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Characterizing the performance of a single-screw expander in a small-scale organic Rankine cycle for waste heat recovery

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HIGHLIGHTS

- The performance of an open-drive single-screw expander is presented.
- A total of 102 steady-state points with R245fa and SES336 have been collected.
- The maximum overall isentropic efficiency of 64.7% was achieved with SES36.
- Internal losses and potential design improvements have been analyzed.
- Experimental data and the expander semi-empirical model are made available.

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ABSTRACT

This paper focuses on the experimental and numerical characterizations of a single-screw expander for waste heat recovery organic Rankine cycle (ORC) applications. A down-scaled industrial ORC test-rig has been tested with two different working fluids, R245fa and SES36. The hot source inlet temperature has been set to 125 °C and the maximum expander inlet pressure was limited to 1200 kPa. A total of 102 steady-state points have been collected by varying the expander pressure ratio between 3 and 9 with rotational speeds in the range from 2000 rpm to 3300 rpm. The experimental results allowed to assess the relationship between internal built-in volume ratio and imposed expansion ratio at different rotational speeds with respect to shaft and overall isentropic efficiency as well as volumetric performance in terms of filling factor. Results showed that while R245fa allowed approximately a 10% higher power output, the single-screw expander was performing at higher isentropic efficiency with SES36 due to higher pressure ratio achievable under the given working conditions and system limitations which also led to a better matching between ORC system and volumetric expander performance. A semi-empirical model has been developed and calibrated to break down the expander internal losses in the case of R245fa. The model has been exercised to investigate the effect of potential design improvements on the overall performance. The friction losses played a major role in the total loss count followed by suction pressure drops and leakages. As a consequence, the effect of lubrication should be further investigated to reduce leakages and friction. This study demonstrates the potential of single-screw technology as volumetric expander for ORC applications.

1. Introduction

The continuing increase of primary energy consumption [1] pushes research towards renewable energy as well as to more efficient ways of utilizing existing technologies. Especially in the industrial processes, the residual or waste heat is usually not efficiently recovered [2]. During recent years, organic Rankine cycle (ORC) systems have gained maturity, becoming a widely accepted technology to convert low grade heat into electricity [3–5].

Positive displacement expanders have been proven to be cost-effective in the low to medium power range, as outlined by Imran et at. [6] in their comprehensive review. The performance of a volumetric expander is affected by internal losses (typically leakage, friction and heat losses) and the operating condition at which it

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Nomenclature

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)
N	rotational speed (rpm)
p	pressure (Pa)
PP	pinch point temperature difference (K, °C)
$\dot{Q}$	heat rate (W)
r_p	pressure ratio (–)
r_v	specific volume ratio (–)
$r_{V,built-in}$	geometric volume ratio (–)
s	specific entropy (J/kg K)
T	temperature (K, °C)
v	specific volume (m^3/kg)
V	volume (m^3)
$\dot{W}$	power (W)
x	quality (–)
z_{sr}	number of starwheel tooth (–)
φ_{FF}	filling factor (–)
ε	effectiveness (–)
η	efficiency (–)

Subscript

ad	adiabatic
cf	cold fluid
ex	exhaust
exp	expander
el	electric
ev	evaporator
gen	generator
hf	hot fluid
is	isentropic
in	inlet
inv	inverter
meas	measured
net	net
oa	overall
opt	optimum
ORC	organic Rankine cycle
pp	pump
r	refrigerant
sc	subcooling
sh	superheating shaft
sr	screw rotor
su	supply
sw	starwheel
th	theoretical
T66	Therminol66

operates in terms of applied pressure ratio. Because of the fixed internal volume ratio (usually in the range 2–7), also referred as built-in volume ratio, the volumetric expander has to be chosen to match with the system optimal pressure ratio. As a consequence, in most of the cases, the volumetric expanders work in the under-expansion area, i.e. the specific volume ratio applied is higher than the built-in one, because the over-expansion losses are significantly more detrimental and the ORC systems are usually optimized for a higher evaporating pressure depending on the working fluid selected [7]. Mathias et al. [8] introduced an expansion-matching ratio as a necessary, but not sufficient, information to maximize the power output. This aspect was further analyzed by Woodland et al. [9] and it was shown that the optimum expander performance in terms of isentropic efficiency is obtained for an imposed expansion ratio slightly higher than the built-in volume ratio due to suction and discharge pressure drops. Additionally, the peak of isentropic efficiency is found for a filling factor close to unity. Hsu et al. [10] investigated under- and over-expansion losses in an hermetic screw-expander with a built-in volume ratio close to 5. The results showed that in the under-expansion region the power output still increases despite a drop in the isentropic efficiency. A trade-off exists between higher power output and decrease in isentropic efficiency. Among positive displacement expanders, scroll and rotary types are often investigated in the low power output range, i.e. below 10 kW, due to their design limitations [3]. Such machines have typically internal volume ratios below 5 (typically from 1.5 to 3.5) [11,6]. For instance, Chang et al. [4] investigated the performance of an open-drive scroll expander (originally an oil-free scroll air compressor) with an internal built-in volume ratio of 4.05 with R245fa as the working fluid with a maximum power output of 2.3 kW. Piston expanders can potentially be employed for higher power output as they have larger built-in volume ratios (reported up to 14) [12], but their overall efficiency is lower than scroll and screw expanders. Rolling-piston expanders have been proposed for low-temperature ORC in the kilowatt-size power output range. Zheng et al. [13] tested a rolling-piston expander in an ORC system with R245fa and a hot source temperature of 90 °C. The maximum power output achieved was 0.35 kW and the isentropic efficiency was 43.3%. In the medium power output range, i.e. 10–300 kW, screw-type expanders are the most suitable positive displacement devices [14]. Generally, they can be divided into two categories: single-screw expanders and twin-screw expanders. The cost-effectiveness of twin-screw expanders for power production is well known [14]. Single-screw machines are mainly employed in vapor compression systems. Recently, researchers have started to look into single-screw expanders as an alternative to twin-screw expanders. One of the main reason is their balanced loading on the main rotor and wide range of operation [15]. Experimental studies on single-screw expander (SSE) have been proposed by focusing mainly on compressed air type machines. For instance, Wang et al. [16] evaluated the performances of a SSE prototype by using air as working fluid with a design inlet flow rate of 1.1 N m^3/min. The experimental tests were carried out at different intake flow, different humidity, constant torque and constant rotational speed. The results showed a maximum power output of 5 kW at 2850 rpm and maximum adiabatic efficiency of 59%. The low adiabatic efficiency value was justified by the poor lubrication system and the use of dry air. Lu et al. [17] investigated a SSE with 175 mm diameter rotor by sing a compressed air refrigeration system. The SSE was able to reach an adiabatic efficiency above 65% with a temperature drop of 70 °C. He et al. [18] analyzed the influence of the intake pressure on the performance of a SSE with 175 mm diameter rotor. The experimental results showed that high values of intake pressure negatively affect the power output. A resonance phenomenon occurred in the range 2000 rpm and 2200 rpm, leading to large leaking. The maximum power output of 22 kW was obtained at 2800 rpm with and the highest adiabatic efficiency was of around 55%. Wang et al. [19] analyzed the influence of the gap sized between rotor/shell and starwheel/shell with compressed air as working fluid. Medium size gaps, i.e. 0.04 mm and 0.05 mm, provided the best overall performance with a maximum