START-UP SIMULATION FOR A SOLAR DESALINATION PLANT

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Abstract

AQUASOL project ("Enhanced Zero Discharge Seawater Desalination using Hybrid Solar Technology"), developed by CIEMAT (National Lab of the Education and Science Spanish Ministry), is a technological development in desalination with solar energy. The objective of this project is to improve the cost and energy efficiency of the process combing a solar field with a double effect absorption heat pump for continuous water production. With the aim of applying the technological innovations developed in this project to industrial applications, it is necessary to minimize production costs keeping the system in safe operation points. For this reason, this paper shows an automatic discrete operator that governs the start-up procedure for the whole system using *Modelica* language and *StateGraph* library. But also, for the start-up simulation it is necessary to describe the process dynamic that includes the models of each component as solar field, storage water system and distillation unit, developed with *Thermal* library components. On the other hand, control loops that optimize the process are included in order to obtain maximum system efficiency. This method makes possible to test an automatic system that can be useful to find the best conditions for operation, but also can be used as assistance to operate the real plant in the most autonomous way despite disturbances.

Keywords: solar desalination, control, modeling

Presenting Author's Biography

Lidia Roca obtained the degree in Electronic Engineering from the University of Granada, Spain, in 2004. She spent part of the academic year 2003/04 in the Plataforma Solar de Almería collaborating with studies related with the modeling of distributed solar collectors. Now is developing her PhD in modeling and control of a solar desalination plant, supervised by Manuel Berenguel (University of Almería) and Luis J. Yebra (CIEMAT).

1 Introduction

There are two different types of technologies in the desalination market: membrane processes (reverse osmosis RO) and thermal distillation (multi-effect MED, multi-stage flash MSF, thermal vapor compression HVC). However, just RO and MSF plants cover the most of the commercial processes. AQUASOL project was launched to improve the techno-economic efficiency of solar MED systems by developing technological features.
The aim of this paper is to propose the optimal transition conditions between states in order to maximize solar energy resources in AQUASOL plant. For this

Fig. 1 AQUASOL solar field

reason, a hybrid model for dynamic simulations is developed with *Modelica* [4] and the *StateGraph* package [5]. Simulation of dynamic hybrid models let evaluate and improve control system whereas experimental costly tests are reduced. However, for the start-up procedure it is necessary to simulate the model of the whole plant, and also the connections to the virtual operators must be defined. In other words, start-up simulation (figure 2) includes a AQUASOL process component with the dynamic model of the system and, on the other hand, the operator virtual machine must decide operation procedure by using the state variables from AQUASOL process as inputs. Consequently, the dynamic of the process is composed of continuous and discrete variables.

The paper is organized as follows; first, AQUASOL system is introduced. Next subsystem models for describing the dynamic behaviour of the process are presented. The third part includes local controllers applied both solar field and first MED effect. In section 5 the start-up procedure with simulations is exposed. Finally, general conclusions and indications for future developments will end the paper.

2 System description

The AQUASOL system (figure 3) sited at Plataforma Solar de Almería located in the southern of Spain, proposes a solar distillation technology that basically consists of a CPC solar collector field, two $12m^3$ water storage tanks, a multi-effect distillation plant (MED) with a $3m^3/h$ nominal distillate production,

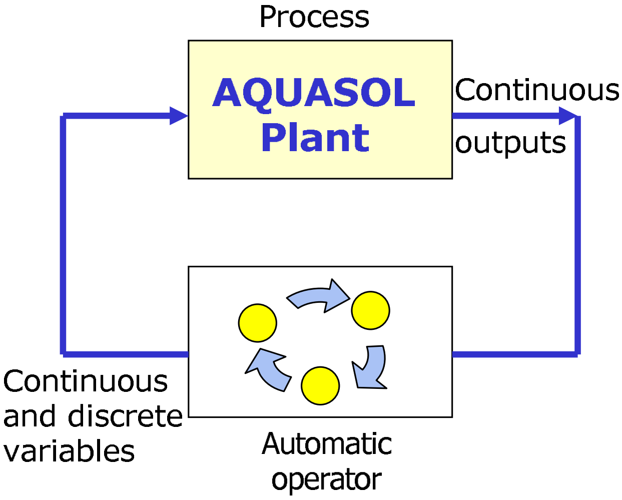

Fig. 2 Automatic operator

and a double effect (LiBr-H_2O) absorption heat pump (DEAHP) [7].

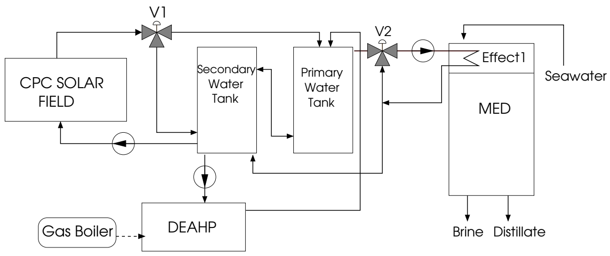

Fig. 3 AQUASOL diagram

The MED plant consists of 14 effects in vertical arrangement at a decreasing pressures from cell 1 to 14. Seawater is pumped and preheated towards the first cell where goes down to the following cells by gravity, and at the same time, part of the water is evaporated. For optimal operation, the inlet feed-water temperature in the first cell must be 66.5^{o}C. It is possible to reach this temperature with heat from a solar field and also by steam generated by an auxiliary gas boiler coupled to a double effect absorption heat pump, DEAHP (LiBr-H_2O), that can work at variable loads of the steam (from 30% to 100%). Solar collector field consists of CPC (Compound Parabolic Concentrator) collectors coupled to two water storage tanks, of $12m^3$ capacity each one, used as energy storage system. Energy supplied by the solar field and DEAHP is transferred to the thermal primary storage tank using water as the heat transfer fluid. To reduce the overall fossil energy expenditure, the low-pressure steam from the last cell in MED is used in the DEAHP, which decreases its consumption from 200 kW to 90 kW. Finally, V2 is a three-way regulation valve used to reach the inlet first effect nominal temperature by mixing water from primary tank with that returned from first effect.
The AQUASOL plant can operate in three different modes; solar, fossil and hybrid. In the solar mode, wa-

ter from secondary tank is pumped to the solar field where is heated to more than 66.5^{o}C returning then to the storage system. V1 is an on-off valve used to recirculate water in the solar field, through secondary tank, until nominal temperature is reached. Through the recirculation mode, cooling situations in primary tank that can occur under some boundary conditions, can be avoided. In this solar mode, inlet MED temperature is reached with solar energy only, while in fossil mode, the MED plant operates with the gas boiler coupled to the DEAHP working at full load, making possible to obtain fresh water in cloudy days and night operation. The two previous modes are combined in hybrid mode when the solar field needs make use of fossil energy to reach the desired temperature in MED plant. In this case DEAHP works at partial load just to be a support but reducing fossil consumption as much as possible.

3 Subsystem models

In order to simulate the start-up system with an automatic operator, each component of the plant must be modeled previously. For this reason, the solar field, first MED effect and storage system models are developed with *Modelica* language by using *Thermal* library. Previous works about modeling solar plants [8],[9] shows the benefits of using *Modelica* as the modeling tool. Besides being an acausal model language with high level specification, *Modelica* is focused on system dynamic of physical processes. In this section the models of solar field, storage system and first MED effect will be explained in such a way that finally, the connection between these components will permit the simulation of the solar operation mode for fresh water production by using just solar energy.

- *Solar field*
  The solar collector field is composed of 252 CPCs (AoSol 1.12X) with a total surface area of approximately 500 m^2, divided into four rows of 63 collectors. Each row is composed of groups of three collectors connected in parallel, and each group of three is linked to another in series. Finally, each group of nine collectors is connected in parallel to the row header pipe. CPC-s are non-tracking collectors with a reflective surface around the cylindrical absorber tubes that concentrates global radiation. The AQUASOL CPC-s are composed of seven absorber tubes each one and its orientation is east-west to maximize energy collection.
  To model the solar field, hydraulic equilibrium is considered. This means collectors are arranged in reverse feeding mode so flow is divided equally in each row. Therefore, it is supposed that outlet temperature of the solar field is the same as the outlet temperature in each group of nine collectors. Solar collector system dynamics can be described using nonlinear distributed parameter PDE models [2]. In this case, the solar description is such as:

$$\rho \cdot C_p \cdot A \cdot \frac{\partial T(t)}{\partial t} = H_{in} + H + Q_I - Q_{loss} \tag{1}$$

As it is shown in equation (1), outlet solar field temperature, T, varies depending on global irradiation disturbances I (included in irradiation flow heat Q_I), ambient temperature T_a (in Q_{loss} term), inlet solar field temperature T_{in} (H_{in} term), and on the manipulated variable mass flow $\dot{m}_F$. Although the heat losses, Q_{loss}, could be represented by a second degree polynomial approximation with the difference between absorber, and ambient temperatures, $(T_{ab} - T_a)$, as the independent variable, it is assumed a constant heat losses coefficient found experimentally by parameter identification techniques under different operating conditions using *Model Calibration* library from *Dymola*. Furthermore, absorber temperature (included in Q_{loss} term) is modeled as the mean temperature, $\bar{T}$, between outlet and inlet water temperature. On the other hand, incident solar power on the collector (Q_I) includes the aperture and efficiency of the collectors, and also an attenuating factor due to the fact that irradiation collected by the collector is not global irradiation, but beam radiation plus a fraction of diffuse that depends on the collector concentration [3].

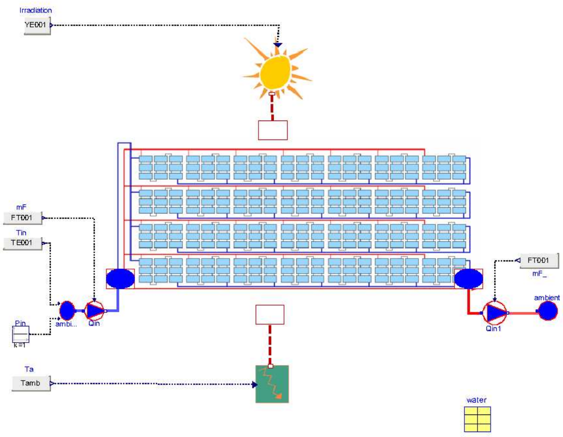

Fig. 4 Solar field model diagram with Dymola

Figure 4 shows solar field model defined using *Modelica* language. Expression 1 has been used in an arranged way in order to use *FlowPorts* and *HeatPorts* connectors of *Thermal* library. Specifically, there are two *FlowPorts* with solar field mass flow and inlet solar field temperature as boundary conditions to evaluate transport energy inside tube collectors, and two *HeatPorts* for irradiation term and thermal losses.
A simulation of the solar field model for the 8th of June 2007 is shown in figure 5. While irradiation follows the typical solar cycle with small disturbances, inlet water mass flow shows step variations to validate the model in a wide operation range. Outlet solar field temperature increases mainly due to global irradiation, but also

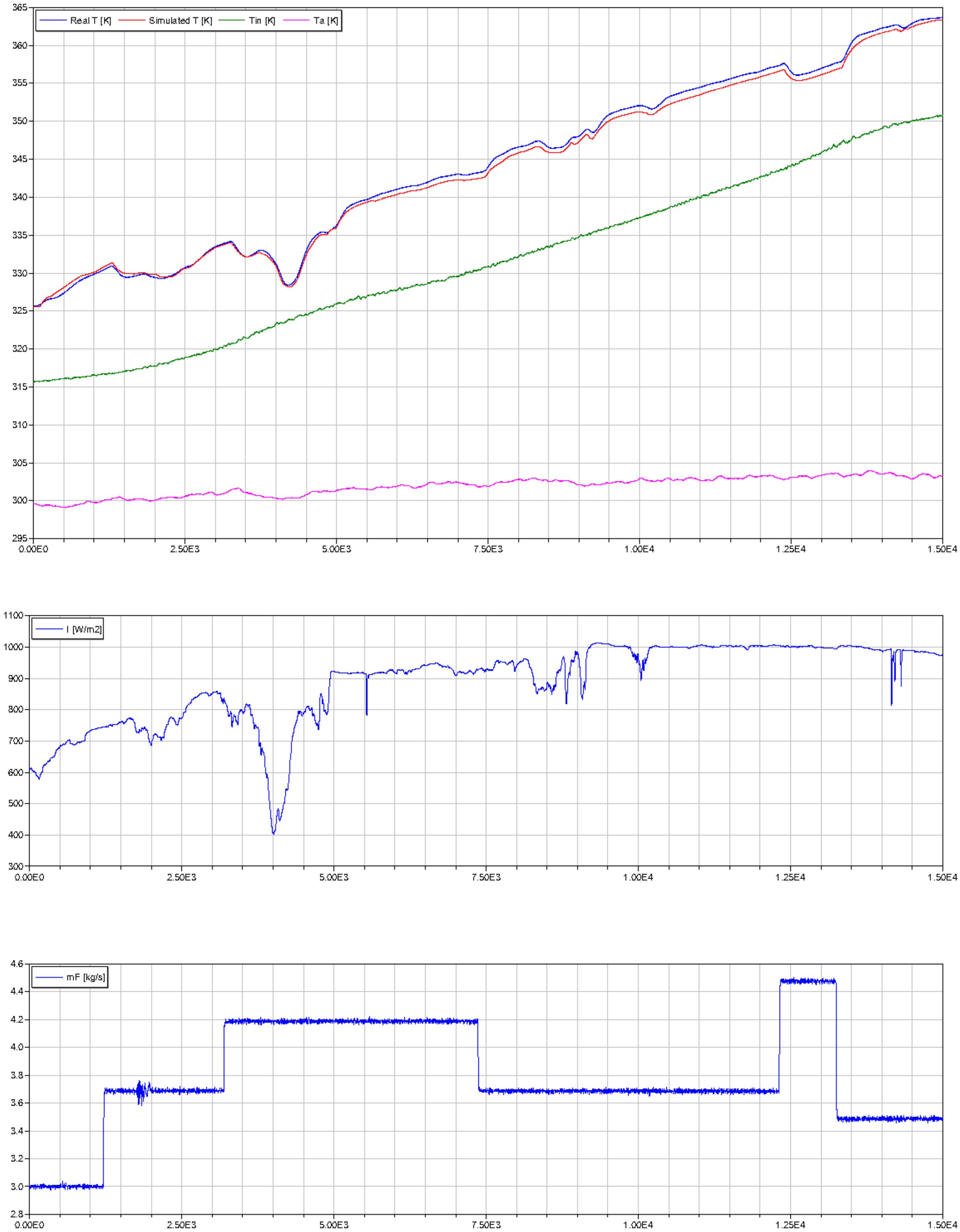

Fig. 5 Solar field model simulation for the 8th of June 2007

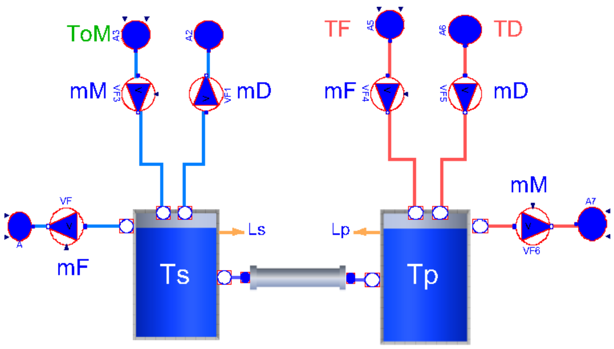

Fig. 6 Storage water system model with Dymola

Tab. 1 Storage water system disturbances

Inputs	Description
$\dot{m}_F$	Inlet solar field mass flow rate
$\dot{m}_M$	Inlet first MED effect mass flow rate
$\dot{m}_D$	Water DEAHP mass flow rate
γ	Regulation valve aperture
T_{oM}	Outlet first MED effect temperature
T_D	Outlet DEAHP temperature

due to the inlet water field temperature positive slope. Both real and simulated outlet temperature lines, show a similar behavior (figure 5). being the maximum difference of about 1^oC.

- *Storage water system*
  Due to the small tank capacity ($12m^3$), it is supposed the effects of stratification negligible, so only a single mean temperature state variable is assumed for each tank. Furthermore, outer surface of both tanks is thermally insulated so no thermal losses are considered at start-up. With the mass and energy balances (equations 2, 3) it is possible to obtain a dynamic model using levels and temperatures in the primary and secondary tank (L_p, L_s, T_p, T_s) as state variables, and the variables shown in table 1 as inputs.

$$A\frac{dL}{dt} = \sum \dot{m}_{in} - \sum \dot{m}_{out} \qquad (2)$$

$$\frac{d}{dt}(\rho ALTc_p) = \sum H_{in} - \sum H_{out} \qquad (3)$$

Input γ in the range of [0,1], is used to model valve V2 as an ideal valve. Notice that because of the different operating conditions, flow direction between tanks changes depending on differential pressure. For this reason, storage system model (figure 6) is composed of two different models: a water storage tank model and a connection pipe between tanks to determine mass flow between tanks depending on tank pressures, pipe geometric properties and flow kinematic.
A simulation of the temperatures reached in the storage water system is shown in figure 7 for the same experimental day of the solar field simulation. In this case, an experiment in the storage system was made just with the solar field and without MED operation. The initial temperatures in primary and secondary tanks are 319.5 K and 317 K respectively, but because of the heat power delivered by the solar field the tanks store energy in sensible heat way.

- *First effect of the MED*
  Inlet MED first effect water is a mixture process that uses regulation valve V2 for mixing water from primary tank with the water returned from the first effect. Therefore, inlet water temperature can be obtained using the ideal valve parameter γ as expression 4 shows.

$$H_{iM} + \gamma H_M + (1-\gamma)H_{oM} = 0 \qquad (4)$$

For the outlet water temperature prediction, first effect is considered as a heat exchanger where the inner fluid is the water from valve V2, and the outer fluid the seawater that is pumped inside the cell. The heat balance that defines the dynamic of the process is shown in expression 5, where H_{iM} and H_{oM} represent flow entalpies for the fluid inside the heat exchanger and Q_{cell1} the transfer heat between outer fluid and the heat exchanger metal. Notice that the metal temperature has been approximated as a media between inlet and outlet water temperature.

$$H_{iM} + H_{oM} + Q_{cell1} = 0 \qquad (5)$$

Furthermore, first effect is characterized with the global heat transfer coefficient and the area of the exchanger. Due to the non availability about this two values, *Model Calibration* library has been applied in different operation days to tune them.
Figure 9 shows an operation day of the distillation unit. Inlet MED mass flow, m_{iM}, is established to $12kg/s$ during the whole operation, whereas inlet temperature, T_{iM}, is varying in the range [342, 347] ^oC. As it can be observed, both real and simulated outlet temperature, T_{oM}, have a similar behavior, being the maximum difference less than 0.5^oC between the two lines.

4 Local Controllers

Another study that must be carried out, before describe start-up procedure, is to define each subsystem controller. Solar field can be controlled in three different ways; low temperature, gain temperature and manual. Low temperature control is useful during night operation in order to avoid frozen situations in collectors. On the other hand, during a typical

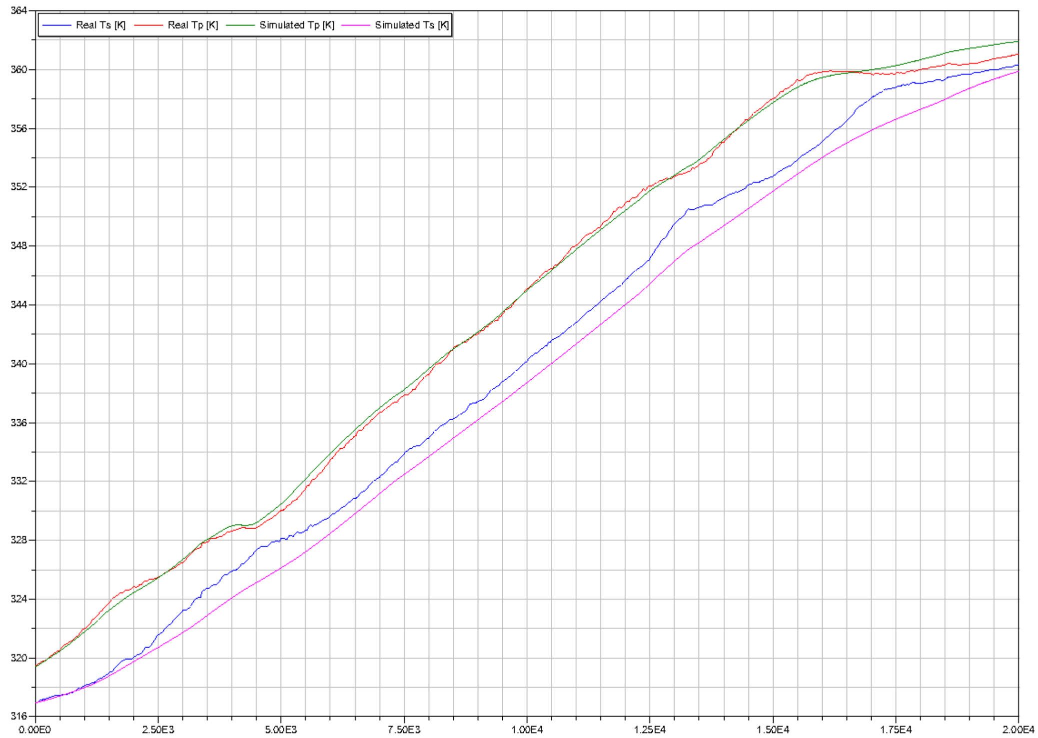

Fig. 7 Storage system model simulation for the 8th of June 2007

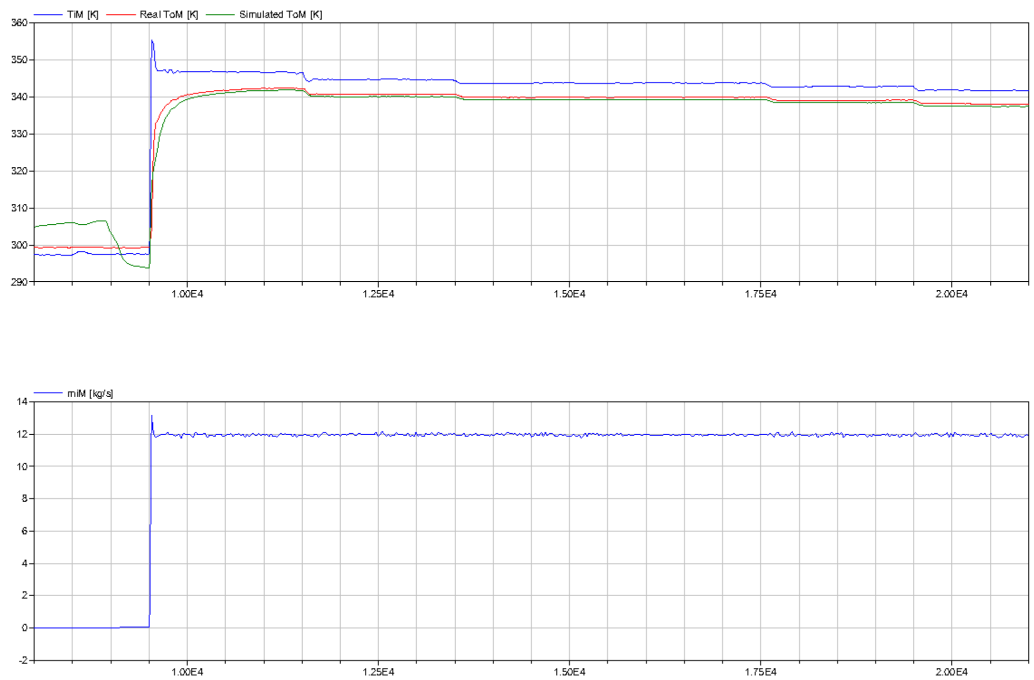

Fig. 9 First MED effect model simulation for the 21st of June 2007

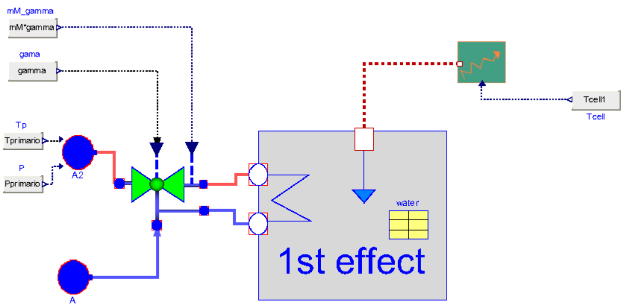

Fig. 8 First MED effect model with Dymola

operation day, solar field control will try to establish a gain temperature between the inlet and outlet solar field water by modifying inlet water flow in order to reach maximum efficiency. Finally, it is important to permit a manual operation over inlet solar field water flow for the operator supervision.
Beside this, another controller is defined in the storage system-first effect loop, using the regulation valve V2 as the manipulated variable. This controller will try to set the inlet first effect temperature to a desired value. Notice the importance of this control loop due to the strict range in which MED must be working. To specify, to operate efficiently the desalination system, inlet MED temperature must be around 66.5^oC. Low temperatures decrease system efficiency but temperatures above 70^oC could produce scale formation inside the heat exchanger.

- *Solar field control*
  As previously was mentioned, solar field must be controlled in three different ways: manual, gain temperature and low temperature. Therefore, a control signal, *sc*, is used to change the control mode in an alternative execution with *StateGraph* (see figure 10).
  In manual mode control, operators select the water flow for the solar field while gain temperature control is used in order to obtained a defined solar field heat power by modifying water flow despite disturbances as inlet temperature, irradiation or ambient temperature. For this control it has been tested a feedback linearization control [6] using a PI as the linear control. Finally, low temperature control is used at night to avoid collectors freezing. In this case, when a minimum temperature is detected in the solar field, pump is turned on at 3 l/s during 5 minutes so it is ensured the whole water renovation inside the field with water from storage system. For this reason, a transition with a *timer* signal has been applied. This transition only fires once the *timer* reaches the defined time that ensures a whole renovation of the water inside the collectors.

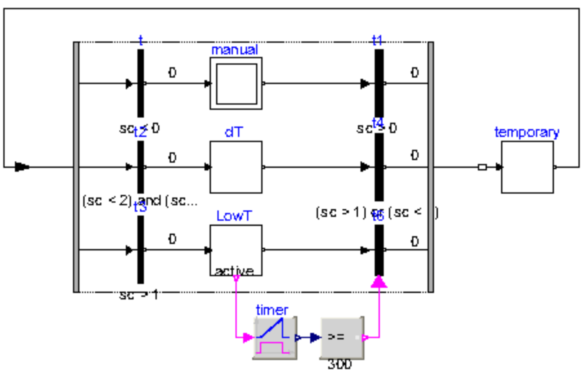

Fig. 10 Solar field discrete control system

- *Inlet MED temperature control*
  In this case a local PI is used to regulate inlet MED temperature by modifying regulation valve between primary tank and MED plant. In this case there is no feedforward algorithm and the PID acts using just the inlet MED water temperature and the reference as inputs.

5 Start-up model

Although the systems are controlled manually by qualified operators, automatic operators are developed to obtain autonomous systems. For the start-up procedure, *Modelica StateGraph* library has been used to define the states and transitions during a typical operation day. Firstly, in order to understand the defined states, three variables will be defined:

1. *Thermal power delivered by solar field, P_F*
   This variable, as it is defined in equation 6, depends on water flow inside solar field, outlet temperature and water properties. Instantaneous thermal power is measured in each sample time in order to make the MED operation decision.
   $$P_F = \dot{m}_F \cdot c_p \cdot T \tag{6}$$
2. *Thermal power delivered to first MED effect* At nominal conditions, MED needs a determined input power. Therefore, it is important to measure this variable (as expression 7shows) for defining operation conditions.
   $$P_{iM} = \dot{m}_{iM} \cdot c_p \cdot T_{iM} \tag{7}$$
3. *Stored energy, E_a*
   The two water tanks have the role of being a heat sensible storage system using water as the stored fluid. Considering states variables defined in the storage system model section, the stored energy, E_a, can be defined as expression 8 shows.
   $$E_a = c_p \cdot \rho \cdot A \cdot (L_p \cdot T_p + L_s \cdot T_s) \tag{8}$$

Although this paper shows the solar operation mode, in case of working with DEAHP, the main parameter that defines transitions between hybrid and solar modes must be the stored energy, E_a. Absorption heat pumps are dynamic systems that used to have high inertias, so stationary conditions are reached after relative long periods of time. In the case of AQUASOL DEAHP, this time is around 30 minutes (depending on disturbances and input variables) so solar mode must finished when stored energy does not ensure 30 minutes of operation at nominal conditions (defined by power expression 7). The reason of including this condition in this paper is future works that must be carried out using hybrid and fossil operation modes.

Experimental procedure of a typical operation day is explained next:

- During the first hours in the morning when a defined irradiation threshold is reached (about $300W/m^2$), the solar field control is established to maintain 10^oC of difference between outlet and inlet temperature to maximize thermal power delivered to the storage system.
- If outlet solar field temperature is less than primary water temperature, water is recirculated through secondary tank to avoid cool down primary tank fluid. On the other hand, when solar field temperature is greater than primary tank temperature, water is pumped to this tank.
- If P_F and E_a overcame an established value, MED is turned on.
- MED will be turned off when solar field thermal power and stored energy will be under the defined limits.

Therefore, for the operation four states are defined:

- Break state: distillation system off and solar field flow depending on control selection.
- Break state with recirculation: water from solar field recirculates through secondary tank with distillation unit off.
- MED operation: distillation system turned on
- MED operation with recirculation: distillation system turned on whereas water from solar field recirculates through secondary tank.

Transitions between states will be based on temperatures reached in each one of the subsystems and operation criteria based on power and thermal energy values (see figure 11).

6 Simulation of a real case

AQUASOL operator (figure 12) that includes operation procedure, models and control loops previously described, has been developed with the objective of

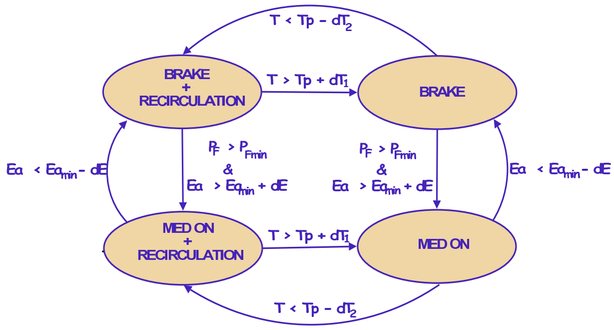

Fig. 11 State machine

testing and optimize transition conditions between the states explained before.

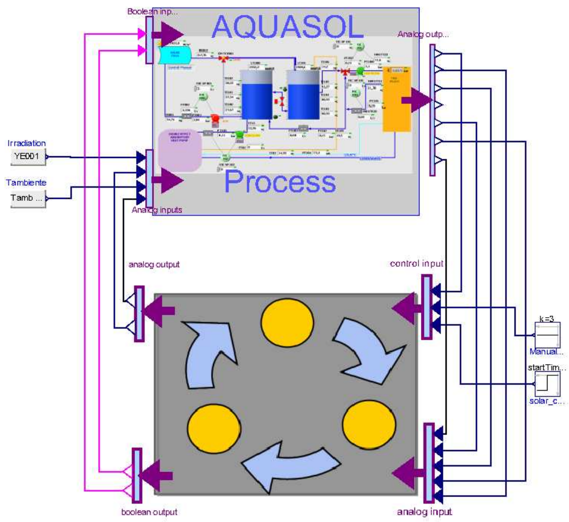

Fig. 12 AQUASOL operator

The top part of figure 13 shows the real irradiation and ambient temperature for the 11th of June 2007, whereas the inlet solar field mass flow it is shown in the bottom part. It is supposed that at the beginning of the experiment solar field flow is established to manual control at $2kg/s$. Once irradiation achieves $500W/m^2$, control is switched to gain temperature so mass flow values change in order to maintain a difference of 10^oC between outlet and inlet solar field water temperature despite irradiation, ambient and inlet temperatures disturbances. Operation modes and temperatures obtained in simulation are represented in figure 14. While outlet solar field temperature, *T*, is below primary tank temperature, valve V1 is off (figure 15) so tanks keep its initial temperatures occurs, V1 is on, so outlet solar field water is pumped to primary tank increasing the temperature in the storage system. It is important to mention that ΔT_1 and ΔT_2 have been selected in order to avoid continuous transitions between modes: if outlet solar field temperature falls down T_p, V1 is off so T increases faster

Fig. 13 Start-up simulation for the 11th of June 2007

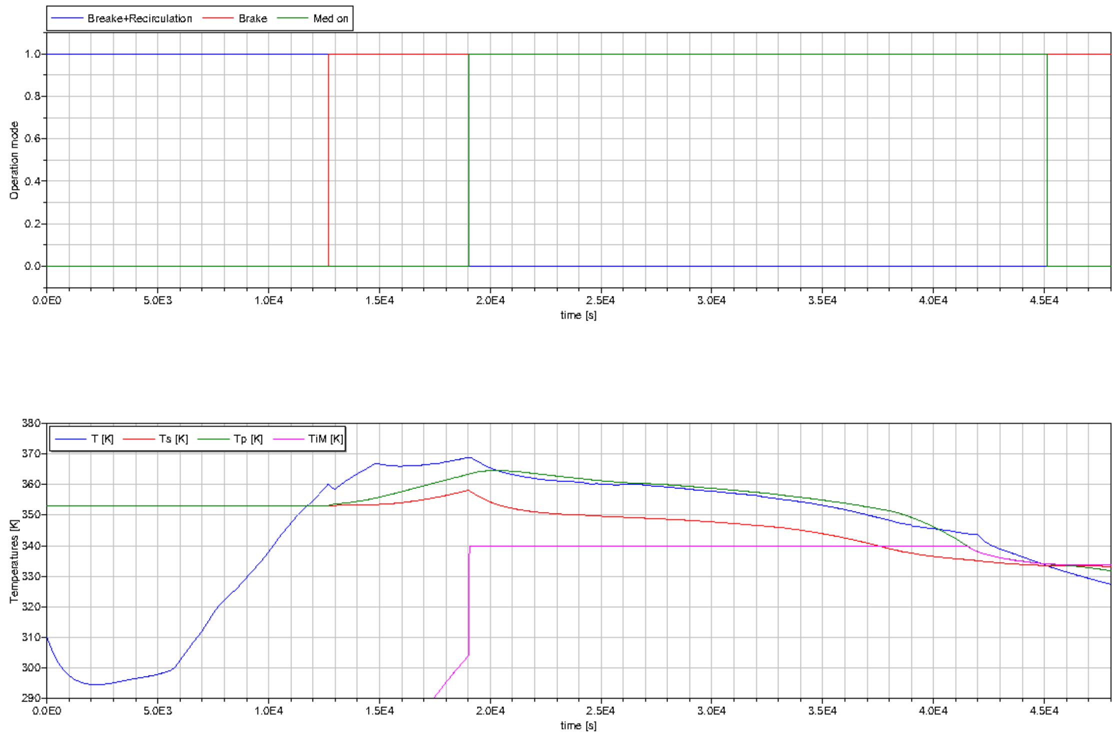

Fig. 14 Start-up simulation for the 11th of June 2007

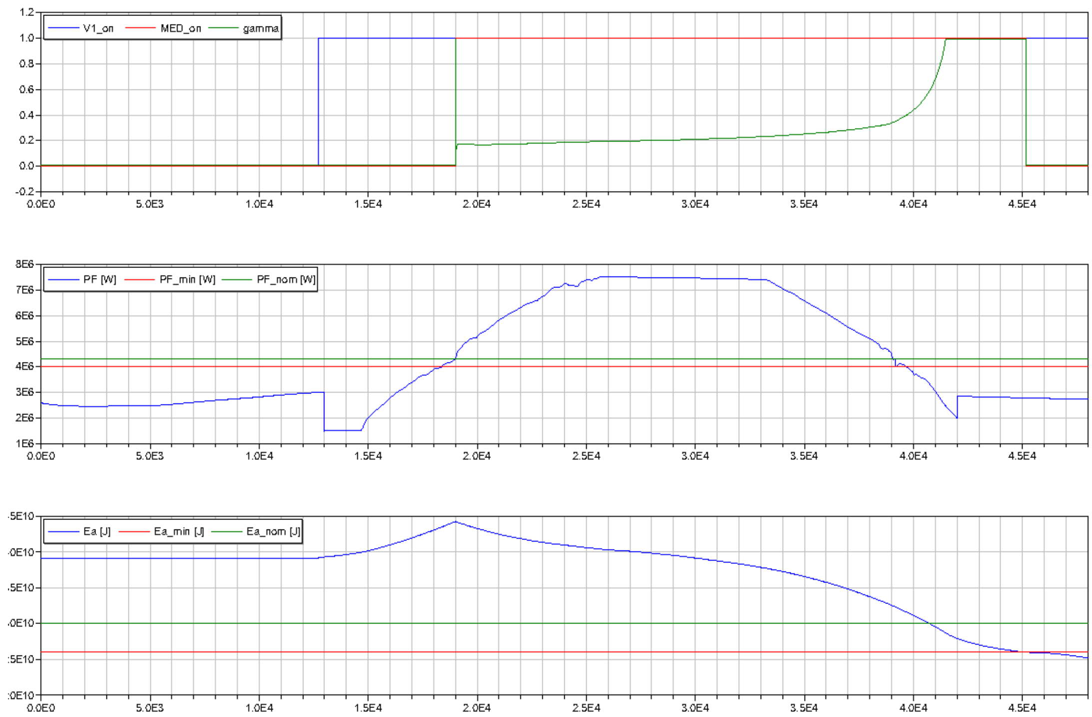

Fig. 15 Start-up simulation for the 11th of June 2007

than before due to solar field is in a close loop. Therefore, V1 would change to on soon after and again T would start to decrease. To avoid continuous mechanical actions over valve V1, it is important to make a good selection of ΔT_1 and ΔT_2. On the other hand, distillation plant is turned on once both thermal power P_F and stored energy, E_a, satisfy the operation conditions. When MED is turned on, V2 is opened and parameter γ (figure 15) is regulated by the local PI that establishes T_{iM} to 340K (67^oC) (see figure 14). Since irradiation starts to decrease, primary tank can't support the energy required for operating MED unit at nominal conditions. Therefore, although γ is completely open, T_{iM} decreases as T_p and E_a do, with the consequence of stopping MED.
Note that in this case, the objective is to extend the operation as much as possible, trying to avoid stop-restart situations. For this reason, only when the energy stored in the tanks is not enough, MED is turned off. As it can be observed in figure 14, at the end of operation T_{iM} is around 61^oC, and although there would be distillation production yet, the low efficiency due to electric consumption is enough to stop the plant. On the other hand, using DEAHP, the change to hybrid mode must happen when $Ea < Ea_{min} + \Delta E$ condition fires. This situation matches with the beginning of the inlet MED temperature drop. Therefore there would be a longer time frame to maintain nominal conditions while DEAHP is establishing.

7 Conclusions and future work

This paper shows a start-up procedure for a solar desalination plant. First of all the physical models for the main components of the system has been describes using *Dymola* tool and *Thermal* library. Based on the whole model, it has been possible to test an automatic system that can be useful in two different ways: firstly the model-operator connection help to find the best conditions to operate the real plant in the nominal operation points, and secondly, the automatic operator can be used as assistance to operate the real plant in the most autonomous way despite disturbances.
For the future, DEAHP model must be included in order to extend solar mode start-up procedure to hybrid and fossil modes. It should be studied the possibility of an optimization procedure for the system operation defining a cost function based on thermal and electric powers. For this optimization problem it could be used the *Design Optimization* library from *Dymola* or convert the system to a *Simulink* S-Function in order to use optimization solvers from Matlab.

8 Acknowledgements

The authors wish to thank CIEMAT, the Ministerio de Educación y Ciencia (DPI2007-66718-C04-04) and to the European Comission for the their support provided for AQUASOL Project (contract np. EVK1-CT2001-00102). This work has been also performed within the scope of the specific collaboration agreement between the Plataforma Solar de Almería and the Automatic Control, Electronics and Robotics research group of the Universidad de Almería titled "Development of control systems and tools for thermosolar plants".

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