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New performance maps for selecting suitable small-scale turbine configuration for low-power organic Rankine cycle applications

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A B S T R A C T

This paper aims to deliver new performance maps for small-scale organic Rankine cycle (ORC) turbines (<20 kW) by assessing the impact of single and two stage turbine configurations on the ORC's performance driven by low-temperature (<100 °C) heat source. Small-scale axial, radial-inflow and radial-outflow turbines are designed and compared with their single and two stage configurations with the aim of improving the performance of the ORC's system by increasing its expansion ratio. Therefore, the preliminary mean-line design is coupled with three-dimensional CFD analysis and ORC modelling for all turbines' configurations to deliver the performance maps for low-power applications. Due to the complex and 3D nature of flow across the turbine stage, CFD analysis was used to investigate in more detail five candidates of small-scale turbines, in single and two stage configurations with three working fluids (R141b, R245fa and isopentane). ANSYS®17-CFX was used to perform 3D CFD analysis of all turbine configurations. RANS equations for three-dimensional steady state and viscous flow were solved with a k-ω SST turbulence model. The performance maps in terms of turbine isentropic efficiency and power output for each turbine configuration are presented according to the operating conditions in terms of expansion ratio, working fluid mass flow rate, and rotational speed with turbine size.

The results revealed that the two-stage axial and radial-outflow turbines' configurations exhibited a considerably higher turbine performance, with overall isentropic efficiency of 84.642% and 82.9% and power output of 15.798 kW and 14.331 kW respectively, with R245fa as a working fluid. Also, the results exhibited that the maximum ORC thermal efficiency for both two-stage configurations was 13.96% and 12.80% for axial and radial-outflow turbines respectively working with R245fa. These results indicated the potential advantages of a two-stage turbine configuration in a small-scale ORC system for the conversion of a low-temperature heat source into electricity as a useful power.

1. Introduction

Recently, with increasing concern regarding the climate change and the need for an efficient and sustainable power system has led to a massive surge of interest in organic Rankine cycle (ORC) technologies. Particularly with low power output and low-temperature heat sources (<100 °C), for a small-scale system, further development is still vital to achieve efficient small-scale ORC turbines. Some ORC systems based on small-scale single and two-stage turbines are applicable for various low-power generation applications (<20 kW), such as in domestic and rural areas and remote off-grid communities.

The preliminary mean-line design (PD) model of small-scale turbines (i.e. axial and radial turbines) based on losses model has been considered in many studies in literature. However, the limitation with preliminary mean-line design model of turbine, it is developed for obtaining velocity triangles, turbine dimensions without consideration for flow inside the stator/rotor blade passage, which has effectively influence on providing efficient expansion through the passage.

In terms of 3D CFD analysis for the radial-inflow turbine (RIT), Harinck et al. (2013) achieved it for a Tri-O-Gen RIT with 2D optimization for the stator. It was manufactured and tested for a 5 kW ORC system with toluene as the working fluid. Sauret and Gu (2014) completed a 3D simulation process of a 400 kW ORC RIT with R143a

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Nomenclature

A	area (m^2)
B	constant of tip clearance loss (–)
b	axial chord (m)/tip width (m)
C	absolute velocity (m s^{-1})
c	chord length (m)
C_L	lift coefficient (–)
D, d	diameter (m)
d_s	specific diameter (–)
f	correction/friction coefficient's (–)
h	specific enthalpy (kJ/kg)
H	blade height (m)
l	length (m)
K	losses coefficient (–)
k	specific turbulence kinetic energy (m^2 s^{-2})
$\dot{m}$	mass flow rate (kg s^{-1})
N	number of blade (–)
n_s	specific speed (–)
o	throat (m)
P	pressure (bar)
$\dot{Q}$	heat (kW)
R_n	reaction (–)
r	radius (m)
S	blade space (pitch) (m)
s	entropy (kJ $kg^{-1}.K^{-1}$)
T	temperature (K)
t	time (s)/blade thickness (m)
U	blade velocity (m/s)/mean flow velocity (m s^{-1})
V	velocity (m/s)
W	relative velocity (m s^{-1})
w	specific work (kJ kg^{-1})
$\dot{W}$	power (kW)

Greek symbols

α	absolute flow angle (degree)
β	relative flow angle (degree)
η	efficiency (%)
ε	clearance (m)
ϕ	flow coefficient (–)
ψ	loading coefficient (–)
ω	specific turbulence dissipation rate (m^2 sec^{-3})
Ω	angular velocity (rad s^{-1})
ρ	density (kg m^{-3})
τ	tip clearance (m)
ζ	enthalpy loss coefficient (–)

Subscript/superscript

1–7	station within the turbine and cycle respectively
accel	accelerating
AS	aspect ratio
blds	blade
cr	critical
e	evaporator
ex	exergy
f	friction
H	high
hyd	hydraulic
is	isentropic
L	low
m	mean
nbp	normal boiling point
P	profile
p	pump
R	rotor
Re	Reynolds number
S	stator
Sec	secondary
sec eff	second law efficiency
sh	shock
T	total
T	turbine/tip
th	thermal
TC	tip clearance
TE	trailing edge
ts	total-to-static
tt	total-to-total
x	axial
θ	tangential/circumferential direction
*	uncorrected

Acronyms

1D, 3D	one and three dimensional
AFT	axial flow turbine
BDA	blade geometric discharge angle
CFD	computational fluid dynamics
EES	Engineering Equation Solver
GWP	global warming potential
ODP	ozone depletion potential
ORC	organic Rankine cycle
PD	preliminary mean-line design
RANS	Reynolds-averaged Navier-Stokes
RIT	radial-inflow turbine
ROT	radial-outflow turbine
SST	shear stress transport

as the working fluid at mass flow rate of 17.24 kg/s for geothermal applications. Their results showed the maximum isentropic efficiency of 83.5%. Fiaschi et al. (2016) performed mean-line design and 3D CFD simulation of the rotor of a micro ORC RIT based on R134a as the working fluid at a mass flow rate of 0.25 kg/s. Their results indicated that the maximum variation between the PD and CFD was 11.6% in terms of power output. The CFD results showed that the turbine isentropic efficiency of 71.76% and power of 5.162 kW were achieved. Russell et al. (2016) completed a design and simulation process for a 7 kW ORC RIT. The maximum turbine efficiency was about 76%, with R245fa as the working fluid. Li and Ren (2016) carried out 3D CFD simulation for the RIT with R123 as the working fluid at the mass flow rate of 21.2 kg/s and expansion ratio of 8. The turbine isentropic efficiency, system thermal efficiency and net power were 84.33%, 13.5% and 534 kW respectively. Rahbar et al. (2016) optimized the transonic rotor of a two-stage RIT working with R245fa and an expansion ratio of 10, using the genetic algorithm. The optimization results indicated that the maximum turbine and ORC system's efficiencies were 88% and 14.8% respectively, corresponding to the power output of 26.35 kW at the mass flow rate of 0.8768 kg/s.

For an axial flow turbine (AFT), Moroz et al. (2013) presented the detailed design of a 250 kW AFT for an ORC power unit with R245fa at low-temperatures up to 150 °C. The structural optimization was carried out to reduce the rotor weight to an acceptable stress. The reported turbine efficiency achieved as a result from the turbine