vibrations and a simplified configuration. Based on these characteristics, ORC systems based on single-screw expanders have recently gained attention [23–25].

As anticipated, a number of studies in the literature is dedicated to characterize and model the performance of scroll- and screw-type expanders. In general, theoretical modelling is an effective tool for predicting and improving the performance of positive-displacement expanders. Mathematical models of expanders have been proposed by many researchers, based on the models of the corresponding compressor. Although the deterministic model is the most common, because of the complex geometry and internal transport mechanisms, empirical and semi-empirical models are often applied to describe the thermodynamic behavior of positive-displacement expanders. In particular, the semi-empirical model consists of a series of thermodynamic equations deduced from mass, energy and momentum conservations, where critical parameters are determined according to experimental data. The work formerly presented by Winandy et al. [26] for a scroll compressor was taken as the starting point of the modelling developed by Lemort et al. [27] for an open-drive scroll expander integrated in an ORC system. Such an expander model allows to investigate the variations of the expander performance with the system operating conditions. As shown in Fig. 1, supply pressure drop (0–1), heat transfer (1–2 and 5–6), internal leakage (2–4) and internal expansion (2–4) stages are included in the whole

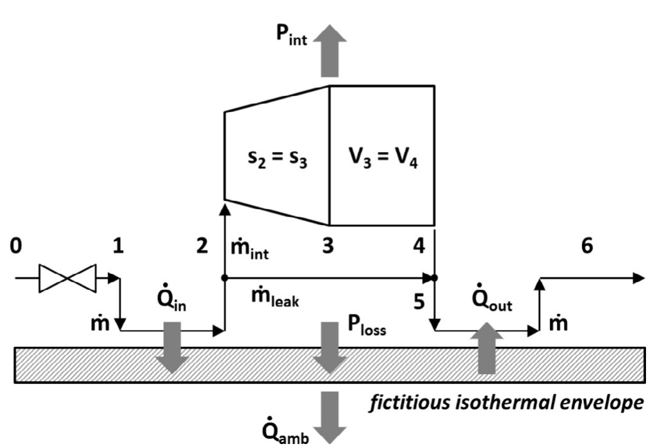

Fig. 1. Conceptual scheme of the semi-empirical model proposed for an open-drive scroll expander by Lemort et al. [27].