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Effect of a regenerator on hybrid solar gas turbine performance in Barranquilla, Colombia

F Moreno-Gamboa¹, J C Acevedo-Paéz², and D Sanin-Villa³

¹ Grupo de Investigación en Fluidos y Térmicas, Universidad Francisco de Paula Santander, San José de Cúcuta, Colombia

² Grupo de Investigación Eureka, Universidad de Santander, San José de Cúcuta, Colombia

³ Grupo Automática, Electrónica y Ciencias Computacionales, Instituto Técnico Metropolitano, Medellín, Colombia

E-mail: faustinomoreno@ufps.edu.co

Abstract. A thermodynamic analysis of a hybrid gas turbine solar plant, represented in three basic subsystems related to the power cycle, the combustion chamber subsystem, and the solar concentrator subsystem, allows evaluating the performance of a hybrid cycle from a reduced number of parameters, which include energy losses in each of its components. The solar radiation values are estimated with an evaluated and validated theoretical model, the combustion chamber uses natural gas as fuel and the numerical values of the system are taken from the Solugas experimental plant in Spain. This work presents an integrated model that allows to estimate the operation of a hybrid solar Brayton power plant in any place and day of the year. The evaluation of the plant in Barranquilla, Colombia is shown from the influence of the regenerator has on the plant performance and solar concentrating system. The results show that the regenerator can increase the overall efficiency of the plant by 29% and allows reaching a maximum temperature of the central receiver of the concentrator of 1044 K at noon, when solar radiation is maximum.

1. Introduction

Pollutant emissions continue to rise, the countries focus their efforts on diversifying their generation systems from renewable sources. In this moment, solar energy is presented as a renewable and clean source of energy that can be used in photovoltaic technology and in thermal power systems, which typically take solar radiation through a concentration system, to improve the use of the resource in a generation cycle [1]. Thermal plants with a central tower solar concentration system receive solar radiation through a heliostat field and it is reflected towards a receiver located at the top of a tower, where energy is supplied to power cycle working fluid [2]. Although this technology has taken important steps, the central tower receiver is still in development, in which different types and configurations are proposed [3].

Concentration system can operate in high temperatures, even above 1000 °C, but must be coupled to gas turbine cycles [4] which have the advantages of its simplicity, lower assembly costs and a wide power range for operation [5]. This technology does not allow the use of storage systems due to the temperature restrictions in molten salt and thermal oil systems, therefore the control of maximum temperatures and operation takes place in the combustion [6]. The Solugas plant, the only heliostat plant and central tower with a gas turbine, is an experimental system that is located in Seville, Spain, and has



a Mercury 50 turbine of 4.6 MW [7]. The parameters described in the literature regarding this plant will serve as a reference for this work [8].

Colombia needs to evaluate concentrating solar thermal systems to generate electrical energy; in this sense, the integrated model of direct solar radiation and the thermodynamic performance are evaluated in Barranquilla, Colombia. The effect of the regenerator is calculated on the main parameters of the plant and the solar concentrator.

2. Solar hybrid thermal power plant and models

This section describes the solar hybrid gas turbine, the details of the solar radiation estimation model and the thermodynamic model of the system.

2.1. Overall plant model

The diagram of the hybrid solar gas turbine plant is shown in the Figure 1(a) and the temperature vs entropy Figure 1(b). The plant is composed of a heat exchanger that delivers to the environment, the working fluid passes through a compressor (process 1-2) and then there is a regenerator (process 2-x); next, there is the solar receiver (process x-y) that receives the concentration of the radiation from the heliostat field and delivers heat to the air through a heat exchanger (\dot{Q}_s). Subsequently, there is a combustion chamber (\dot{Q}_c) (process y-3) that burns natural gas and delivers heat to the air through a heat exchanger. System power is generated in non-ideally turbine (process 3-4).

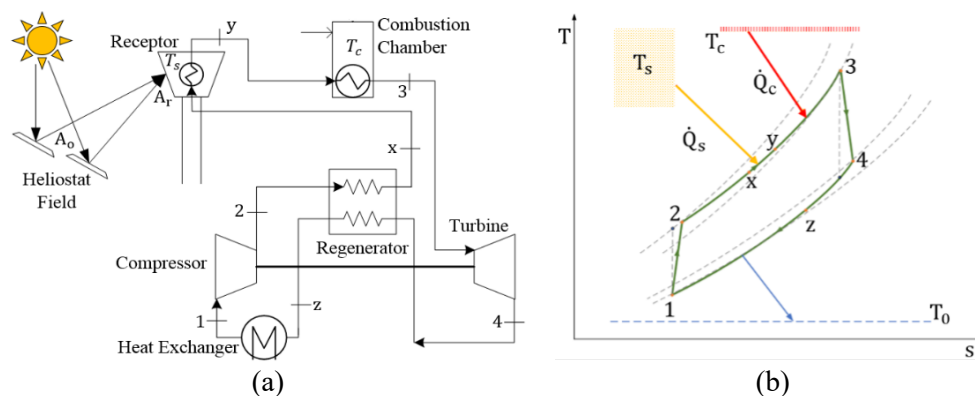


Figure 1. (a) scheme of the plant; (b) temperature vs entropy diagram of the system.

2.2. Solar estimation model

In Colombia there is no access to direct solar radiation data in many parts, therefore the solar resource is estimated with the daily integration model (DI model), developed by Gueymard [9]. The model is considered the most accurate after being compared [10], with similar models [11]. In DI model direct radiation (I_B) is defined in Equation (1) [9].

$$I_B = r_t \bar{H}_H - r_d \bar{D}_H, \quad (1)$$

where \bar{H}_H and \bar{D}_H represent the long-term monthly daily average for total and diffuse radiation, which are readily available from the National Aeronautics and Space Administration (NASA) prediction of energy resources website [12]. In order to distribute the radiation values over the day, the hour to day relationships for diffuse radiation (r_d), and global radiation (r_t) are introduced.

2.3. Power plant thermodynamic model

After passing through the regenerator, the working fluid receives heat from the solar concentration system, in which initially the heat received by the heliostat field is the area of the field and direct solar radiation. The efficiency of the solar concentration power system (η_{cs}) (see Equation (2)), can be defined

as a function of the optical efficiency (η_0), where A_o is heliostat field, A_r is receptor area, T_s is the temperature of the central tower receiver, T_0 is the ambient temperature, U_1 is the conduction and conversion heat transfer coefficient, α is the emissivity of the central receiver, and σ is the Stefan-Boltzmann constant [8].

$$\eta_{cs} = \left(I_B A_o - I_B A_o (1 - \eta_0) - A_r \left(U_1 (T_s - T_0) + \alpha \sigma (T_s^4 - T_0^4) \right) \right) / (I_B A_o). \quad (2)$$

Fuel consumption (\dot{m}_f) is a function of its lower calorific value (Q_{lhv}), the efficiency of the combustion process (η_{cc}), the mass flow rate (\dot{m}), and the effectiveness of the heat exchanger (ε_{cc}) (see Equation (3)) [8]. Additionally, h represents the enthalpy of each state.

$$\dot{m}_f = \dot{m} (h_3 - h_y) / Q_{lhv} \eta_{cc} \varepsilon_{cc}. \quad (3)$$

The regenerator is represented by its effectiveness (ε_r) in Equation (4) [8].

$$\varepsilon_r = (h_x - h_2) / (h_4 - h_2) = (h_z - h_4) / (h_2 - h_4). \quad (4)$$

The relation between heat supplied by the solar concentrator to the power cycle with respect to total heat delivered is defined with the solar factor (f) in Equation (5) [8], where (\dot{Q}_s) is heat delivered by the combustion chamber, and (\dot{Q}_H) is the total heat delivered.

$$f = \dot{Q}_s / \dot{Q}_H = \dot{Q}_s / (\dot{Q}_c + \dot{Q}_s) = (h_y - h_x) / (h_3 - h_y) + (h_y - h_x). \quad (5)$$

The power output (P_n) and power cycle efficiency (η_{mt}) are defined in Equation (6) and Equation (7) [8] respectively.

$$P_n = \dot{m} ((h_3 - h_4) - (h_2 - h_1)), \quad (6)$$

$$\eta_{mt} = P_n / \dot{Q}_H = ((h_3 - h_4) - (h_2 - h_1)) / (h_3 - h_x). \quad (7)$$

The overall efficiency plant (η) is represented in Equation (8) [8].

$$\eta = P_n / (\dot{m}_f Q_{lhv} + I_B A_o). \quad (8)$$

Finally, the fuel conversion rate (r_f) is defined as the power generated over the heat of the fuel consumed in the Equation (9) [8].

$$r_f = P_n / (\dot{m}_f Q_{lhv}). \quad (9)$$

3. Result and discussion

This section is divided into two parts; first one focuses on validation of solar model and thermodynamic model. The second part shows results of the operation on an average day of the year and the influence of the regenerator in the system operation.

3.1. Validation models

Due to the availability of direct radiation data, the validation of the DI model is carried out in Seville, Spain, on July 20th with data taken from Meteosevilla website and the global radiation ($\bar{H}_H = 7.8 \text{ kWh/m}^2/\text{day}$) while the diffuse radiation ($\bar{D}_H = 1.7 \text{ kWh/m}^2/\text{day}$). The latitude of the place is 37.38° north. The data obtained with the DI model and those obtained in Meteosevilla are compared

by means of mean absolute bias error (MABE), achieving a value of 0.2010085 and root mean square error (RMSE) with a value of 0.226616, which are considered acceptable according to [10].

Validation of thermodynamic model are presented in the Table 1. The results of the model compared with the bibliography are observed, among them the power output (P_n), thermal cycle efficiency (η_{mt}). Additionally, the maximum error of the overall efficiency (η), and the solar fraction (f) is above 1%, that indicated by a good correlation of model. The details of validation, parameters and models can be found in previous works [13]. The plant models and thermodynamic properties of the working fluid are assessed using the Modelica language and compiler Dymola.

Table 1. Thermodynamic model assessment.

	P_n	η_{mt}	η	f
Model	4635.400	0.385	0.302	0.338
Reference	4600.0 [14]	0.390 [14]	0.300 [8]	0.341 [8]
Error %	0.700	1.000	0.660	0.880

3.2. Simulation and results analysis

The function of regenerator is recovers heat from the exhaust turbine and uses it to preheat the compressed air before the compressed air enters the solar concentrator and the combustor and reduce the external energy requirement. This section presents the influence of the regenerator in the daily operation of plant, evaluating the performance without regenerator ($\epsilon_r = 0$) and when the regenerator is in normal operating conditions ($\epsilon_r = 0.77$).

In Figure 2(a) the variation of the power is observed on mean day of year with respect to the hourly ambient temperature (T_0) [15]. Power output is influenced by the ambient temperature, when decreasing T_0 the net power increases. The relative amplitude of the power is 3% throughout the day and the regenerator has no influence on the cycle net power. In Figure 2(b), the influence of the regenerator on η_{mt} is presented, which has a profile similar to P_n . Solar concentrating system does not affect thermal engine efficiency. The average of thermal engine efficiency values changes from 0.2523 when $\epsilon_r = 0$ to 0.3346 when $\epsilon_r = 0.77$.

In Figure 2(b) the evolution of η , which is reduced when the solar concentrating system operates due to heat losses. Overall efficiency is also affected by the regenerator. In this sense, when both $\epsilon_r = 0.77$, the overall plant efficiency presents a maximum of 0.3090 and a minimum of 0.2656 representing a relative breadth of 14%. A reduction to $\epsilon_r = 0$, implies that presents a maximum value of 0.2328 and a minimum of 0.2063, which is a relative amplitude of 11.33%. The above is due to when $\epsilon_r = 0$, more fuel is required for the operation of the plant and therefore the influence of the solar concentration system on the overall efficiency is reduced.

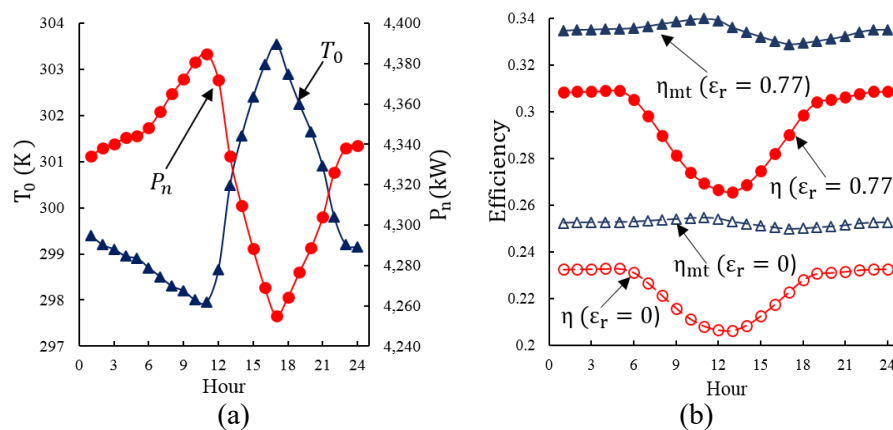


Figure 2. (a) ambient temperature and power; (b) regenerator influence on overall efficiency and thermal engine efficiency.

The regenerator reduces the total supplied heat requirement (\dot{Q}_H) and fuel consumption. Figure 3(a) presents the influence of the regenerator on fuel consumption. When there is no solar radiation the average increase in fuel consumption without the regenerator is 32.2% and when the solar radiation is maximum the increase in \dot{m}_f is 25.6%. The regenerator saves 21.1% of fuel per day and the solar concentrator achieves an additional saving of 7.6%.

If solar radiation increases, heliostat field receives more energy and the f also grows (see Figure 3(b)). The solar factor reaches a maximum value at noon, where the contribution of the concentration system is 26.19% of the heat supplied when $\varepsilon_r = 0.77$ and 21.2% when $\varepsilon_r = 0$. Additionally, with the regenerator, the fuel conversion factor (r_e) can have an average increase of 34.4% at night and an increase of 44.2% around noon when the solar factor is maximum. This increase is due to the reduction in fuel consumption compared to solar contribution.

The efficiency of the solar system is only defined for a particular time interval when direct radiation occurs (see Figure 4(a)). These curves present a wide plateau during the hours with good irradiation but are minor during sunrise and sunset. The operation of the regenerator produces a variation of 2% in the solar concentrator efficiency.

The regenerator also produces a strong influence on receiver temperature and solar concentrator outlet temperature as shown in the Figure 4(b). The values of T_y change from 856 K when $\varepsilon_r = 0$ to 1007 K when $\varepsilon_r = 0.77$ at noon, when the solar resource is not available the value of T_y increases 22.1%. The working temperature of the solar collector presents the maximum value at noon where T_c change from 894 K when $\varepsilon_r = 0$ to 1044 K when $\varepsilon_r = 0.77$.

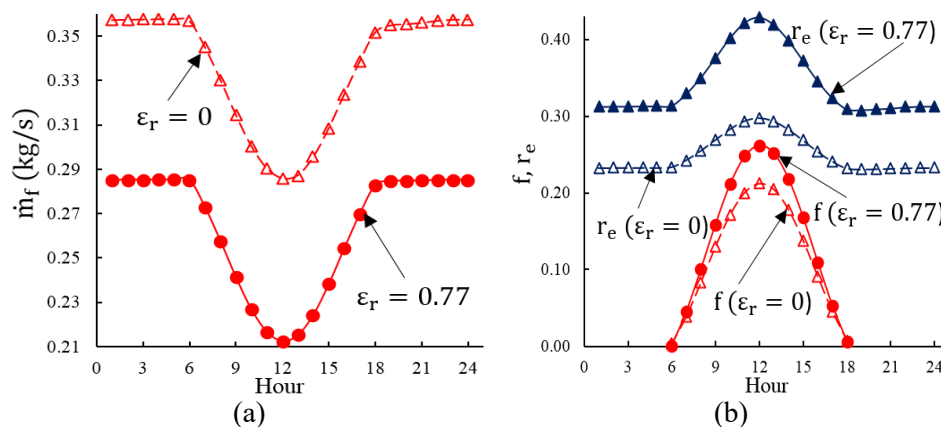


Figure 3. (a) influence of the regenerator on fuel consumption; (b) influence on fuel conversion rate and solar factor.

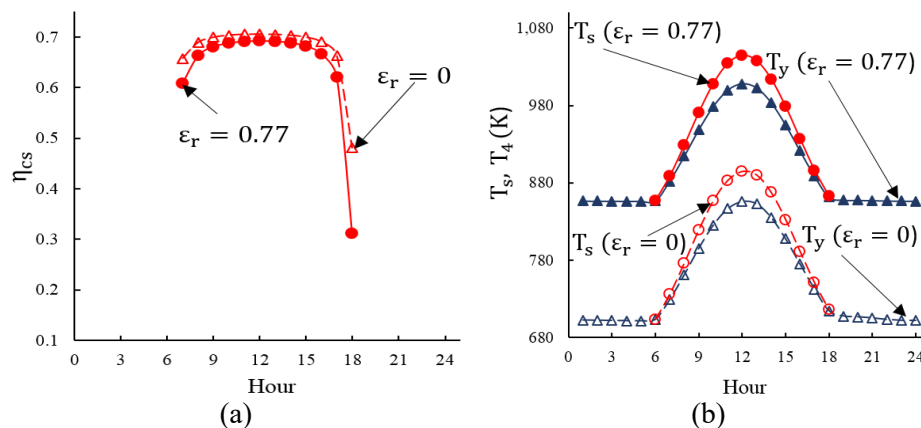


Figure 4. (a) evolution of solar concentrator efficiency; (b) the working receptor and concentrator outlet temperature.

4. Conclusions

An integrated model for a Brayton hybrid cycle solar plant is presented and validated. The model estimates the direct radiation and operation of the plant in Barranquilla, Colombia. In order to obtain representative predictions, the simulation incorporates values of average hourly ambient temperature, the lower heating value of natural gas and the location of city.

The power plant it can work either in only combustion mode on hybrid mode, where fuel consumption is reduced by 7.2% during the day. When the regenerator does not operate its effectiveness is zero and under design conditions the effectiveness is 0.77 and the fuel consumption is reduced 32.2% in one day. Increased regenerator effectiveness also increases overall cycle efficiency, thermal engine efficiency and fuel conversion rate.

The predictions of our model reveal that the working temperature of solar collector increases with regenerator effectiveness, improving the participation of the concentration system by increasing the solar factor. However, the increase in receiver temperature also increases heat losses and slightly decreases the concentrator efficiency.

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