Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 82 (2015) 978 – 985

Energy Procedia

ATI 2015 - 70th Conference of the ATI Engineering Association

A case of study of a concentrating solar power plant with unfired Joule-Brayton cycle

F.Rovense[a],*

[a]University of Calabria, Rende 87036,Italy

Abstract

A solar closed air Brayton cycle, with rated power of 50 MW, was considered. The system is composed of a concentrating solar tower with volumetric receiver, an intercooling and regenerating gas turbine and an evaporative tower cooling system. The characteristic feature of the system is a control strategy able to adjust the plant in a large range of load, maintaining net electric conversion efficiency almost constant. The concentrating solar power (CSP) plant operates without adding fuel and can heat air up to a maximum temperature of 850 °C, at the solar tower outlet. The numerical analysis was performed by SAM for the solar tower and by Thermoflex © for the assessment of the performance of the whole system. The thermal energy input was calculated on the basis of the DNI of the TMY from Seville. Results show an electricity production greater than 75GWh per year, with a significant sparing fossil fuel consumption and avoided CO_2 emissions.

© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the Scientific Committee of ATI 2015

Keywords: Control System; Concentrating Solar Brayton Cycle; Intercooled regenerated gas turbine; Volumetric receiver

1. Introduction

The solar source, as known, is not a resource that ensures regularity of energy production; consequently, its random nature leads to the search of systems able to capture the incident energy on the terrestrial sphere in an effective and continuous manner. A particular category of systems that are suitable for this application and are currently being developed in installations at an experimental stage [1] [7], or in certain cases also commercial [2] are known as concentrating solar Brayton cycle. They are promising in term of efficiency, low emissions and limited consumption of cooling water.

---

* Corresponding author.
E-mail address: francesco.rovense@unical.it.

1876-6102 © 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the Scientific Committee of ATI 2015
doi:10.1016/j.egypro.2015.11.855

To compensate the lack of thermal power during the clouds transient, generally in this kind of systems fuel is used by combustors to make always at nominal values the operating point. In this article the possibility of combining an innovative control system for a solar concentrator closed intercooled regenerated Brayton cycle, is analysed. Among the expected benefits of such a system, there is a good energy yield, which is almost constant regardless of the intensity of solar radiation, without the emission of greenhouse gases.

This technology, in fact, avoids the use of combustors, and thus it increases the heat energy from fossil fuels, ensuring, at the same time, a large margin of regulation.

Nomenclature

UA	Product of heat exchange coefficient global for the exchange surface
Avg	Average value calculate for every months Opt
Opt	Optimal value
i	Represent the number of the month on thesum
P	Average pressure of the air on cycle
Vc	Volume control
MW	Molecular weight of the air
R	Universal constant of ideal gases
T	Average temperature of the air in the principal cycle
TIT	Temperature Intel Turbine

2. Plant description

The system object of study, shown in Fig. 1, is constituted by the plant of solar concentration, a gas turbine, the regulation system, a cold exchanger, and a cooling tower. The red line in Figure 1 represents the route of the air from the entrance, while the blue line indicates the path of the water in the cooling circuit of the plant.

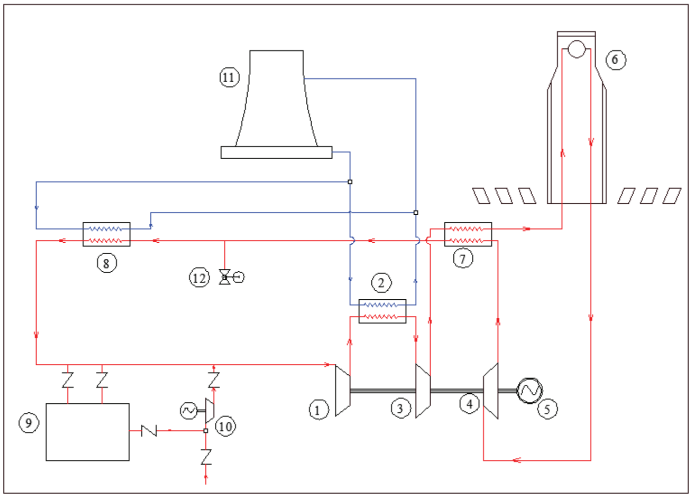

Fig.1. Complete plant: 1. L.P. Compressor; 2. Intercooler; 3. H.P. Compressor; 4. Turbine; 5. Generator; 6. Solar tower; 7. Regenerator; 8. Heat exchanger; 9. Air compressed tank; 10. Auxiliary compressor; 11. Cooling tower; 12. Vent valve.

2.1. Concentrating solar plant

The concentrating solar plant, assumed for the analysis, consists of the solar tower and the field of heliostats. The heliostats are in a North field configuration, sited in the town of Sevilla.

The area of a single heliostat is 120 m^2 [3], optimized for the height of the tower and the receiver used. The total number of heliostats is calculated by Thermoflex, according to the thermal power required for feeding a gas turbine of 50 MW peak electric power. The choice of the receiver is in strong connection with the control system described in this work. The two main types currently available, volumetric and tubular, differ in the thermal inertia. The clouds, that pass by can decrease the direct incident radiation on the receiver surface from hundreds of W/m^2 to null values [4], with sudden variations of the temperature existing in the cavity, less accentuated in the tube type receivers, where the transient is in order of minutes [5]. The volumetric receivers have instead, transients that do not exceed few seconds. In this paper, however, we will not go into detail on the quality of the receiver, assuming an almost nil thermal transient. Thus, it will be assumed that a sudden change of DNI, will cause an instantaneous change in temperature; so a volumetric receiver and its behaviour have been simulated.

2.2. Intercooled and regenerated gas turbine

The gas turbine, simulated in Thermoflex, is composed of one stage of intercooling compression with a value of β of 10.There is a regenerator after the intercooling compression. It is expected, that the mass flow evolving inside the loop changes with the converted power, an analysis was performed to determine the size of the regenerator.

It was detected the exchanged power and the UA factor for each hour, by using the “design more” option offered by Thermoflex. All these values have been introduced in the formula:

$$UA_{Opt} = \frac{\sum_{i=1}^{12}(UA_{avg} * Heat\ Power_{avg})_i}{\sum_{i=1}^{12} Heat\ Power_{\ i}} \tag{1}$$

It was calculated a weighted average of UA (1,337.56 kW/°C), which was then set as nominal value.

2.3. Heat exchanger

The heat exchanger restores the temperatures at the beginning of the cycle, cooling the air leaving the turbine. Previous analysis [6] shows that an excellent performance is obtained with an initial temperature of the cycle of 30-35 °C; the lowering of this temperature, would lead to an increase in the work yield, but in a higher expense for exchange surfaces, which would be too large. The product UA is calculated with the same methodology used for the product UA of the regenerator but, in this case, the refrigerating fluid is water. The results obtained from the calculation code returned a value of 1,039 kW/°C.

2.4. Control System

The aim of this system is to maintain the outlet temperature from the receiver, i.e. the TIT, constant, at a values of 800 °C. The DNI variation makes it necessary to place or drip air in the system. The control system evaluating and acting on parameters like pressure or mass flow of air in exit from a tank or from a auxiliary compressor. In the Brayton cycle plant, this control system allows to maintain the volumetric flow constant, varying the mass flow rate; it is possible to do this changing the density, i.e. increasing the inlet gas-turbine pressure.

By means of the ideal gas law, it is calculated the pressure variation that determines a change of fluid density in according with the mass variation and the volume invariability:

$$P * V_c = \frac{M_v * R}{MW} \tag{2}$$

In the present work, we have calculated the mass flow variation in the cycle with Thermoflex, associated with the pressure increase due to solar radiation.

The auxiliary tank and the compressor are connected to the system at compressor inlet, because in this configuration it is possible to work with lower pressure ranges.

3. Results

The control strategy is crucial for the performance of the entire plant. In Fig. 2 it is possible to note that this kind of system allows an almost constant value of 36% of efficiency during all operating hours. As the figure shows, the low temperatures, in the morning of January, cause a loss of 13% efficiency.

The generated power has peak values of 50 MW. The estimate of the yearly energy yield is about 75 GWh/year, providing 1500 of operating hours.

The Fig. 3 shows the energy production during the year considered on Seville, where the annual DNI expected is 2068 $\frac{kWh}{m^2}$. The data used for the energetic analysis are related to TMY3 [8] and are been updated and detected during year 2014.

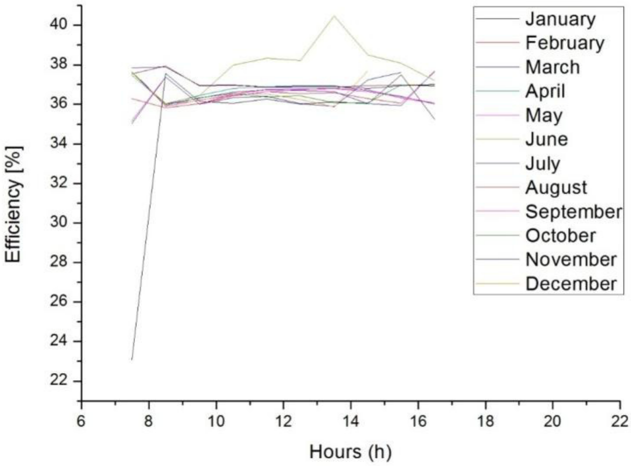

Fig.2 Plant efficiency for all months

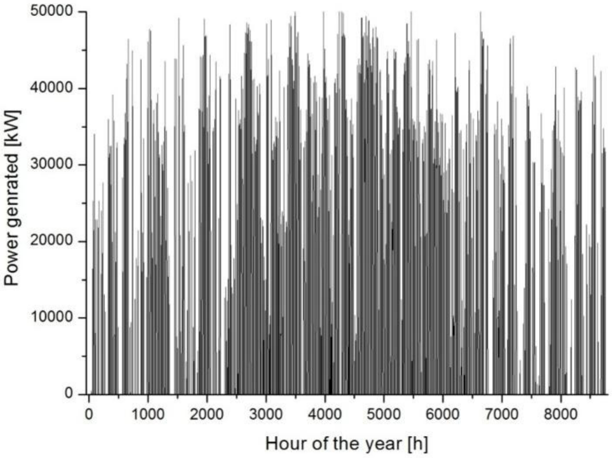

Fig.3 Energy production during all year for every hour.

3.1. Performance analysis

An example of operation, to demonstrate the feasibility of the system, the capacity control and the low energy consumption to operate the control of the plant, follows. The case in which the control system is constituted by auxiliary tank, at a pressure of 6 bar, with an accumulation volume of $50m^3$ and at a temperature of 30 °C, and compressor was analyzed. The latter element can, if necessary, withdraw mass from the tank or, in the event the pressure of the accumulator is too low, suck air from the ambient. Similarly, in the event that the tank has a pressure higher than the system circuit, the control system can drip mass, by means of the regulating valve.

In this example, we considered the day of year number 72 (March, 13), with different clear sky correction factors, in order to highlight the behaviour of the control device, for intervals of 10 minutes.

The controlled variable is TIT, with a set point of 800 ° C and an accuracy of tenths of a degree. To do this, it is necessary to check precisely the density of the working fluid by acting on the pressure. With an increase of solar radiation, in fact, the compressor inlet pressure has to be increased, to assure more mass flow and keep the TIT constant. In the considered case, the outgoing air from the cold exchanger has a constant temperature of approximately 30 °C, with a flow rate of $148.8\frac{kg}{Sec}$, at a pressure of about 8 bar. The temperature of the compressed air added to the main circuit, independently from which it is withdrawn (i.e. from the tank or from the atmosphere if pressure level is not enough) has been assumed to be 30 °C. The following Fig. 4 shows the trends of the tank pressure and the required intake of the main compressor.

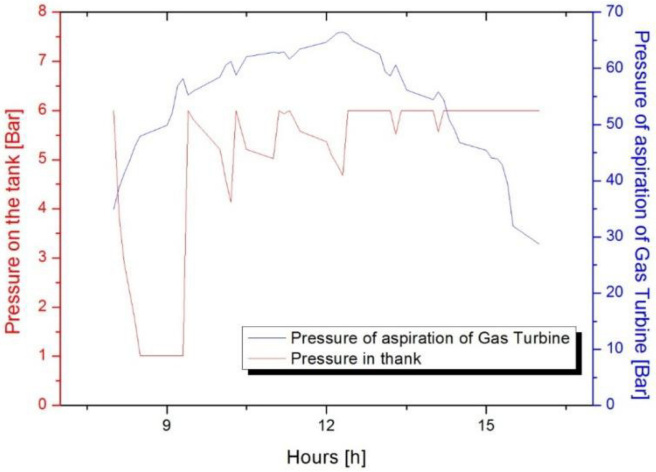

Fig.4Example of control during a cloudy day.

The blue line displays the trend of the pressures necessary for the compressor to implement the described control. Its development follows the solar radiation. The red line shows the trend of pressure in the accumulator tank instead. During the first hours, starting at 8.00 AM, in which the direct solar radiation has low values, the necessary pressure for the system to ensure the appropriate operating conditions is approximately 4 bar. Considering that the initial pressure of the control tank is 6 bar, there is a difference of pressure with the main system one; thus, the control of the system will be possible by valve, with the exit of air from the tank, to increase the pressure at the inlet of the main compressor. When the difference of pressure between the circuit and the tank is not sufficient to use the tank, then the auxiliary compressor, that will pick up other air from the tank, will come into operation. In the example that we are showing, at 8.40 AM, the control system stops to drip mass from the tank. Now, the compressor begins to suck from the atmosphere, because the pressure inside the tank is too low. At 9.40 AM, always in reference to the day in question, when the irradiance starts to lower, it is not necessary to compress further air into the main circuit. The adjustment system no longer has to intervene by introducing air, but extracting mass flow from the working circuit, to fill the tank with the mass flow at condition of turbine exit. So the pressure level of the tank is returned to initial conditions with this mass flow.

At 12.40 PM, decreasing the solar radiation incident on the receiver surface, it will be necessary to decrease the mass that flows in the circuit; then its pressure drops and the tank can be charged again. When the pressure within the tank is already at the maximum allowed, it is necessary to bleed air towards the atmosphere. The bleeding point is at the turbine outlet, before the heat exchanger, since it will not be necessary to cool the discharged mass flow. The utilization of a low pressure storage tank has allowed to save energy used for the compressor to make the control. Below in Fig.5, the trend of power compressor versus time is shown.

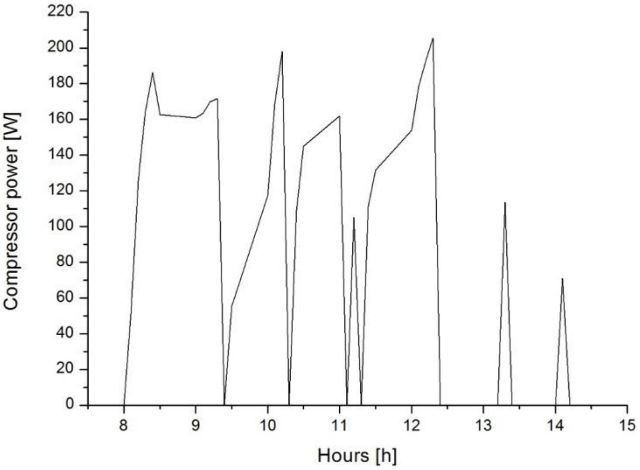

Fig.5 Power used by the auxiliary compressor to make the control

It is possible to note there are some hours where the power supplied is zero, because the pressure is regulated by the tank. The energy expended, in this case, for the regulation is of 7.8 kWh (against 31kWh always necessary to the compressor if the intake of air is from the atmosphere) in relation to a produced of 166 MWh of energy product with a net electrical efficiency of 35%.

4. Conclusions

The validity of a control system was analysed, in this work, for a concentration solar plant, with a closed cycle gas turbine. This system can ensure an almost constant TIT, with values of 800 ° C. The most important effect is the ability to obtain constant and competitive values of efficiency (36%) without CO_2 emissions or fuel use. Also the energy spent, as shown in the example, is almost negligible compared to the theoretically producible.

In addition to these advantages, a more extensive use, compared to plants that use combustors for the regulation, where the continuous variations of pressure limits its use, lies ahead. The impossibility for these systems to produce energy in the presence of cloudy days or with continuous meteorological disturbances must be mentioned. The cause has to be found both in the continuous pressure variations, that would compromise the useful life of the combustor and receiver, and in the cost of the fuel, which in certain cases is not justified by the energy production. In the proposed control system the only sensible element is the receiver, but only for quality construction; disadvantage that could be solved by use of others advanced materials.

This plant, for the size chosen, could be configured as a power plant of grid feeding, in which a renewable source becomes a sizable production node, providing a contributions more than symbolic to the decarbonizing of the electric sector.

Last, but not least, is the economic aspect; the government incentives to finance project for zero emission energy production are increasing. This allows to develop more installations, with low environmental impact, thus stimulating a scale economy and a higher diffusion.

Acknowledgements

Special thanks to Professors Mario Amelio, Vittorio Ferraro and Michele Scornaienchi of DIMEG of University of Calabria for continued technical support and Professor Manuel Silva Pèrez with Groupofthermodynamics of Sevilla University for research contribution.

References

[1] P.Heller, M.Pfa¨nder,T.Denk, F.Tellez, A.Valverde, J.Fernandez, A.Ring. *Test and evaluation of a solar powered gas turbine system.*Solar Energy 80 (2006) 1225 – 1230

[2] M.Quero, R.Korzynietz, M. Ebert, AA. Jiménez, A. del Rio, JA. Brioso. *Solugas-Operation experience of the first solar hybrid gas turbine system at MW scale*. SolarPACES 2013

[3] CJ.Noone, M.Torrilhon, A.Mitsos. *Heliostat field optimization: A new computationally efficient model and biomimetic layout*. Solar Energy 86 (2012) 792–803

[4] Deutsche Forschungs- und Versuchsanstalt fur luft-und Raumfahrt E.V. (DFVLR). In M.Becker and M.Bohmer, editors: *GAST The Gas-Cooled Solar Tower Technology Program*, Berlin, Heidelberg, New York, London, Paris, Tokyo; SpringerVerlag 1989, p 47-50

[5] AL. Avìla-Marìn. *Volumetric receivers in Solar Thermal Power Plants with Central Receiver System technology: A review.*Solar Energy 85 (2011) 891–910

[6] G. Suriano, Master thesis:*Characterization of a thermodynamic solar tower plant combined with an intercooler and regenerated closed Brayton cycle*, University of Calabria, Relators: M.Amelio; V.Ferraro;M.Scornaienchi.

[7] Commonwealth Scientific Industrial Research.*Solar Air Turbine Project. Final report: project results.* Organisation Principal Research Scientist, CSIRO Energy Transformed Flagship

[8] S. Wilcox and W. Marion.*Users Manual for TMY3 Data Sets.*Technical Report NREL/TP-581-43156 Revised May 2008

Biography

Francesco Rovense is a PhD Student at DIMEG of University of Calabria. Has a master degree in Energy engineering and just started researching work in the fluid machines department on Concentrating Solar Power Systems field.