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Towards a More Efficient Generation of Central Tower Hybrid Thermosolar Gas Turbine Power Plants

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Abstract. In this communication we present a novel model for the pre-design of hybrid thermosolar Brayton plants. The plant is described as a whole allowing to predict overall performance. It is considered as composed by three subsystems: solar field and receiver, combustion chamber, and power block. Overall efficiency is obtained as a combination of subsystems efficiencies. Solar field efficiency is computed in detail for any location and any meteorological condition. Most important losses are considered, including shadowing, blocking, spillage, atmospheric attenuation, and so on. A simplified model is taken for the thermal losses in the receiver, including radiation losses. For the power block a detailed thermodynamic model based on an irreversible Brayton cycle is assumed. Multi-stage compression and expansion and regeneration are included in the model. All these ingredients allow for obtaining precise estimations of plant performance at off-design conditions as diary power and efficiency curves, consumption, emissions, and fuel conversion efficiency, in terms of a relatively reduced number of parameters with clear physical meaning, avoiding complex and over-detailed computations. Annual averages are also susceptible to be computed. And so, sensitivity analysis and optimization suggestions can be performed in the framework of the model. Model predictions for several subcritical working fluids (including air, nitrogen, carbon dioxide, and helium) and different plant configurations, are analyzed. The importance of considering the plant as a whole, *i.e.*, to choose the main parameters of the gas turbine (operation temperature, pressure ratio, number of stages, etc.) in concordance to the details of the solar subsystem (concentration ratio, operation temperature of the receiver, etc.) is highlighted.

INTRODUCTION

Hybrid thermosolar plants constitute a promising technology in the transition to diversified, clean, and efficient energy production strategies [1]. In this contribution a central tower concentrating solar power (CSP) plant is hybridized in series with a combustion chamber burning natural gas. This system allows an almost stable electric energy production in the scale of a few megawatts. Although not completely free of pollutant emissions, these plants allow for a predictable energy production (which is always attractive from the viewpoint of economic balances) with reduced emissions and remarkable performance records. In the particular case that the power unit is a Brayton gas turbine other advantages are added: very reduced water consumption (that is a definite point in arid regions with good insolation but poor hydric resources), reliability, scalability, and wide operation experience [2].

During the last times several projects have been conducted in order to check the feasibility of the hybrid thermosolar Brayton technology and the economic issues associated to the price of the produced electricity. Some prototype plants have been built and analyzed, several of them in Spain (as the recent project SOLUGAS [3]). In summary, all these developments have arrived to similar conclusions: the technology is feasible, but there are some open lines to work along in order to achieve competitive prices. Among others two lines are of greater importance. First, the development of solar receivers capable to work under very high temperatures (above 1000 K) in an

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efficient and unfailing way. And second, to improve the efficiency of the thermodynamic cycle the power unit follows, which greatly determines overall plant performance and so, the levelized cost of the produced electricity.

This work is focused on the last point. A mathematical simulation model that our research group developed during the last years will be aimed to search appropriate working fluids and thermodynamic configurations for the Brayton cycle the plant develops [4]. The model includes a detailed calculation of the optical efficiency of the heliostat field, estimations of the heat losses in the receiver, and a flexible thermodynamic model for the heat engine that considers all the main loss sources in this kind of plants. The plant is considered as a whole, so any subsystem (heliostat field, receiver, heat exchangers, power unit, etc.) influences the overall plant behavior. Another advantage of the framework is that dynamic calculations (for instance, curves in hourly terms) can be estimated, although in this contribution only results for design point conditions will be shown.

MATHEMATICAL MODEL AND NUMERICAL IMPLEMENTING

In this section the main assumptions of the mathematical model developed to simulate the overall plant are briefly described. The whole system is considered as an assembly of three main subsystems: the solar one (heliostat field and solar receiver), the main combustion chamber, and the power unit. The latter is considered as a multi-stage gas turbine with an arbitrary number of compressors, N_c, and an arbitrary number of turbines, N_t. The links between subsystems are the required heat exchangers. In ref. [4] detailed explanations about the mathematical formalism can be found. The overall thermal efficiency, η, can be expressed as the product of the thermal efficiencies of the subsystems and a factor coming from the heat exchangers. Explicit equations can be found in [4].

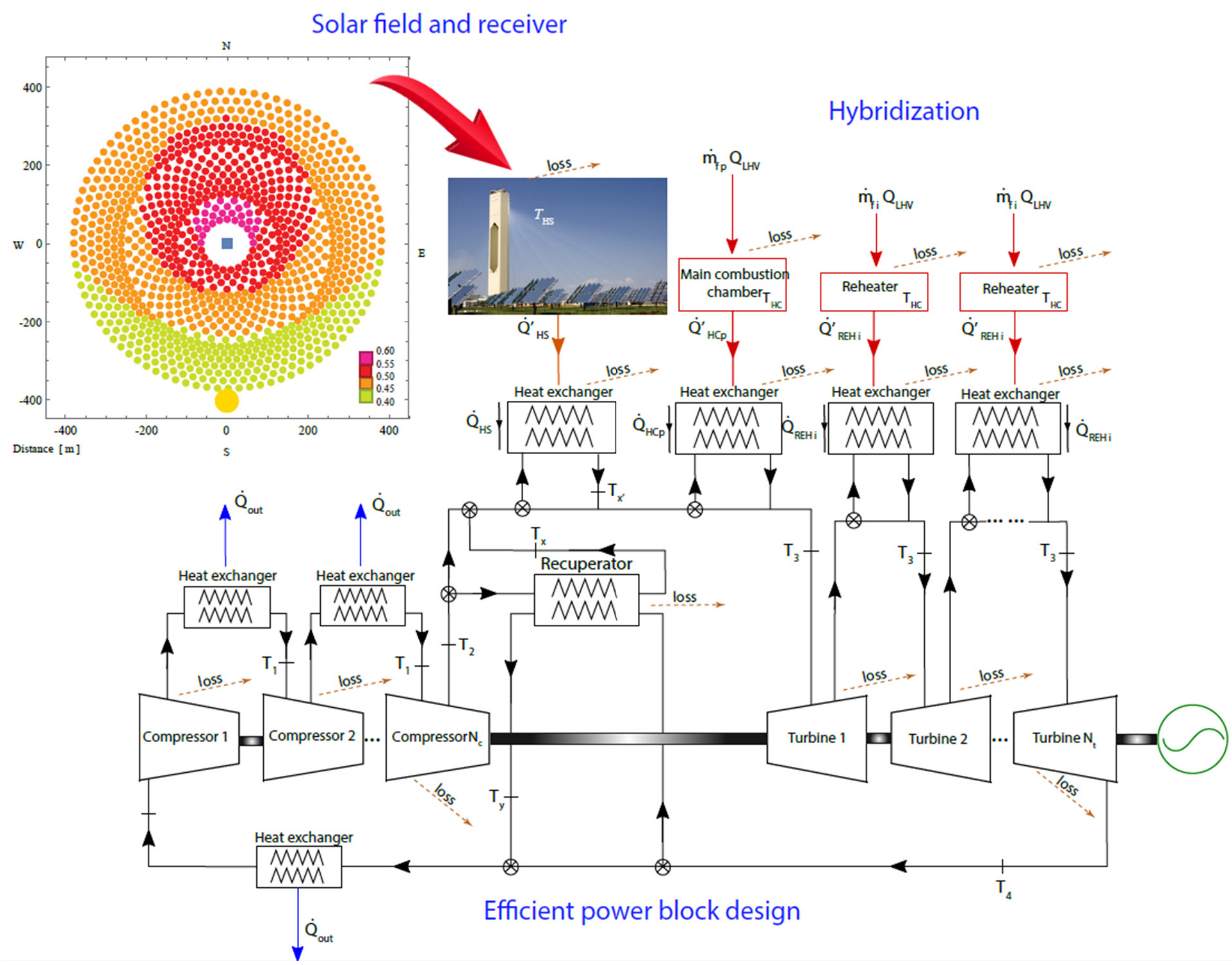

FIGURE 1. Component diagram of the whole plant including solar subsystem with solar field efficiency map, hybridization scheme and multi-step compression and expansion.

At difference with [4], where an average optical efficiency, η_0, was assumed, in this work detailed calculations in order to obtain η_0 for a particular geometry and size of the heliostat field have been developed. Heliostats have been placed in the solar field in different rows and considering all the space they can occupy during the solar tracking together with a safety distance. The optical efficiency of each heliostat is defined as a product of several losses factors. The main factor of this optical efficiency is the cosine effect ($\cos \omega$), which accounts for the cosine of the Sun radiation's incident angle in the heliostat surface and it is calculated by means of a study of the geometry of the Sun-heliostat-receiver system [5]. Blocking effect (f_b) represents the energy lost due to the reflection of some part of the radiation coming from a back heliostat in an ahead one. On the other hand, the shadowing effect (f_{sh}) corresponds to the energy loss because of the shadow projected by a heliostat on another one. Both shadowing and blocking factors are also considered in the model, in this case as constant factors [5]. It is important to note that heliostats present an actual mirror reflectivity (ρ) that determines the amount of solar radiation that they can reflect towards the receiver [6]. When this solar radiation goes from the heliostat to the receiver, some part of it is absorbed by the molecules of the ambient air, so the attenuation (f_{att}) also results in an energy loss. And, finally, another important energy loss source is the spillage (f_{sp}) of the incoming radiation in the absorption area of the receiver [6]. Then, the global heliostat optical efficiency (η_0) is calculated as the average over all heliostats.

TABLE 1. Comparison between Thermoflex® data corresponding to Solar Titan 250-30000S gas turbine [7] and records from our model simulated in Mathematica®. (I) stands for input data and (O) for output records.

Variable	Thermoflex® data	Mathematica® simulation (our model)	Relative deviation (%)
Working fluid mass flow (kg/s)(I)	67	67	0
Overall pressure ratio (I)	23.4	23.4	0
Power output (MW) (O)	21.10	20.91	-0.89
Heat Rate (kJ/kWh) (O)	9256	9041	-2.33
Thermal efficiency (O)	0.389	0.398	2.37
Turbine inlet temperature (K) (O)	1450	1451	0.04
Turbine outlet temperature (K) (O)	736	758	2.95

The power unit, as mentioned before, is taken as a multi-stage gas turbine running a closed irreversible Brayton cycle (see Fig. 1). Irreversibility sources include: non-ideal compression and expansion processes, pressure decays in heat absorption and heat release processes, non-ideal heat exchangers, and losses in combustion processes. A detailed *T-S* diagram of the cycle considered can be found in [4] as well as the main hypothesis and mathematical developments. Four subcritical working fluids are considered to be analyzed: dry air, nitrogen, helium, and carbon dioxide. For all of them temperature dependent correlations for specific heats are considered (see [4] for details). As fuel, natural gas is assumed, although it is feasible to make predictions for other fuels, such as biogas.

TABLE 2. Values of the solar field parameters employed in the simulation [6,8].

Parameter	Value
Rows number	19
Visibility	23 km
Pointing	Simple
Height of the tower supporting the receiver	150 m
Height of the receiver	10.5 m
Diameter of the receiver	8.4 m
Height of each heliostat	10.95 m
Width-height ratio of each heliostat	1
Separation distance between adjacent heliostats	3.285 m
Minimum radius of the heliostat field	65 m
Standard deviation due to sun shape	2.51 mrad
Blocking factor	0.95
Shadowing factor	1
Actual mirror reflectivity	0.836

This thermodynamic model was validated by our group for the numerical parameters of SOLUGAS project [3,4]. However, the present model is validated by comparison with another real similar plant built by Torresol Energy in Fuentes de Andalucía (Sevilla): GEMASOLAR [8]. Output records are validated for the mono-stage case and taking dry air as working fluid. The main difference between this plant and our assumptions is the thermodynamic cycle itself: the steam turbine in GEMASOLAR is replaced by a gas one. And also a combustion chamber has been added for the hybridization with natural gas instead of employing the molten salt storage of GEMASOLAR. A second validation process has been carried out by using a commercial software (Thermoflex [9]). Table 1 contains a summary of results for the validation of the power unit. The adequate number of heliostats rows in the design point and, so, number of heliostats have been chosen by comparing with Thermoflex simulation's outputs (19 rows, 1037 heliostats). Meteorological data are chosen from Meteosevilla [10] for the design point (12:00h of 20 June 2013). Receiver and heliostats geometry and also numerical values of solar field plant parameters are taken from GEMASOLAR plant [8] and from Collado [6] (see Table 2).

ANALYSIS AND RESULTS

In this section the numerical results obtained within the model outlined before are presented. Three main points of interest are surveyed in relationship with the overall plant records: the type of working fluid performing the thermodynamic cycle, the number of compression/expansion stages in the gas turbine, and its overall pressure ratio. Figure 2 displays the overall plant thermal efficiency, η, in terms of the pressure ratio, r_p, for all the fluids considered. Single stage configurations are denoted with N=1 (in this case results for recuperative and non-recuperative plants are plotted), two-stage configurations with N=2, and so on. The limit case of an arbitrary large number of steps is also shown. This particular configuration is plotted as a way to show the eventual (unachievable) upper limit for the plant overall efficiency. For some particular values of r_p, the maximum temperature in the turbine could be exceeded (in the figure this is shown with dashed lines). From the figure, it is observed that globally He leads to considerable larger overall efficiencies when comparing different fluids. For instance, with N=2 overall efficiencies about 0.45 could be obtained for pressure ratios around 10. On the other side, CO_2, would give the lowest ones, even for high pressure ratios. For air and nitrogen and N=1, the non-recuperative configuration leads to better overall efficiencies over r_p=25. In all fluids, curves for N=1 displays a maximum in terms of r_p, while for multi-stage configurations curves increase monotonically with r_p (except for He).

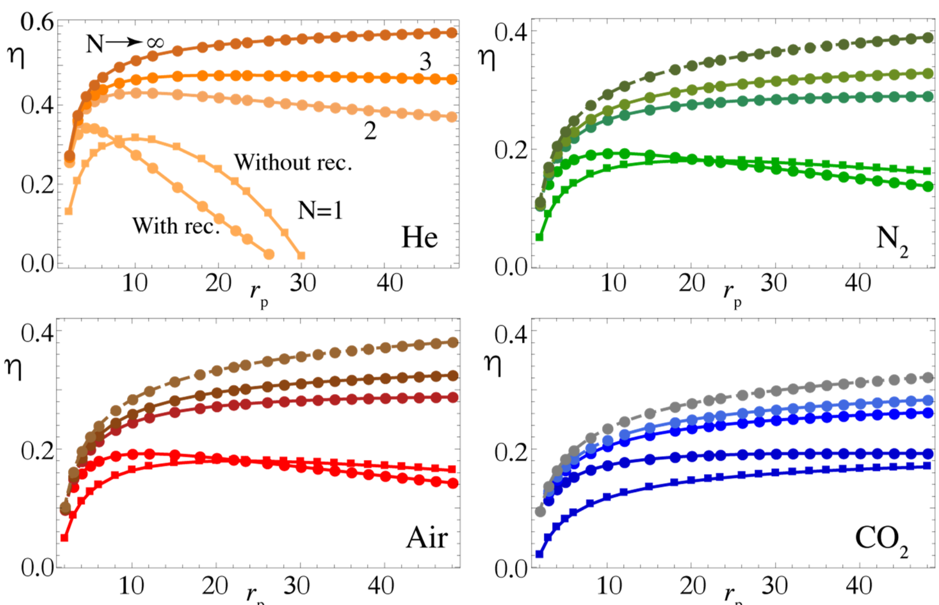

FIGURE 2. Overall thermal efficiency, η, of the hybrid thermosolar plant as a function of the overall pressure ratio, r_p. All the fluids considered are shown. Curves marked with circles correspond to recuperative plant configurations and those marked with squares to non-recuperative ones. Dashed lines between dots indicate that eventually too high temperatures in the turbine could be reached.

The fuel conversion rate, r_e, is plotted in Fig. 3. This variable is defined as the ratio between the power output and the heat input associated to fuel combustion, *i.e.*, has an economic significance in relation with the operation cost of the plant. For N_2, air, and CO_2, this parameter increases with the pressure ratio only for N=1 and a non-recuperative plant. In all other cases, curves monotonically decrease with r_p. This decrease is very rapid for low values of the pressure ratio, and then it remains almost unchanged. Largest values are found for CO_2. The case of He is different. The slope of the curves of r_e depends on the interval of pressure ratios, the number of stages and the existence or not of internal recuperation. For air and nitrogen the following conclusion could be achieved: for small pressure ratios (below approximately 25), the most interesting configuration from the viewpoint of r_e (or fuel consumption) would be a single stage recuperative one. For larger pressure ratios, improved r_e is obtained for a single stage non-recuperative layout.

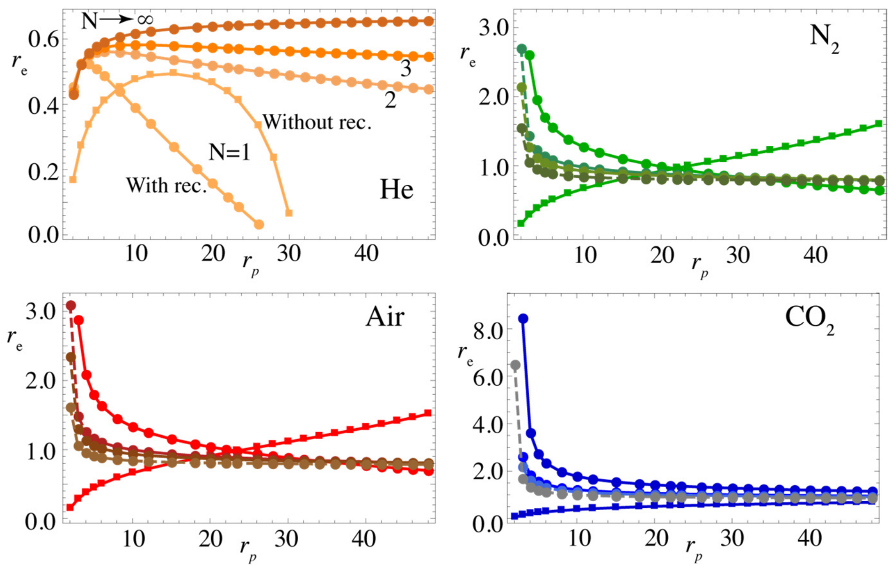

FIGURE 3. Fuel conversion efficiency, r_e, of the plant. Details as in Fig. 2.

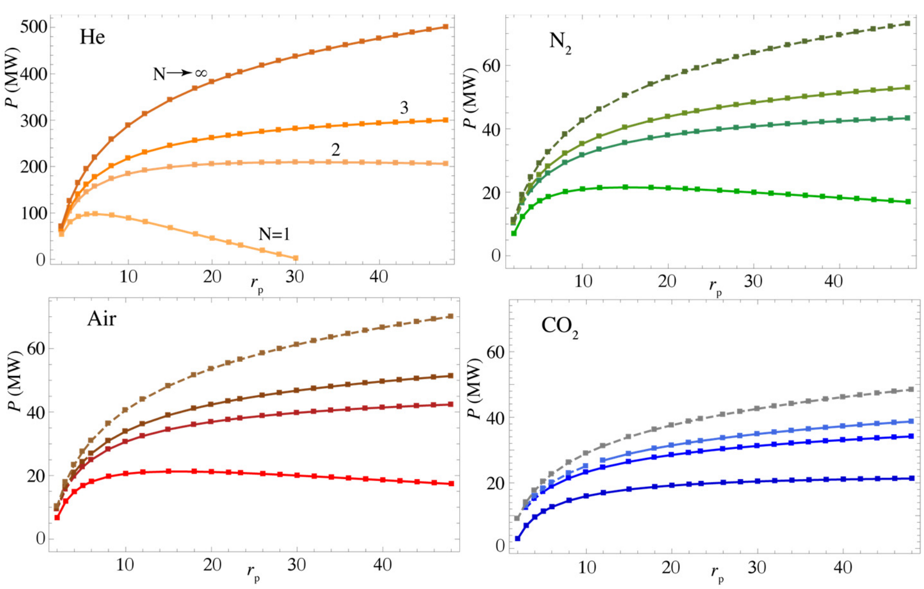

FIGURE 4. Power output, P, of the plant. Details as in Fig. 2.

The power output, P, is displayed in Fig. 4. It is much higher for He than for the other fluids, whichever value of the pressure ratio is considered. This is a consequence of the fact that the same working fluid mass flow is considered in all cases. Within this constraint, the power output is proportional to the constant pressure specific heat of the fluid, c_p. In the case of He, the average value of c_p in the temperature interval of interest is about 4.5 times higher than for the other fluids, and this is reflected in the numerical values of power output. With respect to the evolution with r_p, in all cases multi-stage configurations show an increasing power output with increasing r_p, towards an asymptotic limit at high pressure ratios. Higher power outputs are obtained with increasing number of compression/expansion stages. Compared to N_2 or air, CO_2 leads to smaller power output, provided that its average specific heat is similar to that of those fluids.

The solar share, f, *i.e.*, the fraction of heat input flow coming from solar resources is plotted in Fig. 5. It decreases with r_p for all fluids except for single stage configurations without recuperation. This means that with increasing pressure ratio more fuel consumption is required to reach the imposed turbines inlet temperature. Globally, the highest values are found for CO_2. In consequence, as commented before, the fuel conversion efficiency for this fluid is larger.

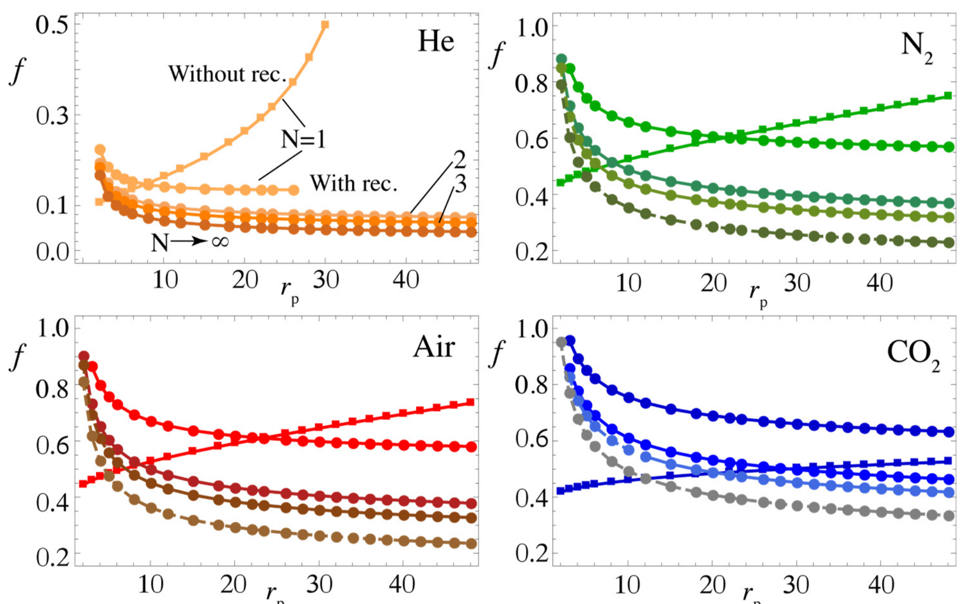

FIGURE 5. Solar share, f, of the plant. Details as in Fig. 2. In the case of He, curves are plotted in the interval or r_p leading to positive overall efficiency, η.

SUMMARY AND CONCLUSIONS

In this communication it was intended to summarize a framework developed in order to analyze the main parameters of the pre-design of future thermosolar central tower solar plants operating under hybrid gas turbine thermodynamic cycles. One of the aims of the framework is to consider the plant as a whole, avoiding an excessive number of parameters by identifying the most important ones in each subsystem. Special attention is devoted to the coupling between subsystems. These subsystems are the solar field and the receiver, the combustion chamber, and the thermodynamic power unit. The solar subsystem is considered in detail. The main optical losses for each heliostat are modelled in terms of the field size and geometry, its location, the heat losses in the receiver, and the particular solar and ambient conditions. Optical efficiency can be predicted at off-design conditions as a time dependent parameter. On the other side, a complete thermodynamic model for the power unit is also developed. The main irreversibility sources in closed gas turbine cycles are accounted for. The model is capable to predict the behavior of different subcritical working fluids and basic ingredients required to the pre-design of the power unit are also taken into account: recuperation possibilities and mono- or multi-stage configurations. With all these elements it is possible to simulate plant output records at on-design conditions and also at off-design ones. These output records depend on a reasonable number of parameters, thus allowing to identify the main bottlenecks in plant performance, to check the possibilities of different configurations, to develop sensitivity analysis, and to perform optimization studies.

Numerical predictions of the model were validated by comparison with an existing plant located at the south of Spain (GEMASOLAR, Torresol Energy) at particular solar and ambient conditions. Four working fluids for the gas turbine were surveyed (dry air, nitrogen, carbon dioxide, and helium). As target variable to analyze the output records it was used the overall pressure ratio of the gas turbine. Non-recuperative and recuperative configurations were analyzed, as well as multi-stage configurations with the same number of compression and expansion stages. Variables as the overall thermal efficiency, the fuel conversion efficiency, the power output, and the solar share were calculated in terms of the plant pressure ratio. In order to achieve the desired objectives a particular pressure ratio interval should be chosen, as well as, the incorporation or not of a recuperator and the number of compression/expansion stages. So, this kind of models can be a helpful tool to determine the most significant plant variables at a pre-design stage.

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