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Improving the efficiency of gas turbine systems with volumetric solar receivers

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ABSTRACT

The combustion process of gas turbine systems is typically associated with the highest thermodynamic inefficiencies among the system components. A method to increase the efficiency of a combustor and, consequently that of the gas turbine, is to increase the temperature of the entering combustion air. This measure reduces the consumption of fuel and improves the environmental performance of the turbine. This paper studies the incorporation of a volumetric solar receiver into existing gas turbines in order to increase the temperature of the inlet combustion air to 800 °C and 1000 °C. For the first time, detailed thermodynamic analyses involving both energy and exergy principles of both small-scale and large-scale hybrid (solar-combined cycle) power plants including volumetric receivers are realized. The plants are based on real gas turbine systems, the base operational characteristics of which are derived and reported in detail. It is found that the indications obtained from the energy and exergy analyses differ. The addition of the solar plant achieves an increase in the exergetic efficiency when the conversion of solar radiation into thermal energy (i.e., solar plant efficiency) is not accounted for in the definition of the overall plant efficiency. On the other hand, it is seen that it does not have a significant effect on the energy efficiency. Nevertheless, when the solar efficiency is included in the definition of the overall efficiency of the plants, the addition of the solar receiver always leads to an efficiency reduction. It is found that the exergy efficiency of the combustion chamber depends on the varying air-to-fuel ratio and, in most cases, it is maximized somewhere between the applied inlet combustion air temperatures of 800 °C and 1000 °C.

1. Introduction

In recent years, the international community has focused its efforts on the development and better understanding of the hybridization of solar energy with conventional power plants. The main motivation of this is to decrease the cost of electricity, as well as to promote regional energy independence, reduce CO_2 emissions and increase the standard of living of a society [1]. The wider development of technologies based on solar energy from the 1980s until today has led to hybridization proposals of several concentrated solar power (CSP) technologies. CSP technologies include parabolic through, solar tower, volumetric receiver, fresnel or dish [2]. The most suitable technology depends on the project, since parameters like the direct normal irradiance, climate conditions, and space availability have to be taken into account.

Until today, most solar thermal plants have been coupled with steam cycles achieving efficiencies of about 42%. This kind of power plant hybridization facilitates minimal modification to the original design of a power plant [3]. However, the coupling of solar plants with gas turbines results in a significantly higher total efficiency [4,5]. There are two main ways to couple solar plants with conventional power plants: either by using the solar energy in the heat recovery steam generator (HRSG) or, if applicable, in the gas turbine (GT) system of the plant.

Several studies related to the hybridization of parabolic trough collectors and volumetric receivers with conventional power plants can be found in literature. Nevertheless, the published works use energy analysis to compare and evaluate energy systems that may lead to misleading conclusions. In the present paper exergy analysis is used as the main evaluation tool of newly proposed hybrid systems. Furthermore, different definitions of the efficiency that can lead to significantly contrasting results among different research studies are discussed.

Antonanzas et al. (2014) [1] analyzed the overall potential for solar thermal integration in 51 combined-cycle gas turbines (CCGTs) in Spain under different operational scenarios. They found that when the air temperature increases, the efficiency of the power plant decreases, while in these periods, the direct normal irradiation (DNI) is higher. Therefore, the hybridization of a combined cycle with a solar plant can

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Nomenclature

$\dot{E}$	exergy rate (MW)
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	thermal energy rate (MW)
r	distance to the tower (km)
$\dot{W}$	power (MW)

Subscripts

at	attenuation
bl	blocking
D	exergy destruction
F	fuel (exergy)
hel	heliostats
int	intercepted
k	component
L	loss (exergy)
P	product (exergy)
ref	reflected
s	shadding
tot	overall system

Greek symbols

ε	exergy efficiency
η	energy efficiency
θ	incidence angle

Abbreviations

CC	combined cycle
COMP	compressor
CSP	concentrating solar power
DNI	direct normal irradiation
GT	gas turbine
HRSG	heat recovery steam generator
ISCC	integrated solar combined cycle
LCOE	levelized cost of electricity
NG	natural gas
pp	percentage points
ST	steam turbine

be used to alleviate the production drop. However, it is not possible to define a specific way for the integration, due to the different operational conditions and locations of the conventional plants. Amelio et al. (2014) [4] evaluated the performance of an integrated solar combined-cycle power plant in Spain (Almería), where parabolic collectors were used to heat up the air entering the combustion chamber of the GT. Once the air was compressed, it flowed through the parabolic collector to be heated with solar energy. To compare the power plant efficiency, with or without solar energy, three expressions for the efficiency were defined. One definition included the solar power available to the collectors; another definition included only the thermal power generated by the collectors, while the last definition excluded the solar energy input. The study showed that the net average annual efficiency of the plant was higher in comparison with the reference combined-cycle efficiency without solar integration, for all efficiency definitions. Alqahtani et al. (2016) [6] studied integrated solar combined-cycle power plants (ISCCs), comprised of a CSP plant (with parabolic trough system an oil as the heat transfer fluid) and a natural gas-fired combined-cycle power plant. The authors compared the levelized cost of electricity (LCOE) of four power plants: standalone CSP, concentrated solar power with energy storage, standalone natural gas combined cycle and ISCC. The authors concluded that the ISCC can reduce the LCOE in comparison with the other hybrid or renewable plants. Saghafifar and Gadalla [7] investigated the hybridization of a 50 MW-power plant with a solar plant involving a volumetric solar receiver in the United Arab Emirates and optimized it thermo-economically. The optimization included several important parameters of the power plant, such as the inlet temperature of the GT system and the pressure ratios of the turbines. It was concluded that the installment of a new hybrid power plant would be more economical than the hybridization of the already existing plant.

Another type of a CSP plant used in hybridization scenarios with ISCCs includes an air receiver that can be either tubular [8] or volumetric [9,10]. A review of solar volumetric receivers can be found in [11]. Spelling et al. [12] developed a dynamic model to determine the thermodynamic and economic performance of a solar combined cycle power plant. The receiver consisted of an open volumetric receiver, where the solar radiation was concentrated in porous ceramic foam. The temperature of the air was increased in contact with the porous material and a packed-bed volumetric air storage unit was used to stabilize the air temperature. The authors found that this hybridization could compete with current solar thermal technologies, in terms of LCOE, depending on the magnitude of the initial investment.

Several different designs for the volumetric receiver can be found in literature. In 2006 Heller et al. [13] presented the results of an experimental prototype solar powered gas-turbine system installed in Plataforma Solar de Almeria in Spain in 2002. A solar receiver cluster able to provide pressurized air at 1000 °C was developed in the framework of the project SOLGATE. This temperature was higher than the 800 °C previously achieved at a pressure of 15 bar by researchers of the German Aerospace Center (DLR) [10]. The air is directly introduced into the combustion chamber of the gas cycle, using a by-pass to control the temperature of the air at the inlet of the combustion chamber. Heller et al. described the configuration of the plant, the component efficiencies and the operation experience, during the successful test of the solar GT for 100 h of operation. Pozivil et al. (2013) [14] also developed a pressurized air-based solar receiver for power generation in GTs. This work presented two prototypes of a solar receiver of 3 kW_{th} and 35 kW_{th}. The use of this receiver allowed the heating of pressurized air in the range of 4–30 bar and 800–1200 °C. The analysis of the volumetric receiver and its integration into a GT showed that the power cycle efficiency increased with higher turbine inlet temperature. On the other hand, the efficiency of the solar receiver decreased at a higher operating temperature, due to the radiation losses. The thermal receiver efficiency was defined as the ratio between the thermal power absorbed by the air flowing through the solar receiver over the concentrated solar flux incident on receiver aperture.

In 2015, del Río et al. [15], based on previous work realized in the framework of the projects REFOS and SOLGATE, worked on the project SOLTREC, where they studied the development and manufacturing of a volumetric receiver for gas-turbine integration. The developed volumetric receiver with a diameter of 1500 mm and thermal power of 1.47 MW_{th} was able to heat up the air to 1000 °C (with solar shares up to 80%). The quartz window of the SOLTREC receiver was an improved version of that of the SOLGATE. With this new prototype, the authors studied the performance and cost reduction potential of the SOLTREC receiver. In 2016, Korzynietz et al. [8] presented the obtained results of the first megawatt scale solar-hybrid plant (SOLUGAS project) with a solarized GT in San Lucar la Mayor (Spain) operated for more than 1000 h. The solar receiver was designed using metallic tubular receiver technology and reached temperatures up to 800 °C. The plant used the GT system MercuryTM 50 of 4.6 MW with an efficiency of 39% and 69 heliostats. The air was preheated up to 800 °C in the solar receiver, and then, if necessary, cooled down to the maximum temperature tolerable