

A virtual lab for modeling and control of a solar collector field [★]

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Abstract: Research and teaching on renewable energies are very important topics worldwide. Most of the renewable energy processes are quite complex to analyze and to study. For that reason, educational resources as support for the teaching and learning of these processes dynamics are very useful. Thus, this paper presents a virtual lab as support to the modeling and control concepts of a solar collector field, as these kind of solar plants are widely used at industrial level requiring control skills. This interactive tool is used as part of several subjects in a Master on Solar Energy at the University of Almería, Spain. Examples about open and closed-loop exercises are presented.

Keywords: Virtual lab, solar energy, control education, modeling.

1. INTRODUCTION

The global concern for sustainable development as well as the depletion of traditional energy sources, have placed renewable energies on the spotlight. Among the diverse alternative energy sources, solar energy is worldwide used in any sustainable development environment with good solar irradiance conditions. However, although solar energy technologies are well known and in an advanced phase of development, installation and use, there is still room for developing new designs and operating strategies aimed at enhancing its performance and dispatchability (Kumar et al., 2018); what highlights the importance of promoting research and education on this field.

Due to its location and irradiance conditions, Spain (south of Europe) is one of most suitable countries for the implementation and research of solar technology in Europe. Even though the solar irradiance is well distributed throughout the Spanish geography, it is specially adequate in the southeast zone. In this context, Almería (southeast of Spain) is one of the Spanish cities that receives more direct and global solar irradiance a year (Sancho Ávila et al., 2012). Therefore, this province plays a fundamental role in the academic and research activities related to solar technology. In fact, the the largest concentrating solar technology research, development and test center in Europe, the Plataforma Solar de Almería (www.psa.es), is located in Tabernas (40 km far from Almería). Moreover, this city has also The Solar Energy Research Center (CIESOL, www.ciesol.es), which is located at the university of Almería (UAL) campus. The availability of these

two facilities has constituted a fundamental framework for the development of specialized courses in solar energy, as well as the creation of the Master's Degree on Solar Energy at UAL^{*}, which allows its graduates to deepen the diverse technologies and applications that currently exist for solar energy.

The processes based on solar energy are nonlinear systems that are usually complex to understand. Many different variables and parameters affect the process behaviour. Traditionally, Matlab-based simulations have been used as support for understanding these systems. However, this solution limits the visualization and analysis of the process under different scenarios, such as solar radiation changes, open- and closed-loop behaviour, different control approaches, etc. Thus, graphical and interactive simulations could contribute to facilitate understanding, by providing an easier and visual educational resource for this purpose. For instance, in (Silva et al., 2011), an interactive didactic simulation tool was developed using LabVIEW to help in the understanding of solar parabolic-trough principles. This tool was used for basic demonstrations for visitors at CIESOL obtaining positive feedback from the users.

Therefore, according to this experience, this work presents the development of a virtual lab as support to basic modeling and control concepts of a solar collector field. Virtual labs are very well-known teaching/learning resources in the control education area (Heradio et al., 2016; Galan et al., 2017). They are desktop or web-based simulation tools that allow making virtual experiments graphically and interactively on a model of the process. Easy Java Simulations (EJS) is one of the most common programming environment to develop virtual labs (Esquembre, 2008, 2015), and it was selected to create the tool presented

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^{*} <http://www2.ual.es/master-solar/>;
<http://cms.ual.es/UAL/en/estudios/masteres/MASTER7106>

in this paper. The resulting virtual lab allows analyzing the nonlinear behaviour of the solar collector field model described by (Álvarez et al., 2009; Camacho et al., 2012). A solar radiation model is included that simulates a clear day for a selected date on the graphical interface. Open- and closed-loop (with different control approaches) simulations can be performed, where it is possible to simulate passing clouds as external load disturbances. Moreover, the results can be stored in a Matlab-format file for future analysis.

The rest of the paper is organized as follows. Section 2 summarizes the process model and the control schemes implemented in the virtual lab. Section 3 is devoted to describe the graphical interface and the virtual lab capabilities. Educational activities and examples are presented in section 4. Finally, the paper ends with conclusions and future works.

2. PROCESS DESCRIPTION

This section describes the process used for the virtual lab implementation, where the model and the control approaches included in the virtual tool are summarized.

A solar collector plant is a Solar Power System (SPS) based on Distributed Collector System (DCS) technology where solar collectors follow the Sun through one or two rotation axes (see a plant scheme in Fig. 1). The heat transfer fluid (HTF) is pumped through the pipes, whereas a tank fluid stores hot fluid that can be used when no solar irradiance is available, that is, it can be considered as an energy buffer. Finally, a three-way valve allows the plant supervisor to decide if the hot fluid is supplied from the solar collector or from the tank. Radiant thermal energy is reflected when any incident light beam is reflected on the focus of the parabola of each collector, where a metal pipe with flowing heat transfer fluid is placed. This fluid is heated and, later, feeds a heat exchanger with the aim of generating electricity in a same way than in a conventional power plant.

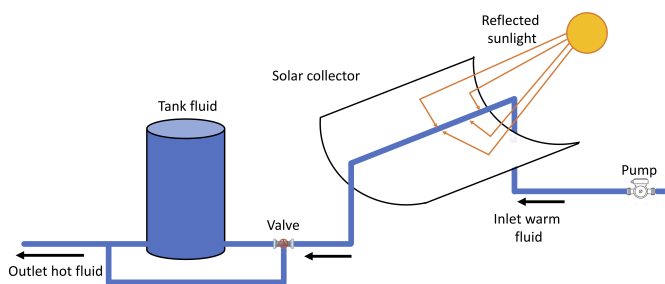


Fig. 1. Scheme of a solar collector plant

2.1 System modeling

A solar collector field is usually modeled through a grey-box model that is calculated from energy and mass conservation equations. Figure 2 shows a cross section of collector pipe in which warm fluid enters at the beginning of the pipe, $x=0$, with a velocity $v(t)$. This fluid is heated by the incident direct solar irradiance, $I(t)$. At the end of the pipe, $x=L$ (being L the length of the pipe), the hot fluid leaves the solar collector and its temperature changes with time

and space $T(t,x)$. The fluid velocity, solar irradiance, ambient temperature, $T_a(t)$, and pipe temperature $T_w(t)$ are supposed to be only time-dependent. Several simplifying assumptions are assumed, such as: the thermal resistance of the pipe is neglected, the fluid is incompressible, and its specific heat capacity and density are considered to be constant.

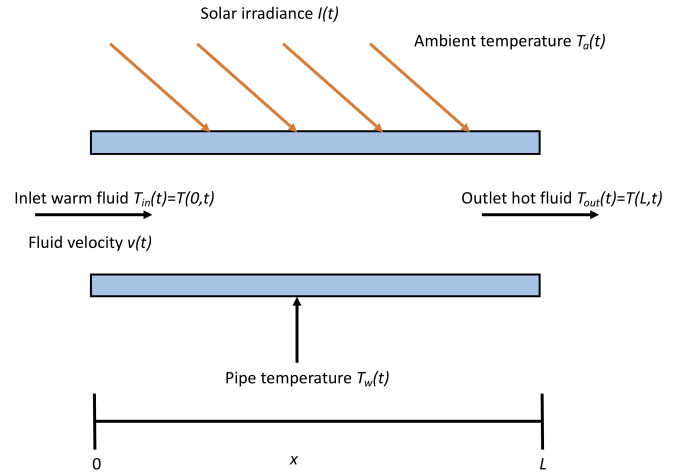


Fig. 2. Scheme of the pipe of a solar collector field

Thus, using these considerations, a distributed parameter model can be developed based on two partial differential equations, one for the temperature of the pipe and the other one for the outlet fluid temperature:

$$A_i \rho C \frac{\partial T}{\partial t} + u_{sf} \rho C \frac{\partial T}{\partial x} = D_i h_i (T_w - T) \quad (1)$$

$$\rho_w C_w A_o \frac{\partial T_w}{\partial t} = I n_o G - h_o G (T_w - T_a) - D_i h_i (T_w - T) \quad (2)$$

where in the previous equations the meanings of the physical variables are: A_i and A_o are the cross-sectional areas for flow inside the pipe and for the pipe wall (m^2), respectively. C and C_w are the specific heat capacities for the fluid and for the metal of the pipe wall ($\text{J}/(\text{kg} \cdot ^\circ\text{C})$), respectively. h_i and h_o are the convective heat transfer coefficients of the inside and outside pipe ($\text{W}/(\text{m}^2 \cdot ^\circ\text{C})$), respectively. ρ and ρ_w are the densities of the fluid and of the metal of the pipe wall (kg/m^3), respectively. D_i is the inside diameter of the inner pipe (m). G is the collector aperture (m) and n_o is the optical efficiency. Finally, u_{sf} is the volumetric flow rate (m^3/s) that is the product between the fluid velocity and the cross-sectional area for the flow inside the pipe, that is, $u_{sf}(t) = A_i \cdot v(t)$. Notice that the time dependence in the variables was omitted for a better representation of the equations.

After linearizing Eqs. (1) and (2) and applying Laplace's transform, it is possible to obtain the transfer function in the Laplace variable s , which relates the outlet hot fluid with its velocity:

$$G(s) = \frac{T(L, s)}{v(s)} = \underbrace{k_a \frac{-\beta_a s + 1}{s(\tau_a s + 1)}}_{P(s)} \underbrace{\left[1 - e^{-\theta s} \left(k \frac{-\beta s + 1}{\tau s + 1} \right) \right]}_{R(s)} \quad (3)$$

where the transfer function parameters, k_a , β_a , τ_a , k , β , τ and θ can be related to the physical variables that appear in Eqs. (1) and (2) (Álvarez et al., 2009).

The transfer function showed in Eq. (3) is able to model the behaviour of the resonance modes, that this kind of systems has in medium and high frequencies, through the irrational transfer function $R(s)$. However, for control purposes sometimes it is not necessary a transfer function that covers all the system frequency range, but a normal rational transfer function that captures the behaviour of the system at low frequencies.

Therefore, the distributed parameter model can be approximated to a lumped-parameter one. To this end, the partial derivative of the fluid temperature with respect to space, $\partial T/\partial x$ in Eq. (1), can be approximated to the term $(T_{out} - T_{in})/L$ (Camacho et al., 2012). Later, if the pipe temperature, T_w , is found from Eq. (2) and replacing it in Eq. (1), it is possible to obtain a mathematical expression that relates the outlet hot fluid temperature, T_{out} with the main process variables that have influence on it, that is, inlet warm fluid temperature, T_{in} , ambient temperature T_a , solar irradiance, I , and volumetric flow rate, u_{sf} . So, the resulting expression can be expressed as follows:

$$A_i \rho C \frac{dT_{out}(t)}{dt} = I(t)\gamma - h_o G(\bar{T}(t) - T_a(t)) - u_{sf}(t)\rho C \left[\frac{T_{out}(t) - T_{in}(t - t_r)}{L} \right], \quad (4)$$

where γ is the product between optical efficiency and collector aperture, that is, $\gamma = n_o G$, t_r is a transport delay (s), and \bar{T} is the working temperature of the equivalent absorber tube, which is modeled as the mean of the inlet and outlet temperatures:

$$\bar{T} = \frac{T_{out}(t) + T_{in}(t - t_r)}{2}. \quad (5)$$

Thus, this final model showed in Eq. (4) is the one implemented in the virtual lab presented in this paper. In this first version, no transport delay t_r has been considered, to avoid increasing computing time and thus losing interactivity. The second version that will be available soon will include it using the approximation in Normey Rico et al. (1998).

2.2 Control schemes

From a control perspective, and according to the model equation (Eq. (4)), the solar field process can be described as:

- Controllable input: solar field water flow rate ($u_{sf} \in \mathbb{R}_+$).
- Controlled output: Outlet solar field temperature ($T_{out} \in \mathbb{R}_+$).
- Disturbances: Inlet solar field temperature ($T_{in} \in \mathbb{R}_+$), ambient temperature ($T_a \in \mathbb{R}_+$), and global irradiance ($I \in \mathbb{R}_+$).

In this paper, two control modes have been proposed for the solar field environment that are those explained to students of the Masters in Solar Energy: i) simple PID based control loop, and ii) PID control loop with

feedforward in parallel configuration. The layout of the closed-loop of the first control mode is shown in Fig. 3. In this case, the control signal ($u_{sf}^{PID}(t)$ in Fig. 3) is directly calculated by means of an ideal PID controller according to the following equation (Åström and Häggglund, 2006):

$$u_{sf}^{PID}(t) = K_p \left[e(t) + \frac{1}{T_i} \int_0^t e(t)dt + T_d \frac{de(t)}{dt} \right], \quad (6)$$

where K_p is the proportional gain ($m^3/(\text{°C}\cdot\text{s})$), and T_i and T_d are the integral and derivative time constants (s), respectively. Note that, all the variables names are according to Fig. 3. Also, it is important to mention that, in this control loop, the PID control signal is equal to the control signal directly sent to the solar collector field, that is, $u_{sf}^{PID}(t) = u_{sf}(t)$.

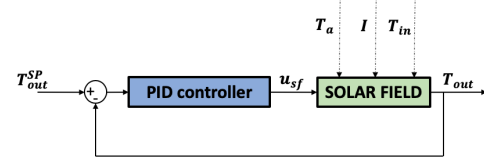


Fig. 3. Closed-loop layout of the simple PID based on control loop mode. T_{out}^{SP} is the outlet solar field temperature setpoint. Note that, the nomenclature (t) has been omitted for the sake of simplicity.

This first control approach is very useful to understand the proposed control problem and as a first approximation. However, one of the main problems associated to this first control mode is that, the PID controller has to deal with the disturbances of the facility, specially with solar irradiance. This is not trivial because of the intermittent and unpredictable behaviour of this variable, which normally introduces high frequency disturbances to the system which can cause high oscillations in the controller. On the other hand, when only a feedback controller is used, a closed-loop reactive behaviour is obtained against load disturbances. Moreover, this control scheme is highly dependent on the operating conditions, as the system exhibits different dynamics when operating at different flow ranges (in closed-loop, flow depends on the operating conditions dictated by disturbances).

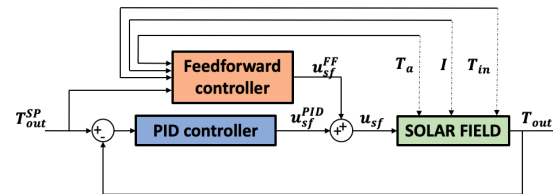


Fig. 4. Closed-loop layout of the PID control loop with feedforward in parallel configuration control mode. Note that, the nomenclature (t) has been also omitted for the sake of simplicity.

For this reason, a second control mode is proposed, where parallel feedforward configuration (Camacho et al., 2012) is included in the control scheme, see Fig. 4. The feedforward is implemented as a static version of the solar field model presented in Eq. (4), which is in charge of

providing the nominal operating point in terms of water flow rate ($u_{sf}^{FF}(t)$), according to the operating conditions and disturbances ($T_a(t)$, $I(t)$, and $T_{in}(t)$), and the outlet temperature setpoint ($T_{out}^{SP}(t)$). In this way, the control signal in this control mode (see Fig. 4) is calculated as:

$$u_{sf}(t) = u_{sf}^{PID}(t) + u_{sf}^{FF}(t), \quad (7)$$

where $u_{sf}^{PID}(t)$ is computed as in the first control mode, whereas $u_{sf}^{FF}(t)$ is calculated as follows:

$$u_{sf}^{FF}(t) = \left[\frac{\gamma L}{(T_{out}^{SP}(t) - T_{in}(t - t_r))} I(t) - \frac{h_o GL(\bar{T}(t) - T_a(t))}{(T_{out}^{SP}(t) - T_{in}(t - t_r))} \right] \frac{1}{\rho C}. \quad (8)$$

Notice that thanks to the feedforward capabilities of this second control approach, in this case the control system reacts instantaneously to changes in the disturbances improving the reactive response of the control scheme presented in Figure 3, while helping the PID feedback controller to work around a the operating point dictated by the feedforward control signal. The feedback loop also compensates for unmodelled dynamics.

3. VIRTUAL LAB

This section summarizes the proposed virtual tool, which has been developed using EJS as programming environment (Esquembre, 2004). The tool includes the process model and the control architectures presented in the previous section. Figure 5 shows a screenshot of the virtual lab. As observed from the figure, the tool is divided in three different parts:

- The area at the left part shows a synoptic representation of the solar collector field. Different elements in the screen are changing when the simulation is working to emulate a realistic situation. For instance, the color for the sun, clouds appears when they are selected from the interface, the color of the pipes and the tank are changing according to the values of the solar radiation and the water temperature, etc. On other hand, the pump is also moving when the input flow is bigger than zero.
- Three plots are shown in the right part of the tool. The graphic at the top shows the different process temperatures: inlet temperature (pink color), ambient temperature (green color) and outlet temperature (blue color). Moreover, the temperature setpoint used in closed-loop control is shown in red color. The plot in the middle shows the water flow rate. Then, the plot at the bottom shows the evolution of the solar radiation. Notice than when passing clouds are simulated from the parameters area, step changes in the solar radiation will be observed in this plot.
- The area at the bottom is dedicated to the virtual lab parameters, grouped in four sections. First, the ‘Solar radiation day and parameters’ section allows to set the date as the input to the solar radiation model. Using this date, the solar radiation for clear day at the location of the Solar Platform of Almería is simulated and used as input to the solar collector field

model. Moreover, other parameters such as collector aperture, G , optical efficiency, $ncol$, and the cross-section area for the flow inside the pipe, A . The ‘Variables and options’ section is divided in three rows. In the first row, initial conditions for the inlet (T_{in}) and ambient (T_a) temperatures, and the value for the reference temperature (Ref) can be set. Also, the current value of the outlet temperature is shown (T_{out}). In the second row, when the simulation is in open loop, the water flow rate is available, (q) to be modified manually. In the third row, the current value of the solar radiation is shown (I), that can be taken from the simulated date or from real data by using the checkbox (From data). Moreover, a checkbox to simulate passing clouds is available (Clouds). With this last option, it is possible to determine the amount of W/m^2 that will be reduced because of a passing cloud. When this option is activated, clouds are drawn at the synoptic zone and the sun is hidden. The ‘Controller parameters’ section allows to modify the PID parameters. Three different controllers are shown, one for the control scheme of Figure 3 without feedforward, one for the control scheme in Figure 4 with feedforward, and a new configuration with the feedforward in series that is not considered in this paper. Furthermore, three checkboxes are available to select one of the control approaches. Finally, the ‘Simulation options’ section contains the classical Play, Pause and Reset options for the simulation, and on the other hand, it includes the possibility to record the simulation results in a Matlab-format file. When the Start Record button is active, the simulation data starts to be recorded until the Stop Record button is pressed. Then, a file called “data.m” is generated with all simulation results.

The resulting virtual lab can be used as a JAVA-based standalone application or embedded in a web browser **.

4. EDUCATION PURPOSES

The proposed virtual tool can be used for different educational activities. In our case, it has been included in the Master’s in Solar Energy, in a subject called “Modeling, control and energy management in solar plants”. This subject is taught once students have a deep knowledge on parabolic troughs technologies from another subject. Students come to this subject with low knowledge and background on automatic control issues. So, the emphasis is placed on understanding basic modeling and simulation approaches for solar plants (both first principles models and black-box models when using first-order systems), basic elements of the control systems involved and basic control schema. Special emphasis is placed on the involved nonlinear dynamics, disturbances, linearization around an operating point (and its definition), the effect of feedback and basic control schemes used at industrial level (PID and feedforward). Having this in mind, first, students can run the virtual lab to operate manually on the system parameters. For instance, open-loop tests can be performed to understand the relationship between the water flow rate with the outlet temperature. This exercise is very

**https://w3.ual.es/~joguzman/material_docente_labs_solar.shtml

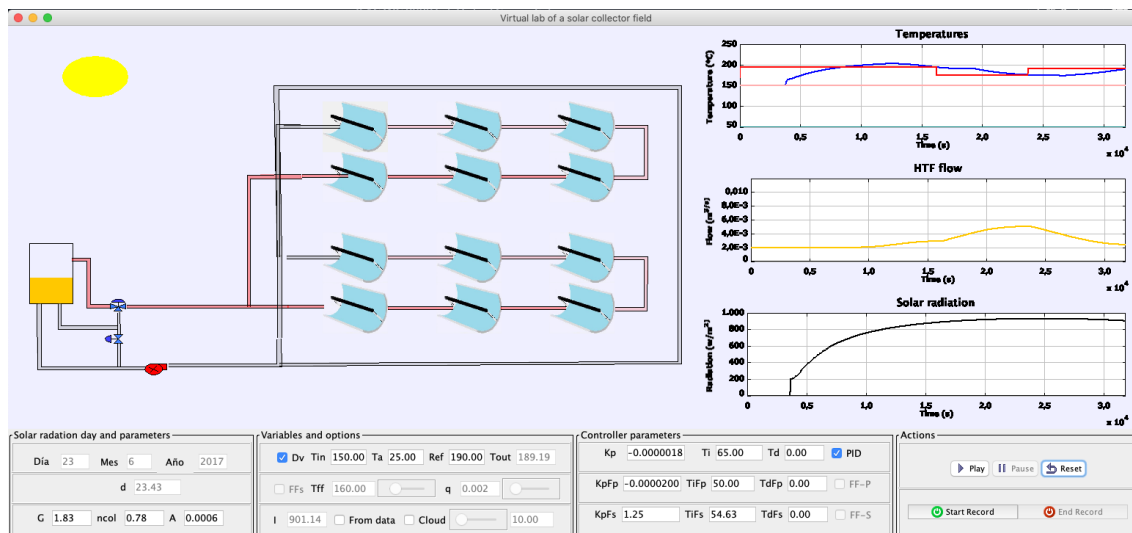


Fig. 5. Main screen of the virtual lab. A closed-loop simulation is shown for step changes in the reference temperature and using the control scheme of Figure 3.

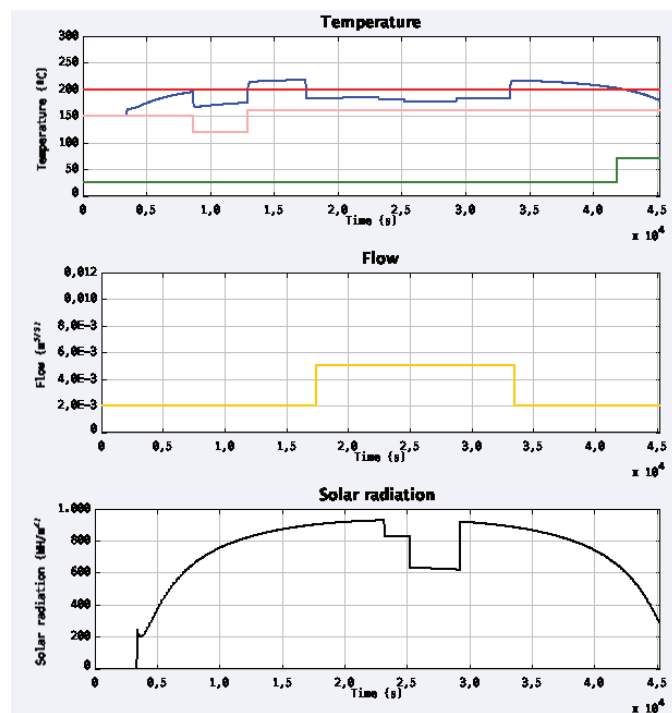


Fig. 6. Open-loop test with step changes on the inputs: inlet flow as manipulated variable; and solar radiation, ambient and inlet temperatures as disturbances.

interesting, since they can learn the nonlinear behaviour of the system and the dependence of the process output with respect to the inlet and ambient temperatures, and the solar radiation daily variation. Figure 6 shows an example where all the process inputs are modified by step changes. Notice that the virtual lab is very useful for this analysis since these changes are very difficult to analyze in the real system. Positive increments are observed for changes in the inlet temperature and the solar radiation, and inverse sign increments are visualized in the relationship between the process output and the water inlet flow. This open-loop option can be also used to configure different operating

points for each simulation and to observe the differences in the process dynamics.

Once the students have understood the process dynamics, they can obtain an approximated linear model of the system for an specific operating point and to design a PID controller. For instance, for an ambient temperature of 25 °C and an inlet temperature of 150 °C, when a step change of 0.0024 m³/s is done in the water inlet flow, that is, a step change of 2.4 l/s, and the solar radiation is approximately constant with a value around 800 W/m², the following first-order transfer function is obtained (with adequate units in the static gain):

$$G(s) = \frac{-7416}{52s + 1}$$

So, if a PI controller within the basic feedback control scheme (Figure 3) is designed by using the pole cancellation method for a closed-loop time constant of 42 seconds, the following controller parameters are obtained: $K_p = -0.00017 \text{ m}^3/(\text{°C} \cdot \text{s})$ and $T_i = 52 \text{ s}$. Figure 5 shows an example for this control design for changes in the reference temperature. At it can be observed, the outlet temperature tracks the reference perfectly in spite of the solar radiation evolution for a clear day. This same control design can be now analyzed for the load disturbance rejection problem against changes in the solar radiation. This result is shown in Figure 7. In this figure, passing clouds are simulated with changes of 400 W/m² and the reference temperature is kept constant at 190 °C. As it can be observed, the PI controller rejects the solar radiation changes, but peaks in the outlet temperature are obtained as the compensation is done using feedback (reactive behaviour).

For a better disturbance rejection, the control scheme of Figure 4 can be used, where the parallel feedforward compensator is included. Figure 8 shows the result for this control scheme for the same PI controller parameters than the simulation presented in Figure 7. Now, it can be seen that the outlet temperature is practically constant all the time with only small peaks at time instants where the solar radiation changes. On the other hand, if the control

5. CONCLUSIONS

A virtual tool of a solar collector field has been presented as support to control education. The tool has been developed using EJS, and it allows to understand modeling and control concepts for this kind of processes. Manual and automatic modes are available, being possible to reproduce the normal activities performed by the operators in these systems. For future works, some other control approaches, such as feedforward in series or feedback linearization solutions will be included.

Students of the Master's in Solar Energy have found this tool quite useful to understand the concepts related to nonlinear dynamics, operating point, open and closed-loop and disturbance rejection in this kind of plants, by interactively visualizing and playing with the tool.

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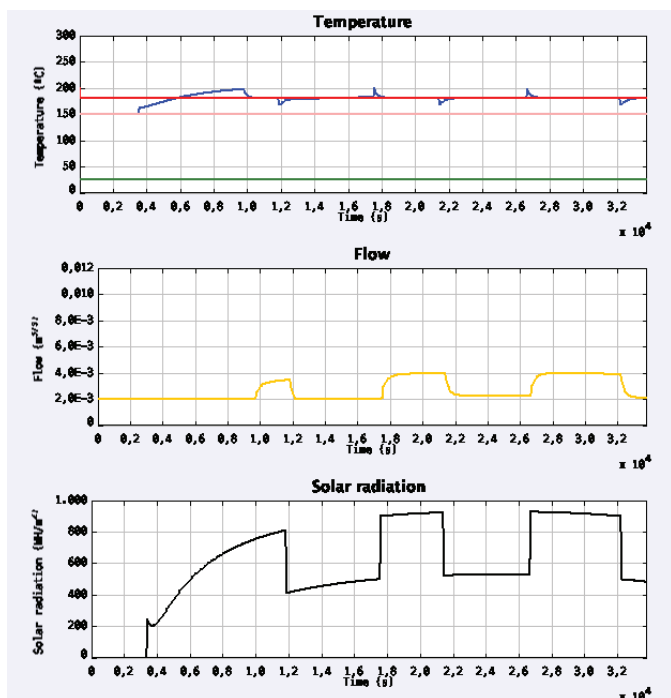


Fig. 7. Closed-loop test. A closed-loop simulation is shown a constant reference temperature and changes on the solar radiation for the control scheme of Figure 3.

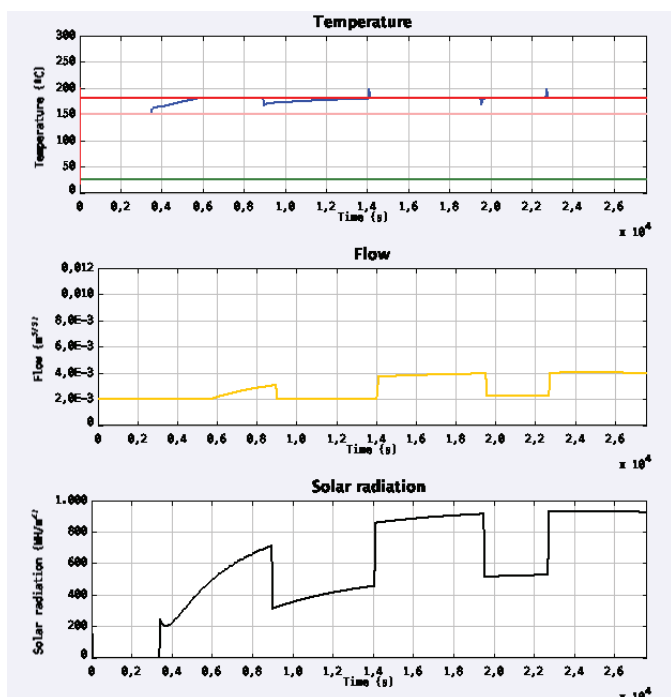


Fig. 8. Closed-loop test. A closed-loop simulation is shown a constant reference temperature and changes on the solar radiation for the control scheme of Figure 4.

signals of Figures 7 and 8 are compared, the feedforward contribution is clearly observed with faster changes when the load disturbance suddenly varies. This comparison confirms the anticipation capabilities of the feedforward control compensator.