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Thermodynamic Simulation of a Hybrid Brayton Thermosolar Plant

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Abstract.

We present a purely thermodynamic model for the prediction of the performance records of a solar hybrid gas turbine power plant. Variable irradiance and ambient temperature conditions are considered. A serial hybridization is modeled with the objective of keeping an approximately constant turbine inlet temperature, which thus delivers an stable power output. The overall plant thermal efficiency depends on the efficiencies of the involved subsystems and the required heat exchangers in an straightforward analytical way. Numerical values for input parameters are taken from a central tower field recently developed near Seville, Spain. Real data for irradiance and external temperature are taken in hourly terms. The curves of several variables are presented for representative days of all seasons: overall plant efficiency, solar field thermal efficiency, solar share, fuel conversion rate, and power output. The fuel consumption assuming natural gas fueling is estimated, as well as greenhouse emissions. The model can be applied to predict the daily and seasonal evolution of the performance of real installations in terms of a reduced set of parameters. This can contribute to improve the design of this kind of facilities in order to get better performance and so better economical records.

Key words

Thermosolar gas-turbines, Hybrid plants, Thermodynamic model, Variable solar irradiance, Seasonal evolution.

1. Introduction

The necessity to diversify the energy sources in power generation and to look for renewable ones is undoubted. For this reason in the last years a big effort has been done in the development of prototypes and experimental plants in order to investigate the viability of thermosolar hybrid Brayton cycle plants.
Thermosolar technology is one of the main ways of solar energy exploitation. A working fluid, usually air, is preheated by concentration solar energy, before entering a combustion chamber. Then the fluid performs a thermodynamic cycle (in this case, a Brayton cycle), generating electrical energy indirectly. In this way fossil fuel and the associated emissions are reduced. At the same time an approximately constant power supply to the grid is obtained, avoiding the use of storage systems. Another advantage of these facilities is their low water consumption, which makes them suitable for electrical generation in arid regions [1].
Efforts done during last years in R+D show the technical viability of these plants, but they also reveal that it is necessary to improve their efficiency, in order to generate electricity at competitive prices.
Apart from R+D projects, prototypes, and experimental installations, several research works have been published in the last times. Some of them make use of commercial simulation environments (TRNSYS®, Thermoflex®, EES®, etc.) or in-house developed software, which allow a detailed description of all plant components and specific calculations on the solar subsystem. 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.
Thermodynamic analyses can provide an integrated point of view of all subsystems and their importance in the overall efficiency. Moreover, they help to predesign future generations of plants based in this concept because their flexibility to survey the adequate intervals of key parameters for optimal plant operation.
There are several theoretical works that start from the ideal Brayton cycle and thereafter refinements are included in the analysis of the thermodynamics of the cycle in order to recover realistic output records. Usually, in these works, the model for the concentrated solar subsystem, although including the main heat transfer losses, is simple. This allows to obtain closed analytical expressions for thermal efficiencies and power output, and then check the model predictions for particular design point conditions, with fixed values of direct solar irradiance and ambient temperature. And in a possible step forward to suggest and guide optimization strategies.

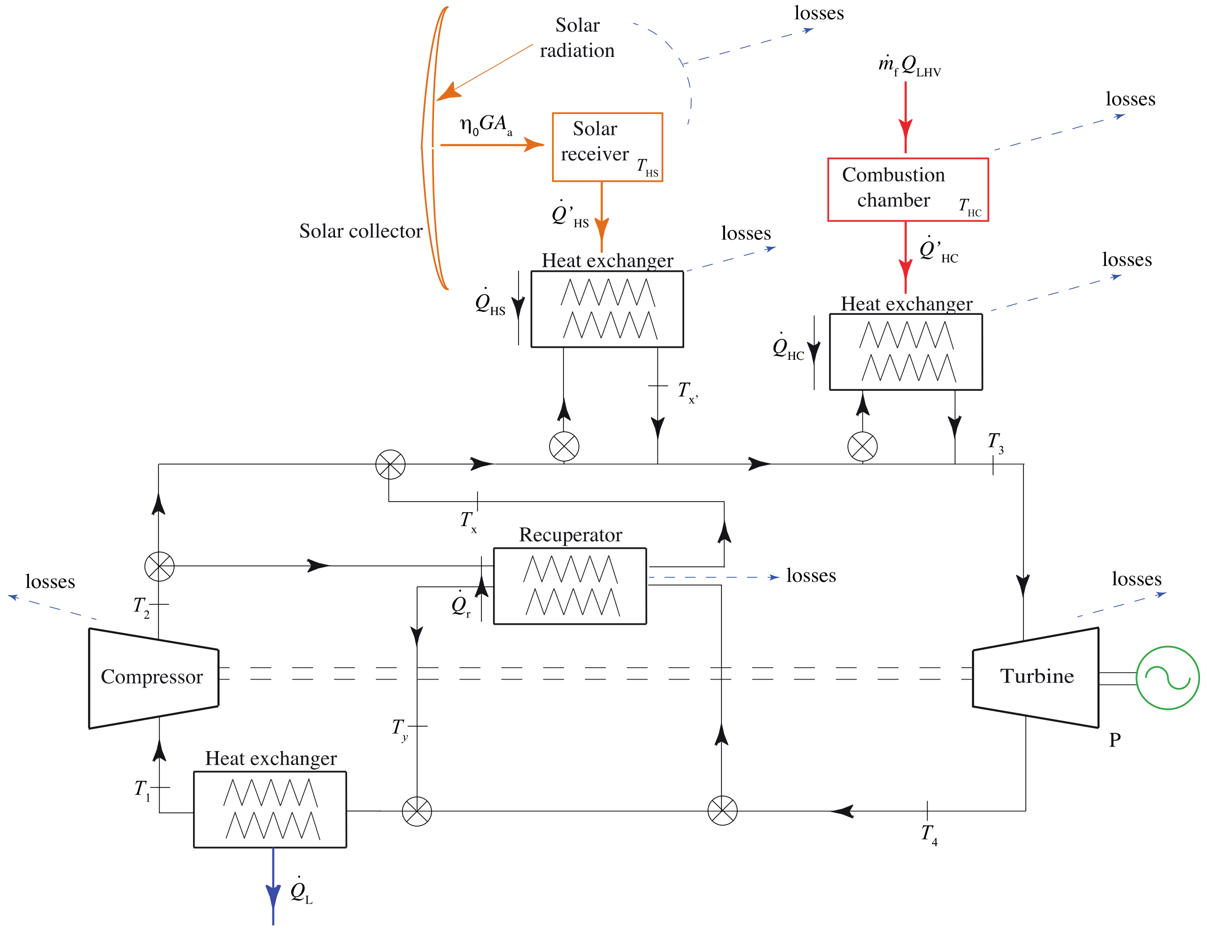

Fig. 1. Scheme of the thermosolar hybrid considered plant

2. Objetives

The main objectives of this work are aligned in the last modus operandi, but with a noticeable novelty, to develop a dynamic model that allows the incorporation of direct solar irradiance and ambient temperature fluctuations at a particular location. We shall present a thermodynamic model for a serial solar hybrid Brayton type plant working in recuperative configuration.

Predictions from our model are compared with data of a real plant developed for the Project SOLUGAS, although it could be applied to any other similar plant.

SOLUGAS is a R+D project, developed by Abengoa company, placed in Sanlúcar la Mayor (Seville) [2] and it constitutes one of the most important ongoing projects about hybrid central receiver systems at a pre-commercial scale. The project intends to generate a stable power output around 5 MW.

Another important goal is to simulate and predict plant's performance over time. Seasonal evolution and output parameters daily curves are studied. In addition, some estimations about fuel consumption and polluting gases emissions associated with energy production are made.

3. Thermodynamic Model

A thermodynamic plant study is presented, based on Sánchez Orgaz et al.'s model (Sánchez-Orgaz, 2010, Sánchez-Orgaz, 2015) and on Olivenza et al.'s [3]. This study is restricted to Concentration Centrals and, especially, to Central Receiver Systems (CRS) [4]. These plants have three main elements: the heliostat field, formed by lots of mirrors that reflect and focus solar radiation to the receiver. This (the receiver) is the second element, it is located at the top of the tower and converts solar radiation into heat at high temperatures. And, finally, the power conversion system, also placed in the tower, which transforms thermal energy into electrical energy.

The model, in which refers to the thermodynamic cycle, starts from a closed Brayton cycle however incorporating the main losses and irreversibility sources: non-ideal turbine and compressor, pressure decays, heat exchangers, heat transfer losses in the solar collector, combustion inefficiencies, etc. (see Fig. 1).

For the solar subsystem a simple model, which takes into account heat losses in the solar collector due to radiation and conduction/convection terms, was assumed. The optical efficiency is an averaged effective factor.

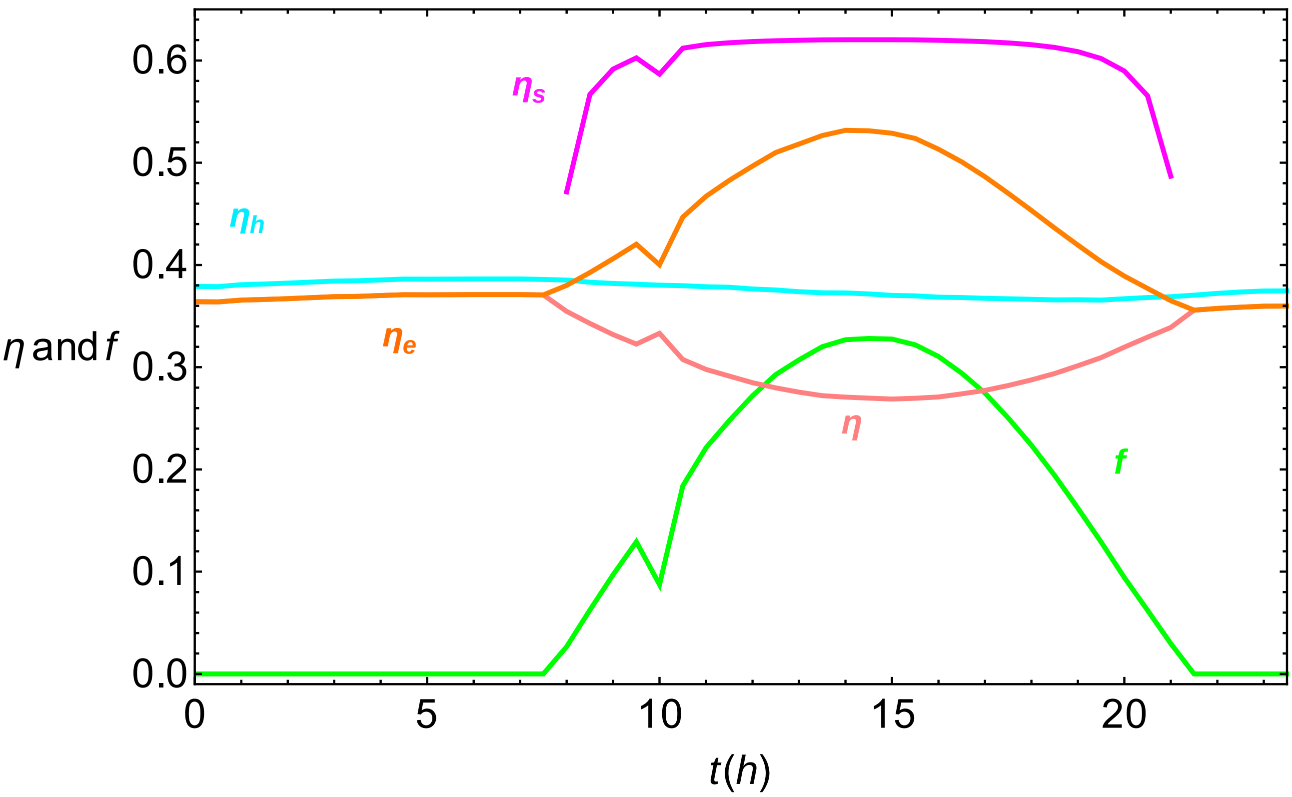

Figure 2. Hourly evolution of plant efficiencies (20 June 2013): solar collector efficiency (η_s), thermal efficiency of thermal Brayton engine (η_h), fuel conversion rate (η_e), overall thermal efficiency (η) and solar share (f).

The overall plant efficiency was obtained as a combination of the efficiency of the plant subsystems (solar η_s, combustion η_c, and gas turbine η_h), the effectivenesses of the heat exchangers connecting subsystems (ϵ_{HS} for solar subsystem and ϵ_{HC} for combustion subsystem) and the solar share fraction (f). Thereby the overall efficiency of the whole system (η) is given by:

$$\eta = \eta_h \eta_s \eta_c \left[\frac{\epsilon_{HS}\, \epsilon_{HC}}{\eta_c f\, \epsilon_{HC} + \eta_s\, (1-f)\, \epsilon_{HS}} \right] \qquad (1)$$

The model allows a direct calculation of the dynamic plant operation, with variable direct solar irradiance and variable external temperature.

4. Results

The SOLUGAS project in Spain was elected as prototypical installation to compare model predictions with. Comparison of model's prediction with respect to output parameters of the experimental plant are very satisfactory (see Olivenza *et al*. 2015 for details).

After the validation in stationary conditions, real seasonal data at the plant location for solar irradiance and ambient temperature were incorporated to our computational scheme and taking representative days for each season, results are presented. Curves of global plant thermal efficiency, efficiencies of the subsystems, solar share, power output, and fuel conversion rate can be drawn in hourly basis.

Dynamic behavior of the efficiencies is represented in Fig. 2. The efficiency of the heat engine (η_h) varies very little during the day, it essentially depends on the external temperature. On the contrary solar efficiency changes especially at dawn and in the evening (η_s is not defined at night). Overall efficiency (η), fuel conversion rate (η_e)

Table 1. Comparative table of estimated fuel consumption rate in different seasons with *and* without solar contribution

Consumption	Winter	Spring	Summer	Autumn
Combustion mode (ton/day)	21.9772	21.9018	21.7503	21.6883
Hybrid mode (ton/day)	21.0981	20.2767	19.1960	20.0886
Fuel saving (%)	4.00	7.41	11.74	7.38

and solar share (f) are approximately constant overnight. The latter two are maximal in the middle of the day, unlike overall efficiency, which is minimum at that time. In Figure 3 the evolution of the fuel consumption rate can be seen. When solar irradiance received is maximum (central hours), fuel consumption is minimum because natural gas required to get the same power is lower. And also, explicit data for fuel consumption rate are presented in Table 1. The differences among fuel consumption are directly transferred to pollution emissions. As an illustration we have in Fig. 4 a bar diagram with the estimated emissions of the main greenhouse gases in real units: CO_2, CH_4, and N_2O. The data in the figure should be taken as a guide, because each plant could have particular technologies to reduce emissions or CO_2 capture mechanisms.

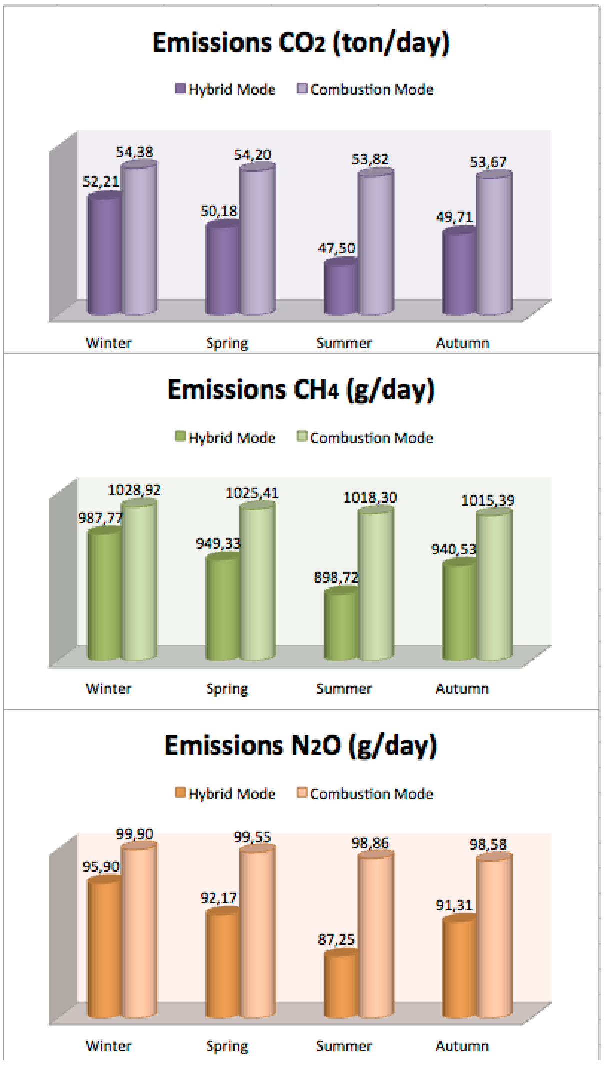

Figure 4. Real units estimation of greenhouse emissions from the considered model.

5. Conclusions

In this paper we have modeled a solar hybrid power plant based on a gas turbine following a closed Brayton cycle.

Main advantages of these kind of plants are: less fuel consumption, reduction of pollutant emissions and low water consumption associated to Brayton cycles (in comparison with other cycles, like the Rankine ones, which requires higher water consumption). These plants are placed in locations where the solar irradiance is high, usually in arid regions, where water availability is scarce, so Brayton cycles seems in advance a good option.

The main emphasis was laid on the thermodynamic model of the closed Brayton cycle, where all the main irreversibility sources were considered avoiding to introduce a huge number of parameters and allowing to obtain analytical equations for all the thermal efficiencies and power output.

Moreover, the utilization of meteorological databases allows to simulate the plant in particular locations and for realistic weather conditions.

Results show that a recuperative plant working in hybrid mode has a fair potential to generate a stable power output of about 5 MW with reduced fuel consumption and reduced greenhouse emissions for a location with

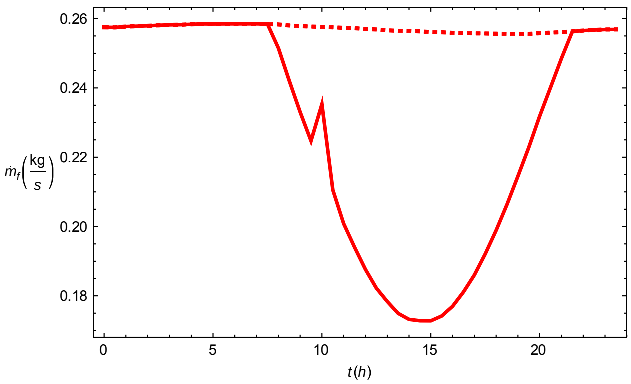

Figure 3. Evolution with time of the fuel consumption rate, $\dot{m}_f$, supposed natural gas (20 June 2013). Solid line refers to the hybrid operation mode and dashed one to the pure combustion mode.

favorable insolation conditions. Likely, the high temperature of the working gas at the recuperator exit, make these plants susceptible to be combined with a bottoming cycle, in order to take advantage for instance of residual heat through heat recovery steam generators (HRSG) and increase global combined efficiency.
Hybridization scheme is simple so the framework presented here should be considered as a starting step for the dynamic simulation of this kind of plants within thermodynamic basis. The implementation of more sophisticated models for the solar subsystem is feasible. It could include daily and seasonal variations of optical and other losses and the particularities of the solar collector field. Also more elaborated models for the involved solar receiver and other heat exchangers could be considered as well as

optimization analyses based on thermoeconomic criteria for particular plants.

Acknowledgement

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References

[1] O. Behar, A. Khellaf, K. Mohammedi, (2013). A review of studies on central receiver solar termal plants. Renew. Sust. Energ. Rev. 23: pp 12-39.

[2] R. Korzynietz, M. Quero, R. Uhlig, (2012) SOLUGAS-future solar hybrid technology, Tech. Rep., SolarPaces. http://cms.solarpaces2012.org/proceedings\\/paper/7ee7e32ece8f2f8e0984d5ebff9d77b

[3] S. Sánchez-Orgaz, A. Medina, A. Calvo Hernández (2010), Thermodynamic model and optimization of a multi-step irreversible Brayton cycle Energ. Conv. Manage., 51, 2134-43; D. Olivenza-León, A. Medina, A. Calvo, (2015), Thermodynamic modeling of a hybrid solar-turbine power plant. Energ. Conv. Manage. 93: 435-447.

[4] M. Romero, R. Buck, E. Pacheco, (2002), An Update on Solar Central Receiver Systems, Projects, and Technologies. Transactions of the ASME, 124: 98