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Development of micro-scale axial and radial turbines for low-temperature heat source driven organic Rankine cycle

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ABSTRACT

Most studies on the organic Rankine cycle (ORC) focused on parametric studies and selection working fluids to maximize the performance of organic Rankine cycle but without attention for turbine design features which are crucial to achieving them. The rotational speed, expansion ratio, mass flow rate and turbine size have markedly effect on turbine performance. For this purpose organic Rankine cycle modeling, mean-line design and three-dimensional computational fluid dynamics analysis were integrated for both micro axial and radial-inflow turbines with five organic fluids (R141b, R1234yf, R245fa, *n*-butane and *n*-pentane) for realistic low-temperature heat source <100 °C like solar and geothermal energy. Three-dimensional simulation is performed using ANSYS^{R17}-CFX where three-dimensional Reynolds-averaged Navier-Stokes equations are solved with k-omega shear stress transport turbulence model. Both configurations of turbines are designed at wide range of mass flow rate (0.1–0.5) kg/s for each working fluid. The results showed that *n*-pentane has the highest performance at all design conditions where the maximum total-to-total efficiency and power output of radial-inflow turbine are 83.85% and 8.893 kW respectively. The performance of the axial turbine was 83.48% total-to-total efficiency and 8.507 kW power output. The maximum overall size of axial turbine was 64.685 mm compared with 70.97 mm for radial-inflow turbine. R245fa has the lowest overall size for all cases. The organic Rankine cycle thermal efficiency was about 10.60% with radial-inflow turbine and 10.14% with axial turbine. Such results are better than other studies in the literature and highlight the potential of the integrated approach for accurate prediction of the organic Rankine cycle performance based on micro-scale axial and radial-inflow turbines.

1. Introduction

The energy production from the low-temperature heat source (i.e. solar energy and geothermal energy) is attracting much attention. The low-temperature heat resources cannot be economically transformed into electricity by using steam Rankine cycle which requires a high-temperature heat source. Therefore, organic Rankine cycle (ORC) has acquired much interest and becoming one of the best efficient technologies which can use the low-grade temperature heat sources for small size power generation applications. The ORC name is stemmed from the utilization of organic fluids that boils at low-temperature heat source and has high molecular mass. The micro ORC system based on axial and radial-inflow turbines is a realistic alternative and promising solution for delivering energy demands instead of conventional and pollutant power generation system. There are many applications where micro ORC systems can be used for generating electricity such as domestic, remote/rural areas, isolated installations and other applications where micro distributed (on site) power generation systems are required. The design of the turbine in micro ORC systems is essential to ensure effective cycle operation.

Many researches carried out regarding the selection of the appropriate working fluids and ORC thermodynamic cycle analysis for low-temperature heat sources such as solar and geothermal energy as reported in [1–17]. Delgado-Torres et al. [1] assessed the energy needed from solar energy to drive ORC s and reverse osmosis desalination. The results showed that the minimum area of the solar collector was of 10–11 m^2/kW based on evacuated tube collector with solar irradiance of 1000 W/m^2. Jing et al. [2] proposed design and optimization of ORC system driven by solar energy based on compound parabolic concentrator with R123 as a working fluid and evaporation temperature of 120 °C. The

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Nomenclature

B	constant of tip clearance loss (–)
b	axial chord (m)
C	absolute velocity (m/s)
c	chord length (m)
C_L	lift coefficient (–)
d	diameter (m)
d_s	specific diameter (m)
f	correction/friction coefficient's (–)
h	specific enthalpy (kJ/kg)/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)
o	throat (m)
p	pressure (bar)
$\dot{Q}$	heat (kW)
R_n	reaction (–)
S	blade space (pitch) (m)
s	entropy (kJ/kg K)
T	temperature (K)
t	time (s)/Blade thickness (m)
U	blade velocity (m/s)
u	mean flow velocity (m/s)
W	relative velocity (m/s)
w	specific work (kJ/kg)
$\dot{W}$	power (kW)
Z	number of blade (–)

Greek symbols

α	absolute flow angle (degree)
β	relative flow angle (degree)
η	efficiency (%)
ε	clearance (m)
ϕ	flow coefficient (–)
ψ	loading coefficient (–)
τ	tip clearance (m)
ω	specific turbulence dissipation rate (m^2/s^3)
ζ	enthalpy loss coefficient (–)

Subscript/superscript

1–6	station within the turbine and cycle respectively
accel	accelerating
AS	aspect ratio
b	blade
c	condenser
cr	critical
e	evaporator
ex	exergy
H	height
hyd	hydraulic
L	low
nbp	normal boiling point
P	profile
p	pump
r	radial
Re	Reynolds number
Rec	recuperator
S	secondary
sec	secondary
sh	shock
t	turbine
T	total
TC	tip clearance
TE	trailing edge
th	thermal
ts	total-to-static
tt	total-to-total
x	axial
*	uncorrected
θ	tangential/circumferential direction

Acronyms

1D, 3D	one and three dimensional
CFD	computational fluid dynamics
EOS	equation of state
GWP	global warming potential
ODP	ozone depletion potential
ORC	organic Rankine cycle
PD	preliminary mean-line design
RANS	Reynolds-Averaged Navier-Stockes
RIT	radial-inflow turbine
SST	shear stress transport

maximum system thermal efficiency was 0.08% with irradiance of 800 W/m^2. Pei et al. [3] designed a regenerative solar ORC for power generation application based on small concentration ration of compound parabolic concentrator. The R123 was used as working fluid with irradiance of 750 W/m^2. The system thermal efficiency was 8.6% which was higher than simple ORC cycle by 4.9%. Wang et al. [4] proposed and designed a low-temperature solar ORC system working by R245fa based on rolling piston expander. Both flat plate and evacuated solar collectors were used in the system. The average power output was 1.73 kW with average turbine isentropic efficiency of 45.2%. Guo et al. [5] investigated low-temperature geothermal ORC based on cogeneration system with eight organic fluids. The organic fluids were chosen based on provided power output. Shengjun et al. [6] performed optimization of the subcritical geothermal ORC working in low-temperature ranged between 80 and 100 °C and R123. The maximum thermal efficiency was 11.1%. Wang et al. [7] performed experimental study to investigate the recuperative ORCs performance based on low-temperature heat source and working with R245fa. The cycle thermal efficiency was improved by improving the expander performance. Wang et al. [8] conducted analysis of regenerative solar ORC based on the flat-plate solar collector and four organic working fluids. The daily average system efficiency was 8.0% depending on R123 and R245fa. Fiaschi et al. [9] proposed and analyzed geothermal ORC combined with heat and power system. A wide range of mass flow rates and temperatures (3–13 kg/s; 80–140 °C) with five organic fluids were investigated. The genetic algorithm was employed in optimization procedure. The optimum organic fluid and operating condition was changed with the heat source level. Wang et al. [10] established evaluation of solar ORC in off-design conditions based on compound parabolic collector with R245fa as a working fluid. The results showed that the average power output reached a maximum values in June or in September. Wang et al. [11] offered thermodynamic analysis for binary geothermal ORC system. The comprehensive scoring method to evaluate the economic and thermodynamic performance based on comprehensive index was employed. The maximum thermal efficiency was 10.75% with working fluid R245fa at evaporating temperature of 84 °C. Zhou [12] carried out thermodynamic analysis of ORC system based on hybridization of solar and geothermal