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Optimum operating temperature of parabolic trough solar fields☆

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ABSTRACT

This paper shows the relationship between the incident solar radiation and the optimum outlet temperature of a solar field to produce the highest amount of electrical power. Various simulations were made for different values of incident solar radiation, calculating for each one the optimum temperature which produces the maximum electrical power and demonstrating that to operate the field at the highest allowable temperature is not the optimal operating point from certain values of solar radiation; a situation which takes special relevance during cloudy days. These simulations were carried out using two connected models, one for the solar field and another one for the power cycle.

1. Introduction

The main technologies for converting solar energy into electricity are photovoltaic (PV) and concentrated solar thermal (CST). Parabolic trough, solar towers, Fresnel collector and solar dishes are the main technologies used for concentrating solar energy. This paper focuses on parabolic trough solar thermal power plants, which consist of a collector field (Fig. 1), a power cycle, a thermal energy storage (TES), and auxiliary elements such as pumps, pipes and valves. The solar collector field collects solar radiation and focuses it onto a tube in which a heat transfer fluid, usually synthetic oil, circulates. The heat gained by the oil is used by the power cycle to produce electricity by means of a steam turbine. Another way to produce the steam needed by the turbine is the direct steam generation (DSG), a type of CST plant where the steam is produced directly in the pipes.

The main goal of a parabolic trough solar field is to collect the maximum solar energy in order to produce as much electrical power as possible. Normally, this is achieved by keeping the outlet temperature of the field around the maximum allowable value, that is 400 °C, due to oil degradation. However, in this paper, we will prove that this way to operate the field does not produce the best results of electrical power generated. That is due to the fact that the electrical power depends on both the oil flow and temperature, in such way, that when the value of solar radiation is low, to operate at a maximum temperature would imply that the oil flow would be so small that the electrical power generated would not be the maximum possible. This problem has been studied before in Lippke (1995), where it was suggested that the optimum strategy is based on adapting the oil outlet temperature to the incident solar radiation, keeping constant the superheating temperature of the steam; it was also studied in Montes et al. (2009) where a constant outlet temperature was used (393 °C). Finally, a more recent study was carried out in Camacho and Gallego (2013) where it was proposed to change the outlet temperature set point according to the value of the solar radiation. The set point is calculated by an optimizer and then is tracked with a series feedforward with a PID controller.

The main novelty of this paper is that the effect of the solar radiation on the optimal outlet temperature was studied with a complete power cycle model rather than only using a formula that only depends on the oil outlet temperature and not taking into account the oil mass flow for calculating the electrical power; which was the case of Camacho and Gallego (2013). In Manzolini et al. (2012) a complete power cycle model it is also used, but its application is to predict the off-design performance of parabolic trough solar plants, instead of using it to calculate the optimum temperature, which is the case of the paper presented here. The calculations obtained with this power cycle model, in spite of its simplicity, agree with the ones found in the literature (García, 2012; Lima et al., 2016; Lippke, 1995), that it is not the case of the results shown in Camacho and Gallego (2013). In addition the simulations made in this paper were not focused on studying particular working days, that is the case of (Lippke, 1995; Camacho and Gallego, 2013) but on determining for different values of solar radiation what the optimum value of outlet temperature should be; something that is specially useful during cloudy days. The models used in this paper were developed to be used also in control purposes by making little changes, like adapting the parameters of the field and power cycle to match those of the target field, and adding dynamic to the power cycle. This

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Fig. 1. ACUREX distributed solar collector field.

dynamic can be assumed to be the same that of the boiler, which is the slowest one of the power cycle.

Using the software Engineering Equation Solver©, the authors have simulated a parabolic trough solar field connected with a power cycle. These simulations have been carried out for different values of solar radiation, calculating for each one the optimum value of outlet temperature which produces the highest amount of electrical power. This optimum value also corresponds to the optimum value of oil flow, due to the fact that both variables are dependent for a given value of *I*. The power cycle used in this paper is a Rankine cycle with a maximum temperature of 374 °C, a maximum pressure of 70.5 bar, and a power range of 800–2330 kW. The selection of a Rankine cycle is due to the fact that it is the same used in the ACUREX field, however, the power range has been increased according to the size increase made to the field used in this paper, and the working temperature has been increased to match those used by the commercial plants.

The paper is organized as follows: Section 2 describes the model of the solar field used for simulation purposes. Section 3 describes the model of the power cycle. Section 4 shows the results obtained by simulations of the solar field connected with the power cycle (Fig. 2). Finally, the paper draws to a close with some concluding remarks.

2. Solar field model

In this section, the mathematical model of a parabolic trough is presented. This model is the same used in Navas et al. (2016) which is at the same time a modification (mainly the modeling of all field loops, instead of modeling only one of its loops and supposing the behavior of the entire field to be the same) of the model proposed by Camacho et al. (1997, 2007a,b, 2012), Camacho and Gallego (2013), Carmona (1985) for the ACUREX field (Fig. 1). Basically, this model can be used to simulate parabolic trough solar fields by selecting parameters like the number of active (the parts where the solar radiation reaches the tube) and passive (joints and other parts not reached by concentrated solar radiation) zones, length of each zone, or collector aperture. The solar field simulated in this paper is supposed to be on the site of the Escuela Superior de Ingeniería de Sevilla. The field consists of 3456 distributed solar collectors. These collectors are arranged in 48 rows (being 3 m the row spacing between parallel collectors) which form 24 parallel loops (each of the loops is 480 m long), each one with 8 modules of 18 collectors. The collectors have dimensions of 3 × 1.82 m and their factory is EuroTrough. Each loop is modeled by the following system of partial differential equations describing the energy balance:

Active zones

$$\rho_m C_m A_m \frac{\partial T_m}{\partial t} = In_0 G - H_l G (T_m - T_a) - dH_t (T_m - T_f) \quad (1)$$

Fluid element

$$\rho_f C_f A_f \frac{\partial T_f}{\partial t} + \rho_f C_f \dot{q} \frac{\partial T_f}{\partial x} = dH_t (T_m - T_f) \quad (2)$$

Passive zones

$$\rho_m C_m A_m \frac{\partial T_m}{\partial t} = -G H_p (T_m - T_a) - dH_t (T_m - T_f) \quad (3)$$

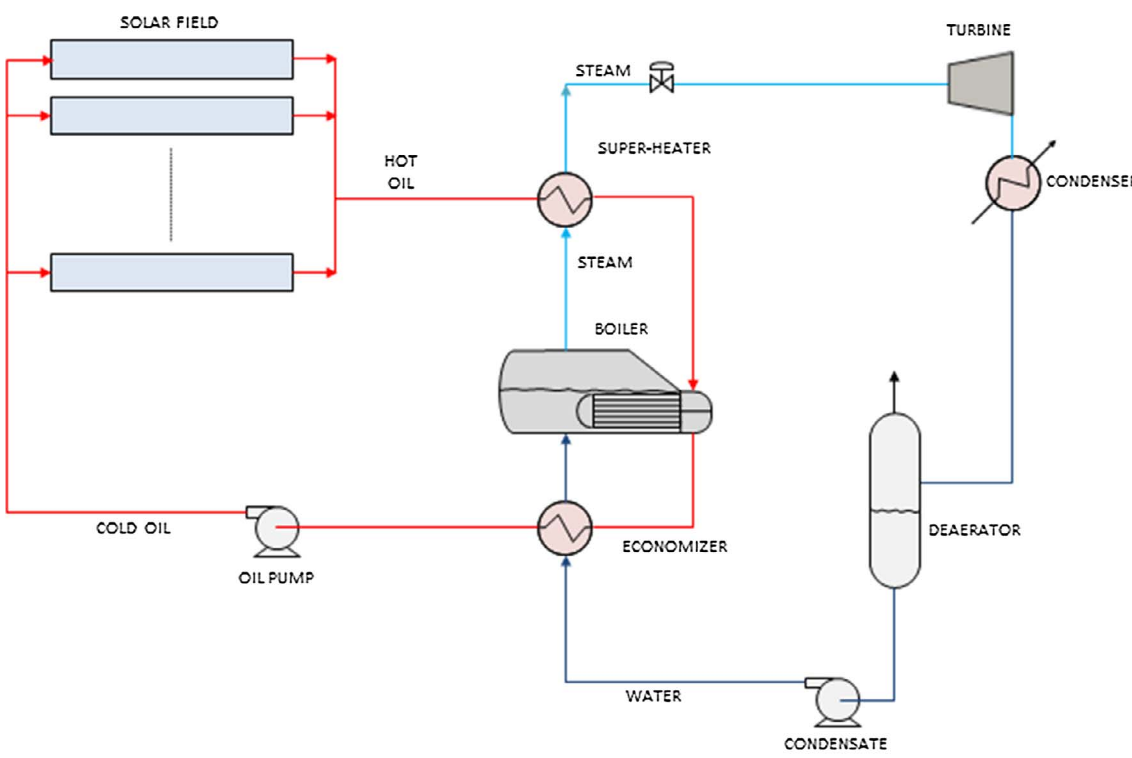

Fig. 2. Diagram of the solar field connected with the power cycle.