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Energy and exergy analyses of a parabolic trough solar power plant using carbon dioxide power cycle

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ABSTRACT

This paper examines both energy and exergy performances of parabolic trough collectors (PTCs), as part of a solar power plant, under different design and operating conditions. The proposed solar power plant utilizes an innovative supercritical carbon dioxide (S-CO_2) power cycle to convert the heat produced by the PTCs to power. In addition, the present system integrates a thermal energy storage (TES) to overcome the intermittent nature of solar energy and extend the hours of operation. Therefore, detailed thermodynamic and heat transfer analyses are conducted to assess heat losses, exergy destructions, and energy and exergy efficiencies. The state-of-the-art PTCs technologies are considered to set the design parameters used in the modeling of the solar field. Furthermore, the effects of varying some operating conditions on the energy and exergy performance of the PTCs and the S-CO_2 power cycle are investigated. These parameters include beam radiation intensity, beam incidence angle, and receiver emittance. Subsequently, the resultant impacts of changing these parameters on the overall solar power plant energy and exergy efficiencies are examined. The energy and exergy efficiencies of the PTC are found to be 66.35% and 38.51%, respectively.

1. Introduction

Solar energy is recognized as one of the most promising energy alternatives that are maturing and expected to play a major role in mitigating the CO_2 emission through a gradual replacement of current fossil fuel energy systems. According to the international energy agency (IEA), the total world energy supply in 2014 reached 13,699 Mtoe, out of which 81% is coming from oil, coal, and natural gas, while 19% is supplied by non-fossil resources with only less than 1.5% renewables contribution, including geothermal, solar, and wind [1]. Despite the significant solar energy potential, which is estimated that during two hours only, the energy of the sunlight reaching the earth surface is more than the entire world demand for a year [2]. Comparing this outstanding potential with the currently limited utilization is the main motivation for further research and development to make solar technologies reliable and economically competitive. The broad solar energy research can generally, be categorized into three broad themes: (1) solar photovoltaic (PV) cells which focus on the utilization of solar light (photonic energy) in a direct conversion process involves the use of semiconductor devices, e.g. [3,4]; (2) solar thermal systems which concentrate and capture solar radiation to be used as heat or converted to power in a thermodynamic cycle, e.g. [5,6]; and (3) fuel production by solar energy where chemical and photochemical processes are used to produce fuel such as hydrogen out of solar energy, e.g. [7,8]. The current study falls under the second the category where thermal energy is concentrated and captured using parabolic trough collector (PTC). The heat is subsequently converted to power using thermodynamic power cycle.

Parabolic trough concentrated solar power (CSP) plants are mainly comprised of a solar field, Thermal Energy Storage (TES), and a power generation block. The solar field consists of parabolic mirrors, receivers, and a single-axis-tracking system. The parabolic mirrors reflect and concentrate sunlight onto the receivers which are positioned along the focal line of the parabolic trough. Receivers, in turn, are connected in a series to form a loop through which heat transfer fluid (HTF) is circulated to absorb the heat generated by a concentrated solar beam. The HTF leaves the field loop with a high temperature to be pumped through a hot header to the TES or directly to the power generation block based on the operating condition. The parabolic trough CSPs are mature technologies, they have been in use since the 1980s when nine Solar Electric Generating Systems (SEGS) were built in the Mojave Desert of Southern California. These SEGS plants have a total of 354 MW installed capacity and achieved an efficiency of 10% [9]. Thereby, parabolic trough CSP systems are considered the most

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Nomenclature

Acronyms

ARS	absorption refrigeration system
CO_2	carbon dioxide
COP	coefficient of performance
CSP	concentrated solar power
C.V.	control volume
EES	engineering equation solver
EV	expansion valve
HCE	heat collector element
HTF	heat transfer fluid
IHE	internal heat exchanger
KACST	king abdulaziz city for science and technology
Mtoe	millions of oil equivalent
NREL	national renewable energy laboratory
PTC	parabolic trough collector
SAM	system model advisor
SCA	solar collector assembly
S-CO_2	supercritical carbon dioxide
SEGS	solar electric generation system
SM	solar multiple
TES	thermal energy storage

Symbols

A	area (m^2)
C	cooling; concentration
C_p	specific heat (kJ/kg-K)
D	diameter (m)
e	internal roughness (m)
ex	specific exergy (kJ/kg)
$\dot{Ex}$	exergy rate (kW)
F	removal factor; Collector efficiency factor
h	specific enthalpy (kJ/kg); Convective heat transfer coefficient (W/m^2-K)
I	direct beam radiation flux (W/m^2)
k	thermal conductivity (W/m-K)
K	incident angle modifier
L	length (m)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure
Q	heat energy (kJ)
$\dot{Q}$	heat rate (kW)
s	specific entropy (kJ/kg-K)
T	temperature (°C)
U	overall heat transfer coefficient (W/m^2)
V	volumetric flow rate (m^3/s)
W	power (kW)
$\dot{W}$	work rate (W or kW)

Greek letters

α	absorptivity
γ	intercept factor
ε	emittance; heat exchanger effectiveness
η	efficiency
θ	incidence angle (°)
μ	viscosity (kg/m-s)
ρ	reflectance; density (kg/m^3)
σ	Stefan-Boltzmann constant (W/m^2-K^4); density (kg/m^3)
τ	transmittance

Subscripts

a	ambient
abs	absorber; absorbed
av	average
b	beam (direct)
c	cover; cold stream; convection
CL	cooling
CON	condenser
CP	circulating pump
cs	cross-section
d	diffuse
D	destroyed
en	energy
ex	exergy
f	factor
h	hot stream
HE	heater
HPT	high-pressure turbine
htf	heat transfer fluid
i	internal; inlet
IHE	internal heat exchanger
k	arbitrary state point
L	loss
LPT	low-pressure turbine
o	outer; exit; optical; output
ov	overall
p	constant pressure; aperture; pump
r	receiver; radiation
R	removal
RE	reheater
rec	rectifier
s	solar
t	total
th	thermal
u	useful; gain
w	wind

advanced and commercially proven technology compared with all other types of CSP plants. PTC has a concentration ratio of 70 to 80 suns and an operating temperature in the range of 290–550 °C [10]. TES can be easily integrated with CSP plants. Alternatively, these plants can be hybridized with fossil-fuel backup system, such as natural gas, to extend their full-load hours of operation. The peak efficiency of PTC-based CSPs is between 14 and 20%, and the annual solar-to-electricity net efficiency is about 11–16%, as reported by Kuravi et al. [11].

The literature contains numerous studies some of which focused on the development and the optimization of the solar field [12,13], while others investigated the conversion cycles and improving their conversion efficiencies [14]. On the performance of PTC, Gaul and Rabl [15] studied the incidence angle modifier for a PTC and investigated the relationship between a PTC test and long-term performance prediction of a solar field. Gupta and Kaushik [16] studied a direct steam generation in a trough-based CSP and conducted an energy and exergy analysis for different plant components. They reported that maximum energy loss occurred in the condenser and the PTCs solar field. However, maximum exergy destruction rate was reported to occur in the PTCs solar field. Reddy et al. [17] performed an energy and exergy analysis for a CSP system. They evaluated the energy and exergy losses and the efficiencies under the operating conditions of specific locations in India. It was found that the energy and exergy efficiencies of the plant increased by 1.49% and 1.51%, respectively, with an increase in