Working fluid effects on the performance of hybrid Brayton thermosolar plants

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Abstract. In this communication a general thermodynamic model for hybrid Brayton thermosolar plants is proposed. The model is flexible and capable to include multistage configurations and recuperation. During the last years was proved that this kind of plants is technically feasible but R+D efforts need to be done in order to improve its commercial feasibility. From the thermodynamic viewpoint it is necessary to increase its overall efficiency. A general model that allows to simulate recuperative or non-recuperative plants, with an arbitrary number of stages and working with different subcritical fluids is presented. Numerical results for multi-step configurations are compared with those for a reference experimental plant, developed during the last years near Seville. Different working fluids and several plant layouts are analyzed.

Key words

Thermosolar hybrid power plants, improved plant design, closed Brayton cycles, working fluids.

1. Introduction

In the last times several prototype facilities working on the so-called hybrid thermosolar Brayton concept have been developed [1]. In these power plants a central receiver collects solar energy through a solar field and transfers it as heat to a working fluid (usually pressurized air) that develops a Brayton-like thermodynamic cycle. This kind of installations may result interesting in geographical regions with good solar irradiance conditions and usually with scarce water resources. They operate in the scale of a few megawatts.

Hybridization comes from the fact that during poor irradiance conditions or during night a combustion chamber in the hot stream of the cycle can supply heat by burning for instance natural gas to guarantee an approximately constant power output rate. Although previous simulation and experimental results [2] show that the technology is attainable, it has been also demonstrated that better overall plant efficiencies are to be achieved in order to produce electricity at interesting prices from the commercial viewpoint. In this framework, our study in this communication is focused to propose novel thermodynamic plant configurations with the objective to reach better performance parameters. Furthermore, the influence of the working fluid will be surveyed. Dry air, nitrogen, carbon dioxide, and helium will be analyzed at subcritical conditions.

2. Thermodynamic Model

A gas-turbine power plant hybridized with a central tower solar concentration system is considered. An sketch of the whole system is depicted in Fig. 1. Briefly, the working fluid enters the first compressor at a temperature T_1, and exits the last one, N_c, at a temperature T_2. Between each pair of compressors, an intercooler ensures that the inlet temperature is always T_1. After the last compressor the heat input in the power unit is divided in three succeeding steps: i) A recuperator maybe used to take advantage of the residual heat after the last turbine; ii) When solar conditions are adequate, the fluid is redirected through the solar receiver and its temperature increases up to T_x; iii) During night or poor insolation conditions the working fluid is conducted directly to the combustion subsystem.
A closed cycle is considered, so the heat input from combustion is done through a heat exchanger associated to the main combustion chamber. Independently of solar conditions the combustion chamber ensures that the first turbine inlet temperature is stable, T_3. The expansion stroke is performed by means of an arbitrary number of turbines, N_t. A number N_t-1 of intermediate reheaters makes that for any turbine the inlet temperature is T_3. Afterwards the expansion process (temperature T_4) the fluid is redirected through the recuperator to another heat exchanger, so the process is closed and cyclic. Details on the submodels for the solar collector and the Brayton heat engine can be found on [3,4]. Particularly, in the Brayton cycle pressure losses in heat input and heat release processes are considered. Also compressors and turbines are taken as non-ideal, and so their isentropic efficiencies appear as model parameters. Losses are also considered for the recuperator, and in all heat exchangers.

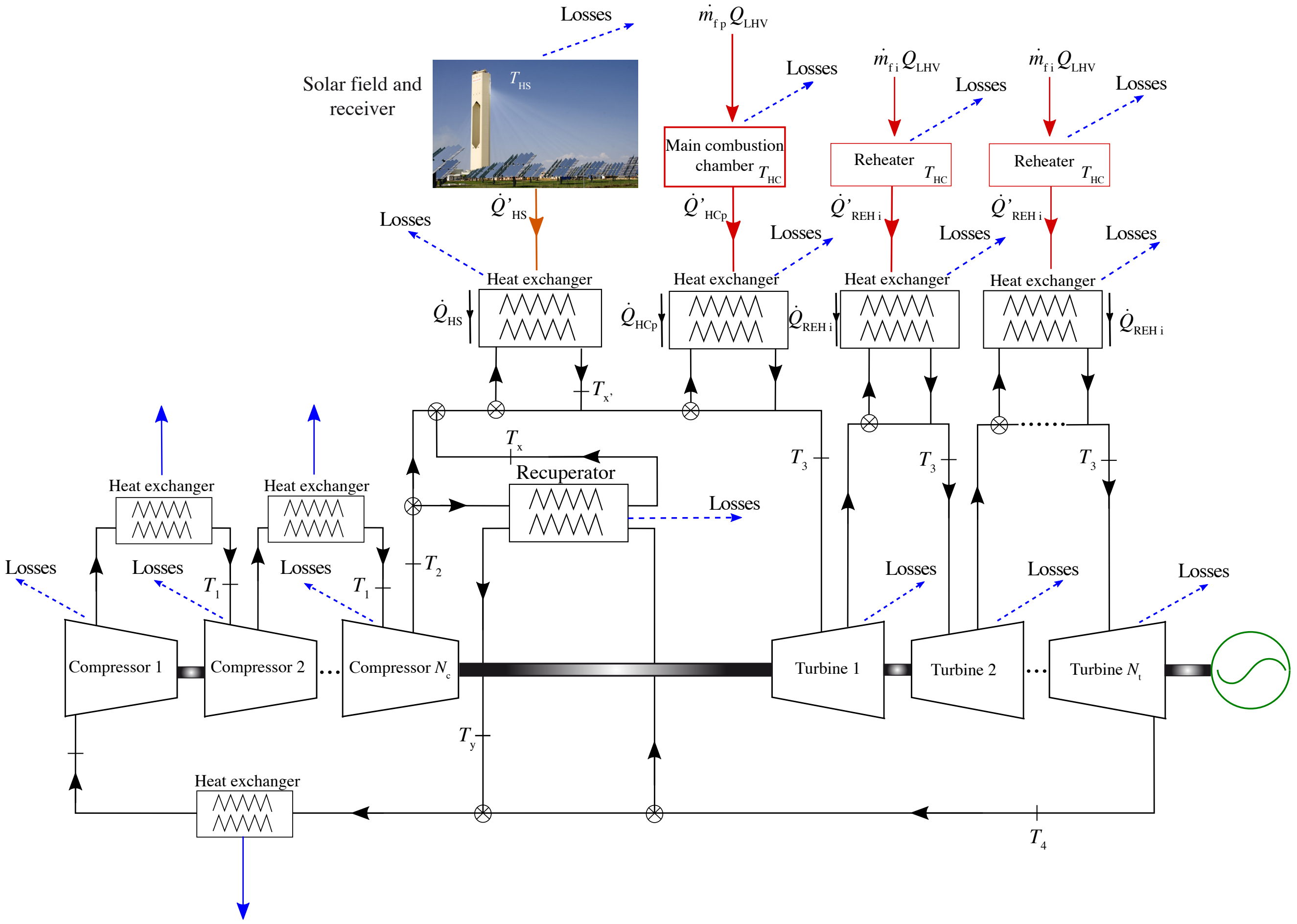

Fig.1. Sketch of the considered hybrid multi-stage Brayton power plant.

3. Numerical Performance Predictions

The thermodynamic model presented in this work in the particular case of single stage compression and expansion was applied in previous works by our group in order to predict the performance records of a project developed by Abengoa Solar near Seville, Spain, called Solugas Project [5]. In this project a commercial single stage gas turbine (Caterpillar Mercury 50) working on air and fueled with natural gas was modified in order to be hybridized with a central tower solar receiver. The comparison of the experimental data on plant performance and the ones obtained with the model were very satisfactory [3]. In this paper the model is enhanced to consider an arbitrary number of compression/expansion steps and different working fluids. Particularly we shall consider dry air, nitrogen, helium, and carbon dioxide. Recent papers deal with the technical advantages or disadvantages of these fluids [6]. We are interested in their thermodynamical behavior on the plant cycle. An illustrative sketch of the p-T plot experienced for the different fluids is depicted in Fig. 2.

Model predictions within the considerations detailed in the previous section are presented hereafter. Solar irradiance and ambient temperature were taken the same that the design conditions on the Solugas Project (G=860 W/m^2 and T_L=288 K). Other parameters can be checked in [3]. Most significant plant efficiencies are plotted in Figs. 3 and 4 in terms of the number of compression, N_c and expansion steps, N_t, assumed identical: N_t=N_c=N. In all the plots the reference values corresponding to the Solugas project (air as working fluid and N=1) are plotted with an open circle.

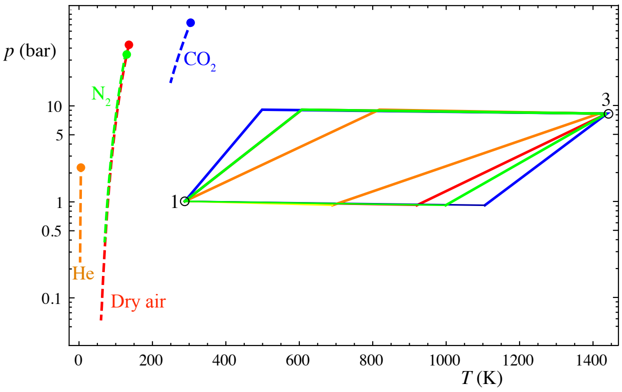

Fig. 2. Semi-logarithmic plot of the gas-liquid coexistence curves of the considered working fluids (dashed lines). The critical points are indicated. Approximate Brayton cycles developed by the gases in the thermosolar plant (single stage case).

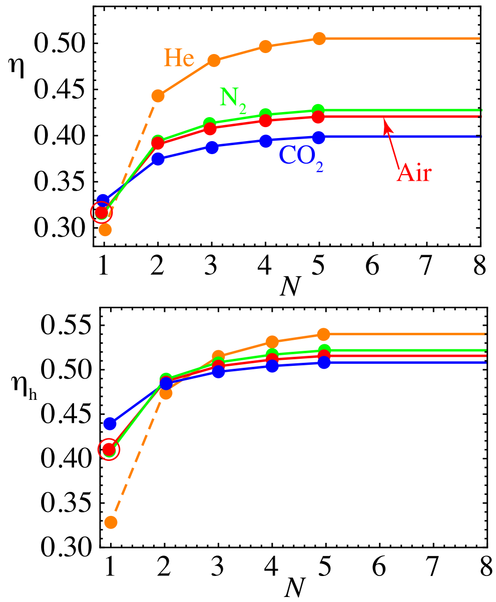

Fig. 3. Plant efficiencies as a function of the number of stages, *N*: η, overall plant efficiency and η□, □□□□□□□□□□□□□□□□□□□□□□□□□□.

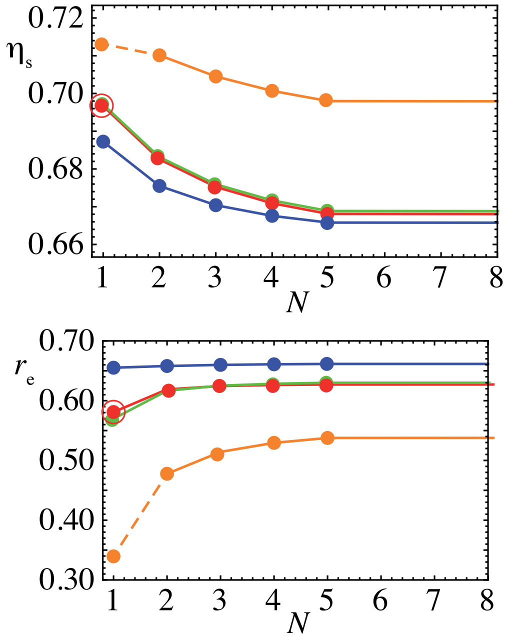

Fig. 4. Top, □□□□□□□□□□□□□□□ efficiency, η_s, and, bottom, fuel conversion efficiency, r_e.

In the case of air, when considering two compressors with intercooling and two turbines with reheating (N=2), the overall plant efficiency, η, experiences an increase about 22% with respect to *N*=1. The addition of more compression/expansion stages could increase overall efficiency up to 36% approximately. The evolution of the global efficiency curves for all fluids are similar: a rapid increase from *N*=1 to *N*=2 and a subsequent slower increase up to an asymptotic value. This evolution for the overall efficiency, η, comes essentially from that of the Brayton heat engine, η_h. The behavior of air and nitrogen is similar. The case of He is different. First, for N=1 no regeneration was considered (this is shown in the plots of Figs. 3 and 4 with dashed lines). This is because for the considered pressure ratio (assumed for all the fluids at the design point of Solugas project, r_p=9.9) is too high for regeneration to be advantageous (see the graph corresponding to He in Fig. 2). And second, the overall efficiencies for N>2 are quite above those for air or nitrogen. This larger values of η for He are mainly associated to the values of the solar subsystem efficiency, η_s, that are larger for He.

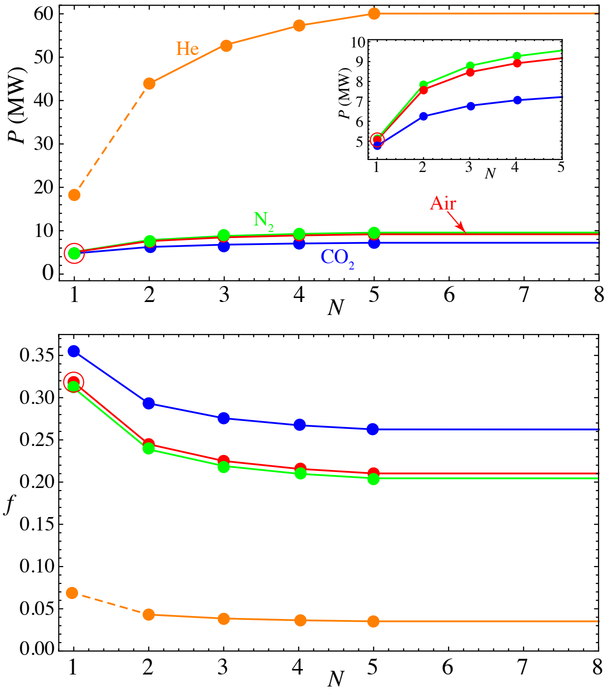

Fig. 5. Power output of the plant for the considered working fluids in terms of *N*. The inset represents a zoom of the bottom curves.

The behavior of the fuel conversion efficiency, r_e (the ratio between the power output and the heat input with an economic cost), is quite diverse and interesting (Fig. 4, bottom). r_e is larger for CO_2 that for the other fluids, and it is almost independent of *N*. These values are about 13 % over that for the reference case. Nevertheless, for air, N_2 and He, r_e increases with *N*. The poorest values of r_e are those for helium.

The power output is much larger for He that for the other fluids as displayed in Fig. 5. This is an effect associated to the conditions in which we are comparing the results for the different fluids. Helium has a constant pressure specific heat about 4 times larger than the other fluids. The numerical magnitude of power output is proportional to the working fluid mass flow and the constant pressure specific heat. As we are assuming that the working fluid mass flow is the same for all fluids, power output for He is for *N*=1 larger than for the rest of considered fluids in the same proportion that the specific heat. This effect is amplified for larger values of *N* due to the heat input in the reheaters between turbines. For the other fluids power output increases with *N* up to approximately *N*=4. For larger *N* power output remains almost constant. The increase is higher for air and nitrogen. The inset in the figure shows that for N ≥ 2 expected power output is larger for N_2 than for air.

The solar share, *f*, (plotted at the bottom of Fig. 5) decreases for all fluids with the number of compression/expansion stages. This is associated to the increase of heat input from combustion in the intermediate reheaters between turbines. Largest solar share is observed for CO_2 and *N*=1, where f ~ 0.35. On the other side, solar heat input for helium is always very small. In other words, in order to increase the fluid temperature from the compressor outlet to the turbine heat input from the combustion chamber is the most important term. The solar subsystem size (aperture area) in the reference plant is undersized for He.

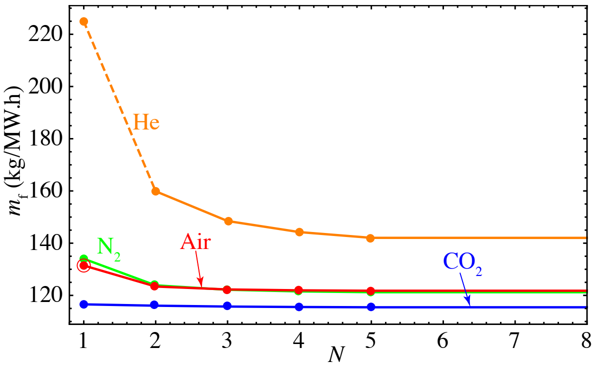

Fig. 6. Specific fuel consumption in terms of *N*.

Specific fuel consumption, m_f, assuming natural gas fueling is shown in Fig. 6. Fuel consumption is maximum for He, specially for *N*=1, where no regeneration is assumed. For N_2 and air, the model predicts about 135 kg/(MW.h) for *N*=1 and smaller values for larger *N*. The main reduction is achieved in the change from *N*=1 to *N*=2. In the case of CO_2, m_f is almost constant. Its numerical value is around 115 kg/(MW.h). The fact that in all cases m_f decreases with *N* means that in spite of the fueling required by intermediate reheaters, the cycles takes advantage of regeneration.

4. Conclusions

We have presented the numerical predictions of plant performance for a power plant working on the concept of hybrid thermosolar gas turbine. This concept has been introduced in the last years and several theoretical and simulation results have been reported in the literature. Moreover, several experimental projects have been developed. These works prove the technical feasibility of this technology, but also show that is still necessary more work in order to improve overall plant performance to obtain electricity at competitive prices. Our thermodynamic model allows to search for improved plant configurations including multistep compression and expansion and to look for adequate working fluids.

Particularly, four different fluids have been checked: air, nitrogen, carbon dioxide, and helium. Numerical values to run the model were taken from a project developed by Abengoa Solar near Sevilla, called Solugas project. Design point conditions were assumed and most significant plant efficiencies, power output, and specific fuel consumption were estimated.
It has been shown that multistep configurations up to a reasonable number of compression/expansion stages (around 2-3) are capable to significantly increase overall plant efficiency, fuel conversion efficiency, and power output. In spite that multistep configurations include reheaters between turbines that require an extra fuel consumption, the specific fuel consumption (fuel consumption per unit power output) is not penalized.

In which respect to the working fluids, nitrogen and air present a similar behavior for all efficiencies, although nitrogen, due to the particularities of the behavior of its constant pressure heat capacity, leads to an slightly better overall plant efficiency and also better power output. In terms of fuel conversion efficiency and specific fuel consumption, out simulations predict that carbon dioxide will have the better performance among the fluids we have analyzed. The case of helium is remarkable. First, because the overall pressure ratio should be fitted in order to take advantage of regeneration and second, because for the same mass flow rate He leads to much high power output than the other fluids. But the predicted fuel conversion efficiency is small due to the fact that the solar field area (taken the same for all fluids) is undersized (very small solar share).

This kind of studies show that there is still a wide margin for improvement in the design of this kind of renewable power plants. Hopefully, the suggestions of this theoretical studies could guide the design of future installations working on this concept, with the aim to obtain clean electricity at competitive prices. More work is necessary from a thermoeconomic viewpoint in order to analyze inversion costs and operation for different plant layout and the associated price for the unit electric power output.

Acknowledgement

The authors acknowledge financial support from JCYL of Spain, Grant SA017P17.

References

[1] E. Okoroigwe and A. Madhlopa, “An integrated combined cycle system driven by a solar tower: a review”, 57 (2016) 337-350.

[2] “Solar-hybrid power and cogeneration plants”, Tech. Report, European Commission (2011). http://ordis.europa.eu/publication/rcn/13318_en.html

[3] R.P. Merchán, M.J. Santos, I. Reyes-Ramírez, A. Medina, and A. Calvo Hernández, “Modelling hybrid solar gas-turbine power plants: thermodynamic projection of annual performance and emissions”, Ener. Conv. Manage., 134 (2017) 314-326.

[4] R.P. Merchán, M.J. Santos, A. Medina, and A. Calvo Hernández, “Thermodynamic Model of a hybrid Brayton thermosolar plant”, Renew. Ener, in press (2017). http://dx.doi.org/10.1016/jrenene.2017.05.081.

[5] R. Korzynietz *et al*., “Solugas - Comprehensive analysis of the solar hybrid Brayton plant”, Sol. Ener. 135 (2016) 578-589.

[6] O. Olumayegun, M. Wang, and G. Kelsall, “Closed-cycle gas turbine for power generation: a state-of-the-art review”, Fuel, 180 (2016) 694-717.