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Modelling and optimization of organic Rankine cycle based on a small-scale radial inflow turbine

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A B S T R A C T

In most of the organic Rankine cycle (ORC) studies, constant expander efficiency is considered for a wide range of cycle operating conditions and for various working fluids. This study presents an optimized modelling approach for the ORC based on radial inflow turbine, where the constant expander efficiency is replaced by dynamic efficiency that is unique for each set of cycle operating conditions and working fluid properties. Considering the size and performance of the ORC, the model was used to identify the key input variables that have significant effects on the turbine overall size and the cycle net electric power output. These parameters were then included in the optimization process using the DIRECT algorithm to maximize the ratio of cycle net electric power output to the turbine overall size (objective function) for six organic fluids. Results showed that, dynamic efficiency approach predicted considerable differences in the turbine efficiencies of various working fluids. The maximum difference of 6.13% between the turbine efficiencies of R245fa and isobutane was predicted. Also the optimization results showed that, the maximum objective function of 0.5748 kW/mm was achieved by isobutane with the cycle net electric power output and the turbine overall size of 90.3 kW and 157.2 mm respectively. Such results are better than the other studies and highlight the potential of the optimization technique to further improve the performance and reduce the size of the ORC based on small-scale radial turbines.

1. Introduction

In recent years, harnessing the renewable energies and waste heat recovery received growing attention in order to reduce the consumption of fossil fuels and diminish the environmental pollutions. organic Rankine cycle (ORC) is a reliable technology for conversion of these low-grade heat sources into electricity. The ORC employs organic fluids (such as hydrocarbons or refrigerants) instead of water as the working fluid and exhibits unique advantages. Utilization of higher density fluids results in smaller plant size compared to the conventional Rankine cycle. Employing dry working fluids leads to vapour phase after expansion and eliminates the issues regarding to the impingement of liquid droplets to the elements in the flow path and reduces the capital and maintenance costs. Lower pressure and temperature levels of the ORC alleviate the safety concerns and reduce the system complexities. Moreover, cost of the ORC is cheaper than other technologies such as thermoelectric generator when it is used in low temperature applications [1]. Several studies were carried out investigating the ORC by focusing on the selection of appropriate working fluid, thermodynamic analyses and optimization of the cycle. Saleh et al. [2] reviewed thirty-one pure working fluids and compared their thermal efficiencies and thermodynamic properties for both sub-critical and supercritical ORCs. Tchanche et al. [3] investigated the suitable fluids for low-temperature solar ORC by studying properties of twenty organic fluids in terms of thermal efficiency, toxicity and flammability. Their study showed that R134a has the most favourable characteristics. Liu et al. [4] performed the analysis of the ORC subjected to the influence of ten working fluids on the thermal efficiency and total heat recovery. Hung [5] obtained the distribution of irreversibility in different component of ORC for five different working fluids and showed that R113 and R123 have better performance. Wei et al. [6] performed the analysis and optimization of the ORC with R245fa for waste heat recovery. They showed that the utilization of exhaust heat should be maximized and the degree of sub-cooling at the condenser should be kept as small as 0.6 K. Tempesti et al. [7], Liu et al. [8] and Liu et al. [9] carried out the thermodynamic modelling study of combined solar and geothermal ORC, two stage ORC and micro biomass-fired CHP respectively. Hettiarachchi et al. [10] and Wang et al. [11] considered the ratio of heat exchanger area to the net power output as a cost effective criteria in optimizing the ORC and showed that R123 and isobutane have the best performance respectively. Rashidi et al. [12] and Dai et al. [13] employed

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Nomenclature

Symbols

A	area (m^2)
b	blade width (m)
BK	blockage factor (–)
C	absolute velocity (m/s)
d	diameter (m)
ER	expansion ratio (–)
f	friction factor (–)
h	enthalpy (J/kg)
Δh_{actual}	actual specific enthalpy drop (J/kg)
i	incidence angle (deg)
k	loss coefficient (–)
l	length (m)
$\dot{m}$	mass flow rate (kg/s)
Ma	mach number (–)
N_s	specific speed (–)
P	pressure (Pa)
Q	heat transfer rate (W)
r	radius (m)
R	reaction (–)
Re	reynolds number (–)
RR	relative roughness (m)
S	entropy (J/kg K)
SC	swirl coefficient (–)
T	temperature (K)
U	rotor blade velocity (m/s)
W	power (W); relative velocity (m/s)
x	quality (–)
Z	blade number (–)

Greek letters

α	absolute flow angle with respect to meridional (degree)
β	relative flow angle with respect to meridional (degree)
γ	ratio of cycle net power output to the turbine overall size (W/m)
ε	clearance (m)
η	efficiency (–)
υ	velocity ratio (–)
ρ	density (kg/m^3)
σ	solidity (–)
φ	flow coefficient (–)
ψ	loading coefficient (–)
ω	rotational velocity (RPM)

Subscripts

1–7	stations within the cycle
eva	evaporator
hyd	hydraulic
m	meridional direction
r	radial
rel	relative
s	isentropic
x	axial
Stage	turbine inlet to turbine outlet
t	total, stagnation
ts	total to static
θ	tangential/circumferential direction

Acronyms

EOS	equation of state
ORC	organic Rankine cycle

the artificial neural network and genetic algorithm to optimize the exergy efficiency of the ORC. Drescher and Bruggemann [14] adopted a new plant design by avoiding the pinch point at the start of vaporization based on the constraints of the biomass ORC. Walraven et al. [15,16] performed the optimization of the ORC based on two different types of heat exchangers to find the optimum heat transfer surface area and pressure drop. Results showed that, ORCs with the plate type heat exchangers have higher efficiencies compared to the ORCs with shell and tube. Imran et al. [17], Wang et al. [18] and Wang et al. [19] conducted the multi-objective optimization of the ORC based on genetic algorithm considering the cycle thermal efficiency, specific investment cost, exergy efficiency and overall capital cost as the objective functions. Despite the numerous published literature [1–19] studying the selection of working fluid, thermodynamic modelling and optimization of the ORC, there has been relatively little published work on the modelling of ORC expanders. Expanders are the key components of the ORC and have significant effects on the overall cycle's cost, size and performance.

Saitoh et al. [20] carried out the experimental study of a solar ORC using scroll expander and obtained the cycle thermal and expander efficiencies of 11% and 65% respectively. Twomey et al. [21] performed the modelling of scroll expander for a small-scale solar ORC in which the model parameters were calibrated experimentally. The results showed the maximum cycle and expander efficiencies of 3.47% and 59% respectively. Clemente et al. [22] conducted the modelling of the ORC for heat recovery of a small-scale gas turbine with six organic fluids. They assessed the performance of various expanders including axial and radial turbines, scroll and reciprocating expanders. Sauret and Rowlands [23] modelled the ORC based on radial turbine for a geothermal power system using five organic fluids. Maximum radial turbine efficiency of 78.5% was achieved with R143a at evaporating temperature of 140 °C. Rahbar et al. [24] proposed a methodology for the preliminary and detailed design of radial turbines for low power capacity systems such as the ORC using mean-line modelling and CFD analysis. Fiaschi et al. [25] built a model for the preliminary design of radial-turbo expanders for the ORC and compared the performance of six different organic fluids for an output power of 50 kWe.

Almost all of the theoretical studies [1–19,22,23,26] considered a constant expander efficiency for a wide range of operating conditions and for various working fluids. However, this does not necessarily yield accurate results (as will be shown in this study) where each fluid may exhibit different performance under different operating conditions. This study presents an integrated approach that combines the mean-line modelling of radial turbine with the ORC model and replaces the constant turbine efficiency with a dynamic efficiency. Such value is unique for each set of cycle conditions, working fluid properties and turbine parameters. Comprehensive parametric studies are conducted using the developed model to investigate the effects of input variables on the turbine overall size and the cycle net electric power output. Based on the results, the input variables that have the greatest effect on the turbine overall size and the cycle net electric power output are included in the optimization process. The DIRECT optimization technique is then employed to maximize the ratio of cycle net electric power output