Engineering Science and Technology, an International Journal xxx (2018) xxx–xxx

HOSTED BY

ELSEVIER

Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

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

Full Length Article

Performance analysis of solar parabolic trough collectors driven combined supercritical CO_2 and organic Rankine cycle

Harwinder Singh *, R.S. Mishra

Department of Mechanical, Production & Industrial, Automobile Engineering, Delhi Technological University, Shahbad Daulatpur, Bawana Road, New Delhi 110042, India

ARTICLE INFO

Article history:
Received 15 November 2017
Revised 10 March 2018
Accepted 26 March 2018
Available online xxxx

Keywords:
Supercritical CO_2cycle
Organic Rankine cycle
Exergetic performance
SPTCs
Organic fluids

ABSTRACT

In this paper, attempts have been made on the detailed energy and exergy analysis of solar parabolic trough collectors (SPTCs) driven combined power plant. The combination of supercritical CO_2 (SCO_2) cycle and organic Rankine cycle (ORC) integrated with SPTCs has been used to produce power, in which SCO_2 cycle and ORC are arranged as a topping and bottoming cycle. Five organic working fluids like R134a, R1234yf, R407c, R1234ze, and R245fa were selected for a low temperature bottoming ORC. Five key exergetic parameters such as exergetic efficiency, exergy destruction rate, fuel depletion ratio, irreversibility ratio, and improvement potential were also examined. It was revealed that exergetic and thermal efficiency of all the combined cycles enhances as the direct normal irradiance increases from 0.5 kW/m^2 to 0.95 kW/m^2. As can be seen, R407c combined cycle has the maximum exergetic as well as thermal efficiency which is around 78.07% at 0.95 kW/m^2 and 43.49% at 0.95 kW/m^2, respectively. Alternatively, the R134a and R245fa combined cycle yields less promising results with the marginal difference in their performance. As inferred from the study that SCO_2 turbine and evaporator has a certain amount of exergy destruction which is around 9.72% and 8.54% of the inlet exergy, and almost 38.10% of the total exergy estruction in case of R407c combined cycle. Moreover, the maximum mount of exergy destructed by the solar collector field which is more than 25% of the solar inlet exergy and around 54% of the total destructed exergy. Finally, this study concludes that R407c combined cycle has a minimum fuel depletion ratio of 0.2583 for a solar collector and possess the highest power output of 3740 kW.

1. Introduction

Supercritical CO_2 cycle can effectively use different heat sources including coal power, solar thermal power, waste heat from the high temperature fuel cell, geothermal energy and natural gas [1]. The utilization of solar energy has become pivotal and it should be enhanced significantly in the near future. So it becomes imperative to upgrade the performance of solar thermal power plants. Moreover, among all the other options, solar parabolic trough collector (SPTC) technology considered as the most instituted solar thermal power technology for electricity production. Hence, for the purpose of exergy analysis, SPTC system considered as the efficient heat source. Nowadays, SCO_2 cycle and organic Rankine cycle integrated with various renewable heat sources are considered for the purpose of power generation, e.g. [2–8]. Cheng Zhou [2] compared the performance of hybrid solar and geothermal energy in a supercritical ORC with the different subcritical hybrid plants, standalone solar as well as geothermal plant. Finally, he concluded that the performance of hybrid plant using a supercritical ORC exceeds by producing 4–17% more electricity than the hybrid plant using a subcritical ORC by utilizing the same energy resources. Jing Li et al. [3] assessed the performance by using 17 dry and isentropic working fluids in a novel solar ORC system with the direct vapor generation (DVG). They found that with the rise in critical temperature of fluid, the collector efficiency reduces continuously and efficiency of a combined ORC and DVG system enhances. They further examined that R123 exhibits the highest overall performance among all other working fluids. Al-Sulaiman [4] conducted an exergy analysis of combined steam and ORC power system integrated by SPTC and he found that R134a shows the highest exergy efficiency of 26% which has the maximum amongst other refrigerants followed by R152a. Niu et al. [5] carried out a optimal arrangement of the solar collectors with a supercritical CO_2 based solar Rankine cycle system along with three different modes of collector arrangement, i.e. five units only in series, parallel and cascade with each five units in series. Lastly, their results found that the solar collectors in a cascade arrangement produce large amount of electric power. Cardemil et al. [6] carried out a thermodynamic study

* Corresponding author.
E-mail address: harrymehrok14@gmail.com (H. Singh).
Peer review under responsibility of Karabuk University.

https://doi.org/10.1016/j.jestch.2018.03.015
2215-0986/© 2018 Karabuk University. Publishing services by Elsevier B.V.

Nomenclature

A_A	aperture area, m^2
A_a	area of the absorber tube, m^2
A_{co}	area of the absorber cover, m^2
Cp	specific heat, [kJ/kg-K]
Col_s	total no. of solar collector per single row in series
Col_p	total no. of solar collector in parallel rows
$D_{co,o}$	outside diameter of cover, m
D	diameter, m
Ex	exergy, kW
Ex_{inl}	inlet exergy, kW
$\dot{E}x_d$	rate of exergy destruction, kW
F	collector efficiency factor
F_R	collector heat removal factor
G_b	direct normal irradiance, W/m^2
h	specific enthalpy, kJ/kg
$h_{coa,i}$	heat loss coefficient between absorber and glass cover, [kW/m^2 K]
$h_{c,amco}$	convection heat loss coefficient between ambient and cover, [kW/m^2 K]
$h_{r,amco}$	radiation heat loss coefficient between ambient and cover, [kW/m^2 K]
$h_{r,coa}$	radiation heat loss coefficient between absorber and glass cover, [kW/m^2 K]
HX	heat exchanger
IMP	improvement potential
K_{air}	thermal conductivity of air, [W/m-K]
K_m	incident angle modifier
L	collector length, m
$\dot{m}_a$	mass flow rate through the absorber tube, kg/s
Nu	Nusselt number
ORC	organic Rankine cycle
$\dot{Q}$	heat rate, kW
Q_{inl}	total inlet heat, kJ
$\dot{Q}_u$	useful heat gain per unit time, kW
s	specific entropy, [kJ/kg-K]
S	absorbed heat flux by absorber tube, W/m^2
SCO_2	supercritical CO_2
tCO_2	transcritical CO_2
T	temperature, K
T_{su}	temperature of sun, K
U_L	overall heat loss coefficient of solar collector between ambient and absorber, [kW/m^2 K]
U_o	overall heat loss coefficient, [kW/m^2K]
$\dot{V}$	volume flow rate, m^3/s
W	width of collector, m
w	specific work output, kJ/kg
Y_{DEP}	fuel depletion ratio
Y^*	irreversibility ratio

Greek letters

ρ_r	mirror's reflectance
α	absorbance of absorber tube
γ	intercept factor
τ	glass cover's transmittance
η	efficiency
ε_{co}	emittance of the cover
ε_a	emittance of the absorber
σ	Stefan–Boltzmann constant, [kW/m^2 K^4]
φ	expansion ratio

Subscripts

a	absorber
a_o	absorber outlet
a_i	absorber inlet
am	ambient
avg	average
f	organic working fluid
co	cover
e	exit
ex	exergy per unit mass flow rate, kJ/kg
elec	electrical
i	inlet
ins	instantaneous
o	outside
0	environmental conditions
Q	property value at state Q
u	useful

of CO_2 based power cycles (i.e. Rankine or Brayton) with four different working fluids such as ethane, toluene, D4siloxane and water for the purpose of relative performance assessment. Ultimately, this study reveals that the first law efficiency of power cycle based on CO_2 could be lower than other fluids, while the exergetic efficiency of CO_2 could be crucially higher than competing fluids. Garga et al. [7] conducted a comparative study between trans-critical condensing CO_2 cycle (i.e. high temperature and pressure) and trans-critical steam cycle. They found that temperature variations did not affect the performance of trans-critical CO_2 cycle and it requires only single heat transfer fluid (HTF) loop as compared to trans-critical steam cycle coupled with two HTF loops in series. Osorio et al. [8] carried out a study to analyze the dynamic behavior of SCO_2 power cycle integrated with a concentrated solar power system (i.e. central receiver), hot and cold energy storage, heat exchange device, recuperator and multi-stage compression-expansion subsystem along with the intercooler and reheater as an integral component employed between the compressor and turbine. Their results showed that the process efficiency and maximum power output is 21% and 1.6 MW respectively. At last, they concluded that the SCO_2 cycle's operating time after optimization was increased from 220 to 480 min because of thermal storage application.

Further, few researchers considered the integrated SPTC with ORC for various applications like waste heat recovery and cogeneration process. Nafey and Sharaf [9] conducted a analysis related to exergy energy and cost evaluation of the ORC using parabolic trough collector as a heat source for generating mechanical power to drive desalination system by using reverse osmosis (RO). Delgado-Torres and García-Rodríguez [10,11,12] performed a detailed thermal analysis of ORC coupled with the parabolic trough collectors and a seawater RO unit to examine the ORC system for the production of water by RO process [10], and in another study, they carried out the various investigations related to preliminary designs of the low-temperature solar thermal collector driven RO desalination for sea water and brackish water. It was found that by using R245fa in a solar thermal driven RO system, the productivity of solar desalination system can be increased up to a maximum value (i.e. below 2%) [11], further they also performed a research to examine the effect of different working fluids such as butane, isobutene, R245ca, and R245fa on the aperture area of the SPTC system for water desalination and power production [12]. Al-Sulaiman et al. [13] carried out a study to assess the performance of a novel system integrated with SPTC and ORC for combined cooling, heating and power (CCHP). They used the part of waste heat from ORC for cooling as well as heating cogeneration,

Please cite this article in press as: H. Singh, R.S. Mishra, Performance analysis of solar parabolic trough collectors driven combined supercritical CO_2 and organic Rankine cycle, Eng. Sci. Tech., Int. J. (2018), https://doi.org/10.1016/j.jestch.2018.03.015