Solar Energy 149 (2017) 195–213

Contents lists available at ScienceDirect

Solar Energy

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

Simulation studies of thermal and electrical performance of solar linear parabolic trough concentrating photovoltaic system

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ARTICLE INFO

Article history:
Received 20 October 2016
Received in revised form 29 March 2017
Accepted 2 April 2017
Available online 13 April 2017

Keywords:
Solar energy
Parabolic trough collector
Concentrated photovoltaic
Compound Parabolic Collector
Optical analysis
Thermal analysis

ABSTRACT

This paper presents thermal and electrical analyses of solar linear parabolic trough concentrating photovoltaic (CPV) collector system under different design and operating conditions. The receiver tube receives concentrated non-uniform solar flux over its outer surface, leading to high local temperature and large circumferential temperature difference. A Compound Parabolic Collector (CPC) has been incorporated as a secondary reflector to homogenize the flux. The co-generation system consists of a Parabolic Trough Collector (PTC) with 5.1 m^2 aperture area (A_{AP}) and a highly reflective mirror with dual axis tracking. The study envisages maximizing electrical output using CPV with non-uniform thermal energy over receiver tube. Various configurations are analyzed which include 2-cell and 3-cell strings without CPC and 3-cell and 4-cell strings with CPC. The detailed thermal and electrical analysis carried out for all the cases using Al_2O_3/Water nanofluid with 0%, 1% and 6% vol. and various synthetic fluids with constant velocity of 0.1 m/s. The flux values for the thermal analysis have been imported from the non-sequential ray tracing optical simulation software ASAP. Maximum thermal and electrical output is computed to be 2592.42 W with 78.2% thermal efficiency by 2-cell without CPC configuration using Syltherm-800 and 692.2 W with 20.88% electrical efficiency by 3-cell without CPC with Al_2O_3/Water ($\varphi = 1\%$) respectively. Reduction in electrical output by ~7.2–9.8% and enhancement in thermal output by ~0.91–1.16% has been observed on replacing nanofluids with synthetic fluids. Long lasting synthetic fluids leads to higher cell temperatures hence higher cell degradation but nanofluids give optimized electrical and thermal output with lower cell temperatures. Numerical results are compared with reference data which shows the reasonable agreement.

1. Introduction

Recent interest in concentrating photovoltaic has led to research and development of multiple CPV systems all across the world (Kerzmann and Schaefer, 2012). Reliability, eco-friendliness, longer life span of around 20–30 years and negligible maintenance cost are few of the characteristics of Photovoltaic/Thermal (PV/T) technologies. Depending on these features PV/T technology is expected to expand significantly in the near future (Riffat and Cuce, 2011). Concentrating photovoltaic/thermal (CPV/T) system facilitates production of electrical and high grade thermal energy simultaneously while operating at elevated temperatures even beyond 100 °C, and the thermal energy can power processes such as production of steam, refrigeration and desalination (Mittelman et al., 2007). Various researches have shown experimental, modeling and analytical results detailing about the CPV/T technologies. Experimental investigation was performed to illustrate electrical and thermal performance of a parabolic trough linear CPV/T system with dual axis tracking mechanism and concentration ratio (CR) of 130. The secondary reflector in the form of two-flat mirrors positioned along-side triple-junction PV module soldered on a ceramic substrate using water as coolant and obtaining the global efficiency of about 70% (Del Col et al., 2014). Another study involved designing, modeling and experimental demonstration of a linear PTC-PV based system with a semi-dense array of five 1 cm^2 lattice-matched III–V triple-junction concentrator cells. The system was developed with the ultimate goal of predicting the solar-to-DC energy conversion efficiency with the system overall optical efficiency of 62.5% (Cooper, 2014). A hybrid PV/T system was developed generating electrical output using PV module and extracting thermal output by cooling the PV cells, experimental results showed an increment in electrical efficiency from 13.2% to 13.4% by PV cooling using water as thermic fluid (Tripanagnostopoulos et al., 2002). Increment in PV cells efficiency is observed when heat is drawn from them, a detailed physical

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http://dx.doi.org/10.1016/j.solener.2017.04.004
0038-092X/

Nomenclature

a	defocussed length (m)
A	aperture Area (m^2)
C_p	specific heat capacity (J/kg K)
CR	concentration ratio
D	outer tube diameter (m)
d	offset distance from vertical axis (m)
f_l	focal length of trough (m)
f	focal length of parabolas of CPC (m)
h	convective heat transfer coefficient (W/m^2 K)
I_b	beam radiation (W/m^2)
L	length of trough (m)
N	number of observations
P	pressure (Pa)
$P_{CPV/el}$	electrical power output from each cell (W)
$P_{CPV/T}$	thermal power output from each cell (W)
P_{SS}	thermal output SS tube (W)
P_{th}	total thermal output from all cell strings (W)
$P_{to/ther}$	total thermal power output (W)
r	radius at any point of tube (m)
R_a	radius of SS tube (m)
Re	Reynolds' number
T	temperature (K)
T_{cell}	cell string temperature (K)
T, t	time–mean and fluctuating temperature (K)
T_f	inlet fluid temperature (K)
T_{fo}	outlet fluid temperature (K)
u	instantaneous inlet velocity (m/s)
U_{in}	inlet velocity (m/s)
U_Z	axial velocity (m/s)
V	velocity at the tube outlet (m/s)
W	width of the trough (m)
w	width of CPC (m)
W_{cell}	width of the cell (m)
x, y	axes
z	axial coordinate, (m)

Greek symbols

α	absorptivity
ε	electric permeability
η_{cnv}	conversion efficiency (%)
η_o	optical efficiency (%)
γ	intercept factor
μ	magnetic permeability
ρ	reflectivity
σ	standard deviation of the distribution of optical errors at normal incidence (mrad)
θ	angular position on the circular tube (degrees)
φ	Nanofluid volume concentration
τ	transmissivity

Abbreviations

ASAP	Advanced System Analysis Program
BRO	Breault Research Organization
CHAPS	Combine Heat and Power System
CPC	Compound Parabolic Collector
CPV	Concentrating Photovoltaic
CPV/T	Concentrating Photovoltaic/Thermal
CR	Geometric Concentration Ratio
DET	Cell Strings
FVM	Finite Volume Method
GaAs	Gallium Arsenide
HTF	Heat Transfer Fluid
IAM	Incidence Angle Modifier
ID	Inner Diameter
OD	Outer Diameter
MS	Mild-Steel
PTC	Parabolic Trough Collector
PV	Photovoltaic
PV/T	Photovoltaic/Thermal
SEGS	Solar Energy Generating Systems
SS	Stainless Steel

Subscripts

AP	aperture
arc	peripheral length of receiver tube
bf	base fluid
cell	cell string
CPV	concentrated photovoltaic
el	electrical
g	glass envelope
in	incidence
max	maximum
nf	nanofluid
o	outlet
p	particle
slope	refers to slope error
sun	refers to sunshape error
track	refers to tracking error
tot	total

model of a hybrid PV/T system based on an analysis of energy transfer due to conduction, convection and radiation was presented resulting in 60–80% total system efficiency (Bergene and Løvvik, 1995). A mathematical model was also developed to compute efficiency of operation of the hybrid collector at various modes of air driven cooling with experimental rig of eight PV cell module (Kuznetsov et al., 2009). A photovoltaic cell within a composite stack of the receiver was modeled for CPV electrical power system as a combination of electricity and waste heat generator (O'Leary and Clements, 1980). Researchers have also simulated flat-plate PV/T collectors focusing on air cooling and employing single crystal silicon PV cells (Cox and Raghuraman, 1985). PV/T solar water heater capacity of 200lts was tested in outdoor condition for composite climate of New Delhi. It is observed that the PV/T flat plate collector covered with PV module gives an average cell efficiency of 11.5% (Dubey and Tiwari, 2008). But, PV cells utilize only a fraction of the incident solar radiation to produce electricity and the remainder is mainly left as waste heat in the cells and substrate raising the its temperature, as a result the cell degrades eventually and efficiency gets reduced (RØyne, 2005) and typically this value of efficiency for concentrator cells is 25% (Sinton et al., 1985). The CPV/T technology recovers part of this heat and uses it for practical applications like solar cooling, water desalination, solar greenhouse, solar still, solar heat pump/air-conditioning system and building integrated photovoltaic/thermal (BIPVT) solar collector. The thermal energy can be dissipated by natural or forced convection as per the requirement for keeping the cells at the desired temperature (Royne et al., 2005) as operating at higher temperatures decreases the cell efficiency and may lead to long term degradation (Darwish, 2011). Current status of CPV technology claims that the multi-junction solar cells based on III–V semiconductors (e.g. triple-junction solar cells made of