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Investigation of a combined cycle power plant coupled with a parabolic trough solar field and high temperature energy storage system

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ABSTRACT

This study was aimed at exergetically investigating a combined cycle power plant coupled with a parabolic trough solar field and high temperature energy storage system. Thermodynamic modeling of the combined cycle was conducted by ASPEN HYSYS simulation software, while the modeling of solar and energy storage section was carried out using MATLAB software. The main goal of the present research work was to reveal the reasons and sources of the thermodynamic losses occurring in the power plant based on the thermodynamic outcomes obtained from modeling. After writing the exergy balance equations for all the subunits of the power plant, their exergetic performance parameters were measured individually. Moreover, the effect of different influential parameters such as gas turbine inlet temperature and outlet pressure, and the R113 working fluid mass flow rate on the exergy and electrical efficiencies of the whole system was also investigated and scrutinized. The exergetic value of the net electric power was found to be 93,580 kW. The overall exergy destruction of the system stood at 216,710 kW. The contribution of solar and energy storage combination, as the main subunit wasting exergy, to the overall exergy destruction of the system was determined at 43%. Moreover, combustion chamber subunit stood in the next rank in terms of exergy destruction, contributing 15.7% of the overall exergy destruction of the power plant. The overall exergy efficiency and electrical efficiency of the power cycle was determined at 38.2% and 47%, respectively.

1. Introduction

It is well-documented that the continuous population growth, growing urbanization, ameliorated living standards [1], as well as an industrial and economic boom, have significantly increased energy consumption during the last century [2]. In this period, fossil-based fuels such as crude oil, natural gas (NG), and coal have got a noticeable impact in supplying the principal portion of the worldwide energy demands which stands for 89% and more [3]. Such intensive use of these fuels, in turn, have not only faced the global energy market with serious crisis but have also boosted energy prices [4]. Additionally, these problems have been significantly drastic considering the harmful environmental effect of fossil-originated fuels [5], that is, climate change and global warming [6]. Hence, exploring renewable, clean, carbon-neutral and cost-effective routes to replace all or part of petro fuels for electricity production seems inevitable [7]. This, in turn, can lead to prevail over such undesirable phenomena and to produce so-called "green electricity" [8].

Solar energy can be regarded as a superior substitute renewable source to supply thermal energy for the power generation [9] due to its environmentally benign and carbon neutral nature [10]. Parabolic trough, solar power tower, Fresnel reflectors, and dish Stirling are the four main techniques used to concentrate the thermal energy of the sun [11]. Currently, solar-only power plants are not yet competitive with conventional fossil-based power plants due to their exorbitant investment costs, lower efficiency [12], intermittent energy supply, and etc. [13]. To address this, hybridization of solar collectors with conventional power plants can be considered as a favorable option [14]. This approach can lead to simultaneously take advantage of renewability and sustainability features of solar energy and to mitigate CO_2 emission and fuel consumption [15]. Hybridization of an oxy-fuel power system and high temperature solar cycle is investigated and analyzed [16]. The results show that energy and exergy efficiencies of the process are 57.2% and 60.7%, respectively. Applying PT for production of thermal energy in different climates in Iran is studied [17]. In this study effect of using different kinds of nan-fluids as the solar system working fluid is presented.

A tremendous amount of examples can be found in the published

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Nomenclature

A	area [m^2]
C_p	specific heat capacity [kJ/kg K]
D_i	internal diameter [m]
D_o	external diameter [m]
$\dot{Ex}$	exergy rate [kW]
ex	specific exergy [kJ/kg]
$\overline{ex}$	standard chemical exergy [kJ/mol]
F'	collector efficiency factor [–]
F_R	collector heat removal factor [–]
h	convective heat transfer coefficient [W/m^2 K]; specific enthalpy [kJ/kg]
h_s	hour angle [°]
h_{fi}	convective heat transfer coefficient within the tube (W/m^2 K)
HHV	higher heating value [kJ/kg]
I_b	beam radiation [W/m^2]
I_T	solar irradiance [W/m^2]
k	thermal conductivity [W/m K]
La	latitude [°]
L	collector length [m]
$\dot{m}$	mass flow rate [kg/s]
N	number of days [–]
Nu	Nusselt number [–]
Pr	Prandtl number [–]
$\dot{Q}$	heat transfer [kW]
Q_u	useful heat gain [kW]
$\overline{R}$	universal gas constant [kJ/mol K]
Re	Reynolds number [–]
s	specific entropy [kJ/kg K]
S	absorbed radiation [W/m^2]
T	temperature [K]
U_L	heat loss coefficient [W/m^2 K]
V	velocity [m/s]
$\dot{W}$	power [kW]
W	aperture width [m]
y	mole fraction [–]

Greek letters

α	absorbance [–]
ε	emissivity [–]
η	electrical efficiency [%]
θ	incident angle [°]
ρ	reflectivity; density [kg/m^3]
σ	Stefan-Boltzmann constant [W/m^2 K^4]
τ	transmittance [–]
ψ	exergy efficiency [%]

Subscripts

0	dead state
a	aperture; ambient
c	convection
CC	combustion chamber
ch	chemical
D	destruction
g	glass cover
$g{-}a$	glass cover to ambient
H	heater
HX	heat exchanger
i	numerator
in	input
out	output
ph	physical
$P\&C$	pump and compressor
r	radiation; receiver
$r{-}g$	receiver to glass cover
SS	solar collector & storage
Tur	turbine

literature where PT solar collectors have been successfully integrated with combined cycle systems. For instance, a novel hybrid design of PT solar field with Bryton cycle of CC power plant having favorable reliability and insignificant financial risk is introduced by [18]. A novel hybrid organic Rankine cycle driven by waste heat and solar energy is investigated by [19]. Six different power plants in Iran climate condition were scrutinized technically and economically [20]. They found that ISCCS coupled with 67 MWe solar field indicated favorable potential to operate in Iran owing to its considerable capability in saving fuel and alleviating CO_2 emission. TRANSYS software was employed to precisely model and numerically simulate the performance of the Hassi R'Mel HTF-integrated solar power plant located in Algeria [21]. Technoeconomic analysis was applied to appraise the effect of PTCs area on the performance of the HTF-ISCCS under two different operation procedures [22]. The results revealed that the cost of the produced electricity increased with the solar field size. A comparative analysis was performed to evaluate the performance of the HTF-ISCCS when combined with solar tower and parabolic trough concentrating methods under Sevilla climate located in Spain by [23]. Three different solar concentrating methods were considered in order to select an optimum technique for integrating with conventionally combined cycles [24]. Accordingly, solar field efficiency for PT, linear Fresnel, and solar tower systems was found to be 61.2%, 58.0%, and 56.2%, respectively. Performance and the economic feasibility of ISCCS coupled with a parabolic trough and Fresnel reflectors were annually analyzed and compared under two different climate conditions [25]. Results revealed that the thermal contribution of PTC is notable. Eight scenarios were employed to conduct an inquiry regarding the superiority of solar-assisted power generation through integrating a PT solar field with a 200 MW coal-fired power plant [26]. They showed that coupling a coal-fired PP with low or medium heat derived from PT solar field is a favorable potential to be applied for power generation. Performance of different hybridization scheme of DSG- and HTF-solar field into a 300 MW coal-fired PP was analyzed [27]. The outcomes depicted that 4302.8 tons of coal per year could be saved using the solar aided coal-fired power generation (SACPG) plant. Three novel CSP technology integration schemes with a coal-fired PP outfitted with carbon capture processes is introduced and assessed by [28]. Nine different SACPG systems were possessing different capacities with and without considering heat storage unit was investigated by [7]. This study was conducted from the life cycle assessment (LCA) point of view. Based on the obtained results from the grey relation analysis SACPG equipped with thermal storage unit acted superior compared to others. A SACPG system was thermo-economically scrutinized by [29] under two working condition of plant i.e., power boosting and fuel saving approaches. They observed that 15.04 g/kWh of coal utilization rate could be saved under fuel-saving operation mode. However, 57.2 MW extra power could be achieved during the power boosting operation mode compared to conventional coal-fired systems. A comprehensive review of integrating solar thermal energy with fossil-originated and renewable power generation systems was performed [30]. Performance of 17 different scenarios of integrating CSP with the biomass plant from the technical, economic, and environmental viewpoints was performed [31]. Recently, an integrated solar-biomass system was presented and