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Energy and exergy analyses of solar tower power plant driven supercritical carbon dioxide recompression cycles for six different locations

Maimoon. Atif[a], Fahad A. Al-Sulaiman[a,b,*]

[a] Mechanical Engineering Department, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia
[b] Center of Research Excellence in Renewable Energy (CoRERE), King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia

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ABSTRACT

In this study, energy and exergy analyses of supercritical carbon dioxide (sCO_2) recompression Brayton cycles driven by solar thermal tower systems were conducted. A mathematical model is used to generate a surround heliostat field layout, which is optimized for the optical performance on an annual basis using differential evolution, an evolutionary algorithm. The model is also used to generate a recompression Brayton cycle, which uses the heat collected at the central receiver through the heliostat field. An auxiliary heat exchanger based on a combustion chamber was also added prior to the expansion turbine to keep the turbine inlet temperature constant, thus keeping the net power output uniform at 40 MW. Lastly, exergy analysis was conducted for the integrated system of the heliostat field and the recompression Brayton cycle. Also, a detailed chemical exergy analysis of the combustion chamber was performed. The developed mathematical model was implemented for six different locations (cities) in Saudi Arabia for a comparative analysis. The selected cities were Tabouk (North), Madinah (West), Dhahran (East), Riyadh (Central), Bishah (South), and Najran (South). The findings reveal that the highest annual average heat collected is for Madinah (938,400 kWh/day), followed by Tabouk (933,100 kWh/day). Consequently, the lowest annual average fuel hybridization of 5.82% is for Madinah followed by Tabouk (6.34%) for daytime hours. On the other hand, the highest annual average total exergy destruction rate is for Dhahran (199,250 kW), followed by Riyadh (192,699 kW) and the lowest is for Madinah (173,690 kW) followed by Tabouk (175,692 kW). Furthermore, the highest average exergy destruction takes place in the heliostat field and the second highest in the combustion chamber. In addition, the exergy destruction rate of the combustion process increases during the winter months when the solar radiation decreases.

1. Introduction

As more sunlight can be concentrated on a single receiver and the loss of heat can be minimized, solar towers can achieve higher temperatures compared to the parabolic trough. Moreover, a solar tower provides an opportunity to increase the capacity factor by using a thermal storage system and to maximize the power generated by allowing a flexible generation strategy along with higher efficiency levels. These advantages, coupled with increased operating experience and reduced costs, can make solar tower technology a tough competitor to the parabolic trough in the future markets [1]. A thermal solar power tower (central receiver system) comprises of a field of mirrors on the ground, which focuses the solar radiation on a receiver mounted high on a central tower. The receiver converts the solar radiation into heat and drives a thermodynamic cycle, which is typically a Rankine cycle or a Brayton cycle, to generate power. Each individual mirror in the field is called a heliostat and the mirrors are equipped with a two axis tracking system.

Noone et al. [2], proposed a biomimetic pattern for the heliostat field layout. The model is based on the discretization of the heliostat surface by dividing it into cells for the calculation of the optical performance parameters, specifically the shading and blocking factor and the intercept factor, which can be time consuming.

Besarati and Goswami [3] analyzed and optimized the same biomimetic heliostat field pattern and proposed a method to identify the heliostats with a potential for shadowing and blocking for the calculation of the shading and blocking factor. This approach was used to conduct a case study for the design of a 50 MW solar tower power plant for Dagget, California.

Pitz-Paal and co-workers [4] at the German Aerospace Center developed a code known as HFLCAL [4] to optimize a heliostat field on an annual basis and performed analysis for two latitude locations,

* Corresponding author at: Mechanical Engineering Department, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia.
E-mail address: fahadas@kfupm.edu.sa (F.A. Al-Sulaiman).

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Nomenclature

A_h	Total area of the heliostats, m^2
A_R	Surface area of the central receiver, m^2
DH	Heliostat diagonal, m
DM	Characteristic diameter, m
DR	Receiver diameter (cylindrical), m
$dsep$	Extra security distance between the heliostats, m
Ex_{solar}	Incident solar exergy rate, kW
Ex_{in}	Exergetic power input to the receiver, kW
Ex_u	Useful exergy gain rate, kW
$Ex_{d,\ i}$	Exergy destruction rate of any component "i", kW
$\overline{E}x_{d,comb}$	Exergy destruction of the combustion process, kJ/kmol
f_{at}	Atmospheric attenuation factor
f_{itc}	Intercept factor
f_{hybrid}	Fraction of fuel hybridization required to generate a constant power
f_{sb}	Shading and blocking factor
F_{view}	Radiation view factor
h	Specific enthalpy, kJ/kg
h_{conv}	Convective heat transfer coefficient at the central receiver, kW/m^2-K
$h_{aux,\ in}$	Inlet specific enthalpy of combustion gasses to the auxiliary heat exchanger, kJ/kg
$h_{aux,\ out}$	Outlet specific enthalpy of combustion gasses from the auxiliary heat exchanger, kJ/kg
$h_{w,\ in}$	Inlet specific enthalpy of coolant to the cooler, kJ/kg
$h_{w,\ out}$	Outlet specific enthalpy of coolant from the cooler, kJ/kg
$\overline{h}_{species}$	Specific enthalpy of any reacting species, kJ/kmol
$\overline{h}_f^o$	Enthalpy of formation, kJ/kmol
H_{prod}	Total Enthalpy of products, kJ
H_{react}	Total Enthalpy of reactants, kJ
$H_{species}$	Enthalpy of any reacting species, kJ
I	Incident normal radiation, kW/m^2
LH	Height of the heliostat, m
LR	Receiver size, m
LW	Width of the heliostat, m
$\dot{m}$	Mass flow rate of the sCO_2 in the Brayton cycle, kg/s
$\dot{m}_{aux}$	Mass flow rate of the combustion gasses, kg/s
$\dot{m}_{fuel}$	Mass flow rate of fuel to the combustion chamber, kg/s
$\dot{m}_w$	Mass flow rate of coolant, kg/s
n_d	A day in the year
$N_{species}$	Number of moles of any reacting species, kmol
Q_{aux}	Rate of addition of auxiliary heat, kW
Q_{conv}	Rate of convection heat losses from the central receiver, kW
Q_{in}	Total energy interception rate by the central receiver, kW
Q_{rad}	Rate of radiation heat losses from the central receiver, kW
Q_u (Q_{net})	Net useful energy gain rate at the central receiver, kW
Q_{out}	Energy rate disregarded at the cooler of the Brayton cycle, kW
Q_{solar}	Total incident solar radiation on the heliostat field, kW
R_1	Radius of the first ring in the first zone of the helistats, m
s	specific entropy, kJ/kg-K
$\overline{s}$	specific entropy, kJ/kmol-K
$S_{gen,\ reaction}$	Entropy generation of the chemical reaction, kJ/kmol-K
S_{prod}	Entropy of the products, kJ/kmol-K
S_{react}	Entropy of the reactants, kJ/kmol-K
$s_{aux,\ in}$	Inlet specific entropy of combustion gasses to the auxiliary heat exchanger, kJ/kg-K
$s_{aux,\ out}$	Outlet specific entropy of combustion gasses from the auxiliary heat exchanger, kJ/kg-K
$s_{w,\ in}$	Inlet specific entropy of coolant to the cooler, kJ/kg-K
$s_{w,\ out}$	Outlet specific entropy of coolant from the cooler, kJ/kg-K
T_{amb}	Ambient temperature, °C
T_{CR}	Temperature of the reactants, °C
T_{CP}	Temperature of the products, °C
THT	Tower optical height or aim point height, m
T_R	Temperature at the central receiver surface, °C
T_{sun}	Temperature of the outer surface of sun, K
T_o	Temperature of the state (or reference temperature), K
t	Time
W_C	Compressor power of the first compressor, kW
$W_{C,\ i}$	Compressor power of the *ith* compressor, kW
W_{net}	Net power output of the Brayton cycle, kW
wr	Ratio of heliostat width to heliostat height
W_T	Turbine power, kW
X_{air}	Excess air percentage
x_{mass}	Fraction of the mass flow rate through the sCO_2 cycle
X_{solar}	Input Solar share
x	X-axis co-ordinate
x_1	First optimizing parameter, m
$x_{2,\ i}$	Second optimizing parameter in *ith* zone, m
y	Y-axis co-ordinate

List of Greek symbols

α_s	Solar altitude angle
α_R	Absorptivity of the central receiver
δ	Solar declination angle
$\Delta\alpha z_i$	Azimuthal spacing between adjacent heliostats in the ith zone, radians
$\Delta R_{\min}$	Minimum radial distance between the rows of heliostats, m
ΔR_i	Radial distance between the rows of heliostats in the ith zone, m
ε	Emissivity of the central receiver
ε_{aux}	Effectiveness of the auxiliary heat exchanger
ε_{HTR}	Effectiveness of the high temperature regenerator
ε_{LTR}	Effectiveness of the low temperature regenerator
η_{opt}	Optical efficiency of the heliostat
η_{maa}	Monthly averaged annual heliostat field layout efficiency
$\eta_{th,R}$	Thermal efficiency of the central receiver
η_T	Isentropic efficiency of the turbine
η_C	Isentropic efficiency of the first compressor
$\eta_{C,i}$	Isentropic efficiency of the *ith* compressor
η_{th}	Thermal efficiency of the Brayton cycle
γ_s	Solar azimuthal angle, radians
ω_s	Solar hour angle, radians
$\omega_{sunrise}$	Sunrise hour angle
ω_{sunset}	Sunset hour angle
ω	Incidence angle, radians
ϕ	Latitude angle, radians
ρ	Reflectivity
σ	Stefan-Boltzmann constant, W/m^2-K^4
σ_{bq}	Standard deviation of beam quality error
σ_t	Standard deviation of tracking error
σ_{sun}	Standard deviation of sunshape error

i.e., 20°N and 40°N. The code uses an analytical function, which computes the reflected image of each heliostat as a circular normal distribution, to calculate the intercept.

Pitz-Paal et al. [5], also performed an annual optimization of a heliostat field to improve the efficiency of solar to chemical energy conversion for the production of solar fuels. Optimization was per-