

INTERACTIVE TOOL TO TEACH SOLAR PARABOLIC TROUGH CONCEPTS

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1. Introduction

Nowadays solar energy is a key factor on global energetic politics. However, in society there is still a lack of understanding of its underlying working principles (Goswami, 2001), even more widespread applications as PV (*photovoltaic*) and solar thermal flat collector, and although it is easy to find working examples in homes, buildings and neighborhoods. Specific educational tools are being developed and their use should contribute to a more conscious knowledge of performance and capabilities of the solar applications. Concentrated solar power CSP has been the latest technology to join this process and, although in principle its main goal is the production of huge quantities of electricity in big plants, it also has a high potential benefit to society in medium-high temperature ($>150^{\circ}\text{C}$) demands and high energy load applications, such as hospitals sterilization systems or industrial heating processes. Specific features of CSP devices as concentration optics, direct normal irradiance utilization and sun tracking requirements make more complex a descriptive approach to systems performance being very suitable in educational activities the support of computer tools, provided that they have a consistent foundation and a realistic interface. Scale models and remote or virtual laboratories, as well as interactive simulators, have become an important resource in the engineering field to provide technical knowledge to plant operators and students, as shown in Guzmán et al. (2007). For example, Johansson (2000) presented a quadruple-tank process laboratory used to perform exercises with interest in the field of the automatic control and chemical engineering, while an interactive tool of the same process is proposed by Dormido and Esquembre (2003) as an inexpensive alternative to the use of scale models. In the case of Ko et al. (2001), a web-based laboratory is used to perform experiments on a coupled tanks system, and Costa-Castelló (2005) proposes an educational laboratory plant to teach automatic control concepts on repetitive control. In the field of mobile robotics, Guzmán et al. (2008) presents an interactive tool designed that allow students to perform experiment with different motion planning algorithms.

In the present work, an interactive didactical simulation tool, developed to help in the transmission of the solar parabolic-trough basic working principles is presented. This tool has been designed to present a high degree of interactivity, following a what-you-see-is-what-you-get (*WYSIWYG*) philosophy. The next objectives were defined during the tool development stage: (i) to provide the users a graphical representation that could catch both, children and adults eye, (ii) to define a friendly way to manipulate the different parameters involved in the simulation, (iii) to provide not only the simulation, but basic theoretical contents on both, the phenomena influencing the process and the model equations applied in this simulator, (iv) to provide an audio guide on theoretical contents to make it easier to access them, and finally, (v) to become useful to help in the transmission of knowledge to people with and without previous knowledge on the matter and different educational levels.

The work is distributed as follows. In section 2, the theoretical contents included within the tool are defined. In section 3, the tool human-user graphical interface is presented, explaining the reasons after each element interaction method and the relation between the different parameters and their graphical feedback. Section 4 introduces the model equations implemented in the simulator and finally, in section 5, conclusions of the experience on using this tool in different kind of events and future work have been defined.

2. Theoretical contents

It is important to highlight that a didactical tool has no sense if there is not theoretical contents to teach through it. That is, the theoretical contents to teach are the most important element, and they must be defined prior to design a didactical tool to help transmitting them. Then, the graphical capabilities of a tool must be

analyzed to choose the best way to apply them to the educational task.

In the case of the solar parabolic trough collectors, there are several phenomena whose influence is worth to explain to all kind of audiences. They are the day-night cycle (including the irradiance and the presence of clouds), the collector angle, and its inlet temperature, the ambient temperature, and the fluid flow velocity. Taking into considerations these parameters, a desirable educational experiment was defined.

The solar irradiance is the most critical element in solar systems. It is the source of energy of solar systems, but cannot be manipulated and is not available during the 24 hours. As first approach prior to explain the influence of the irradiance it was desired to show its availability by means of the simulation of a day-night full cycle with clear sky. For this task, a sun icon able to cross the sky and a chart to represent the irradiance evolution have been included in the tool. People can observe the influence of the sun evolution (or solar time) in the irradiance value, and at the same time, they can observe the typical irradiance curve in the chart as result of the simulation.

Next, the influence of the clouds, an obstacle for the solar irradiance to reach the collector surface, is presented. This is made by setting the cloud in the middle of the sun predefined trajectory, then when the sun is partially covered by the cloud, irradiance starts to decrease, reaching to zero when the sun is totally covered. By means of this experiment, people can observe that, when an obstacle is placed between the sun and the collector, the irradiance reaching its surface decreases. In the chart, they can observe that, the perfect curve introduced previously has a noticeable fall of irradiance during a period equal to the one where the sun was covered by the clouds.

The collector angle is also a critical factor in the solar parabolic-trough systems. If the orientation is not correct, the beams does not reach the collector cylindrical surface with the correct angle, and the fluid temperature cannot be increased. To transmit this concept to the users of the system, after introducing the different elements in the system and the way in which they are operated, the next experiment steps could be performed: (i) set a fixed angle for the parabolic-trough collector and simulate a 24 hours period with it, (ii) set the sun in a fixed position in the sky, whenever an acceptable irradiance level is expected, trying to focus the parabolic-trough collector to increase the outlet temperature, (iii) set the sun to automatically follow its predefined trajectory among the sky, and set the collector to automatically track the sun perfectly.

Performing (i), people can observe that the outlet temperature presents a temperature increment during the short period that the sun was placed in the position where the collector was focused into. Performing (ii) allows them to realize that the parabolic-trough collector focus on the sun must be close to perfect or not effect will be obtained, and (iii) presents them a comparison among the irradiance and the parabolic-trough collector outlet temperature evolution during a perfect tracking.

As next step, they would be able to modify the parabolic-trough collector inlet temperature. They can fix all the other parameters and modify only the inlet temperature to study the way in which it affects its outlet temperature.

After experimenting with the inlet temperature, they could experiment modifying the ambient temperature, to realize that even if low values result in higher thermal losses to the ambient in the collector, the effect of its variations in the allowed range (20 to 30 °C) is minimal. That is, ambient temperature variations with a big magnitude are necessary to cause a noticeable influence in the parabolic-trough system.

Finally, the effects of flow variations of the fluid can be analyzed. The effect of variations of this parameter can be difficult to understand if the process is not explained in a simpler way, so, it is advisable to present an example of the influence of velocity in the temperature increment when moving through a hotspot. For example, a comparison among the water flowing to pass through the collector, and the hands moving through a fire, and how when they move fast, the temperature increment is low while a slow movement results in higher temperature increments could be helpful for the audience to understand the fluid flow influence. Then the simulator can be used to validate the fluid effects, showing in the charts how when the volumetric flow decreases, the plant outlet temperature increases, and when the flow increases, the outlet temperature decreases. Users can modify this parameter freely to observe the magnitude of this influence.

It is important to highlight that, during all the experiments, not only the commented parameters but the parabolic-trough collector performance is shown in the charts.

3. Interactive Tool

This didactical tool has been created using LabVIEW™, a graphical programming environment developed by National Instruments™ that allows to program with a drag-and-drop philosophy using graphical function blocks in an attractive graphical environment instead of writing lines of text. Furthermore, it integrates its own mathematical environment, used during the development of this tool to define the models equations.

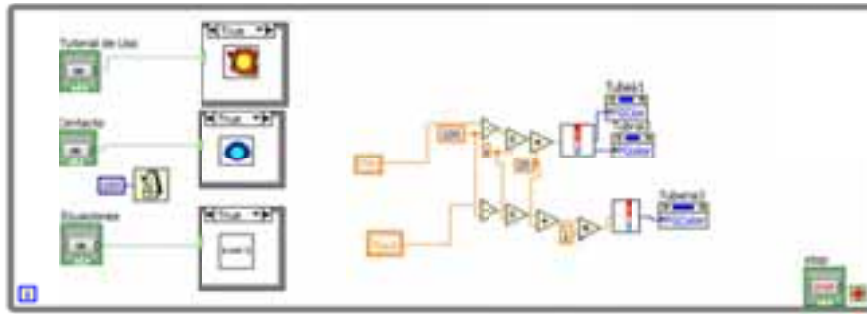


Fig. 1: LabVIEW™ graphical programming development interface

In the next subsections, the developed tool characteristics have been detailed.

3.1. Features

The educational tool presented in this work presents these features:

- A friendly tactile human-machine interface (*HMI*), where each element can be manipulated by means of a tactile screen, besides the mouse and keyboard.
- An operation simulator based on static models of the parabolic-trough collector, irradiance, etc.
- An exposition mode, where the tool performs continuous simulations without any user interaction.
- A *WYSIWYG* approach to the human-machine interaction. Elements able to be manipulated are easily recognized and its manipulation has been defined to be friendly. Also, the tool provides information to the user by means of multiple ways, using intuitive elements to provide an adequate feedback of the current plant state to the users.
- Charts to observe the different parameters evolution through the time are available to the users.
- A theoretical screen to provide some physics fundamentals concepts to the users, and another one to provide a mathematical description of the static models used in the tool to the users.
- An audio guide is defined for each theoretical concept. This way, the contents provided in the texts are deeper detailed, and even most important, this feature allows people unable to read to hear the most basic explanations. Furthermore, it was tried that each icon used in the application was representative enough to understand its task.

The interface is divided into a toolbar, a main screen and three popup subscreens. The toolbar (Fig. 1) includes the tool title, information about the developers and a set of 3 buttons to access to each subscreen. The mathematical equations subscreen is accessed by pressing the blackboard with mathematical operations button, the physics fundamentals one by pressing the notebook button, and the developer information by pressing the contact book button.

The main screen (Fig. 2) contains the simulator graphical representation, that is, a concentration parabolic-trough solar collector, a set of elements to manipulate the different parameters defined (irradiance, collector angle, flow, ambient temperature, inlet temperature and the clouds that acts as a disturbance to the irradiance incidence on the collector surface) and the charts.

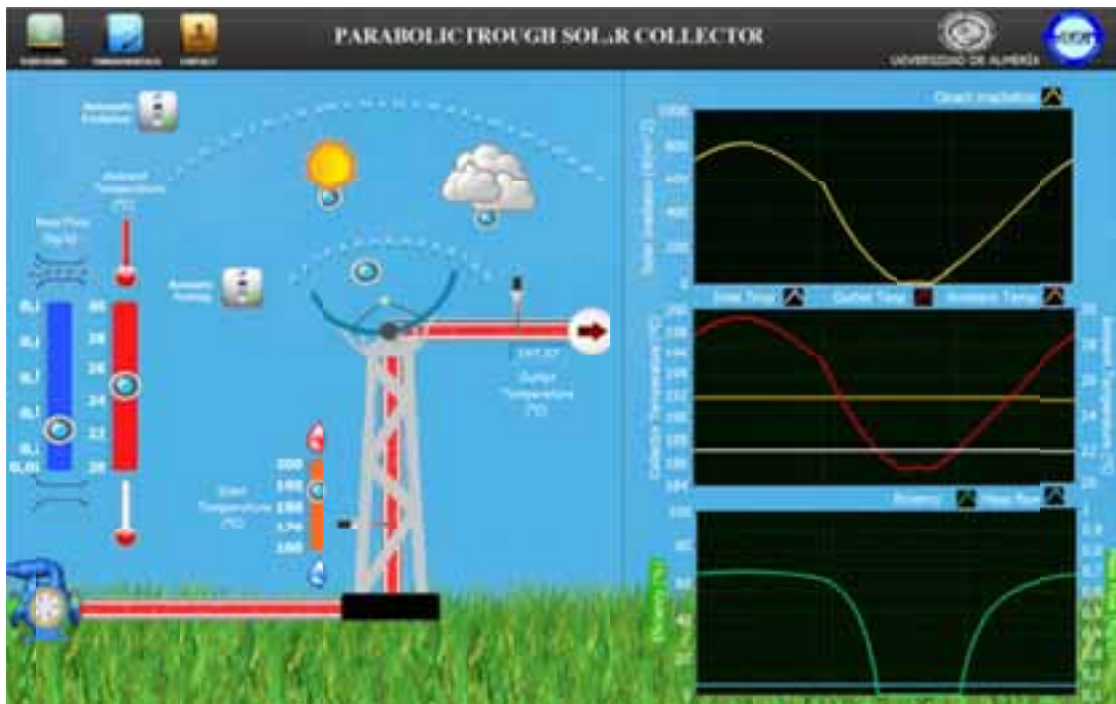


Fig. 2: Interactive Simulation Tool Main Screen Graphical Interface

The mathematical equations subscreen (Fig. 3) presents the models applied to represent the system behavior, explained in detail in section 4. As can be observed, a button with a musical note icon is placed close to each equation and informational table. Pressing these buttons plays the recorded speech for each of them.

The physics fundamentals subscreen (Fig. 4) includes a description of the way that the collector is operated, the tracking process, the need of a circulatory pump and the flow effect in the system, the system performance, and finally, the clouds influence. Also, close to each item a speech button was placed.

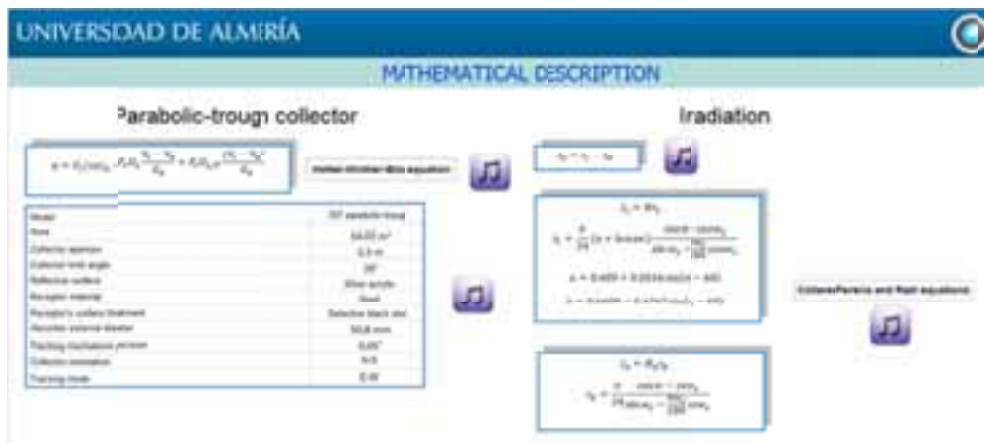


Fig. 3: Application screen where the equations are described and explained.

The system graphical representation has 2 milestones that, combined, provide the user with feedback on the simulation/experiment state:

- 1) Items state graphical evolution

The user receives feedback on the current state of the simulation by means of the variation of the position and colors of different elements.

- 3) Charts to plot the parameters value evolution

Each parameter evolution is represented visually in a chart, allowing users to observe not only their value evolution during the experiment, but the relation among the different parameters.



Fig. 4: Application screen where the fundamentals of the solar parabolic-trough collectors are defined.

3.2. Principles. Interaction and feedback

Each onscreen element that can be manipulated has a common element, the drag-able button. It has two functions, to highlight the elements that can be manipulated and to be dragged to perform the own manipulation.

Next, the different strategies defined to provide a visual interactive information feedback for each parameter are described.

3.2.1 Irradiance

In this case, the position of the sun along the sky is a powerful visual representation related to the maximum irradiance level available at each time for the collector, so it was used. An interactive sun was set in the background, and a predefined trajectory along the sky was defined for it to follow. The sun indicator can be manually dragged along the trajectory to modify the irradiance value. The initial position corresponds to 5:00 (solar time), while the final position correspond to 19:00.

Furthermore, an interactive sky background that varies depending on the sun position was added to the interface. Three main regions were defined, night (dark blue), sunrise/dawn (red), and midday (lightblue).

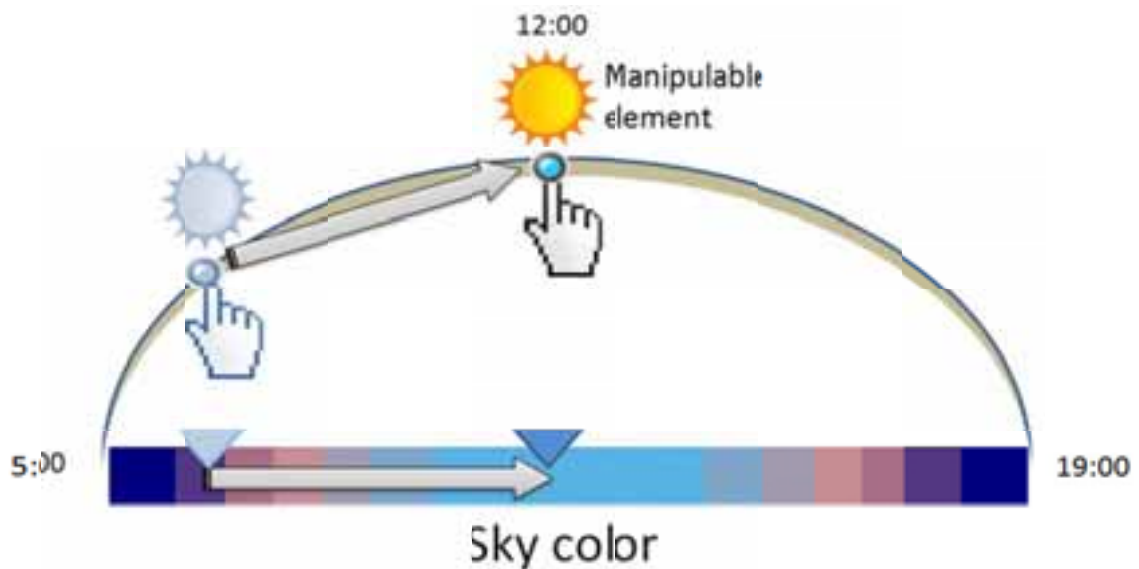


Fig. 5:Sun manipulation and feedback design

Additionally, the user can activate/deactivate the sun automatic evolution through the sky by means of a switch button (section 3.2.7) labeled as “Automatic Evolution”. The inclusion of this option allows the tool to simulate the typical day-night cycle or to set fixed conditions

3.2.2 Clouds

It is possible to place a cloud in the sun trajectory along the sky to show its effects on the collector behavior. This element is manipulated in the same way than the sun (irradiance representation), and its influence is defined by how close to the sun it is (see Fig. 6). When the position of both elements fits perfectly, the cloud causes the collector irradiance to become zero. When the cloud center is moved from the sun center position, irradiance starts rising again, reaching the clear sky value when the cloud surface is not on top of the sun surface.

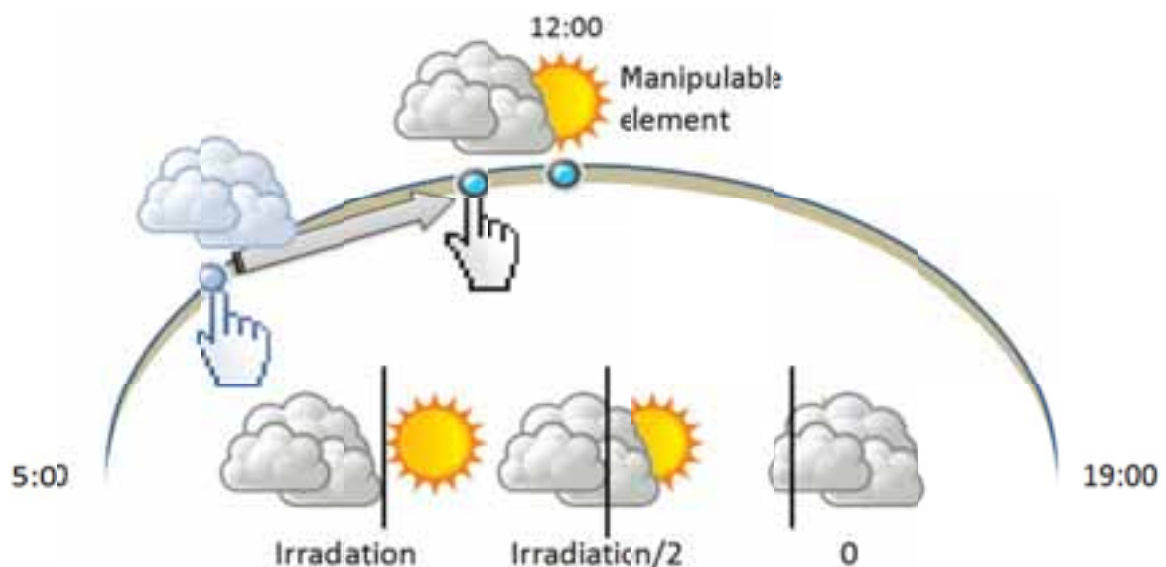


Fig. 6:Clouds manipulation and feedback design

2.2.3 Flow velocity

The flow velocity can be manipulated by means of a slider. Its highest and lowest values are represented by a schematic pipe, with and without flow respectively (Fig.7).

This slider affects to both, the graphical representation of the pump and the fluid inside the pipe:

- In the case of the radial pump, the faster the velocity is set, the faster the pump rotation is.

- In the case of the fluid, the number of bubbles and their velocity is affected by the flow velocity slider. These bubbles in the pipes will move faster whereas the fluid velocity is increased, and a higher number of them will be visible.

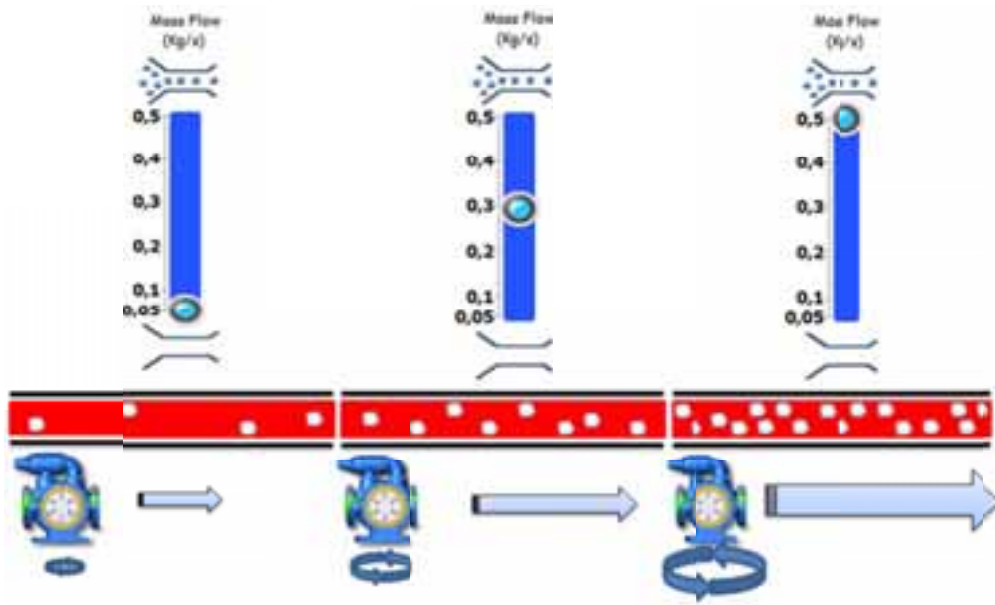


Fig. 7: Pump flow manipulation and feedback design

3.2.4 Collector inlet temperature

The solar collector inlet temperature is also defined by means of a slider. In this case, the highest and lowest values are represented by a red and blue fluid drop respectively (Fig.8). The variation of the inlet temperature is represented graphically in the fluid, by means of varying its color tone.

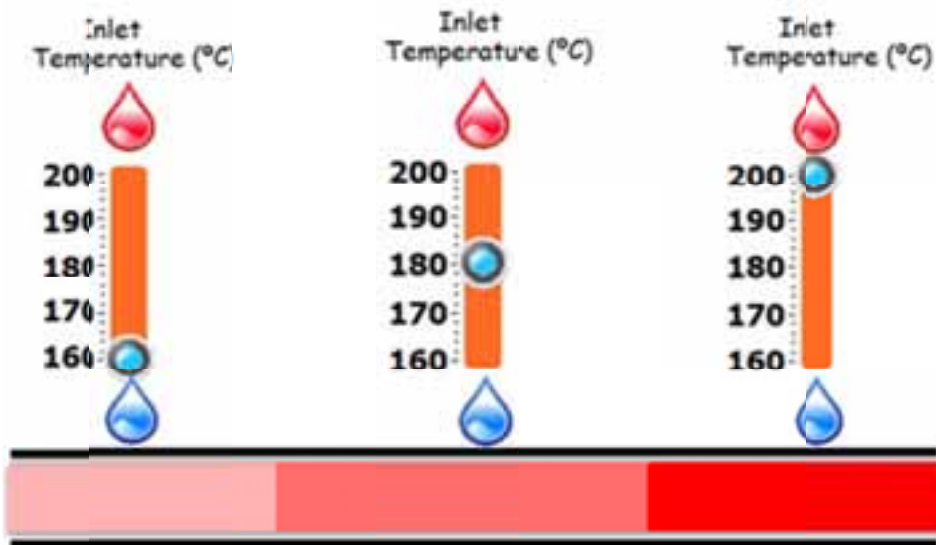


Fig. 8: Inlet temperature manipulation and feedback design

In the case of the fluid graphical representation, it was decided to use a red gradient to represent the fluid temperature. This way, users have always in mind that they can set a hotter or colder inlet temperature, but the minimal fluid inlet temperature is always high during operation. A pale red was used to represent the minimal value, turning into a brilliant red as it gets closer to the maximum value in the range.

2.2.5 Collector angle

The collector angle is one of the parameters that, just like the irradiance or the clouds, has been defined to be

manipulated using the own collector graphical representation. A drag-able button with a pre-defined trajectory, equivalent to the one defined for the sun, was set in the screen. When the drag-able button position is modified, the collector angle is modified to obtain a perfect focus on the sun at the solar time defined by the button. Just as in the case of the irradiance, the initial position corresponds to 5:00 (solar time), while the final position correspond to 19:00.

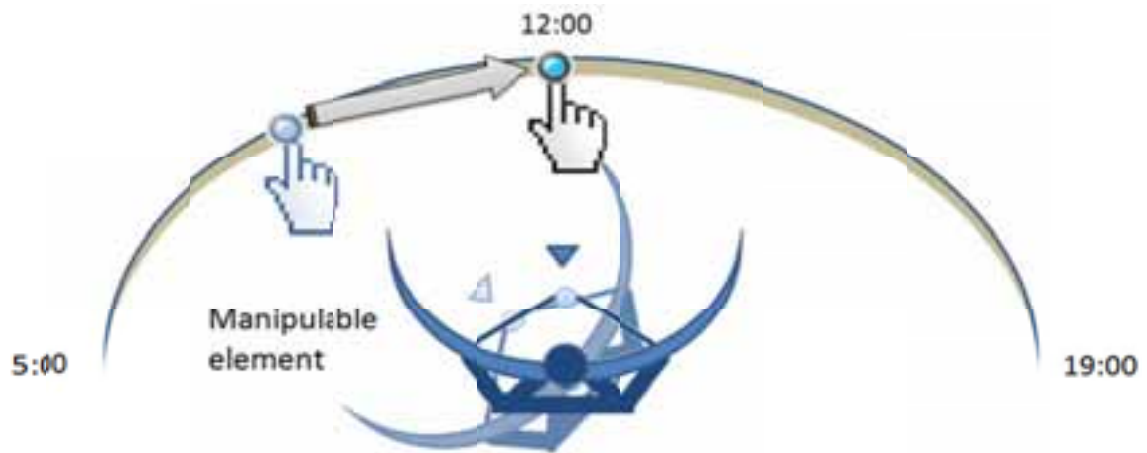


Fig. 9:Collector angle manipulation and feedback design

Additionally, the user can simulate a perfect sun tracking by pressing the switch button labeled as “Automatic Tracking”. When activated, the collector angle is constantly updated automatically attending to the sun current position.

3.2.6 Ambient temperature

In the case of the ambient temperature, several modifications of the background attending to its value were considered, but in place of transmitting this additional information, mixed with the other variable graphical representation it resulted confusing. Due to this reason, the ambient temperature value variations are not represented or manipulated visually in any other way besides the slider that can be observed in Fig. 1, and the chart. Its slider maximum and minimum values are represented by a full and empty thermometer respectively.

3.2.7 Others. Switching buttons and outlet temperature

Among the interactive elements, there are two switch buttons (Fig. 10) whose functions, as commented before, are to activate/deactivate the sun automatic evolution and the collector automatic sun tracking.



Fig. 10:Switch buttons manipulation and feedback design

It is necessary to highlight that, when both switch buttons are activated, the system perform continuously day-night cycle simulations with perfect tracking (Fig. 11).

Finally, the collector outlet temperature evolution can be observed in the chart, but at the same time, its instantaneous value is shown in a box labeled as “Outlet Temperature”, that simulates a sensor measure.

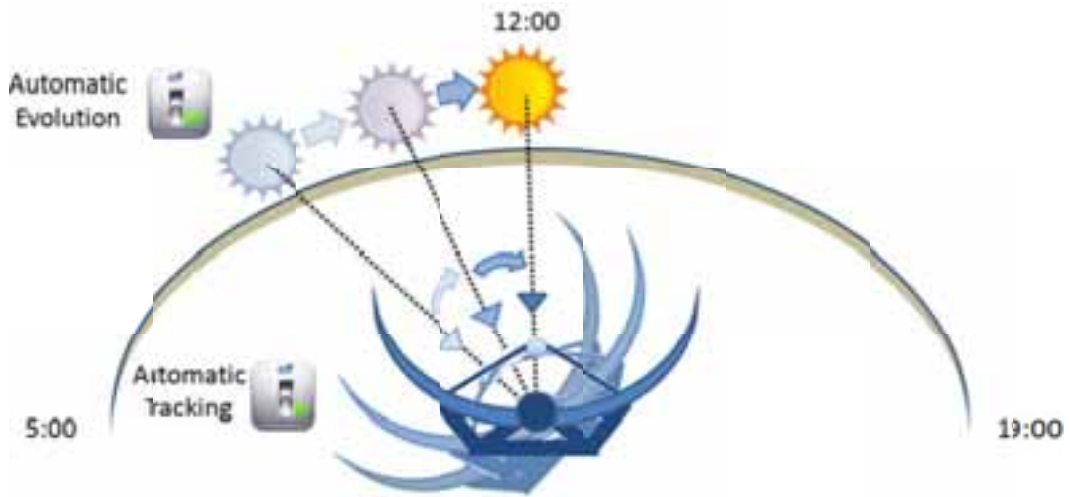


Fig. 11:Automatic sun evolution and automatic tracking activation.



Fig. 12:Interactive Simulation Tool Main Screen Graphical Interface

4. Model equations

4.1 Overview

A simplified model of parabolic collector was developed, based on the second-order Hottel-Whillier-Bliss equations, coupled with an optical incidence angle modifier in the collector tracking plane. The radiation model is based on the Collares-Pereira-Rabl equations (Duffie and Beckman, 2006).

4.2 Efficiency

The useful energy in a concentrating collector is given by the absorbed energy minus the losses to the environment, and is given by the equation,

$$Q_u = Q_a - Q_L \quad (eq. 1)$$

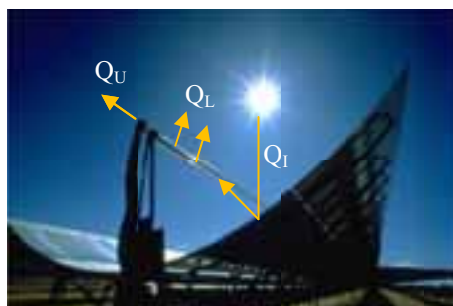


Fig. 13: Heat transfer in the parabolic trough collector

Where Q_a represents the absorbed energy and Q_L the losses. The absorbed energy is given by:

$$Q_a = G_b \eta_0 A_c \quad (eq. 2)$$

Where G_b represents the direct irradiance in a horizontal plane, A_c represents the collector aperture area, and η_0 represents the optical efficiency. The losses to the environment Q_L are given by:

$$Q_L = A_R U_L (T_R - T_A) \quad (eq. 3)$$

Where T_R is the receiver's temperature, A_R is the receiver area and U_L the overall loss coefficient. By combining equations (2) and (3) with equation (1) it results in,

$$Q_u = G_b \eta_0 A_c - A_R U_L (T_R - T_A) \quad (eq. 4)$$

By introducing the removal factor F_R the equation becomes,

$$Q_u = F_R (G_b \eta_0 A_c - A_R U_L (T_i - T_A)) \quad (eq. 5)$$

Considering an overall loss coefficient linear with temperature we obtain,

$$F_R U_L = c_1 + c_2 (T_i - T_A) \quad (eq. 6)$$

which results in,

$$Q_u = F_R G_b \eta_0 A_c - A_R c_1 (T_i - T_A) - A_R c_2 (T_i - T_A)^2 \quad (eq. 7)$$

To obtain the efficiency, the useful energy should be divided by the incident energy $G_b A_c$, which results in the equation,

$$\eta = F_R \eta_0 - \frac{c_1 (T_i - T_A)}{C G_b} - \frac{c_2 (T_i - T_A)^2}{C G_b} \quad (eq. 8)$$

where C represents the concentration ratio and is given by,

$$C = \frac{A_c}{A_R} \quad (eq. 9)$$

By doing the following substitutions,

$$F_R \eta_0 = a_0 \frac{c_1}{C G_b} = a_1 \quad \frac{c_2}{C G_b} = a_2$$

the second order semi-empirical equation for efficiency is obtained, which is based on the collector aperture area,

$$\eta = a_0 - a_1 \frac{\Delta T}{G_b} - a_2 \frac{\Delta T^2}{G_b} \quad (eq. 10)$$

where a_0, a_1 and a_2 are coefficients that are experimentally determined, ΔT is the temperature differential between the fluid and the ambient, and G_b is the direct irradiance.

An incidence angle modifier $k_{\alpha\tau}$ is added to the equation to account for the influence of the incidence angle in the collector tracking plane resulting in,

$$\eta = a_0 k_{\alpha\tau} - a_1 \frac{\Delta T}{G_b} - a_2 \frac{\Delta T^2}{G_b} \quad (eq. 11)$$

The transient effects due to the capacitance of the collector are not taken in account to simplify equations, so a stationary model is used.

4.3 Characterization

The coefficients a_0 , a_1 and a_2 used were the ones that characterize the parabolic trough collector from Industrial Solar Technologies (IST), and have the following values:

Tab. 1: Coefficients used to characterize the collector

Coefficient	a_0	a_1	a_2
	0.762	0.2125	0.001672

The value of $k_{\alpha\tau}$ was obtained by interpolating an experimental curve from a real collector, and is used to illustrate the importance of correct tracking of the sun.

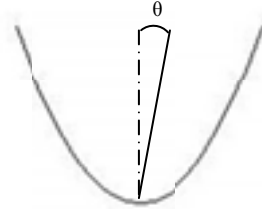


Fig. 14: Angle of incidence in the collectors tracking plane

4.2 Outlet Temperature

The water outlet temperature is given by an energy balance to the fluid, considering an incompressible fluid, resulting in the following equation,

$$Q_u = \dot{m}C_p(T_o - T_i) \quad (\text{eq. 12})$$

The thermal efficiency based on the collector aperture area is given by,

$$\eta = \frac{Q_u}{A_c G_b} \quad (\text{eq. 13})$$

By combining equation (12) and equation (13) it results in,

$$T_o = T_i + \frac{\eta A_c G_b}{\dot{m}C_p} \quad (\text{eq. 14})$$

Where T_o is the outlet temperature T_i is the inlet temperature, A_c is the collector area, m is the mass flow rate and C_p is the water specific heat at constant pressure.

4.3 Radiation

The hourly direct radiation is given by the total radiation minus the diffuse radiation, and is presented in the following equation,

$$I_b = I - I_d \quad (\text{eq. 15})$$

The diffuse and total hourly radiation can be estimated from the average daily radiation by using the following equations,

$$I_d = H_d r_d \quad (\text{eq. 16})$$

$$I = H r_t \quad (\text{eq. 17})$$

4.3.1 Total Radiation

The coefficient to convert total daily radiation to total hourly radiation is given by,

$$r_t = \frac{\pi}{24} (a + b \cos w) \frac{\cos w - \cos w_s}{\sin w_s - \frac{\pi w_s}{180} \cos w_s} \quad (\text{eq. 18})$$

Where W is the hour angle and W_s is the sunset hour angle in degrees. The coefficients a and b are given by,

$$a = 0.409 + 0.5016 \sin(W_s - 60) \quad (\text{eq. 19})$$

$$b = 0.6609 - 0.4767 \sin(W_s - 60) \quad (\text{eq. 20})$$

4.3.2 Diffuse Radiation

The coefficient to convert the diffuse daily radiation to hourly radiation is given by,

$$r_d = \frac{\pi}{24} \frac{\cos w - \cos w_s}{\sin w_s - \frac{\pi w_s}{180} \cos w_s} \quad (\text{eq. 21})$$

The values of daily irradiance H_d and H_t are introduced in the database for the location in consideration.

5. Results and conclusions

This educational tool has been exposed in Parque de las Ciencias de Granada (Spain) from May to September 2010. During this event, users were able to interact freely with the tool by themselves, or to attend to scheduled lessons where concepts related to solar energy and parabolic-trough collectors were introduced by a teaching agent with the help of the tool, to support the theoretical contents exposition. All kind of users interacted with the tool, and an interesting fact to take into account was the number of parents using the tool together with their children. To create an educational resource able to catch children eye, but where the way that the concepts and the interaction is defined is also interesting for adults, is a good strategy to catch both groups attention and to have a high probability of both groups using the tool. Furthermore, it has also been used as a teaching support for visitors of the CIESOL Solar Research Center, Almería, Spain. The duration of these sessions use to be close to one hour, and during them, thirty minutes were used to introduce the concepts defined in this work and to perform the experiment defined in section 2. The feedback received was very good, encouraging the future work in the educational tools field. As future work, a similar tool more oriented to be used by the users at home, where they can spend more time readying more detailed theoretical explanations on physics fundamentals and have more time to perform experiments with the system, will be developed. This new tool will present also a more detailed process, where dynamical models will be used to characterize the system dynamics, and the definition of new parameters will be included..

6. Acknowledgements

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