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Thermodynamic analysis of an integrated transcritical carbon dioxide power cycle for concentrated solar power systems

Abdullah A. AlZahrani[a,b,*], Ibrahim Dincer[b]

[a] Department of Mechanical Engineering, College of Engineering and Islamic Architecture, Umm Al-Qura University, Al Abdeyah, Makkah 5555, Saudi Arabia
[b] Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario L1H 7K4, Canada

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ABSTRACT

This paper investigates the thermodynamic performance, through energy and exergy efficiencies, of a conceptual design of a reheat transcritical carbon dioxide (T-CO_2) power cycle for concentrated solar power (CSP) plants. Herein, a parabolic trough collector (PTC) solar field is used to harvest solar energy and provide the thermal energy to the T-CO_2 power cycle. Thermal energy storage (TES) is also integrated to overcome the intermittent nature of solar energy and maintain stable thermal energy supply to the power cycle. Furthermore, the T-CO_2 power cycle is integrated with an absorption refrigeration system (ARS) to enhance the cycle efficiency and production stability by sustaining low condensation temperature at various weather conditions. A parametric study through energy and exergy analyses is conducted considering the performance of each subsystem independently, and that of the overall integrated CSP. The energy and exergy efficiencies, thermal losses, and exergy destruction rates are evaluated under the different design and operating conditions for the T-CO_2 power cycle and the ARS. For example, the effects of variations in the maximum cycle temperature and pressure on both the power cycle's energy and exergy efficiencies and integrated system efficiencies are investigated. In addition, the impacts of variations in these parameters on the integrated CSP energy and exergy efficiencies are examined. The T-CO_2 power cycle achieved energy and exergy efficiencies of 34% and 82%, respectively. The integrated CSP (solar-to-electric) energy and exergy efficiencies are about 20% and 55%, respectively.

1. Introduction

The serious environmental consequences of the increase in Greenhouse gas (GHG) produced mainly by conventional energy systems are the primary cause for pursuing alternative energy resources that can eliminate or at least reduce GHG emissions. Carbon dioxide (CO_2) is a major constituent of GHG with a concentration increased significantly from 280 part per million (ppm), before the industrial revolution, to 382 ppm in 2006 as reported by the National Oceanic and Atmospheric Administration (Abas and Khan, 2014). In analogy, the global average temperature has experienced an increase by about 0.8 degrees over the last six decades (Ruedy, 2014).

The current research investigates the use of a concentrated solar power (CSP) plant as an alternative to fossil fuel power plants which emit a significant amount of CO_2 into the atmosphere. The parabolic trough collectors (PTCs) are considered the most mature solar concentration technology with the largest CSP market share (Chacartegui et al., 2016). It is recently estimated that about 87% of the total CSP installed capacity is PTC based solar power plants (Desai and Bandyopadhyay, 2017). A PTC based solar field consists of an array of parabolic concentrators which reflect and focus solar radiation on the focal line where receiver tube is positioned for heat absorption. A heat transfer fluid is circulated through the receivers to transport heat to the power block. The PTC solar field produces a maximum output temperature of 400 °C. Thus PTC is usually optimized to maintain an output temperature that achieves the highest efficiency (Navas et al., 2017). The global CSP installed capacity increased to reach over 5 GW in 2016 from just below 0.5 GW in 2008 (NREL, 2017), with 2.2 GW in Spain only (Sallaberry et al., 2017; Sharma et al., 2018). Despite the high cost of CSP produced electricity compared with other renewable resources such as photovoltaic (PV), several benefits maintained a growing interest in CSP. These advantages are: (1) the low cost of thermal energy storage, (2) the higher efficiency compared with commercial PV systems, and (3) the higher capacity utilization factors (Sharma et al., 2018).

Furthermore, the present research focuses on the development of an innovative reheat transcritical carbon dioxide (T-CO_2) power cycle. The interest in using CO_2 as a working fluid in power cycles has been

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[*] Corresponding author at: Department of Mechanical Engineering, College of Engineering and Islamic Architecture, Umm Al-Qura University, Al Abdeyah, Makkah 5555, Saudi Arabia.

E-mail address: aarzahrani@uqu.edu.sa (A.A. AlZahrani).

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Nomenclature

A	area (m^2)
C	cooling
C_p	specific heat (kJ/kg K)
D	diameter (m)
ex	specific exergy (kJ/kg)
$\dot{Ex}$	exergy rate (kW)
h	specific enthalpy (kJ/kg); convective heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (MPa)
Q	heat energy (kJ)
$\dot{Q}$	heat rate (kW)
s	specific entropy (kJ/kg)
T	temperature (°C)
U	overall heat transfer coefficient (W/m K)
V	volumetric flow rate (m^3/s)
W	power (kW)
$\dot{W}$	work rate, W
η	efficiency
μ	viscosity (kg/m s)

Subscripts

a	ambient
abs	absorber; absorbed
av	average
CON	condenser
D	destroyed
des	desorber
en	energy
eva	evaporator
ex	exergy
f	factor
h	hot stream
HE	heater
htf	heat transfer fluid
i	internal; inlet
k	arbitrary state point
L	loss
o	exit; output
ov	overall
p	constant pressure; pump
r	receiver; radiation
RE	reheater
rec	rectifier
s	solar
SP	solution pump
t	total
th	thermal

Acronyms

ARS	absorption refrigeration system
CO$_2$	carbon dioxide
COP	coefficient of performance
CSP	concentration solar power
EES	engineering equation solver
EV	expansion valve
HEX	heat exchanger
HPT	high pressure turbine
HTF	heat transfer fluid
IHE	internal heat exchanger
LPT	low pressure turbine
PTC	parabolic trough collector
S-CO$_2$	supercritical carbon dioxide
TES	thermal energy storage

growing over the last four decades motivated by some advantages pertained to CO_2 power cycles compared with conventional cycles. For instance, CO_2 power cycles achieve higher efficiency, reduce machinery size, high heat transport capacity, and lower leakage and cost compared with helium-based cycles (Dostal, 2004; Feher, 1966; Sarkar, 2009).

The first proposal of a supercritical carbon dioxide (S-CO_2) Brayton cycle is credited to Feher (1966). Since then, several researchers have theoretically studies various configurations of S-CO_2 power cycles. Notably, the work done by Dostal (2004) has resumed previous investigations on using S-CO_2 as a working fluid for power cycles. In his study, a number of CO_2 Brayton power cycles are modeled and optimized for nuclear applications. The recompression cycle was reported to outperform other configurations in terms of cost, size, and thermal efficiency. The S-CO_2 recompression Brayton cycle was further investigated by Sarkar (2009) who carried out a second law analysis. Seidel (2011) developed a simulation model for an S-CO_2 Brayton cycle for CSP applications. The model is used to assess the annual efficiency and energy production of the different S-CO_2 Brayton cycle configurations with focus on S-CO_2 regeneration Brayton cycle. The annual net efficiencies reported was in the range of 41.5% with minor variations between water cooled and hybrid-cooled configurations. Similarly, Chacartegui et al. (2011) investigated different configurations of CO_2 cycles for a central receiver solar plants. Pérez-Pichel et al. (2012) conducted a thermal analysis of S-CO_2 power cycles and reported an efficiency of as high as 43%.

More recent studies considered various aspects of S-CO_2 Brayton cycles, for example, Reyes-Belmonte et al. (2016) optimized an S-CO_2 recompression Brayton power cycle for innovative solar plant applications. Mecheri and Le Moullec (2016) studied the S-CO_2 Brayton cycle for conventional coal-fired power plants and showed a net cycle efficiency in the range of about 46–50%. Padilla et al. (2015) proposed and exergetically analyzed four S-CO_2 reheat Brayton cycles. AlZahrani and Dincer (2016) focused on hydrogen production utilizing regenerative S-CO_2 Brayton power cycle in a high temperature solar tower plant. They reported an average power cycle efficiency in the range of 35–47% varying with the solar tower outlet temperature range of 527–1027 °C. Cheang et al. (2015) conducted a benchmarking study on various S-CO_2 cycles to compare their performance with Rankine steam cycles for CSP applications. Santini et al. (2016) compared different CO_2 cycles with conventional steam Rankine cycle considering Mochovce 3 nuclear power plant as a reference case study. Though their research outcomes showed a marginal energy efficiency improvement, of about 0.5%, compared with steam Rankine cycle, the reduction in the plant weight is expected to be significant of about 40%.

On the other hand, the T-CO_2 power cycles have received some attention. The research group of Zhang et al. (2007) have dedicated considerable research efforts to develop and test a Rankine cycle powered by evacuated-tube solar collectors with S-CO_2 as working fluid. For example, Niu et al. (2011) experimentally investigated the heat transfer characteristics of the S-CO_2 fluid in the solar collectors of a Rankine cycle. The results demonstrated a substantial effect of the CO_2 properties near the critical point on the heat transfer behavior of the CO_2 fluid. Additionally, Niu et al. (2011, 2013) optimized the solar collectors' arrangement of an S-CO_2 Rankine cycle system. The