Solar Energy 166 (2018) 351–370

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Monthly assessments of exergetic, economic and environmental criteria and optimization of a solar micro-CCHP based on DORC

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ARTICLE INFO

Keywords:
Dual loop ORC
Exergoeconomic
Exergoenvironment
Optimization

ABSTRACT

This research performs an analytical simulation of a novel solar-driven combined cooling, heating and power (CCHP) system based on a dual organic Rankine cycle (DORC) using heat transport fluids of water and Copper (II) oxide (CuO)/water nanofluid. The major design parameters are encompassed to evaluate the monthly thermodynamic efficiencies, total product cost and environmental impact (EI) rates of the system for four selected organic fluid groups, namely R134a-R245fa, R1234yf-R245fa, R1234ze-R236fa and R423A-R236fa. According to results, a considerable positive influence is observed in the energy and exergy efficiencies within 16.71% and 24.34%, respectively for R1234yf-R245fa in November. The lowest EI rate is achieved by 1.2% for R1234ze-R236fa in April as turbine 1 inlet pressure increases and the highest decrement in EI rate is calculated within 2.48% for R1234yf-R245fa in September with an increase in turbine 2 back pressure. In addition, two well-known decision making techniques comprising LINAMP and TOPSIS are applied to identify the ultimate optimal performance of the system among the solutions gained from the non-dominated sorting genetic algorithm (NSGA-II) approach. Referring to the optimization results, the maximum improvement in the exergy efficiency and product cost can be obtained within 33.49% through the LINMAP method and 23.67% through the TOPSIS procedure, respectively and the highest improvement in the EI rate is calculated by about 22.7% with 0.01788 nanoparticle volume fraction for R134a-R245fa through the LINMAP method.

1. Introduction

Global warming and depletion of fossil fuels are two major concerns for providing energy. More efficient energy systems and intensive utilization of renewable energy sources are required for the sustainability of energy systems in the future. Combined cooling, heating and power (CCHP) system is one of the most promising technologies producing multi-demand of energy for a customer, simultaneously. This ability of CCHP systems causes higher efficiency, lower fuel consumption and consequently lower emission of pollutants. In addition, incorporating the solar energy technologies to the CCHP system is an effective solution to mitigate the pollutant emissions to the environment.

Flat plate solar collectors are the assuring energy adaptation technologies in the ground of low rank heat employment. The thermal efficiency of flat plat solar collectors are considerably low due to the low convective heat transfer coefficient between the absorber and the heat transfer medium and more heat losses to the environments. One of the effective methods to increase the thermal performance is to replace the working fluid with nanofluids. Several investigations have been carried out on the effects of applying nanoparticles, i.e. Alumina (Al_2O_3), Zinc oxide (ZnO), Silicon dioxide (SiO_2), Titanium oxide (TiO_2) and Copper (II) oxide (CuO) on the thermal efficiency, heat transfer coefficient, size reduction of the flat plat collector and its associated energy and cost saving (Alim et al., 2013; Faizal et al., 2013; Yousefi et al., 2012).

On the other hand, ORC is the beneficial subsystem that can be used in CCHPs for mechanical power production and, subsequently, electrical power production through an electrical generator. ORC is usually used when a low- or medium-temperature energy source is available (Al-Sulaiman et al., 2012). Providing cooling effect in CCHPs can be done by utilizing an absorption refrigeration cycle (Moradi and Mehrpooya, 2017; Wang et al., 2016; Wang and Yang, 2016) or an ejector refrigeration cycle (Boyaghchi and Heidarnejad, 2015; Ebrahimi and Keshavarz, 2015). The ejector refrigeration cycles are more effective systems because the ejector with the simple configuration recovers the expansion process losses and lessens the compression power (Disawas and Wongwises, 2004; Harrell and Kornhauser, 1995; Kornhauser, 1990; Sarkar, 2012; Wongwises and Disawas, 2005).

Various single loop ORC-CCHP configurations fueled by solar energy have been proposed and modeled using the energy and exergy concepts.

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https://doi.org/10.1016/j.solener.2018.03.069
Received 30 November 2017; Received in revised form 2 March 2018; Accepted 25 March 2018

Nomenclature

A	area (m^2)
b	environmental impact per unit of exergy (Pts/kJ)
$\dot{B}$	environmental impact associated with an exergy stream rate (Pts/s)
c	cost per unit of exergy ($/kJ)
$\dot{C}$	cost rate ($/s)
C_P	specific heat (kJ/kg K)
Cl	clearness index
CRF	capital recovery factor
di	deviation index
d_m^+	distance of each criterion from the ideal point
d_m^-	distance of each criterion from the non-ideal point
EI	environmental impact
ex	specific exergy (kJ/kg)
$\dot{Ex}$	total exergy flow rate (kW)
F	criterion
F'	collector efficiency factor
F_R	heat removal factor
G_t	total radiation rate falling on the titled collector (W/m^2)
G_b	beam irradiation rate falling on the tilted collector (W/m^2)
G_d	diffuse irradiation rate falling on the tilted collector (W/m^2)
H	terrestrial average monthly irradiation on a horizontal surface, (kWh/m^2 day)
h	specific enthalpy (kJ/kg)
hr	annual number of operation hour (h)
h_w	wind convection heat loss coefficient (W/m^2)
i	interest rate (%)
k	thermal conductivity (W/m K)
L	collector length (m)
N	system lifetime (year)
M	mass of equipment (kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
$\dot{Q}$	heat transfer rate (kW)
R_b	beam radiation tilt factor
S	absorbed solar radiation (W/m^2)
SH	shape factor
T	temperature (K)
t	time (s)
U	overall heat transfer coefficient ($W/K\,m^2$)
V	velocity (m/s)
$\dot{W}$	power (kW)
Y	component-related EI (Pts)
$\dot{Y}$	component-related EI rate (Pts/s)
$\dot{Z}$	capital investment cost rate ($/s)

Greek letters

$(\tau\alpha)$	fraction of absorbed radiation
ε	emissivity
σ	Stefan–Boltzman constant, 5.6697×10^{-8} $W/m^2\,K^4$
ϕ	solar zenith angle (°)
θ	incident angle (°)
τ	transitivity
β	collector tilt angle (°)
ρ	density ($kg/\,m^3$)
ρ_G	ground albedo
ω	life cycle inventory associated with the production (mPts/kg)
Φ	maintenance factor
η	efficiency (%)
φ	nanoparticles volume fraction
δ	thickness (m)

Subscripts

0	dead state
a	air
back	back
bf	base fluid
C	collector
Con	condenser
cooling	cooling load
D	destruction
e	exiting stream
edge	edge
Ejc	ejector
Eva	evaporator
ex	exergy
F	fuel
glass	glass cover
HE	heat exchanger
heating	heating load
i	entering stream
ins	insulation
k	kth component
L	loss
m	mth solution existing on the Pareto frontier
n	nth criterion
net	net
nf	nanofluid
np	nanoparticle
P	product
pump	pump
plate	absorber plate
q	number of points on Pareto frontier
r	number of criteria
ST	storage tank
sun	sun
th	energy
top	top
Tur	turbine
u	useful

Superscripts

.	rate
tot	total
En	Euclidian non-dimensionlization procedure

For instance, Al-Sulaiman et al. (2011) developed a new solar CCHP based on the single loop ORC and the single-effect absorption chiller to produce the cooling effect. The proposed system was examined using three modes of operation. They were: solar mode during the low-solar radiation time of the day, solar and storage mode during the high solar radiation time of the day, and storage mode during night time. The exergy efficiencies and exergy destruction rates were examined under the variation of the ORC evaporator pinch point temperature, ORC pump inlet temperature, and turbine inlet pressure. Wang et al. (2015) used the energy analysis to study and optimize a new ORC-CCHP system equipped with the flat plat solar collector which operated in three modes, namely power mode, combined heat and power mode,