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Thermodynamic modelling and analysis of a solar organic Rankine cycle employing thermofluids

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ABSTRACT

This paper presents thermodynamic modelling and simulation study of a small scale saturated solar organic Rankine cycle (ORC) which consists of a stationary, flat plate solar energy collector that is utilised as a vapour generator, a vane expander, a water-cooled condenser and a pump. Simulations are conducted under constant condensing temperature/pressure and various cycle pressure ratios (PR) for 24 organic thermofluids including Hydrocarbons (HCs), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Hydrofluoroethers (HFEs) and Hydrofluoroolefins (HFOs). Special attention is given to the influence of PR and fluids' physical properties on the solar ORC performance as well as fluids' environmental and safety impacts including global warming potential (GWP), flammability and toxicity. The simulation results indicate that when the same fluid is considered, pressure ratio of the cycle leads to various operating conditions such as collector (evaporating) pressure which results in various collector, expander and cycle efficiency. For instance, increasing the pressure ratio of the cycle enhances the net work output and the thermal efficiency of the cycle, whereas it decreases the flat plate collector efficiency. The results also indicate that the proposed system produces the maximum net work output of 210.45 W with a thermal efficiency of 9.64% by using 1-butene. Furthermore, *trans*-2-butene, *cis*-2-butene, R600, R600a, R601, R601a and neopentane (HC), R227ea and R236fa (HFC), RC318 (PFC) and R1234ze (HFO) show promising solar ORC thermal performances. However, the flammability problem of HCs and global warming potential issue of HFCs and PFCs limit their applications, owing to the safety and environmental concerns.

On the other hand, in terms of the environmental impact, thermofluids such as RE347mcc, RE245fa2 (HFEs) and R1234ze, R1233zd (HFOs) offer an attractive alternative, yet they were neither the most efficient, nor generated the highest amount of net work output. This paper provides thermofluids' selection guidelines to achieve maximum efficiency within solar thermal energy technologies while keeping environmental impacts into considerations.

1. Introduction

The World has been facing numerous environmental problems such as air pollution, ozone layer depletion, acid rain and global warming, mainly due to increasing consumption of fossil fuels [1]. Extracting fossil fuels in the future will become gradually challenging. Increasing demands of energy from non-renewable sources remain unsustainable. Therefore utilising renewable energy sources as an alternative has been of great importance for domestic heating and electricity generation [2,3].

Renewable energy sources such as solar thermal, geothermal, biomass and waste heat can be categorised as low-grade temperature energy sources and they have potential in reducing consumption of fossil fuels [4,5]. However, conventional Rankine cycle is not an economical and efficient alternative for the conversion of heat from renewable energy sources [4]. A conventional Rankine cycle employing organic compounds rather than water is called as organic Rankine cycle (ORC) and it is the most accepted technology for converting low-grade heat energy source into mechanical work [6].

A considerable amount of research has been conducted on the installation of solar ORCs where non-stationary flat plate collectors are used as a heat source of the cycle. Experimental study on the performance of such systems with a selected pure fluid including various types of organic compounds such as HFCs (R134a, R245fa), HFEs (HFE 7000) and inorganic compounds (CO_2) has been conducted. Manolakos et al. conducted an experimental study on a low-grade solar ORC using pure R-134a as the working fluid.

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Nomenclature

A	area, m^2
Bo	boiling number
C	constant
C_b	bond conductance
C_p	specific heat, J/kg K
Co	convection number
d	radius of the stator to the centre of the rotor
D	diameter, m
e	eccentricity, m
f	friction factor
F	fin efficiency
F'	collector efficiency factor
F_R	heat removal factor
Fr	Froude number
G	mass flux, kg/m^2 s
h_{sp}	single phase heat transfer coefficient, W/m^2 K
h_{tp}	two phase heat transfer coefficient, W/m^2 K
$h_{nc,B}$	nucleate boiling factor
$h_{c,B}$	convective boiling factor
h	enthalpy, J/kg
h_{fg}	heat of vaporisation, J/kg
k	thermal conductivity, W/m K
k_{ratio}	heat capacity ratio
$\dot{m}$	mass flow rate, kg/s
M	molecular weight, g/mol
N	dimensionless parameter
n	number of vanes
Nu	Nusselt number
ORC	organic Rankine cycle
P	Pressure, bar
PR	pressure ratio
Pr	Prandtl number
r	radius, m
$r_{v,built\text{-}in}$	built-in ratio of the expander
Re	Reynolds number
S	solar radiation, W/m^2
T	temperature, °C
U	heat loss coefficient, W/m^2 K
$\dot{Q}$	heat, W
v	velocity, m/s
V	volume, m^3
W	tube spacing
$\dot{W}$	work, kW
x	vapour quality

Subscripts

a	ambient
col	collector
$cond$	condensation
$crit$	critical
cw	cooling water
cyc	cycle
dsg	designed
$evap$	evaporation
exh	exhaust
exp	expander
f	fluid
g	vapour
i	inner
in	inlet, incoming
int	intake
is	isentropic
l	liquid
lat	latent
max	maximum
mec	mechanical
nbp	normal boiling point
o	outer
out	outlet
ov	over
p	plate
pp	pinch point
rot	rotor
s	isentropic
snb	sensible
sp	single phase
$stat$	stator
t	top
tp	two phase
T	total
u	useful
ud	under
wf	working fluid

Greek symbols

υ	kinematic viscosity, m^2/s
ν	specific volume, m^3/kg
ϕ	heat flux, W/m^2
ρ	density, kg/m^3
Υ	angle between the vanes, deg
θ	angle of a specific vane from the origin

The generated mechanical work is utilised for reverse osmosis (RO) desalination [7–9]. Wang et al. designed and constructed a solar sourced ORC, where R245fa is used as the working fluid of the system. They reported that 1.64 kW average shaft output was obtained from the new designed R245fa expander [10]. Another experimental study of a small scale solar ORC using R245fa is established by [11]. The effect of a recuperator for the constant flow rate condition was analysed in their study, and it was concluded that the recuperator does not lead to an increase in the thermal efficiency of the system [11]. Yamaguchi et al. conducted an experimental study on supercritical solar ORCs, using CO_2 [12]. Another solar ORC, utilising inorganic fluid (CO_2) was also investigated in Ref. [13]. In both studies it is concluded that CO_2 offers a feasible alternative to be used in solar thermal power applications.

On the other hand, selection of the most suitable working fluid for solar ORCs and optimisation of the system for various operating conditions, including both simulation and experimental studies has attracted many researchers. Rayegan [14] compared 117 organic fluids on the basis of their effects on thermal efficiency, net power output and exergetic efficiency of the solar ORC. They claimed that fluids with higher critical temperature were considered to be the best [14]. Torres [15] presented a theoretical study of solar ORC where solar collector is used as thermal energy source of the cycle. In their analysis, they considered four different models of stationary solar collectors with twelve substances, including organic (HCs and HFCs) and inorganic (ammonia) fluids. Aperture area needed per unit of mechanical power output was set as a comparison criteria and it was generalised that dry fluids need lower