Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 50-1 (2017) 109–114

Optimum Control of Parabolic Trough Solar Fields with Partial Radiation ⋆

Sergio J. Navas * **Francisco R. Rubio** ** **Pedro Ollero** ***

* *Departamento de Ingeniería de Sistemas y Automática, Universidad de Sevilla, Spain (e-mail:snavas1@us.es).*
** *Departamento de Ingeniería de Sistemas y Automática, Universidad de Sevilla, Spain (e-mail: rubio@us.es)*
*** *Departamento de Ingeniería Química y Ambiental, Universidad de Sevilla, Spain (e-mail: ollero@us.es)*

Abstract: This paper describes the main problems of operating parabolic trough solar fields during days with partial radiation. An optimal control strategy is proposed to solve these problems and it is assessed against a classical one, which uses a feedforward and a PI controller with a fixed set point of oil outlet temperature. Some simulations have been made using MATLAB to demonstrate that using the optimal control strategy better results can be achieved.

Keywords: Solar, Control, Optimization, Parabolic Trough, Simulation, Partial Radiation

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 most used technologies for concentrating solar energy. This paper focus on parabolic trough solar fields, which consist of a collector field (Fig. 1), a power cycle 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 oil is heated up and then used by the power cycle to produce electricity by means of a turbine.

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 show that this way to operate the field does not produce the best results of electrical power generated. This problem has been studied before in Lippke (1995), where it was suggested that the optimum strategy is based on adapting the fluid outlet temperature to the incident solar radiation, keeping the 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.

On the other hand, using a PI with a feedforward controller that manipulates the oil flow to keep constant the outlet temperature of the field, like in Camacho et al. (1997)-Camacho et al. (2012)-Carmona (1985), while a cloud is passing through the field may provoke temperature peaks in some loops. This situation is due to the fact that when the cloud passes the controller will decrease the oil flow in order to keep the outlet temperature constant, however, in the loops that are not covered by the cloud, the solar radiation is not reduced, so that their temperature will be increased above the security limit. If this situation happens the collectors are programmed to get out of focus to prevent oil degradation, but that would involve a loss of energy and it is not considered in this paper as a possible solution.

In this paper the effect of the solar radiation on the outlet temperature was studied with a complete power cycle model (Fig. 2) reduced to a correlation that relates the electrical power generated by the condensation turbine with the mass flow and outlet temperature of the oil. In Camacho and Gallego (2013) it is used a similar approach but they use a correlation that only depends on the outlet temperature, that implies efficiency results higher than the ones found in the literature Lippke (1995); in addition the simulations made in this paper were carried out taking into account a model of the entire field, not assuming that the behavior of one loop is the same than the other ones. Therefore, the authors propose that using an optimal controller with constraints can prevent the appearance of temperature peaks and also maximize the electrical power generated by the field depending on the value of solar radiation.

The paper is organized as follows: Section 2 describes the models of the solar field, passing clouds and power cycle used for simulation purposes. Section III describes both

---

⋆ This work was supported by the projects DPI2013-44135-R and DPI2015-70973-R granted by the Spanish Ministry of Science and Innovation.

10.1016/j.ifacol.2017.08.019

control strategies tested: the feedforward with a PI control and the optimum control. Section IV shows the results obtained by simulations made in MATLAB. Finally, the paper draws to a close with some concluding remarks.

Fig. 1. ACUREX distributed solar collector field

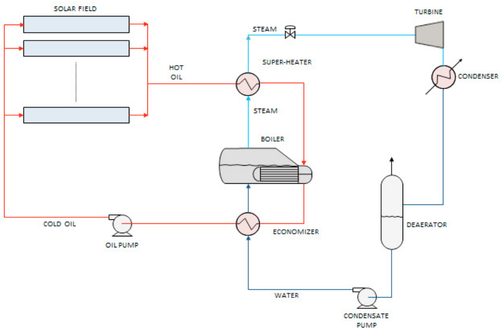

Fig. 2. Diagram of the solar field connected with the power cycle

2. SYSTEM MODELING

The model of each of the parts which have been used to simulate the operation of a solar field during the days with partial covering is presented. These parts are: the solar collector field, the passage of the clouds and the power cycle.

2.1 Solar Collector Field Model

In this subsection, the mathematical model of a parabolic trough solar field is presented. This model is the same used in Navas et al. (2016) which is at the same time a slight modification of the model proposed by Camacho et al. (1997)-Camacho et al. (2012)-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. It is composed of 24 loops and has dimensions of 144x240 m^2. Each loop is modeled by the following system of partial differential equations describing the energy balance:

Active zones

$$\rho_m C_m A_m \frac{\partial T_m}{\partial t} = I n_0 G - H_l G (T_m - T_a) - L H_t (T_m - T_f) \qquad (1)$$

Fluid element

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

Passive zones

$$\rho_m C_m A_m \frac{\partial T_m}{\partial t} = -H_p (T_m - T_a) - L H_t (T_m - T_f) \qquad (3)$$

where the sub-index m refers to metal and f refers to the fluid. The model parameters and their units are shown in table 1.

Table 1. Solar field model parameters description

Symbol	Description	Units
t	Time	s
x	Space	m
ρ	Density	Kg/m^3
C	Specific heat capacity	J/(K kg)
A	Cross sectional area	m^2
T	Temperature	°C
$\dot{q}$	Oil flow rate	m^3/s
I	Solar radiation	W/m^2
n_0	Optical efficiency	Unit-less
G	Collector aperture	M
T_a	Ambient Temperature	°C
H_l	Global coefficient of thermal losses for active zones	W/(m^2 °C)
H_t	Coefficient of heat transmission metal-fluid	W/(m^2 °C)
H_p	Global coefficient of thermal losses for passive zones	W/(m^2 °C)
L	Length of pipe line	m

The density ρ, specific heat C and coefficient of thermal loss H_l depend on fluid temperature. The coefficient of heat transmission H_t depends on temperature and oil flow. The incident solar radiation I depends on hourly angle, solar hour, declination, Julianne day, local latitude and collector dimensions Camacho et al. (1997)-Camacho et al. (2012)-Carmona (1985). In order to solve this system of partial differential equations, a two stage finite difference equation has been programmed, considering each segment of 1 m for the passive zones and of 3 m for the active zones and solving (1)-(2)-(3).

2.2 Modeling of the Passing Clouds

The modeling of the passing clouds is necessary to know how the radiation of the sun is distributed throughout the field. This can be achieved creating a matrix which represents the whole field extension. Each element of the matrix is assigned the value of the incident solar radiation