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Parametric analysis and optimization of a solar assisted gas turbine

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ABSTRACT

The objective of this study is to analyze and optimize a solar assisted gas turbine system. Parabolic trough collectors are used in order to supply a part of the demanded heat input, reducing the natural gas consumption and leading to an environmental friendly system. Emphasis is given in the pressure losses in the collector field loop which reduce the pressure level in the turbine inlet, leading to lower electricity production. In the first part of this study, the gas turbine and the collector field are investigated separately and in the second part, the solar assisted gas turbine is investigated parametrically and it is optimized. In the optimization part, a multi-objective optimization is performed by setting as goals the minimization of the collector area, of the fuel consumption and of the inversed electricity production. The final results proved that 1050 collector modules lead to 0.3389 kg/s natural gas consumption and to electricity production equal to 14.81 MW_{el}. This optimum solution leads to 64% fuel savings with a 2.8% penalty on the produced electricity. The system is analyzed in steady state conditions with the Engineering Equator Solver (EES).

1. Introduction

The worldwide energy consumption has increasing rate the last years because of the population growth, the industrial development and the new lifestyle trends [1–3]. Simultaneously, the fossil fuel depletion and the environmental problems caused by the carbon dioxide emissions indicate the need of using renewable and alternative energy sources [4,5]. Solar energy seems to be a promising way for substituting fossil fuel partially, producing cleaner and in many cases cheaper energy [6,7]. The high availability of solar energy and the great range of application which can use this energy source, make the utilization of solar energy vital for our society.

Solar energy can be utilized by solar collectors which are devices where the incoming solar energy is captured and it is transformed to useful energy in thermal collectors or in electricity in photovoltaic panels. The solar energy utilization can be applied in the building sector for domestic hot water production, space heating and space cooling with sorption machines, as well as in industrial sector for heat production is chemical and other processes [8]. Moreover, solar energy can be utilized as the heat source in thermodynamic cycles for electricity production and in cogeneration, trigeneration or poly-generation plants [9,10]. In low temperature applications, flat plate collectors and evacuated tube collectors are the most usual collectors. In high temperature levels, concentrating technology is usually used with parabolic trough collectors (PTC), linear Fresnel collectors and solar dish collectors to be the most usual devices [11–14]. PTC is the most mature technology among them and at this time there are numerous applications where these collectors operate.

The conventional power plants produce electricity with Rankine or Brayton thermodynamic cycle [15], while newer and efficient plants use combined cycles [16]. These power plants are usually characterized from high power levels where the fossil fuel consumption is huge. Solar energy utilization in these plants can lead to great reduction in fuel consumption or to totally renewable energy systems. Moreover, Stirling engines coupled with solar dish concentrators gain more and more attention the last years, but these systems are preferred in isolated areas [17,18].

The use of solar collectors in combined power cycles have been studied by many researchers. More specifically, they have investigated the use of solar collectors in the heat recovery system in order to increase the system performance. Montes et al. [19] examined the use of a PTC field in combined cycles for Almeria and Las Vegas climate conditions. They examined two configurations; the first one is a conventional combined cycle while the in other the solar collectors produce steam directly. The final results proved that the conventional system is most suitable for Las Vegas, while the system with direct production is the best choice for Almeria. Mokheimer et al. [20] examined the use of various solar technologies in combined cycles. They examined the use of PTC,

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Nomenclature

A	area, m^2
C_r	concentration ratio, –
c_p	specific heat capacity under constant pressure, J/kg K
D	diameter, mm
E	exergy flow, W
f	focal length, mm
f_r	friction factor, –
F	objective function –
G_b	solar beam radiation, W/m^2
h	specific enthalpy rate, W/m^2K
h_{ca}	convection coefficient between cover and ambient, W/m^2 K
Hu	lower heating value, J/kg
k	thermal conductivity, W/m K
L	tube length, mm
M	molecular weight, kg/kmol
m_a	air mass flow rate, kg/s
m_B	fuel mass flow rate, kg/s
m_g	gas mass flow rate, kg/s
N_P	parallel series, –
N_{PTC}	total number of modules, –
N_S	modules in series, –
Nu	mean Nusselt number, –
p	pressure, bar
P_C	work in compressor, MW
P_{el}	electricity production, MW
Pr	Prandtl number, –
P_T	work in turbine, MW
Q	heat flux, W
R	air gas constant, J/kg K
R_C	gas constant, J/kmol K
Re	Reynolds number, –
T	temperature, K
u	working fluid velocity, m/s
W	width, mm

Greek symbols

ε	emittance, –
γ	heat capacity ratio, –
ΔP	pressure drop, kPa
η	efficiency, –
λ	air ratio, –
μ	dynamic viscosity, Pa s
μ_α	stoichiometric air-fuel ratio, kg_{air}/kg_{fuel}
π_c	compressor pressure ratio, –
$\pi_{c,opt}$	optimum compressor pressure ratio, –
ρ	density, kg/m^3
σ	Stefan–Boltzmann constant [$=5.67 \cdot 10^{-8}$ W/m^2 K^4]

Subscripts and superscripts

a	aperture
abs	absorbed
am	ambient
c	cover
ci	inner cover
co	outer cover
col	solar collector
el	electrical
el, max	maximum electrical
ex	exergetic
fm	mean fluid
GEN	generator
in	inlet
is, C	isentropic in compressor
is, T	isentropic in turbine
loss	losses
m	mechanical
max	maximum
min	minimum
opt	optical
out	outlet
r	receiver
ri	inner receiver
ro	outer receiver
s	solar
s, tot	total solar
sun	sun
th	thermal
u	useful
u, tot	total useful

Abbreviations

EES	engineer equator solver
Goal	optimization goal
LFR	linear fresnel reflector
PTC	parabolic trough collector

linear Fresnel reflectors (LFR) and solar tower, as well as the conventional system. The final results proved that PTC and LFR are the most sustainable solutions for Saudi Arabia. Baghernejad et al. [9] investigated a trigeneration system which includes gas turbine, water/steam Rankine cycle, PTCs and absorption chiller. They optimized the suggested system with exergoeconomic criteria and the final results lead to a total exergetic performance close to 56%. Amelio et al. [21] also examined the use of solar collectors in a combined cycle, but they used the solar field as an assisting heat source in the gas turbine for reducing the fuel consumption in the combustion chamber. The final results showed 22% reduction in the fuel consumption when the system operates at nominal conditions, and 15.5% reduction on an annual basis.

In this direction, many researchers examined the use of solar energy in the gas turbines in order to reduce the fuel consumption or to eliminate it. Parabolic trough collectors, solar dish collectors and solar towers are the main technologies that have been examined in the majority of the literature studies. Santos et al. [22] conducted a detailed study of a solar assisted gas turbine system. They gave emphasis in the design of the gas turbine, while a general model was applied for the solar collector technology. Their results proved that the hybridization of a gas turbine with solar energy is beneficial leading to reduced fuel consumption and to lower carbon dioxide emissions. Klein et al. [23] investigated the use of a solar tower in a gas turbine with recuperator and storage system. According to their results, the storage efficiency reached to 88% and the utilization factor of 85% was achieved. Barigozzi et al. [24] also investigated the use of a heliostat field with a gas turbine. They concluded that the fuel consumption of the system can be reduced but there is a decrease in the power production; something that has to be taken into account in the system design.

Aichmayer et al. [2] performed a preliminary study of a micro gas turbine coupled with a solar dish collector. They concluded that this system can be beneficial and sustainable in the future. However, they stated that the most difficulties exist in the volumetric receiver, where the safety margin was calculated to 16%. Le Roux et al. [25] performed first and second law analysis in an open-cavity tubular solar receiver for a small-scale solar thermal