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Thermodynamic modelling of the power cycle: Solar Thermal Generation in the canton of Arenillas-Ecuador

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Abstract. Solar thermal energy is a type of non-conventional renewable energy (NCRE) that takes advantage of the sun's heat to heat a fluid called heat carrier, then in a heat exchanger it produces steam at high pressure and temperature that generates electricity in a conventional thermal process, this process being of crucial importance since the production of electrical energy on a large scale depends on its efficiency. The technology chosen here is that of parabolic cylinder thermosolar (PCT), that reflect solar radiation and concentrate it in a tube located in its focal line. Inside it is a thermal fluid heated up to almost 400 ºC. The objective of the present investigation was the thermodynamic modelling of the power cycle of PCT plant that works under a modified Rankin cycle. The research is quantitative in nature since it allowed us to assess how the different thermodynamic processes occur, and it is also non-experimental, descriptive, explanatory and propositional, establishing causal relationships based on secondary sources. The result was a real temperature-entropy diagram (T-S) in which the thermodynamic modelling of the power cycle is represented.

Key words. Parabolic cylinder thermosolar plant, thermodynamic process modelling, power generation.

1. Introduction

In an effort to reduce greenhouse gases (GHG), different measures have been proposed, one of the main ones being the implementation of non-conventional renewable energies (NCRE) such as thermosolar, photovoltaic and wind power [1].
High-temperature solar thermal energy or thermo solar energy is a form of energy production in which direct solar irradiation is concentrated to produce high-temperature steam or hot air, in such a way that it can be used in a conventional power plant to produce electrical energy [2]. Currently there are three types of solar thermal technologies: Central tower, parabolic trough collectors and parabolic disk power plants [3]. Concentrated solar power technologies (CSP) are based on the principle of operation whereby the direct irradiation from the sun is concentrated in a punctual or linear focus by means of mirrors, called heliostats. The receiver absorbs the heat and transfer it to a fluid called heat transfer fluid (HTF) [4]. All CSP are made up of three separate but coupled systems: the solar field, the thermal storage (TES) and the power block (water/steam cycle) [5]. The thermodynamic modeling of the power cycle in a thermosolar plant by parabolic trough collectors works under a modified Rankin cycle [2].
Each Solar Thermal power plant is different in terms of its implementation and therefore the efficiency depends on the thermodynamic modelling to be used, being one of the fundamental elements in the process the proper selection of the heat transfer fluid, that depends on the climate characteristics of the site of implementation of the CSP [6]. Therefore, the statement of the problem of this scientific research is that the inadequate selection of the type of HTF causes energy inefficiency in the entire thermodynamic system of the power cycle. In the general performance of CSP systems, HTF is one of the most important components, also because it requires a large quantity for the operation of the solar thermal plant, therefore, it is important to minimize cost and maximize efficiency [7]. The HTF can be stored in an insulated hot tank for future use when direct sunlight is not available. According to current research, HTFs can be classified into six groups based on the type of material: Air and other gases. Water vapour. Molten salts. Thermal oils. Organic fluids. Liquid metals [7,8,9].
Also, certain characteristics of the HTF must be taken into account before making a decision [8,10]. Desired properties include: low melting and high boiling temperatures, thermal stability, low vapour pressure (< 1 atm.) at high temperatures, low corrosion with metal alloys used to hold the HTF, low viscosity, high thermal conductivity, high heat capacity and low cost.
Therefore, it is important to analyse graphically through specialized software the modified Rankin cycle for the HTF that is chosen, based on the environmental conditions determined by the study site, with these data and through the simulation the basic CSP design parameters are determined [7]. The software used allows, in a simple and

intuitive way, to design, analyse and carry out complex calculations on thermodynamic cycles.
The first CSP plant of South America is found at the Atacama's desert in Chile, called Cerro Dominador, which is of the central tower type.

In the present research work, the implementation of a CSP of the parabolic cylinder type is proposed in the Arenillas canton, province of El Oro in Ecuador, given the levels of direct irradiation existing in the site. We must note that thermosolar plants, unlike photovoltaic ones, have theoretically an indefinite useful life [11].

With a plant of this type and with an installed capacity of 10 MW (Megawatts), produced energy can be supplied directly to the 69 kV bar of the Arenillas substation, through a dedicated line, allowing the implementation of distributed generation [12]. In addition to the importance in the reduction of polluting gases, such as carbon dioxide (CO_2), it uses a free resource, completely removable and independent of geopolitical issues. Also, it can be designed for distributed generation due to the thermal storage system that includes. This thermosolar plant would be an important improvement in terms of product and service qualities. In addition, the area where it is planned to construct it is located at the end of the National Transmission System (SNT) (CENACE, 2021), which implies at the date to suffer many electrical power outages and blackouts.
Based on this background, the objective of this scientific research is to thermodynamically model the power cycle of a parabolic cylinder thremosolar (PCT) plant, that works under a modified Rankin cycle.

2. Materials and methods

The HTF (heat transfer fluid) in thermosolar power plants is a fundamental part of it, mainly if it has a thermal storage block. The same one that constitutes a very complex system that implies the handling of fluids with special characteristics.
The thermal storage block is planned to be built in the Arenillas canton of the El Oro province, in Ecuador. The location was selected after carrying out several on-site inspections, taking into account that it is next to the electrical substation of the local distributor, and the characteristics of the terrain, without significant unevenness, nor the presence of water sources or wildlife interest.
The chosen site has coordinates X=603509.847 and Y= 9607771.608 in UTM WGS 84, zone 17S, and is at an altitude of 30 meters above sea level. Then we proceed to determine the irradiation values using METEONORM. In Figure 1 we give the values recorded in an annual graph in which the monthly irradiation is specified in kilowatt hour, corresponding the maximum to March (181 kWh) and the minimum to July with "only" 131 kWh.

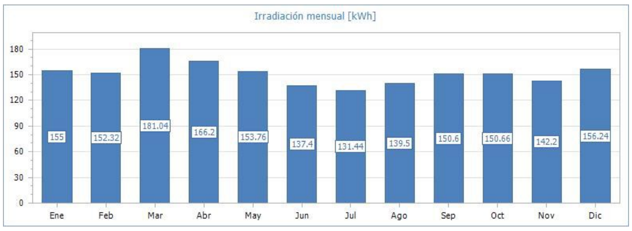

Figure 1. Solar irradiation in the location of the CPT plant.

These direct and diffuse solar irradiation data were obtained for the year 2020 from the real-time measurement history software carried out at PVGIS and METEONORM for the entire world. For the determination of the coordinates, Trimble GPS with submetric precision and corrected by differential correction was used. The entire system is modelled in ESRI's ARCSIG.
Respecting the climate, it is variable between humid and dry, being quite pleasant all along the year. Maximum temperatures fluctuates between 24 and 30 ºC.

The performance of the HTF system will be analysed through simulation in specialized software, since in addition to the ability to receive heat from the mirrors and drive heat exchanger to feed a steam turbine, this HTF can be stored in an insulated hot tank for future use when sunlight is not available. As noted before, and based on current research, HTFs can be classified into six groups based on the type of material. These include: Air and other gases, water vapour, molten salts, thermal oils, organics, and liquid metals [8.9].
Also, certain characteristics of the HTF must be present before making a decision [8,10], being the most important its density and the minimum and maximum temperature operation for every fluid. For the chosen HTF, Therminol VP-1, those values are, respectively, d = 765,5 kg/m^3, T_m = 12 ºC and T_M = 400 ºC.

3. Results

To perform the study of the PCT plant, we will choose an average ambient temperature of the implementation site of the PCT is 27 degrees Celsius with a maximum temperature of 34 degrees Celsius and a minimum of 17 degrees Celsius. Therefore, based on the analysis of multi-criteria decisions for the selection of the type of heat transfer fluid from those existing in plants of this type already in operation and based on the use of best practices when observing the minimum operating temperatures, it opts for the Thermonol VP-1.

In Figure 2 we represent the thermodynamic processes that take place in the complete cycle. It starts from point *1* at 100 bar of pressure, with a maximum operating temperature of 400 °C, from point *1* to point *2* the first turbine occurs, therefore we have an adiabatic process (isentropic) with an efficiency of 0.8. Then at point *2*, we have a pressure of 3 bar. From point *2* to *3*, an isobaric process occurs and therefore exist heat exchange, increasing the temperature to the initial value of 530 °C. A low pressure turbine 2 is then given from point *3* to *4* with again an efficiency of 0.8 and a fixed outlet pressure of 0.1 bar. It continues from point *4* to *5* with a heat exchange giving an isobaric process and then from point *5* to *6* an isothermal process at a temperature of 45.8 °C until reaching the saturation limit. From point *6* to *7* there is a pumping that is an adiabatic process (isentropic) with another efficiency of 0.8 and an initial pressure of 100 bar. Finally, from point *7* and *8* back to point *1* there is an isobaric process, that is, heat exchange again, passing for points 9 and 10, given by the program adapting to the saturation curve of water. As a result, it is obtained a simulated temperature-entropy (T-S) diagram. We have prepared another thermodynamic cycle modelling for the cycle, shown in Figure 3.

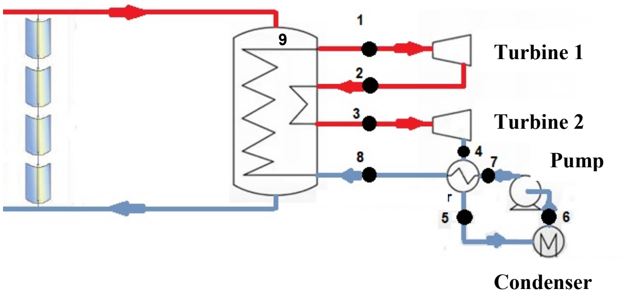

Figure 2. Scheme of the thermodynamic process.

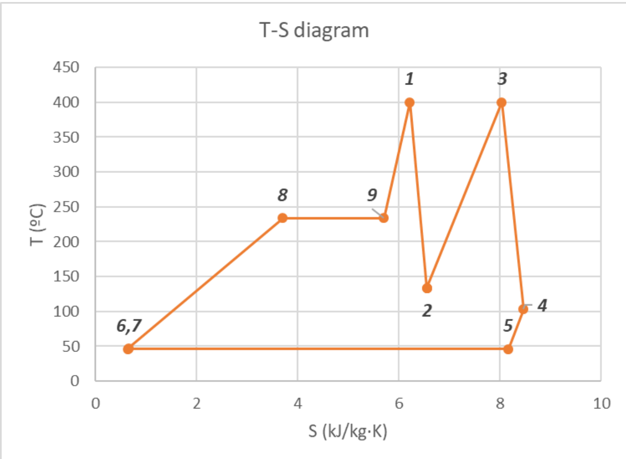

Figure 3. Thermodynamic modelling of the power cycle in a temperature-entropy (T-S) diagram.

This modelling can be detailed in the properties calculated for the seven states and seven processes in the magnitudes of pressure (P), volume (V) and temperature (T) for the state, and entropy (S), enthalpy (H), work (W), heat (Q), internal energy (U), change in internal energy (ΔU) and change in enthalpy (ΔH), some of them given in Table 1.

Table 1. Obtained thermodynamic data for the energies generated or absorbed in each process.

Process	W (kJ)	Q (kJ)	ΔU (kJ)	ΔH (kJ)
Process 1-2	550.6	0.0	-525.0	-677.0
Process 2-3	0.0	729.2	600.2	777.0
Process 3-4	582.2	0.0	-543.3	-702.5
Process 4-5	0.0	-108.2	-199.3	-263.3
Process 5-6	-4.1	-2,395.8	-2,245.0	-2,391.8
Process 6-7	-12.6	0.0	2.5	12.6
Processes 7 to 1	0.0	2,891.0	2,909.9	3,245.0
Cycle	1,116.2	1,116.2	0	0

The obtained energy of the total cycle is about 1,116 kJ/kg, being the input heat is 3,620 kJ/kg and the output 2,504 kJ/kg, reaching the thermodynamic equilibrium as it was expected. Remember that this heat is free, obtained from the solar radiation.
It is also observed in Table 1 that the resulting energy balance is null for ΔU and ΔH, while Q = W for the complete cycle. Respecting entropy, balance is also null being a maximum entropy variation of 7.8 kJ/kg·K.

4. Discussion

Therminol VP-1 HTF has a behaviour during the Rankin cycle that brings important benefits in terms of efficiency and performance, such as having excellent heat transfer properties, combining thermal stability and low viscosity, behaving a reliable fluid in temperatures ranging from 12 to 400 ºC [13]. From the behaviour observed in the Rankin cycle, it can be said that Therminol VP-1 allows precise temperature control since it can operate as a heat transfer fluid in the vapour generation phase.

Of the PCT plants already in operation, the most used heat transfer fluids are organic oils produced from the eutectic mixture of biphenyl and diphenyl oxide [14], being Therminol VP-1 a HTF based on that composition, but with some added compounds. Thus, thermal degradation, known as thermal cracking, and oxidative stress are observed at a degree much lower than most of usual HTFs in the specific environmental conditions of the research proposed [13].

With the data obtained and using the specialized software, we simulated a CPT plant with 10 MW of installed power to be placed in a dry equatorial climate. The minimum speed of the flow of the HTF is 0.3 m/s while the maximum reaches 3.7 m/s. Likewise, the minimum and maximum mass flow is 1 kg/s and 12 kg/s respectively, which allows a thermal efficiency of 35.6% for the complete cycle, which is the standard for this type of power plant. This implies that in order to generate approximately 10 MWe (megawatts of electricity) from the turbine generator terminals, a thermal cycle power of 28 MWt (megawatts of thermal energy) is required. The design of the thermal storage tanks was planned so the energy can be stored up to 6 hours [15].

This kind of thermosolar plants can be a real option to obtain green and free energy in all sunny countries, which includes a great part of Latin America, due to the viability of the system, the long life of the installation and the low maintenance it needs. In addition, it is no pollutant to air, water or land, and this is a noiseless system even in full operation. Actually, prize of this technology is higher than other based in removable sources as wind or photovoltaic, but due to standardization of the PCT technology, it will be competitive in a near future. Also, it is important to note its higher efficiency per power unit installed compared with other NCRE technologies.

4. Conclusion

The power cycle of a cylinder parabolic thermosolar power plant, CPT, modified with a Rankin cycle, is modelled thermodynamically through the use of specialized software. The thermodynamic system is efficient as can be determined from the energy and entropy balances.
In the place we are going to put the CPT plant, to generate 10 MWe of electric power, we will need 28 MWt of thermal power, obtained from the solar field. In addition, the CPT plant is planned to store thermal energy in a two tanks system, which allows for up to 6 hours of electricity production without sun.

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