# Object Oriented Modelling and Simulation of ACUREX Solar Thermal Power Plant

L.J. Yebra[1], M. Berenguel[2], J. Bonilla[1], L. Roca[3], S. Dormido[4], E. Zarza[1]
[1] C.I.E.M.A.T., Almería, Spain; [2] U. of Almería, Spain;
[3] Aunergy Thermosolar S.L., Almería, Spain; [4] U.N.E.D., Madrid, Spain

Corresponding author: L.J. Yebra, C.I.E.M.A.T., Research Centre for Energy, Environment and Technology - Solar Platform of Almería, Ctra. Senés s/n, 04200 Tabernas, Almería, Spain; `luis.yebra@psa.es`

**Abstract.** Research and development of advanced control systems to optimise the overall performance of Parabolic Trough Collectors (PTC) solar power plants is a priority line research at CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas - *Research Centre for Energy, Environment and Technology*). These developments are been made at one of the CIEMAT's research centres, Plataforma Solar de Almería (PSA), highly specialised in solar energy technologies. The development of dynamic models for use in simulation and control of this type of solar power plant is presented in this article, focused on the ACUREX solar plant. The developed models are based in the thermohydraulic modelling framework `ThermoFluid`, within the `Modelica` modelling language. The ACUREX facility is presented with the main modelled components and their respective modelling assumptions. In some cases, as in the collector field, a brief relation between long term used components models and new versions is presented. A simulation of a typical real experiment is realized and predicted model values are presented and commented.

## 1 Introduction

This paper presents the current status of the research performed within the framework of modelling and simulation of Parabolic Trough Collectors (PTC) in the scope of Solar Power Plants. The work is mainly oriented to the development of dynamic models of solar energy plants to be used in the design of automatic control systems aimed at optimising overall performance.

**Figure 1:** ACUREX facility at Plataforma Solar de Almería.

The system used as test-bed plant is the ACUREX facility, see figure (1). Actually, it is a system formed mainly by a PTC solar field, a stratified storage tank, an oil pump and a on-off valve. This facility is the experimental prototype of commercial solar power plant scaled to 1 $MW_t$ in which a wide kind of experimentation can be performed. It is located at Plataforma Solar de Almería (PSA), which is part of CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas - *Research Centre for Energy, Environment and Technology*), National Lab of the Spanish Government attached to the Ministry of Science and Innovation).

The model presented in this paper will be used in the design of hybrid model predictive control and intelligent control schemes to optimise plant performance, even under start-up and shutdown situations and in spite of highly variable load disturbances due to the daily cycle of solar radiation and passing clouds.

## 2 The Parabolic Trough Collectors Facility ACUREX

In this section, an overview of the basic components and operating procedures for the ACUREX plant is presented. A schematic diagram is shown in figure (2), in which the most important components are depicted.

The ACUREX facility is formed mainly by four components[1]: the solar field, the tank, the oil pump and a three-

[1] There are more subsystems that would not be detailed for the sake of the extension.

way valve. The solar field is composed of 480 distributed solar collectors modules, arranged in 10 parallel rows. Each row contains 4 groups with 12 modules each group, i.e., 48 modules. In all of them, the operation is based on the concentration of incoming direct solar radiation onto the absorber tube located in the geometrical focal line of a cylindric-parabolic mirror. As the sun position changes during the day, each PTC of the facility has to change its orientation as the solar radiation vector does. The absorber tube in 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. Traditionally in PTCs the HTF used has been thermal oil, which is the case of ACUREX field and current commercial plants. The HTF augments its internal energy, and transport the collected energy to the tank. The total solar energy collecting surface is 2672 m2 and the axis of the collectors are oriented East-West, with one degree of freedom (elevation) solar tracking system. The heat transfer fluid is a commercial thermal oil which can be heated up to 300 C without straying its thermal properties. In figure (3) the solar field arrangement is shown.

The oil is stored in a thermal storage tank of 140 m3 capacity. The oil at low (inlet) temperature is pumped trough a pipe (called supply pipe) from the bottom of the tank to the field and deposited via a collecting pipe (called return pipe) at the top of the tank. The oil properties permit stratified energy storage according to its density, allowing the use of only one tank for both cold and hot oil, the hottest oil being situated at the top of the tank. The stored energy is then transformed via a conversion system (not depicted) that can either be a steam turbine for generating electricity, or a desalination plant. With respect the three-way valve it lets lead the outlet field hot oil to the top or bottom of the tank. The oil pump lets to control the inlet oil mass flow rate into the field from the bottom of the tank.

The objective of this plant is to supply regulated thermal energy to the demanding process that is connected to the storage tank through a conversion system, typically a heat exchanger. To fulfil this global objective some other minor objectives must be accomplished too. One is to implement an efficient control strategy that ensures that the outlet temperature of the field tracks the reference signal and at the same time rejects the disturbances (mainly solar radiation disturbances). The outlet field temperature control strategy is done by manipulating the oil-flow pumped

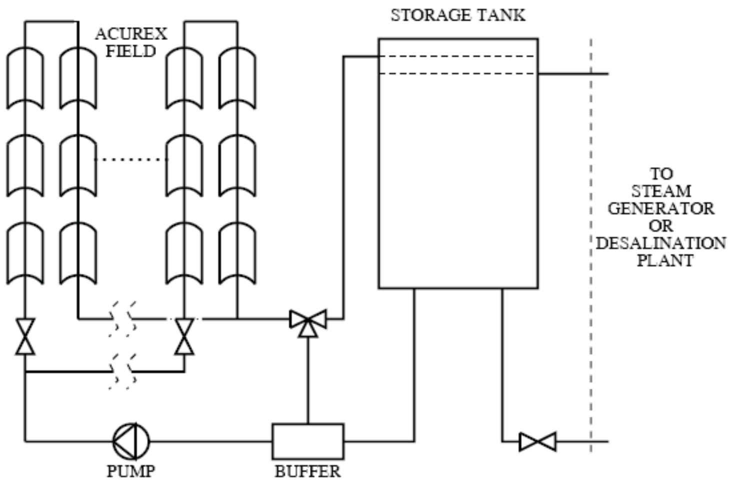



**Figure 2:** Simplified schematic diagram of ACUREX facitity.

**Figure 3:** View of solar field of ACUREX facitity.

into the field. Another objective is the automatic operation of the plant, including start-up, shutdowns, or partial fossil fuels burning as auxiliary support energy source. There are constraints both in the manipulated variable as well as in the controlled variable: the oil flow rate is limited to vary from 2 l/s to 10 l/s, whereas the maximum outlet oil temperature equals 300 C and maximum temperature gradient in the field cannot exceed 80 C.

A comprehensive document that describes the state of the art in PTC technology is [16].

# 3 Object Oriented Modelling of ACUREX plant

In this paper we will concentrate in the modelling of the thermo-hydraulic part of the system, skipping the rest the remaining subsystems (pneumatic, mechatronic, etc.) needed to maintain the proper instantaneous orientation of the PTC group, and assuming a known input radiation power in the absorber pipe, as a consequence of the radiation reflected in the cylindric-parabolic mirrors. For a detailed explanation of this subsystems read [16] and [15].

Due to the fact that the main phenomena of interest is the thermofluid dynamics, the object oriented Modelica language ([1]) has been used to develop these models with the Dymola tool ([6]). Within this modelling language the ThermoFluid library ([12],[7]) is a framework over which develop own libraries and final component models ready to be instantiated as components for simulations.

The work analyses each of the components of the thermo-hydraulic circuit and explains the modelling assumptions, trying to justify each one as they are oriented to get - by means of the symbolic manipulations that Dymola tool performs - a not high index DAE system for the complete model, in which the number of nonlinear algebraic loops is minimised. For this purpose, all the components are classified, following the modelling methodology derived from the Finite Volume Method (FVM) [10], in Control Volumes (CV in ThermoFluid nomenclature) and Flow Models (FM in ThermoFluid nomenclature).

In some cases information about the future control system architecture to be implemented is introduced in the modelling phase. This methodology, from a strict point view, breaks the work flow of first model and then design the control system based in this model. But it helps to simplify the design of the models and enhances the numerical behaviour of the whole modelled system in the simulation execution phase, without a significant loss of accuracy.

Due to the existence of components whose internal implementation may vary depending on the modelling hypotheses dependent of the experimentation framework, the polymorphism and the Modelica language constructs for classes and components parameterisation has been extensively used and specifically applied in PTCs models.

Figure 4 shows the developed top level Modelica model of the ACUREX facility, in which the different components can be distinguished: tank, field, buffer and three-way valve.

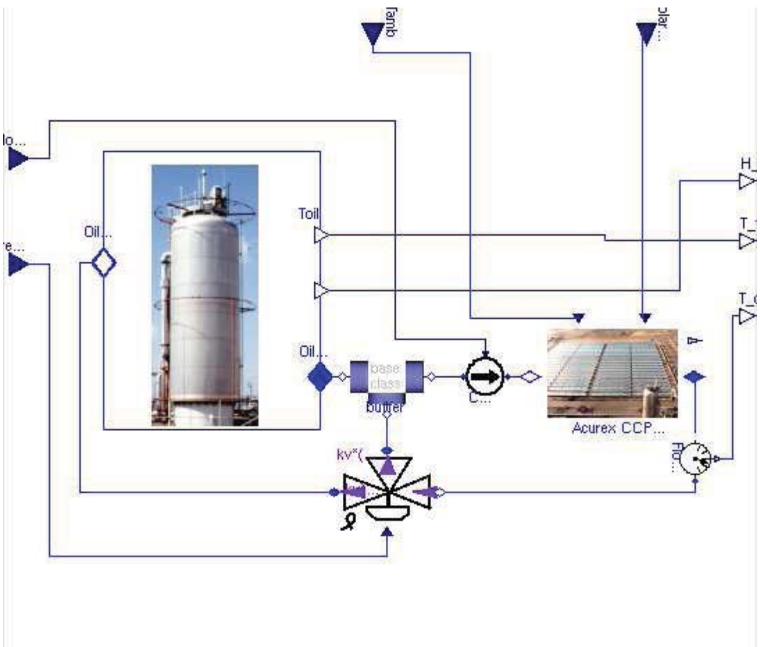



**Figure 4:** Modelica model of ACUREX plant.

### 3.1 ThermoFluid usage

The dynamic behavior expected to be predicted by the models is mainly the thermal one, so the steady state formulation for the momentum balance is selected for the utilized ThermoFluid base classes. The selected time scales for the thermal dynamics are for control design and simulation purposes.

The thermo-hydraulic interface for all the models is formed by connectors from the *Interface* package, for single component media and steady-state momentum balance statement.

The modelling methodology adopted from the beginning for the design of the classes was: *if there exists any class in ThermoFluid that implements the physical phenomenon to model, use it with the corresponding parameterization. If not, design the classes using inheritance from the high level partial classes from ThermoFluid; in other cases then use proper ThermoFluid interfaces and base classes and develop the class with the lacking behavior expressed in differential and algebraic equations from first principles*.

# 4 Subsystems models

In the next subsections the most important components models will be detailed and the modelling hypotheses will be explained and justified.

## 4.1 Parabolic Trough Colectors Solar field

The PTC is one of the most important component in the facility. Indeed it is actually the component which name is ACUREX, and therefore the facility's one. Its aim is to carry most of the part of the solar direct incident irradiance in the mirror to the absorber tube. To achieve this aim, the manufacturing process uses advanced material sciences and technologies to minimise the power loss in direction to absorber tube. In [8] and [16], an analysis of the energy flows into the absorber from the sun is developed. By other side this subsystem accumulates several uncertainties due to the age of some components, feature that contributes to the enrichment of the modelling and simulation process. Up to date the model presented in [5] has been extensively used for dynamic simulations and for control systems design, giving very good results. To improve some modelling assumptions and benefit from the advantages of object oriented modelling [2], a family of polymorphic models have been developed, all of them sharing the same interface but with differing dynamic behaviours. In this paper is shown one of the developments made from CIEMAT, but other ones, subject to confidential restrictions, share the same interface. The family of models include different modelling features:

- Lumped and distributed parameters models.
- Linear and nonlinear models.
- With(out) delays, constant or variables.
- Different first principles and experimental correlations for several physical phenomena.

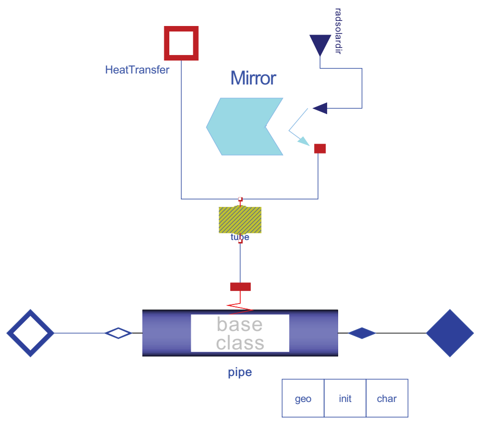



**Figure 5:** PTC Modelica model.

In the figure 5, the main components of a PTC are shown, and enumerated in the following:

- Cylindric-Parabolic mirror surface. It reflects the incoming direct solar radiation to the focal line of the mirror.
- Absorber metal pipe. It absorbs the major part of the energy reflected by the mirror.
- Energy loss to the environment by conduction-convection and radiation.
- Medium model, that is, the HTF. In the case of this work, an industrial oil is the selected medium.
- Distributed CV, with a discretisation level of $n$ in which mass, energy and momentum is conserved.

For modelling effects, this component could be considered as a heat exchanger composed of one pipe with water and/or steam as media fluid, and a circular wall allowing thermal interaction with the fluid. This hex is fed by solar energy through the external perimeter of the circular wall and, at the same time, some energy flow is leaving through this external perimeter by conduction-convection and radiation processes.

Thus the dynamic behaviour of each PTC will vary along each row depending on the thermodynamic and transport state of the thermal oil in each PTC. With the configuration shown in figure 5, the PTC is fully discretised in $n$ CVs in the major length direction, in which mass, energy, and momentum balances are stated. Momentum conservation is stated in staggered CVs with respect to those ones in which mass and energy balance is stated; see [10], [14] and [12]. The number of CVs, $n$, is a trade off between accuracy and computing cost, so the final choice is the minimum $n$ that models dominant dynamics for control purposes. Currently we are working with values in the interval $[2,5]$ per PTC. The wall is discretized with the same discretisation level.

To solve the PDE system stated from balance equations, ThermoFluid provides partial classes [12] in which the discretisation with the Finite Volume Method (FVM) ([10]) is applied. One of these classes is *Volume2PortDS_pT*, which implements this mass, energy and static momentum conservation equations in a staggered grid formed by $n$ subvolumes. For the solid media, there exists final use classes that implement energy conservation in distributed solids, *.Walls*.

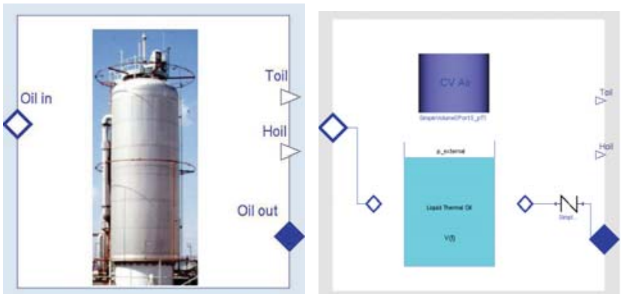
To close the system of equations, it is mandatory to introduce the heat transfer coefficient between the water-steam flow and the solid media. This coefficient depends of heat transfer correlations using adimensional fluid numbers (Reynolds, Prandtl, Pecklet,...), geometry of the contact surface and thermodynamic and transport properties of the fluid (i.e. oil ). Some of the correlation parameters strongly depend on the experimentation and parameter adjusting phase of the modelling work. See [11]. This modelling work is introduced through extensive use of polymorphic partial Modelica classes.

### 4.2 The storage tank

As in other components the tank is modelled with several approaches that captures different dynamics:

- Longitudinal gradient of temperatures in distributed parameter model.
- Lumped parameter model of stored oil approximation.

At all cases, the tank is pressurised with an non-reactive gas at the top of the oil bulk. Mechanical interaction without mass/heat transfer is supposed between the oil and the gas volume and have been modelled as shown in the schematic Modelica diagram with volumes components, in figures (6(a)) and (6(b)).




(a) Modelica model icon of storage tank (b) Schematic Modelica diagram of tank model

**Figure 6:** Modelica model of the storage tank.

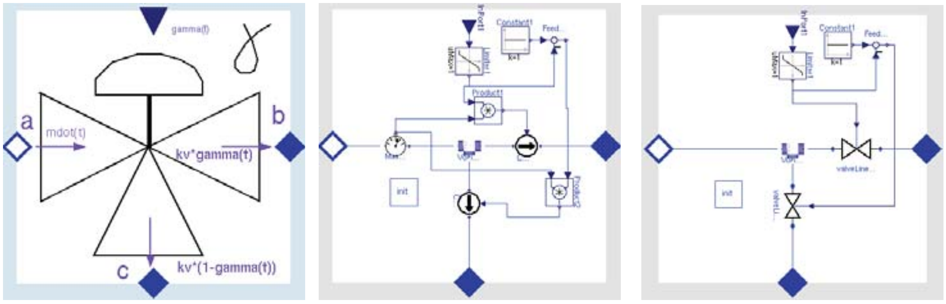
### 4.3 Oil Pump

In this kind of active FM [12], the authors decided to make a simplifying assumption based on the gained experience in control of Parabolic Trough Fields with thermal oil as medium, case of ACUREX field of CIEMAT-PSA [4], [5], and similar cases with other mediums like water-steam as medium in DISS facility [16], [13]. This assumption consists that the oil pump is controlled in a cascade scheme [3] with a local control loop whose dynamics is much faster than the rest of the thermohydraulic system. This assumption has been experimentally validated in blowers and water pumps, and helps simplify these components models until the possibility of modelling them as steady-state quasi-ideal mass flow rate generators. This approximation avoids the time-consuming work of fitting the nonlinear multivariate curves of the pumps and injectors. So, the algebraic equation for these components is $\dot{m} = \dot{m}_{ref}$, where $\dot{m}_{ref}$ is the setpoint of the local pump/injector control loop and it is assigned in a connector to the model, as can be seen in figure 4.

### 4.4 Three-way valve

This component, with the pump, is the second actuator more important of the system. It leads the hot oil from the PTC field to the bottom or top of the tank, contributing the generation of a spatial vertical distribution of temperatures inside the tank. Although is modelled as a continuous actuator with saturation, it is used frequently as an on-off actuator.

Again, intensive use of object oriented capabilities has been used in the valve modelling. For example, passive and active flow models approach are presented, in which valves and dependent pumps are replaceable components. The concept is directly illustrated in figure (7).




(a) Modelica model icon of three-way valve.

(b) Schematic Modelica diagram of three-way valve: implementation with active FM.

(c) Schematic Modelica diagram of three-way valve: implementation with passive FM.

**Figure 7:** Modelica model of the three-way valve. Icon representing interface (7(a)) and different implementations (7(b)) and (7(c)).

### 4.5 Hybrid automatic operation-and-control system

Although the ACUREX plant is usually operated manually by qualified human operators with high performance, the development of automatic operators is tackled to obtain more autonomous systems. For the whole operation procedure, Modelica *StateGraph* [9] library has been used to implement this model subsystem which includes the states and transitions during a typical operation day. In addition, this library offers features to define conveniently discrete event and reactive systems in Modelica models. Since Modelica is used as an action language, the translator tool guarantees that the modelled StateGraph has deterministic behaviour. StateGraph models can be combined with components of any other Modelica library and can therefore be very easily used to control a continuous plant, in this case, the ACUREX plant. Figure (8) shows the operation-and-control component.

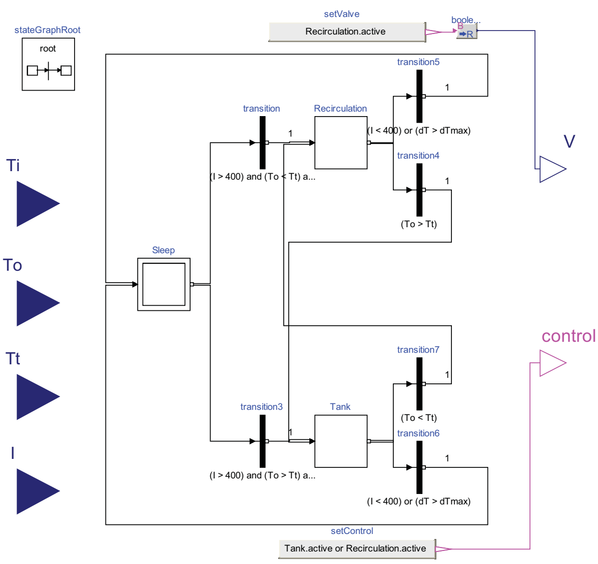



**Figure 8:** State Graph component for the ACUREX automatic operation-and-control system.

The operator model provides the following interface. Inputs:

- Ti: inlet solar field oil temperature ($^{o}$C)
- To: outlet solar field oil temperature ($^{o}$C)

- Tt: tank oil mean temperature ($^{o}$C)
- I: irradiance(W/m$^2$)

And outputs:

- V: three-way valve with 2 positions:
  - 1: solar field oil recirculation
  - 2: oil from solar field to the tank
- control: boolean signal that informs if the solar field control must be activated

Then, the state machine component follows an experimental procedure of a typical operation day as is explained next:

- At the beginning of the day, the solar field is out of focus, with the pump off (*Sleep mode*).
- When irradiance exceeds more than 400 W/m$^2$, the system may change to one of the following states where the control system must be activated:
  - If Ti$<$Tt then the system changes to *Recirculation mode* so that the solar field is decoupled from the storage system.
  - If To$>$Tt then the system changes to *Tank mode* and the water from solar field flows to the storage system.
- When the solar field temperature gain (To-Ti) exceeds more than the value *dTmax* (defined as a parameter), the system changes again to *Sleep mode*. This situation also occurs when irradiance falls more than 400 W/m$^2$

This module, in a more complex version, includes the control algorithm too.

# 5 Simulation results of a typical operation cycle

In this section the results of the simulation of one simple - but typical - actual experiment are shown. It have been used experimental values of solar irradiance which have been measured at PSA (see figure 9).

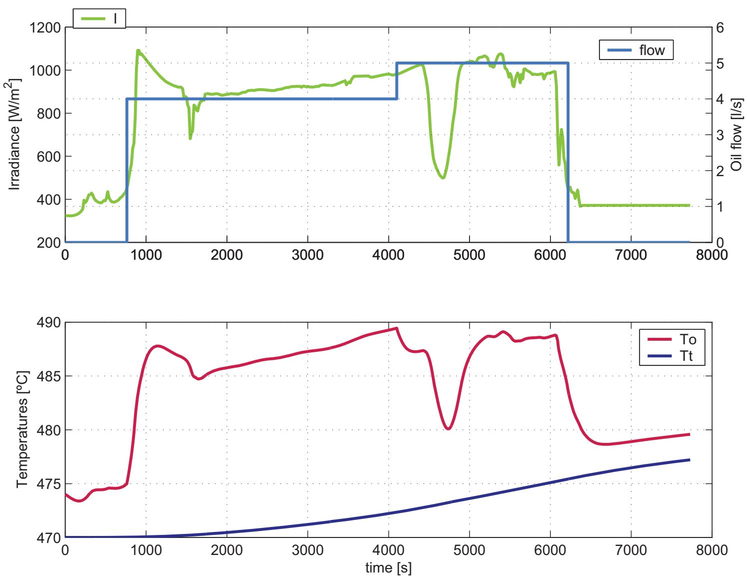



**Figure 9:** Simulation results for outlet and inlet temperature of the field (To and Tt), for the inputs assigned in the upper graph (solar irradiance and oil flow rate)

At the beginning of the day, solar irradiance is under the minimum value which has been defined to start the operation. Therefore, the oil pump is off, the mode is *Sleep* (see figure (10)), and there is no oil flowing through the solar field.

When solar irradiance exceeds more than 450 W/m$^2$, since outlet solar field is in a low value (compared with the temperature in the tank), the mode change to *Recirculation* so that the storage system is decoupled from the solar field changing the valve V1 position. Then, the oil pump is activated and the control output informs that the solar field control system must be activated.

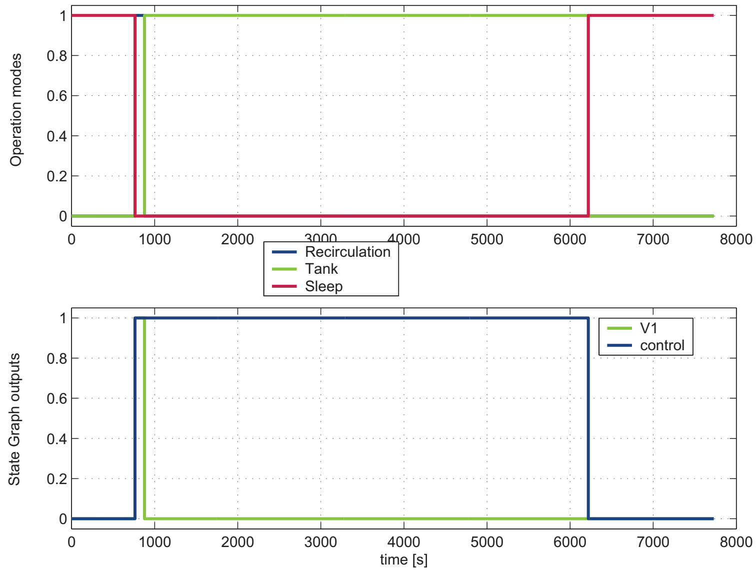



**Figure 10:** Simulation results.

After a short period of time, the mode change to *Tank*. In this discrete state the tanks begins to increase its stored energy due to the inlet thermal power from the solar irradiated field.

Solar irradiance shows a hard fallen in the middle of the simulation. Nevertheless, the outlet solar field temperature values are high enough to maintain *Tank* mode.

At the end, dense clouds produce solar irradiance values under 400 W/m$^2$. Then, solar field change to *Sleep* mode and oil pump is deactivated.

The operation of the plant simulated in this section, supposing the models were calibrate, would result in an irreversible damage in the plant due to overheating of the oil out of the allowed limits.

This simplified cycle is the base of the development of optimal operation-and-control systems, which in addition is based in during 25 years accumulated heuristic knowledge of human operators and mixed with dynamic optimisation techniques, give rise to optimal automatic control systems for solar thermal power plants.

# 6 Concluding remarks and Ongoing work

This article shows the development of a dynamic model for the CIEMAT's ACUREX facility using the object oriented modelling methodology. The major part of the components are based in the ThermoFluid framework for thermo-hydraulic modelling. The main ACUREX components and main operation principles have been described. For the main components, the modelling hypotheses and the composition Modelica diagrams developed with the Dymola tool have been presented. References to the underlying physical phenomena have been made in these composition diagrams, without entering into detail of quantitatively describing them through differential and algebraic equations; instead, the basic bibliography and the ThermoFluid classes that implements them have been referenced. Finally, a simulation of the system is executed with the boundary conditions of a experiment. Some temperature results of the model simulation are represented with the corresponding experimental measured values. The graphs show that the differences between the experiments results and predicted values from the model are relatively small.

The ongoing work to develop consists in refining the main models parameter calibration based on the experimental results of the actual plant. In this work, the validation of empirical correlations for heat transfer and pressure loss will be an important issue.

The final aim is to develop control and automatic operation systems that would help this type of plants operate in the most autonomous way and in spite of large disturbances. Automatic start-up and shutdowns of the plants is one of the main objectives in this direction.

# 7 Acknowledgements

This work has been financed by CIEMAT research centre and with CICYT-FEDER funds (projects DPI2002-04375-C03, DPI2004-07444-C04-04, DPI2004-01804 and DPI2007-66718-C04-04). This support is gratefully acknowledged by the authors.

# 8 References


[1] Modelica Association. Modelica, a unified object oriented language for physical systems modeling. language specification 2.2. Technical report, Modelica Association, http://www.modelica.org, 2005.

[2] K.J. Åström, H. Elmqvist, and S.E. Mattsson. Evolution of continuous-time modeling and simulation. In R. Zobel and D. Moeller, editors, *Proceedings of the 12th European Simulation Multiconference, ESM'98*, pages 9–18, Manchester, UK, June 1998. Society for Computer Simulation International.

[3] K.J. Åström and B. Wittenmark. *Computer-Controlled Systems*. Prentice Hall, 1997.

[4] M. Berenguel. *Contribuciones al control de colectores solares distribuidos*. PhD thesis, Escuela Superior de Ingenieros Industriales de Sevilla, Espa?a, Marzo 1996.

[5] E.F. Camacho, M. Berenguel, and F.R. Rubio. *Advanced Control of Solar Plants*. Springer, 1997.

[6] A.B. Dynasim. *Dymola 5.3 User Manual*. Dynasim, A.B., http://www.dynasim.se, 2004.

[7] J. Eborn. *On Model Libraries for Thermo-hydraulic Applications*. PhD thesis, Department of Automatic Control, Lund Institute of Technology, Sweden, March 2001.

[8] L. González, E. Zarza, and L. J. Yebra. Determinación del modificador por ángulo de incidencia de un colector solar ls-3, incluyendo las pérdidas geométricas por final de colector. Technical Report DISS-SC-SF-29, CIEMAT-PSA. Almería. España, Agosto 2001.

[9] Martin Otter, Karl-Erik Årzén, and Isolde Dressler. Stategraph—A Modelica library for hierarchical state machines. In *Modelica 2005 Proceedings*, 2005.

[10] S.V. Patankar. *Numerical Heat Transfer and Fluid Flow. Series in Computational and Physical Processes in Mechanics and Thermal Sciences*. Taylor & Francis, 1980.

[11] W.M. Rohsenow, J.P. Hartnett, and Y.I. Cho. *Handbook of Heat Transfer*. McGraw-Hill, 1998.

[12] H. Tummescheit. *Design and Implementation of Object-Oriented Model Libraries using Modelica*. PhD thesis, Department of Automatic Control, Lund Institute of Technology, Sweden, August 2002.

[13] L. Valenzuela, E. Zarza, M. Berenguel, and E.F. Camacho. Direct steam generation in solar boilers. *IEEE Control Systems Magazine*, 24:15–29, April 2004.

[14] H.K. Versteeg and W. Malalasekera. *An Introduction to Computational Fluid Dynamics*. Addison Wesley Longman Limited, 1995.

[15] E. Zarza. Aplicaciones industriales de los colectores cilindro-parabólicos. Technical Report R09/01EZ, CIEMAT-PSA, Crta. Senés s/n. 04200 Tabernas. Almería. España, 2001.

[16] E. Zarza. *La Generación Directa de Vapor con Colectores Cilindro-Parabólicos. El Proyecto DISS*. PhD thesis, ESII Sevilla, España, Noviembre 2003.