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Energy analysis of a particle suspension solar combined cycle power plant

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ABSTRACT

The key to achieve an economically more attractive concentrated solar power plant is to work at higher operating temperatures, allowing both higher power conversion efficiencies resulting in a smaller heliostat field for a given energy output, and higher temperature ranges in the storage tanks, with increased energy storage density and smaller size, hence less expensive. This fostered the development of using particle suspensions as heat transfer media. This paper presents a theoretical framework for the energy analysis of a particle-in-tube solar power plant, hybridized, with topping air-Brayton cycle turbine, and bottoming steam block. From studying the effects of essential design parameters on the energy efficiency, the heat transfer efficiency of the turbine air preheater is of paramount importance to increase the solar contribution within the hybrid concept, while the energy efficiency moreover increases by an optimum air-Brayton cycle turbine operation (mostly through the pressure ratio, less by the operating temperature). The overall efficiency of the concept varies from about 40% when using combined low and high pressure Brayton cycle turbines only, to over 48% in a fully combined air-steam concept. Energy efficiency findings are in agreement with the literature data.

1. Introduction and objectives

Most of our consumed energy is provided using traditional primary energy sources like natural gas, fuel oil, coal and nuclear fission, or additionally by secondary sources, such as biomass, hydropower, wind and sun. About 85% of our current energy consumption is generated by the combustion of fossil fuels and only about 15% is covered by renewable energy sources [1]. However, the amount of solar energy that reaches the earth every hour, exceeds the annual energy consumption, although only countries between 45°N and 45°S latitude benefit from enough solar irradiance to exploit concentrated solar power energy [2]. Concentrated Solar Power (CSP) is a power generating technology that uses heliostats to focus solar irradiation onto a receiver where a heat transfer fluid (HTF) is used as heat collector and carrier [3]. An interesting feature that makes CSP plants a promising renewable energy source, is their ability to provide power on demand when a thermal energy storage is integrated [4], resulting in a future low-carbon energy grid [5]: excess energy that has been captured during daytime is used to extend power generation during the night or during cloudy moments [6]. Despite these promising aspects, CSP plants are currently more expensive than other alternative renewable energy sources such as photovoltaic cells and wind turbines [2]. Major improvements can however be made to reduce operating costs and make CSPs more competitive [7]. Early plants, built nearly 30 years ago, are based on Parabolic Trough Collector technology using thermal oil as HTF, resulting in low temperatures ($< 390\,^{\circ}$C) and low-efficiency power blocks ($\sim 35\%$) [1]. Molten salts were the first higher temperature option, although problems of decomposition ($\geq 560\,^{\circ}$C) and solidification (≤ 220–$250\,^{\circ}$C) [1] represent serious drawbacks. Various CSP options are illustrated in Refs. [2,4].

1.1. Enhancing concentrated solar power plants through improved essential components and system integration

SPTs are gaining increasing attention due to their advantages such as a possible hybridization, a high efficiency, ease of energy storage, moderate operating costs and good scale-up potential [2,3]. From a literature survey of recent publications, some essential improvements emerge, as discussed below.

A first focus of general concern is hybridization, since it can guarantee a 24/24 h, 7/7 days operation and has been commonly applied by using a back-up fuel in PTC or molten salt SPT. It has been recently studied for alternative cases. Zhang et al. [8] studied the intergation of a SPT within an existing coal-fired power plant in Southern Croatia. Hussain et al. [9] studied different solar-biomass systems for hybrid power generation in Europe, whiler Bai et al. [10] evaluated the

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Symbols

C_p,C_{pa}	specific heat capacity of solids and air, respectively, J/kg K
D	characteristic linear dimension, m
d_{sv}	surface-to-volume particle size, m
F_a	flow rate of air, kg/s
F_{fuel}	flow rate of fossil fuel boost, kg/s
F_{H_2O}	flow rate of water, kg/s
F_p	flow rate of solids, kg/s
$h_{isotropic,out}$	outlet enthalpy of the steam for an isotropic turbine, J/kg
$h_{real,out}$	real output enthalpy of the turbine, J/kg
h_{ST1}	output enthalpy of the steam boiler, J/kg
h_{ST3}	inlet enthalpy of the steam turbine, J/kg
$h_{real,out}$	real output enthalpy of the turbine, J/kg
$h_{turbine,in}$	inlet enthalpy of turbine, J/kg
k	specific heat capacity ratio of air
L	length of a tube, m
m	mass flow rate of a component, kg/s
ΔP	pressure drop, Pa
P_{pump,P_1}	electric power of pump P_1, W
P_{ST}	net power of steam turbine, W
P_1,P_2	inlet and outlet pressure of compressor air, respectively, Pa
Q_{GT}	heat input of gas turbine, W
Q_p	heat content of particle suspension, W
Q_{ST}	heat input of steam turbine, W
$Q_{thermal}$	total amount of heat supplied by the air, W
Q_{total}	total heat input of the combined cycle system, W
Re	Reynolds number
$\mathrm{r_p}$	pressure ratio of turbine
S	entropy of a component, J/K
$T_{a,o}$	real air temperature at outlet of compressor, K
$T^*_{a,o}$	theoretical temperature after isentropic compression, K
T_{amb}	ambient air temperature, K
T_{GT2}	inlet air temperature of air pre-heater, K
T_{GT3}	outlet air temperature of air pre-heater, K
T_{GT4}	inlet air temperature of turbine, K
T_{GT5}	outlet air temperature of turbine, K
T_{HC1}	outlet temperature of particles after receiver, K
T_{GT2}	inlet temperature of particles in air pre-heater, K
T_{GT3}	outlet temperature of particles from air pre-heater, K
T_{GT5}	inlet temperature of particles in receiver, K
v	velocity of the fluid, m/s
V_2	volumetric flow rate of gas, m^3/s
W_{bl}	reversible work of blower, W
η_{ac}	isentropic efficiency of compressor
η_{bl}	efficiency of blower
η_{ex}	isentropic expansion efficiency of turbine
η_{G}	generator efficiency
η_{me}	mechanical efficiency
$\eta_{\mathrm{steamcycle}}$	efficiency of the overall steam cycle
$(\eta_{\mathrm{th}})_{\mathrm{ST}}$	thermal efficiency of the steam boiler
$\eta_{\mathrm{th,theory}}$	theoretical efficiency of the turbine
$\eta_{\mathrm{th,real}}$	real efficiency of the turbine
η_{total}	total efficiency of the combined cycle system
η_{overall}	total efficiency of turbine
μ	dynamic viscosity of the fluid, kg/m·s
ξ	friction factor
ρ,ρ_a	density of the fluid and air, respectively, kg/m^3
ρ_s	density of solids, kg/m^3

Abbreviations

CSP	Concentrated Solar Power
HF	Heliostat Field
HP	High Pressure
HPP	Hybrid Power Plant
HTF	Heat Transfer Fluid
LP	Low Pressure
LCOE	Levelized Cost of Electricity
PTC	Parabolic Through Collectors
SPT	Solar Power Tower

thermodynamics of such a solar-biomass hybrid power generation system. A resource and thermodynamic assessment of hybrid solar-biomass power plants in India was specifically examined by Sahoo et al. [11]. A hybrid solar-biomass power plant without energy storage was also assessed [12]. Gasification of biomass offers additional possibilities of hybrid solar-thermal applications [13]. Bai et al. [14] studied the integration of a two-stage biomass gasification in a hybrid solar-biomass power generation system. Tanaka et al. [15] examined the thermodynamic performance of a hybrid power generation system using syngas as back-up fuel in CSP processes. Special attention is also paid to the hybridization with other renewable energy sources, such as wind, photovoltaic or even photovoltaic/concentrated CSP hybrid systems [16].

A second focus of improvement considers the heliostat field, representing 30–35% of the capital investment of a SPT power plant. Its efficiency determines the overall solar thermal efficiency to a major extent, together with the receiver efficiency. Research and development to enhance its performance are hence important as illustrated by recent heliostat-related research. Atif and Al-Sulaiman [17,18] developed a differntial evolution method to optimize the heliostat field layout. The impact of the heliostat field design on teh power plant efficiency was studied by Mutuberria et al. [19], while Noone et al. [20] proposed biomimetic algorithms for the HF optimization. Computational design methods of the heliostat field were also developed by Besarati and Goswami [21]. A precise sun-tracking control of heliostats can increase the HF efficiency to well in excess of 70% [22], thus reducing the size of the HF and the land area occupied [23]. The optical components of the solar concentrators [24], and the optical cleanliness of the heliostats as a result of either surface erosion [25] or dust deposits [26] are considered important, and efficiency losses up to 10% have been reported if heliostats are dust-covered [26].

A third focus stresses the receiver efficiency as an important design and operation parameter. It has continued to be the subject of extensive research. As stated before, the key to achieve an economically more attractive solar power plant is to work at higher operating temperatures. e density [2,7]. This fostered the development of using particle suspensions as HTF. When using powders, the molten salt lower solidification temperature limit is removed and higher operating temperatures are limited only by the equipment's material capabilities [1,7]. The increased thermodynamic efficiency will allow to use a smaller heliostat field and energy storage, recognized as more efficient and less expensive. The economic consequences for other parts of the SPT plant will be more difficult to predict, since working at higher temperatures potentially requires more expensive manufacturing materials for the receiver and power generation block. The cost reduction of the solar field and storage is however expected to outweigh the increased cost of the power block and the receiver. The potential of using particle suspensions as HTF has been highlighted in particle-in-tube receivers [3,7] where an excellent heat transfer coefficient between the tube wall and the upflowing suspension was measured [27]. The hydrodynamics of the system were confirmed by 3D-simulations [28]. The contribution of the radiation heat transfer from the wall to the particles

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