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Optimization of heliostat field in a thermal solar power plant with an unfired closed Joule-Brayton cycle

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Abstract

In the last decades, concentrating solar power (CSP) has been gaining increasing attention as a sustainable technology for producing electricity. Nowadays, in the world, 483.6 MWs are produced by CSP plants of which 457 MW are already in commercial stage, whereas the other 430 MWs are under construction. In this paper, a solar tower with an unfired closed Joule-Brayton cycle of 10 MW peak power, located in Seville, is analyzed. The cycle, that employs only atmospheric air, without fuel consumption, relies on the possibility to vary the mean density of the air flowing in the plant. By using an auxiliary compressor and a bleed valve, a variable mass flow rate can be obtained so to keep the temperature at turbine inlet constant. On the other hand, in the concentrated solar plant, the number of installed heliostats can reflect towards the receiver the nominal thermal power, even with reduced values of the DNI. With the increase of the radiation, when the thermal energy flux achieves the limit tolerable by the receiver, a part of heliostats is defocused. On the contrary, in the presence of transients, due, for example, to clouds or in case of low solar radiation, the mirrors will be all, or in part, oriented towards the receiver face, so to keep constant the receiver outlet air temperature at the design value. Both the above mentioned control systems, without any fuel addition, act with the common goal of maintaining constant the air temperature at turbine inlet. However, they intervene at different times: at rated power, heliostats work, while the air flow rate is kept constant at the maximum value; when the nominal conditions are no longer achievable (the DNI values are insufficient), the adjustment is performed through the modulation of the pressure base control system, focusing the entire surface of the mirrors on the receiver. The analysis shows how the interaction between these systems influences the number and size of heliostats to be installed in the solar field. The study of the state of art has demonstrated that, in tower systems currently in operation, without storage, a solar multiple of 1.3 is generally used; our contribution shows how, with the air density control system, this value may be reduced, with consequent benefit on the heliostats cost. The numerical tests have been carried out by using the WINDELSOL software to optimize the heliostat field configuration and the THERMOFLOW, for the thermodynamic analysis.

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Keywords: concentrating solar power,solar-gasturbine, optimization of heliostat field, solar tower plant,control system

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1. Introduction

The use of solar energy as a source of energy production has reached a technological maturity such as to enable its adoption not only for the direct production of electricity, but also for the indirect production of energy carriers, like hydrogen [1][19]. Nowadays, the adoption of concentrating solar power (CSP) plants is spreading more and more. About 483.6 MWs of energy are produced by CSP plants: 457 MWs are generated by commercial towers, whereas 430 MWs are expected to be produced in a near future. [2]. In this paper, we propose a solar thermal power plant, that uses an air unfired Joule-Brayton cycle in closed loop. Nowadays, some examples of this kind of energy systems, in Europe, can be found in Spain [3] or in France [4].

The considered system, (shown in figure 1), is composed by a solar tower and heliostats field, an intercooler and regenerated gas turbine, a low temperature heat exchanger, an auxiliary compressor and a bleed valve. No combustor is used, though typically employed in this kind of plant [3,4] , and the only thermal energy source is represented by the direct solar radiation.

The analysis proposed in this paper is aimed at determining the best configuration of the heliostats field, the solar multiple, and the tower, for the specific control system, so to minimize the LCOE.

Nomenclature

GT	Gas turbine
DNI	Direct normal radiation [W/m^2]
TIT	Temperature inlet turbine [°C] =T_3
SM	Solar multiple
$P_{1\,min}$	Minimum level of pressure base [bar]
$P_{1\,max}$	Maximum level of pressure base [bar]
LCoE	Levelized cost of electricity [$/kWh]
CSP	Concentrated solar power
β	Compressor/expansion ratio
T_1	Cycle base temperature [°C]
TOT	Temperature outlet turbine [°C] = T_4
ΔM_c	Mass variation in the cycle [kg]
$\Delta \rho_c$	Density variation in the cycle [kg/m^3]
V_c	Air volume of the system [m^3]
ΔP_c	Pressure base variation [bar]
R	Universal constant gas [J/kgK]
T_c	Average temperature of cycle [°C]
W_s	Specific work [kJ/kg]
W_t	Turbine work [kJ/kg]
W_{c1}	Compressor work of first compressor [kJ/kg]
W_{c2}	Compressor work of second compressor [kJ/kg]
c_p	Heat capacity [kJ/kg°C]
T_2	Temperature outlet second compressor [°C]
$P_{th\,SF}$	Thermal power solar inlet solar field [kW$_{th}$]
$\dot{m}$	Mass flow of the cycle [kg/sec]
ΔH	Enthalpy variation of the air between second compressor stage point and inlet turbine point [kJ/kg]
α	Pay back factor
i	Real discount rate
n	Useful life of plant [Years]
k_{ins}	Annual rate of insurance
C_{inv}	Investment cost [$]
$C_{O\&M}$	Operating and maintenance cost [$]
E_{net}	Net energy product [GWh]