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Contents

List of Figures

1 Acurex Facility

The test-bed plant under consideration is the ACUREX facility at the Plataforma Solar de Almería (PSA), a research centre belonging to the CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas - Research Centre for Energy, Environment and Technology), a dependency of the Spanish Ministry of Science and Innovation, see Figure 1.1. The present system consists mainly of a PTC solar field, a thermocline oil storage tank, an oil pump and an on-off valve. This facility is the experimental prototype of a commercial solar power plant scaled to 1 M Wt in which a wide range of experimentation can be performed.

Figure 1.1: ACUREX facility at Plataforma Solar de Almería.

1.1 Description of the facility

This section presents an overview of the basic components and operating procedures of the ACUREX plant. A schematic diagram is shown in figure (1.2), in which the most important components are depicted.
The ACUREX facility is made up mainly of four components[1], the solar field, the tank, the oil pump and a three-way valve. The solar field is composed of 480 distributed solar collector modules arranged in 10 parallel rows. Each row contains four groups with 12 modules in each group, i.e., 48 modules all of which work based on the concentration of incoming direct solar radiation onto the absorber tube located in the geometrical focal line of a parabolic-trough reflector. As the sun position changes during the day, each PTC has to change its position with the solar radiation vector. The absorber tube in

[1]Other subsystems are not described for the sake of brevity.

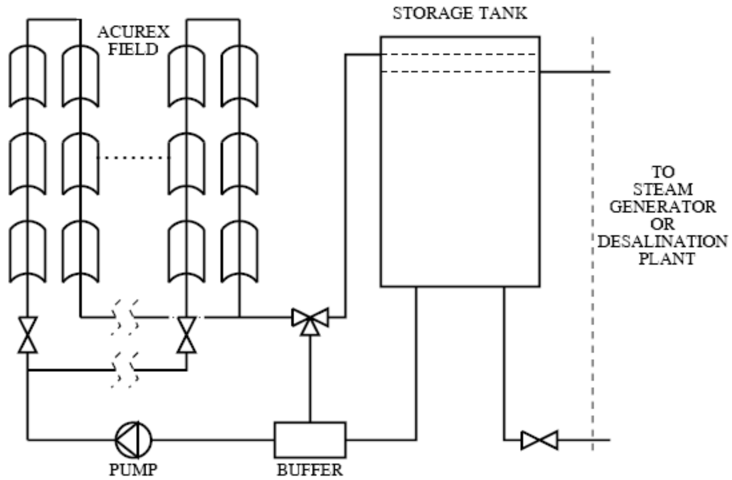


Figure 1.2: Simplified schematic diagram of ACUREX facility.

each PTC acts as an energy exchanger, receiving solar energy and transferring it to a thermo-hydraulic circuit with a heat transfer fluid (HTF) as the medium. Conventional PTCs use thermal oil as the HTF, and this is the case of the ACUREX field and current commercial plants. The HTF accumulates internal energy, and transports it to the tank. The total solar energy collecting surface is 2,672 m^2 and the collector axes are oriented East-West, with a one degree of freedom (elevation) solar tracking system. The heat transfer fluid is a commercial thermal oil which can be heated to 300°C without adverse effects on its thermal properties. Figure (1.3) shows the solar field arrangement.

Figure 1.3: View of the ACUREX solar field.

The oil is stored in a 140-m^3 thermal storage tank. The low-temperature oil (inlet) is pumped through a pipe (called the supply pipe) from the bottom of the tank to the field and delivered to the tank by a collecting pipe (called return pipe) at the top. The oil properties permit its energy storage to be stratified by density, allowing the use of a single thermocline tank for both hot and cold oil, with the hottest oil at the top of the tank. The stored energy is then transformed by a conversion system (not shown) which can be either a steam turbine for generating electricity or a desalination plant. The three-way valve allows the hot oil from the field outlet to be directed to the top or bottom of the tank. The oil pump controls the inlet oil mass flow rate into the field from the bottom of the tank.

The purpose of this plant is to supply regulated thermal energy to the demand process that is connected to the storage tank through a heat exchanger. This involves some other minor objectives, which must also be accomplished. One is an efficient control strategy that ensures that the field outlet temperature tracks the reference signal rejecting any disturbances (mainly solar radiation disturbances). The outlet field temperature is controlled by manipulating the oil-flow pumped into the field. Another objective is automatic plant operation, including start-up, shutdowns, or fossil-fuel burning as an auxiliary support energy source. There are constraints on both the manipulated variable as well as in the controlled variable. The oil flow rate can only be varied from 2 l/s to 10 l/s, the maximum outlet oil temperature is 300°C and maximum temperature gradient in the field cannot exceed 80 °C.

See [3] for a comprehensive document describing state-of-the-art PTC technology.

2 Parabolic-Trough Collectors

Parabolic-Trough Collectors (PTCs) are solar concentrators which convert the direct solar radiation into thermal energy, heating a heat transfer fluid. A PTC is basically a mirror in the form of a parabola, which collects solar radiation and concentrates it on the absorber tube located in the parabola's focal line through which the heat transfer fluid is pumped, acquiring thermal energy from the solar radiation. Fig 2.1 shows an ACUREX parabolic-trough collector.
The main components of a PTC are the following:

- *Parabolic-trough receiver,* it is a mirror in the form of a parabola, which collects solar radiation and concentrates it on the absorber tube.
- *Absorber tube,* located in the parabola's focal line through which the heat transfer fluid is pumped, acquiring thermal energy.
- *Solar tracking system,* optical concentration requires the collector to follow the daily movement of the sun rotating along its tracking axis.
- *Metallic structure,* which holds and allows the receiver to track following the sun's trajectory.

The most important components from a energy-oriented modelling point of view are the parabolic-trough receivers and the absorber tube. It is assumed that the collectors follow properly the sun's trajectory, more information about this issue can be obtained in [3] [1].

Figure 2.1: An ACUREX parabolic-trough collector [2]

2.1 Elements

The key elements of the ACUREX field are the parabolic-trough receivers and the absorber tube, both of them are described briefly in this section.

2.1.1 Parabolic-trough receivers

The ACUREX field consists of 80 distributed solar collectors, with 6 modules each one. These collectors are arrange in 20 rows which form 10 parallel loops along an east-west axis, each of the loops is 172 metres long. Each collector's module is 3.05 m long by 1.83 m wide.

2.1.2 The absorber tube

The ACUREX absorber tube incorporated a Glaverbel thin-glass second-surface silvered reflector (W-mm-thick glass) and a black-chrome-coated steel absorber tube inside a non-evacuated borosilicate glass outer tube with anti-reflective coating [2].

2.2 Optical Model

This sections explains in detail the optical model which is intended to be used in the virtual CSP facility. Figure 2.2 shows an overview of the most important optical parameters for a parabolic-trough collector. The considered optical model has into account each of these parameters, moreover all of them have been specifically estimated for the thermal solar power plant under consideration, the Acurex facility.

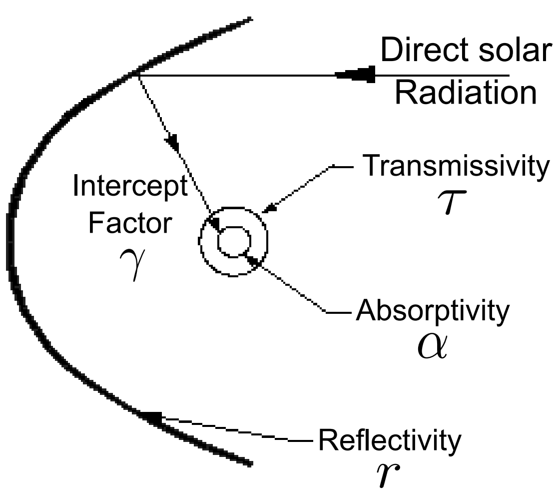


Figure 2.2: Optical parameters of a parabolic-trough collector [3]

A brief description together with estimated values for all of these parameters are detailed in the following subsections.

2.2.1 Optical Parameters

Reflectivity (r)

It is the fraction of incident radiation reflected by the parabolic-trough collector. The value estimated for a Acurex parabolic-trough collector is 88% when the collector is clean although this value can decrease due to the soiling of the collector [3].

Intercept factor (γ)

The intercept factor is the fraction of reflected radiation which reaches the absorber tube. The value estimated for a Acurex parabolic-trough collector is 90%.

Transmissivity (τ)

Transmissivity is the fraction of incident radiation that passes through the glass cover. This value estimated for the glass cover in the Acurex parabolic-trough collectors is 88%.

Absorptivity (α)

It is the fraction of radiation absorbed by the steel pipe. This value, estimated for the Acurex alloy steel pipe, is 85%.

2.2.2 Incidence angle modifier

The incidence angle (θ) is defined as the angle between the solar vector and the vector perpendicular to the parabolic-trough collector aperture. Due to the parabolic-trough collectors can only track the sun's trajectory in one axis, there is a optical loss associated with that incidence angle. The incidence angle modified model considered was proposed in [4] and it is shown in equation (2.1).

$$
\begin{aligned}
K(\theta) &= 0.991 + 4.455 \cdot 10^{-3} \cdot \theta - 5.48 \cdot 10^{-4} \cdot \theta^2 + 1.426 \cdot 10^{5} \cdot \theta^3 \\
&\quad - 1.252 \cdot 10^{-7} \cdot \theta^4 \qquad (0° \leq \theta < 80°), \\
K(\theta) &= 0 \qquad (80° \geq \theta \leq 90°).
\end{aligned} \tag{2.1}
$$

2.2.3 Optical performance

The global optical performance (η_{opt}) for a parabolic-trough collector, considering the optical model described above, is defined by equation (2.2).

$$\eta_{opt} = r \cdot \gamma \cdot K(\theta) \cdot \tau \cdot \alpha. \tag{2.2}$$

The optical model defined in equation (2.2) has been implemented using the Modelica language. Figure 2.3 shows the optical performance (η_{opt}), considering a incidence angle $\theta \in [0°, 90°]$.

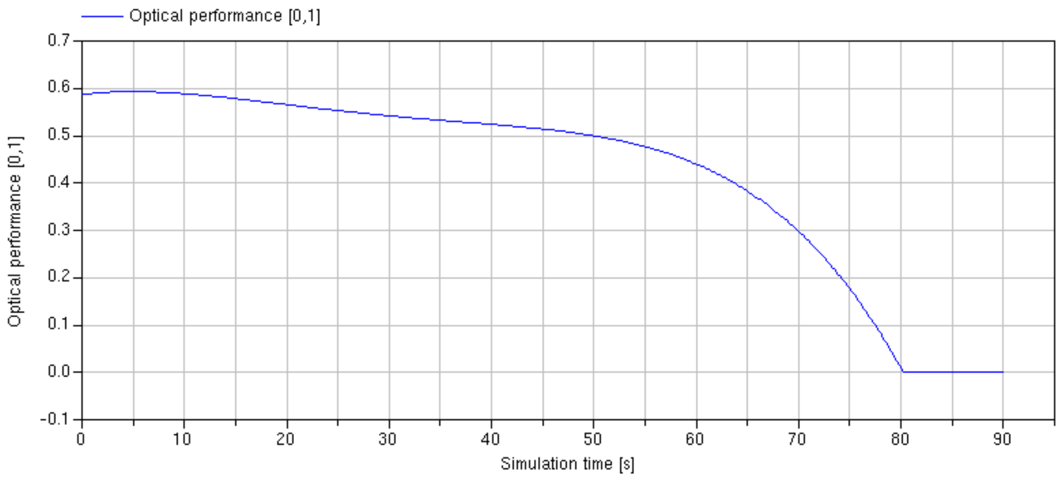


Figure 2.3: Optical performance, $\theta \in [0°, 90°]$

3 Modelling and Simulation

A model which estimates the solar power considering only optical losses (according to the optical model described in the previous section) has been also implemented using the Modelica language.

Inputs	**Description**	**Units**	
Irradiance (E_d)	Direct solar irradiance	$[W/m^2]$	
Day (d)	Day of the experiment	-	
Month (m)	Month of the experiment	-	
Year (y)	Year of the experiment	-	
Hour (hh)	Initial hour	-	
Minute (mm)	Initial minutes	-	
Second (ss)	Initial second	-	
Parameters	**Description**	**Value**	**Units**
Num. Collectors (n_c)	Number of collectors	80	-
Num. Modules (n_m)	Number of modules per collector	6	-
Width (w)	Collector's width	3.05	$[m]$
Height (h)	Collector's height	1.83	$[m]$
Distribution (dis)	North-South, East-West	East-West	-
Inclination(inc)	Field inclination	0	[°]
Reflectivity (r)	Receiver reflectivity	0.88	[0,1]
Intercept factor (γ)	Receiver intercept factor	0.9	[0,1]
Transmissivity (τ)	Cover glass transmissivity	0.88	[0,1]
Absorptivity (α)	Steel pipe absorptivity	0.85	[0,1]
Variables	**Description**	**Value**	**Units**
Area (A)	Field area	2,679.12	$[m^2]$
Incidence angle [IA] (θ)	Solar vector IA	Ref. [1]	[°]
IA modified ($K(\theta)$)	Solar vector IA modified	Eq. 2.1	[0,1]
Optical performance (η_{opt})	Collector's optical performance	Eq. 2.2	[0,1]
Output	**Description**	**Units**	
Solar power (P_s)	Estimated solar power	$[W]$	

Table 3.1: Model inputs, parameters, variables and outputs

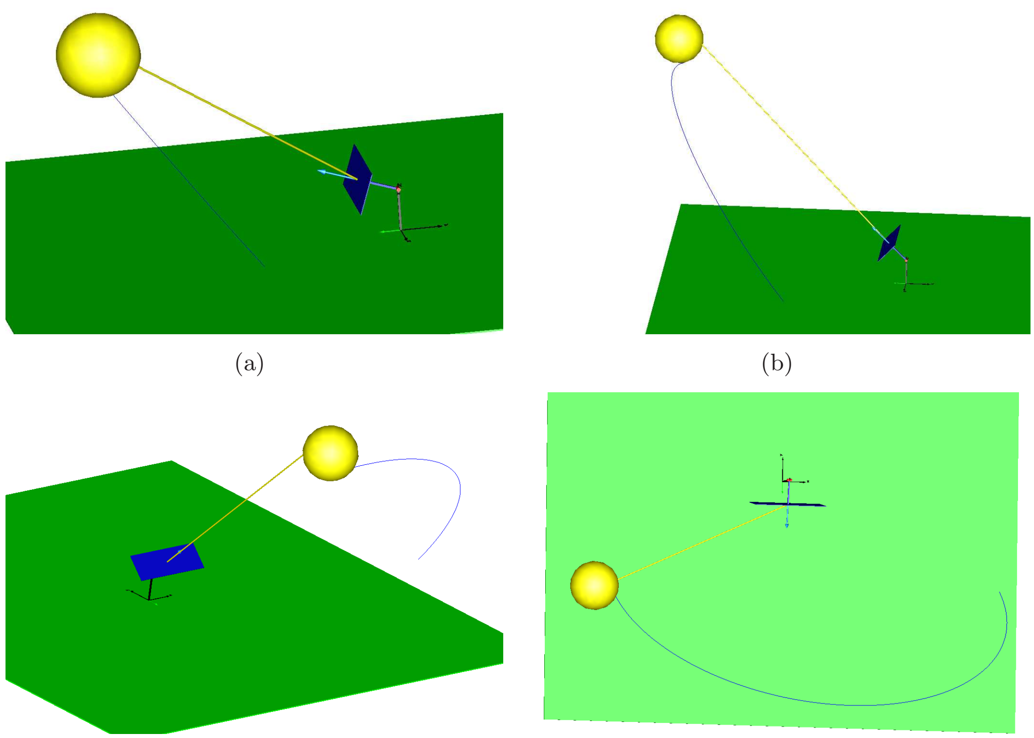
3.1 Modelica Model

The model inputs are the direct solar irradiance (E_d) and the initial time (hh, mm, ss) and date (d, m, y). The only output is the produced solar power (P_s), according to Equation 3.2. Each variable is defined in Tab. 3.1. The model considers the optical performance (η_{opt}), see Equation 2.2, the collecting surface area (A) defined in Equation 3.1 and also the solar vector to compute the incidence angle (θ). The solar vector is computed according to a developed PSA algorithm in [1], the inputs for this algoirthm are distribution ($dist$), inclination (inc), date (d, m, y) and time (hh, mm, ss). The table 3.1 summarizes all the model inputs, outputs, parameters and calculated variables.

$$A = n_c \cdot n_m \cdot w \cdot h, \tag{3.1}$$

$$P_s = E_d \cdot A \cdot \eta_{opt} = E_d \cdot (n_c \cdot n_m \cdot w \cdot h) \cdot (r \cdot \gamma \cdot K(\theta) \cdot \tau \cdot \alpha). \tag{3.2}$$

Fig. 3.1 shows some snapshots of the 3D Modelica model. The 3D model is not to scale, but the solar trajectory (elevation and azimuth), the solar vector, the parabolic-trough collector incidence angle and the colector position (PSA geographic coordinates) has been considered accurately.



(a) (b) (c) (d)

Figure 3.1: Snapshots of the 3D parabolic-trough optical model

3.2 Simulation Results

This section illustrates simulation results obtained with the develop Modelica model. The input date, for this example, is 27/09/2001 whereas the input time is 7:13:20 AM, the simulation is performed for 32,000 seconds that it is until 04:06:40 PM, where the collectors are taken out of track. Fig. 3.2 shows other required input, the direct solar irradiance, for the date, the initial time and the simulation time previously mentioned.

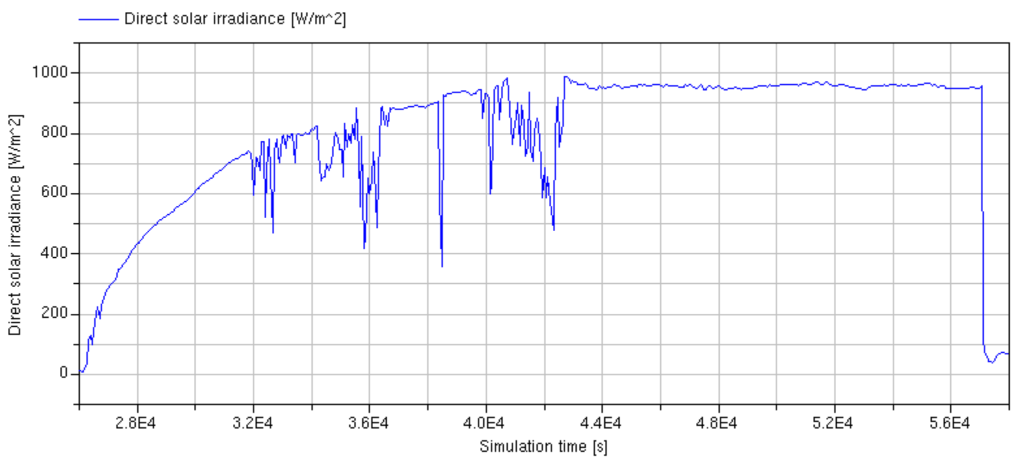


Figure 3.2: Direct solar irradiance

The computed incidence angle (θ) and optical performance (η_{opt}) are shown in Fig. 3.3 and 3.4 respectively. And finally, the solar power (P_s) is shown in Fig. 3.5, where the maximum solar power corresponds to 1534 KW.

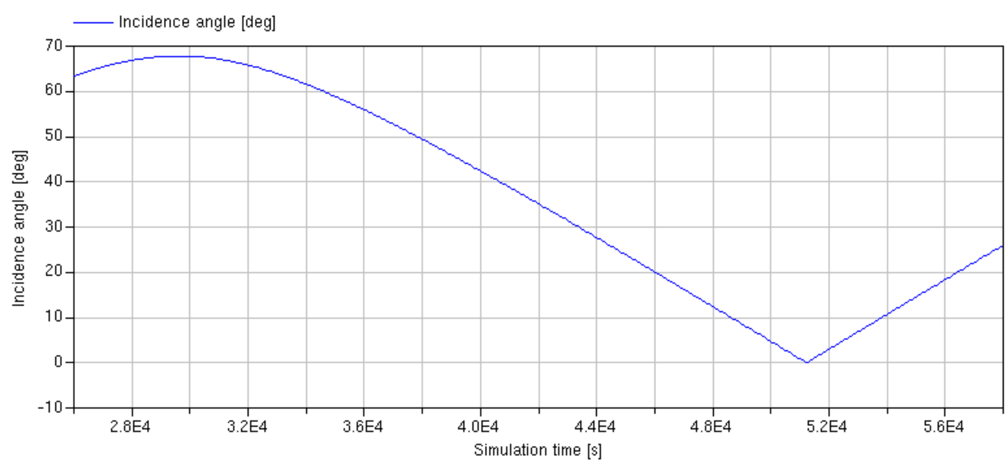


Figure 3.3: Incidence angle in simulation

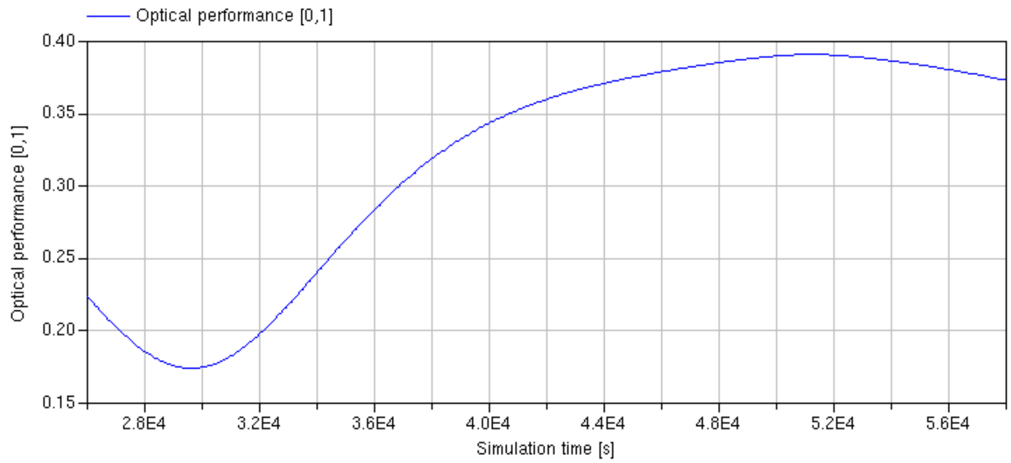


Figure 3.4: Optical performance in simulation

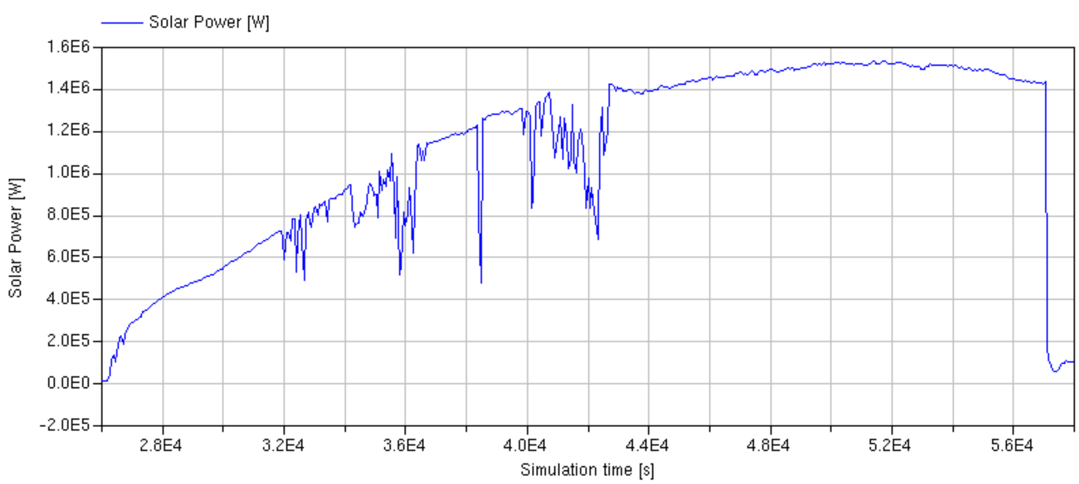


Figure 3.5: Solar power in simulation

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