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Modeling hybrid solar gas-turbine power plants: Thermodynamic projection of annual performance and emissions

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ABSTRACT

The annual performance, fuel consumption and emissions of a hybrid thermosolar central tower Brayton plant is analyzed in yearly terms by means of a thermodynamic model. The model constitutes a step forward over a previously developed one, that was satisfactorily validated for fixed solar irradiance and ambient temperature. It is general and easily applicable to different plant configurations and power output ranges. The overall system is assumed as formed by three subsystems linked by heat exchangers: solar collector, combustion chamber, and recuperative Brayton gas-turbine. Subsystem models consider all the main irreversibility sources existing in real installations. This allows to compare the performance of a real plant with that it would have in ideal conditions, without losses. Furthermore, the improved version of the model is capable to consider fluctuating values of solar irradiance and ambient temperature. Numerical calculations are presented taking particular parameters from a real installation and actual meteorological data. Several cases are analyzed, including plant operation in hybrid or pure combustion modes, with or without recuperation. Previous studies concluded that this technology is interesting from the ecological viewpoint, but that to be compelling for commercialization, global thermal efficiency should be improved (currently yearly averaged thermal efficiency is about 30% for recuperative plants). We analyze the margin for improvement for each plant subsystem, and it is concluded that, the Brayton heat engine, by far, is the key element to improve overall thermal efficiency. Numerical estimations of achievable efficiencies are presented for a particular plant and real meteorological conditions.

1. Introduction

During the last years, extensive research and development efforts have been devoted to use concentrated solar energy as heat source (at least partially) to generate electric energy. It constitutes a promising strategy to make use of renewable resources in order to reduce fossil fuel requirements and to limit the emission of greenhouse gases. Particularly, solarized gas-turbine power plants have been developed at different scales. From small-scale solar dish units for distributed generation in the range of kW [1–4], to central tower installations capable to produce several MW to the grid [5,6]. Apart from being easily scalable, gas-turbines can be combined with Rankine or other cycles, do not require too much water for operation, and are extremely versatile [6–10].

In central tower gas-turbine plants an heliostat field collects solar energy and then focus it to a tower with a central receiver that transfers the solar power to a working fluid that performs a Brayton-like cycle. These plants can work on a hybrid configuration, a combustion chamber burning usually natural gas is incorporated in order to get a turbine inlet temperature approximately constant [11,12]. This avoids the necessity to include storing devices in the plant and the power release to the grid is independent of solar irradiation fluctuations.

Experimental projects and prototypes developed up to date show that this technology is viable [13–16] and its interest from the ecological viewpoint is undoubted. Nevertheless, thermoeconomic studies reveal that improvements in plant efficiencies are required to produce electricity at competitive prices [17–19]. Thus, active research lines on this objective are still imperative. Research objectives are being pursued at least by means of two different strategies. In the first one, detailed models for plant components and different arrangements are analyzed. This can include the design and optimization of the heliostat field, the central tower, the receiver, the thermodynamics of the diverse components of

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Nomenclature

A_a	aperture area of the collector
c_w	specific heat of the working fluid
f	solar share
G	direct solar irradiance
$\dot{m}$	mass flow rate of the working substance
$\dot{m}_f$	fuel mass flow rate
P	power output
$\lvert\dot{Q}_C\rvert$	heat losses at the combustion chamber
$\lvert\dot{Q}_H\rvert$	total heat-transfer rate absorbed from the working fluid
$\lvert\dot{Q}_{iHC}\rvert$	heat losses at the heat exchanger associated to the combustion chamber
$\lvert\dot{Q}_{HC}\rvert$	heat rate input from the combustion chamber
$\lvert\dot{Q}'_{HC}\rvert$	heat rate transferred from the combustion chamber to the associated heat exchanger
$\lvert\dot{Q}_{HS}\rvert$	heat rate input from the solar collector
$\lvert\dot{Q}_{iHS}\rvert$	heat losses at the solar receiver
$\lvert\dot{Q}'_{HS}\rvert$	heat rate transferred from the solar collector to the associated heat exchanger
$\lvert\dot{Q}_l\rvert$	losses associated to heat transfers in the solar field
$\lvert\dot{Q}_L\rvert$	heat-transfer rate between the working fluid and the ambient
Q_{LHV}	lower heating value of the fuel
$\lvert\dot{Q}_o\rvert$	optical losses at the solar subsystem
r_e	fuel conversion rate
r_p	overall pressure ratio
T_{HC}	working temperature of the combustion chamber
T_{HS}	working temperature of the solar collector
T_L	ambient temperature
T_x	working fluid temperature after the heat input from the recuperator
$T_{x'}$	working fluid temperature after heat input from the solar collector
T_y	working fluid exhaust temperature
T_3	turbine inlet temperature
U_L	effective conduction-convection heat transfer parameter
α	effective emissivity
η	overall thermal efficiency
η_C	combustion chamber efficiency
η_H	thermal efficiency of the Brayton heat engine
η_S	solar collector efficiency
η_0	optical efficiency
ε_{HC}	combustion chamber heat exchanger effectiveness
ε_{HS}	solar collector heat exchanger effectiveness
ε_L	cold side heat exchanger effectiveness
ε_c	isentropic efficiency of the compressor
ε_r	recuperator effectiveness
ε_t	isentropic efficiency of the turbine
γ	adiabatic coefficient of the working fluid
ρ_H	irreversibilities due to pressure drops in the heat input
ρ_L	irreversibilities due to pressure drops in the heat release

the heat engine performing the thermal cycle and even the fluid dynamics of the gas in the turbine equipment. In this framework detailed and precise numerical calculations can be made with the help of commercial simulation tools or with software developed by the research groups [20–23]. However, it is not easy to extract direct physical information about the main losses sources in the plant and to plan global strategies for the optimization of the plant design and operation as a whole. Additionally, the consideration of fluctuating meteorological conditions it is not straightforward.

An alternative strategy is to develop a theoretical model for the overall plant, reducing the number of parameters, hence allowing a simplified and realistic picture of plant operation and to estimate its performance records. This standpoint is specially interesting for optimization, at least to provide a first order guideline for overall plant design in order to accomplish an optimum performance [24–28].

Optimization studies are divided in single-objective or multi-objective. In single-objective optimization works each objective or figure of merit is stated in terms of the model parameters and then optimized with a simple mathematical procedure. Model variables are related to the particularities of the thermodynamic cycle followed by the working fluid and to the losses or irreversibilities. Objective functions can mainly incorporate thermodynamic, ecological or thermoeconomic ingredients [25,26,29–31]. On the other side, multi-objective techniques intend to propose optimal combinations of parameters leading to a good compromise for different objectives. Specific mathematical techniques are required to generate different configurations of variables with evolutionary algorithms, non-dominated combinations for the considered objectives, and to make decisions for electing a reduced number of plausible combinations of parameters [27,32–35].

The aim of this work is to locate the bottlenecks in the overall efficiency of this kind of plants. This is, from our viewpoint, a key step in the development of future generations of efficient hybrid thermosolar central tower installations. A theoretical thermodynamical model software was previously developed by our group [24]. It is implemented in Mathematica® and has been validated at design point conditions by comparison with measures from a real installation [24,36]. The model has been enhanced to consider seasonal and meteorological fluctuations in order to analyze realistic yearly averages. In this framework, the subsystems constituting the plant are clearly identified and the main irreversibility sources modeled and quantified. The model is general and susceptible to be applied to different scale installations, and also to different locations and meteorological constraints. It can incorporate oscillations on solar irradiance and external temperature, so the curves of plant performance along a day or seasonal mean values can be estimated [36]. These points make the model specially suited for optimization purposes. A theoretical framework was previously developed for purely solar gas turbines (non-hybrid configuration) [37,38]. Special emphasis was laid on the effect of recuperation on the overall thermal efficiency. A multiobjective optimization procedure was also performed in order to provide feasible intervals for the main plant parameters for an optimum plant design [32].

In this paper, the model is applied to a particular plant recently developed near Seville, Spain. Real yearly averaged data for direct solar irradiance and ambient temperature at such particular location are considered. This gives reliable numerical information, since in several previous works fixed values for solar irradiance and ambient temperature (design point conditions) are taken, sometimes not enough close to real annual mean values. Several plant configurations (with or without recuperation) and operation modes (pure combustion mode or hybrid functioning) are surveyed. Numerical values for thermal and fuel conversion efficiencies are presented as well as for solar share (defined as the ratio between the solar heat input and the total one) and estimated fuel consumption and emissions. The importance of losses and the margins of improvement for each plant subsystem are analyzed.