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First Principles System Level Modelling of TCP-100 Facility for Simulation of Operation Modes ⋆

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Abstract:
This paper presents a set of first principles based models for system level simulation of the complete new TCP-100 research facility at Plataforma Solar de Almería (CIEMAT). This new research facility replaced the 32 years old ACUREX facility with which so many advances in Automatic Control were reached by the research community. The presented models will be validated with experimental data and the presented simulations are based in the parameter selection from providers' data sheets and the engineering design project. Results of several simulation experiments for a typical operation day are presented in which the system is operated passing through different operating modes.

Keywords: dynamic modelling, first principles, simulation, operation of solar PTC plants

1. INTRODUCTION

Modelling and Control of solar thermal power plants is among the research activities performed at Plataforma Solar de Almería (PSA, PSA-CIEMAT). In the past the ACUREX experimental research facility was the main one used for the development of mathematical models and control techniques.

The first modelling and control works were made by R. Carmona, Director of PSA center in the period from 1985 to 1987. Carmona defended his dissertation in 1985 (Carmona (1985)) presenting a non-linear distributed mathematical model of the ACUREX field and proposing an adaptive control temperature technique (Camacho et al. (1986)). Many control strategies for solar systems have been tested in this facility in its 32 years of life (Camacho et al. (2007); Andrade et al. (2013); L.Brus et al. (2010); Gallego et al. (2013)). Nowadays the TCP-100 facility has replaced ACUREX field and it was specially designed to continue the research activities in Automatic Control, aimed at contributing to the enhancement of the efficiency of this plant technology.

Many parabolic trough collectors (PTC) plants have been commissioned in the last 15 years. Only in Spain around 45 PTCs power plants have been setup and more than 26 abroad, built or under construction (PROTERMOSOLAR (2017)).

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The main approach followed in the research activities developed so far was to define as control objective the regulation of the outlet temperature of the PTC field around a desired set-point. Complementary additional objectives dealing with the automatic start-up, different operating point operation changes and shutdown of the plant, will be developed for the new TCP-100 research facility topology. In this paper, a system level dynamic model based on first principles of the TCP-100 facility and different simulation experiments validating the design operational modes are presented.

Previous modelling works related to this facility is the non-linear distributed parameter model presented in Gallego et al. (2016).

The paper is organized as follows: section 2 summarizes the plant TCP-100. Section 3 presents the mathematical models developed and simulated used in this paper. Section 4 presents the simulation results for experiments to be performed for typical operation days. Finally, section 5 provides some concluding remarks and future works.

2. TCP-100 FACILITY DESCRIPTION

The facility is formed by two thermofluid circuits thermally connected by a heat exchanger. Fig. 1 shows a representation of both circuits with two heat transfer fluids (HTFs): Syltherm 800 for the primary and Therminol 55 for the secondary. The solar field is in the primary circuit and shown in Fig. 3. In each of the circuits there is one tank: tank T-2 in the primary with $10m^3$ volume and a

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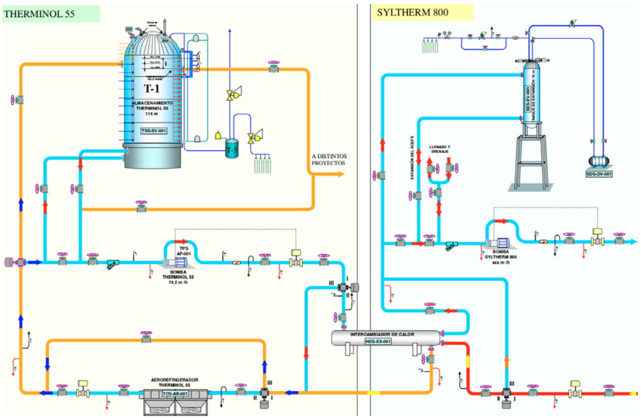

Fig. 1. Schema of the TCP-100 facility. Both circuits are connected by the heat exchanger: primary at the right where the solar field is connected with Syltherm 800 HTF and secondary at the left part, including storage tank and cooler, with Therminol 55 HTF.

Fig. 2. Lateral view of the first TCP-100 PTC in the first loop at Pataforma Solar de Almería (PSA-CIEMAT). It is composed of 8 modules of 12 meters length.

storage tank T-1 in the secondary with a volume of 115 m^3. The pumps for each circuit are placed after both tanks and can be controlled. There is an oil cooler in the secondary circuit.

The storage tank T-1 and the exchanger may be bypassed during the daily operation to let the control system to choose the operational mode at each time. Some of the preliminary operation modes are:

(1) Stopped facility. In this mode both circuits are in stand-by. Both pumps are stopped and the solar field unfocused.
(2) Both pumps working and solar field unfocused.
(3) Storage tank T-1 charging with cooler stopped.
(4) Storage tank T-1 charging with cooler working (variable charge).
(5) Storage tank T-1 discharging.
(6) Solar field cooling.

2.1 TCP-100 solar field description

The TCP-100 solar field is formed by three loops of PTCs, composed each of them by two PTCs in a North-South orientation. Each PTC is 100m length, formed by 8 modules and all in parallel. Fig. 2 shows the first PTC in the first loop.

Fig. 3. Top view of the TCP-100 field at Plataforma Solar de Almería (PSA-CIEMAT). The three loops are shown, with two PTCs in each of them, numbered from 1 (rightmost) to 6 (leftmost). The first loop is formed by the connected pair 1-2 (right loop), the second loop by 3-4 (center loop) and the third by 5-6 (left loop).

The PTCs in each loop are connected in the South extreme, and the *colder* PTC will be always the first in the row, placed at the right part of each loop in Fig. 3.

Remarkable features of the new solar field are those aimed at the experimentation of advanced control techniques, with an important quantity of sensors and actuators with respect to its predecessor ACUREX. New features are summed up:

- Inlet and outlet solar field temperature sensors.
- For each loop, inlet and outlet temperatures are measured. Inside the loop, for each PTC: inlet, outlet and middle point temperatures sensors are located.
- Volumetric flow rate for each loop.
- Control valves in each of the loops to regulate mass flow rate in each loop.

3. MODELLING OF THE TCP-100 FACILITY

The objective of the model of the facility is to simulate at system level the different operational modes of the facility. First principles modelling techniques Cellier (1991) are used to develop system models of each of the main components. Modern object oriented modelling techniques (Åström et al. (1998), Fritzson (2004)) have not been applied yet for this case although are in development. The models have been implemented in the modelling language Modelica (Modelica Association (2007a)) using Dymola tool (Elmqvist (2012)).

The mathematical models developed are presented for each of the main components of the facility in the next subsections.

3.1 Parabolic Through Collectors model and solar field

Although previous works present more detailed PTC models (Yebra (2006)) based on Computational Fluid Dynamics CFD principles (Patankar (1980)), we present in this case a first order non-linear concentrated parameters model obtained from the statement of energy balance as presented in (Michael J. and Gilman (2011)). It is basically implemented using the following assumptions:

- Mean temperature in the HTF T_f as arithmetic mean between inlet T_i and outlet T_o temperatures.
- High thermal conductivity assuming the metal absorber pipe with a mean temperature T_m.
- Equal inlet and outlet mass flow rates $\dot{m}_i = \dot{m}_o$.
- Energy balance stated in the fluid (Eq. 1), metal tube (Eq. 2) and glass envelop (Eq. 3).
- Momentum conservation dynamics is not applied focusing the modelling in the thermal dynamics. No pressure distribution along both circuits is computed.

$$M_f cp_f \frac{dT_f}{dt} = \dot{m}_i cp_i T_i - \dot{m}_o cp_o T_o + \dot{Q}_{cnv,fm} \quad (1)$$

$$M_m cp_m \frac{dT_m}{dt} = \dot{Q}_{abs,m} - \dot{Q}_{cnv,fm} - \dot{Q}_{l,m} \quad (2)$$

$$M_g cp_g \frac{dT_g}{dt} = \dot{Q}_{abs,g} + \dot{Q}_{l,m} - \dot{Q}_{cnv,air} - \dot{Q}_{rad,Sky} \quad (3)$$

A novelty in this model is the statement of the energy balance in the glass envelope (Eq. (3)). It is usually neglected and included in the heat losses from the PTC approximated by correlations. In Eq. (1): $\dot{Q}_{cnv,fm}$ is the convection heat flow between the fluid and the metal pipe. In Eq. (2): $\dot{Q}_{abs,m}$ is the absorbed heat flow from solar irradiance and $\dot{Q}_{l,m}$ are the losses to the glass envelop. In Eq. (3): $\dot{Q}_{abs,g}$ is the absorbed heat flow from solar irradiance in the glass envelop, $\dot{Q}_{cnv,air}$ is the convection losses to the ambient and $\dot{Q}_{rad,Sky}$ the radiation losses. All the expressions have been implemented as shown in (Michael J. and Gilman (2011)).

The loop model is formed by composition of three instances of this model following the topology shown in Fig.(3), corresponding with each of the PTCs in each row. Three rows are connected in parallel assuming the steady state energy balance in the output junction computed in Eq. (4).

$$\dot{m}_{o,f} cp_{o,f} T_{o,f} = \sum_{i=1}^{3} (\dot{m}_{o,i} cp_{o,i} T_{o,i}) \quad (4)$$

with

$$\dot{m}_{o,f} = \sum_{i=1}^{3} \dot{m}_{o,i} \qquad cp_{o,X} = cp_{o,X}(T_{o,X})$$

This approach generates a 18 order explicit non-linear ordinary differential equations (ODEs) system for the solar field with four inputs: mass flow rate ($\dot{m}_{i,f} = \dot{m}_{o,f}$), inlet temperature T_{in}, solar radiation I and ambient temperature T_{amb}. The state variables are the mean temperatures of the fluid, absorber pipe and glass envelop in each PTC.

3.2 Modelling of the tanks

Both tanks are modelled with the same hypothesis:

- Perfect mixing. It is assumed a mean temperature for the fluid stored in the tank and there is no stratification.
- First principles thermal losses modelling, including isolation material.
- Bypass tank option. Used in recirculation.

Although storage tank T-1 in the secondary circuit is a stratified tank, the perfect mixing approach is enough detailed for the analysis objectives of the model and keeps it with the required simplicity. Buffer tank T-2 in primary circuit will not present stratification in its operation so perfect mixing fits to the expected real behaviour. The thermal losses are modelled with the heat flows between the mediums (Syltherm800 or Therminol55) and the environment using the thermal parameters from the providers data sheets. The bypass option is needed to model the real behaviour in the plant in both tanks, that can be bypassed by properly switching some valves.

The main model equations are energy balances: Eq. (5) in the medium; Eq. (7) in the metal case and Eq. (8) in the isolation.

$$M_f cp_f \frac{dT_f}{dt} = \dot{m}_i cp_i T_i - \dot{m}_o cp_o T_o - \dot{Q}_{cnv,fm} \quad (5)$$

Where M_f is the fluid mass inside the tank. $\{cp_f, cp_i, cp_o\}$ are the specific heat of the fluid in the tank (mean), inlet pipe and outlet pipe. $\{\dot{m}_i, \dot{m}_o\}$ are the inlet/outlet mass flow rates and $\{T_f, T_i, T_o\}$ the temperatures (mean, inlet and outlet). $\dot{Q}_{cnv,fm}$ the heat flow rate losses, dominated by the conduction-convection phenomena Eq. (6).

$$\dot{Q}_{cnv,fm} = h_c A_m (T_f - T_m) \quad (6)$$

The tanks metal part is isolated from the ambient. The mean losses to the ambient are modeled by energy balance in the metal Eq.(7) and the isolation envelop Eq.(8).

$$M_m cp_m \frac{dT_m}{dt} = \dot{Q}_{cnv,fm} - \dot{Q}_{cnd,m-is} \quad (7)$$

$$M_{is} cp_{is} \frac{dT_{is}}{dt} = \dot{Q}_{cnd,m-is} - \dot{Q}_{cnv,is-a} - \dot{Q}_{rad,is-a} \quad (8)$$

The heat flows by conduction-convection $\dot{Q}_{cnd,X}$ and radiation $\dot{Q}_{rad,is-a}$ are not presented for space limitations and can be read in the bibliography (Incropera and DeWitt (1996)).

For accounting purposes, the estimation of the energy stored in the tank is obtained by Eq. (9).

$$E_{st} \approx M_f cp_f T_f \quad (9)$$

Each tank model as presented in this subsection is a 3rd order non-linear ODE model with four inputs: $\dot{m}_i/\dot{m}_i$ inlet/outlet mass flow rate, T_i inlet temperature and T_a ambient temperature. Three state variables: T_f mean media temperature, T_m mean metal temperature and T_{is} mean isolation temperature.

3.3 Modelling of the heat exchanger

The heat exchanger (EX) has been modelled following similar hypothesis as the previous models, summed up in the next list:

- Dynamic statement of energy balance in one control volume (CV) (Patankar (1980)) for each fluid/side and in the metal material between them.
- Perfect mixed assumption in each CV.
- Heat transfer parameters obtained from EX builder data sheets for selected fluids in both sides. No heat transfer correlation applied in this model.

- Steady state mass balances in each sides: $\dot{m}_{i,1} = \dot{m}_{o,1}$ and $\dot{m}_{i,2} = \dot{m}_{o,2}$.
- Bypass options in the model.

Eqs. (10, 11, 12) represent the dynamic balances for primary CV, metal part and secondary CV. The sub indexes mean: $_{f,j}$ mean property in fluid in primary ($j = 1$) or secondary ($j = 2$); $_m$ reference to metal mass; heat flows $\dot{Q}_j$ entering in the CV j; and $_{i,j}/_{o,j}$ the property computed at the inlet/output of CV j.

$$M_{f,1} cp_{f,1} \frac{dT_{f,1}}{dt} = \dot{m}_{i,1} \left(cp_{i,1} T_{i,1} - cp_{o,1} T_{o,1} \right) + \dot{Q}_1 \quad (10)$$

$$M_m cp_m \frac{dT_m}{dt} = -\dot{Q}_1 - \dot{Q}_2 \quad (11)$$

$$M_{f,2} cp_{f,2} \frac{dT_{f,2}}{dt} = \dot{m}_{i,2} \left(cp_{i,2} T_{i,2} - cp_{o,1} T_{o,1} \right) + \dot{Q}_2 \quad (12)$$

The conduction-convection heat transfer parameters hA_j defined in Eq. (13) uses data sheet values from the provider and the thermal losses are neglected by the isolation.

$$\dot{Q}_j = hA_j \left(T_m - T_{f,j} \right) \quad (13)$$

It can be concluded that the EX model is a 3rd order explicit ODE model with two inputs $\{m_{i,j}\}$ and three states $\{T_{f,j}, T_m\}$ for $j : 1, 2$.

3.4 Modelling of the Air cooler

The air cooler model is based in a dynamic energy balance in one CV in which the losses to the ambient by conduction-convection are modulated by a control/input signal u_{ac}, as shown in Eqs. (14,15). Modelling assumptions are similar to those used in EX although energy balance in the metal case has been neglected in this case. Parameters $\{h_d, A_d, K_d\}$ are obtained indirectly from the device design specifications.

$$M_f cp_f \frac{dT_{f,c}}{dt} = \dot{m}_i \left(cp_i T_i - cp_o T_o \right) + \dot{Q}_d \quad (14)$$

$$\dot{Q}_d = h_d A_d \left(T_f - T_a \right) + K_d u_{ac} \quad (15)$$

The air cooler model is a 1st order ODE model with four inputs: m_i inlet mass flow rate, u_{ac} percentage of activation, T_i inlet fluid temperature and T_a ambient temperature. It has one state variable $T_{f,c}$.

3.5 Modelling heat transfer fluids properties

Fluid properties in both circuits: Syltherm800 for primary and Therminol55 for secondary, are provided by manufactures as tables with the unique dependence of temperature of the fluid. For each point in the circuit in which a thermal property is needed a temperature should be previously computed. The assumption of perfect mixing let us state dynamic balances to obtain a mean temperature as state variable in each CV, that is used as input to the tables provided avoiding non-linear algebraic loops. In other cases the iterative non-linear solution is not avoidable. No pressure dependence is reported by manufacturers in the fluids properties, so models based on thermal dynamics might be the right system level models to work with.

The variables computed from fluid providers data sheets are: densities $\rho(T)$, specific heat $cp(T)$, viscosity $\mu(T)$ and thermal conductivities $\lambda(T)$. With these properties heat transfer coefficients based on correlations from Thermodynamics (Incropera and DeWitt (1996)) are implemented. In the case of this work, the implementation has been made by direct instantiation of Tables blocks in the Modelica Standard Library (MSL) (Modelica Association (2007b)).

3.6 Modelling of solar conditions

For solar boundary conditions modelling the Modelica library Paratrough (Romera (2015)) has been directly used in addition to experimental data from PSA center. Library Paratrough provides a set of components that predict the solar resource and medium models for solar thermal power plants.

The models used from Paratrough library are stated finally as algebraic equations that do not augment the order of the final ODE system.

4. SIMULATION OF TCP-100 FACILITY

In this section are shown the results of different simulation experiments of the TCP-100 facility based on the models presented in previous section. Model parameters are selected from the set defined in the data sheet or in the engineering project. The operating conditions are defined by the initial conditions of the model and the inputs commanded to the plant.

Figs. 4 and 5 show the simulation results of a typical operation day. The facility is supposed to be started-up at relative time hour 0, time at which there is enough sun irradiance for normal plant operation as shown in Fig.4. The upper graph shows the sun irradiance obtained from an experimental day at Plataforma Solar de Almería. Both circuits are at ambient temperature and the pumps run at their nominal conditions while the solar field is still unfocused, staying in this state (mode 0) during 0.1 hour. After that the solar field is focused and begins to get all sun radiation collected in its aperture surface heating up the plant from initial ambient conditions. This is the operational mode 1. In this mode the storage tank (T1) temperature begins to increase. This model only predicts the mean temperature from the real stratified vertical distribution. In lower subfigure are represented: T_Tank_Therm55 as the mean temperature in the storage tank T-1; T_Tank_Syl800 as the mean temperature of the primary circuit buffer tank T-2; and T_out_PTC_field as the outlet temperature of the solar field and hotest in the whole facility. After 6.25 hours of continuous operation T_out_PTC_field reaches the maximum temperature level allowed for Syltherm800 HTF (400°C) and then the solar field is unfocused. Since at this moment the solar field passes from being the hot source to dissipate heat flow by the modelled losses equations. The primary circuit descreases its temperature until it reaches the temperature level of the secondary circuit when the heat transfer through the EX reaches a minimum due to both sides temperature similarities. The cooling rate of the facility is too limited in these results. To accelerate the cooling the air cooler -in the secondary circuit- is activated at 100% at hour 8. Since then all the facility is cooled down until 23 relative hour in which both circuits (include the

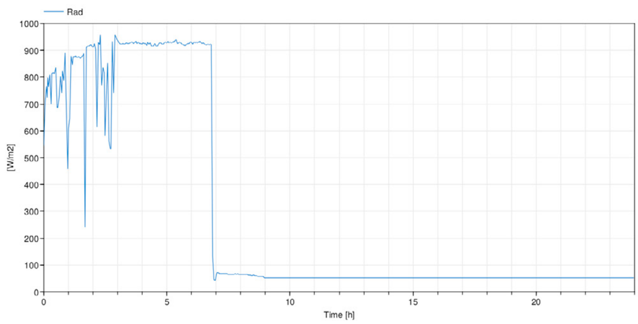

Fig. 4. Experimental solar radiation applied to the simulation of a typical operation day for the TCP-100 facility.

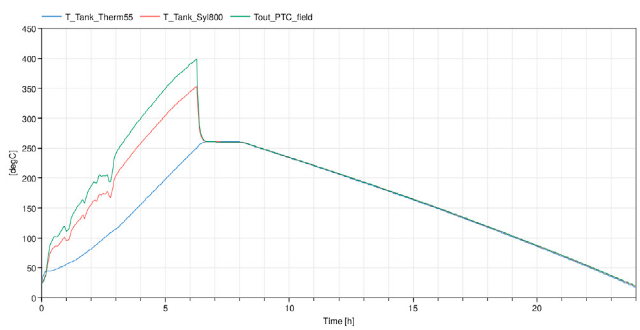

Fig. 5. Simulation results of a typical operation day under solar radiation conditions in Fig. 4. In the lower the next representative temperatures are shown: T_Tank_Therm55 as the mean temperature in the storage tank T-1; T_Tank_Syl800 as the mean temperature of the primary circuit buffer tank T-2; and T_out_PTC_field as the outlet temperature of the solar field and hotest in the whole facility.

storage tank T-1) reach ambient temperature again. It is important to note several details in this simulation with nominal parameters. The first one is that at 6.25 hours of operation the inlet temperature of the solar field (equal to T_Tank_Syl800) is about 350°C concluding that in this conditions the first principles model with nominal values returns the expected 50°C predicted in the engineering design calculations. The second one is that facility can be operated normally in this way, each day, performing different control experiments during different consecutive days. This was one of the design conditions that the presented models reproduce even under the simple modelling hypothesis exposed.

Fig. 6 presents a simulation in which the unique change in the inputs with respect to the previously presented has been the relative time when the air cooler was activated at 100%. In this case the cooler was activated at hour 3 instead of hour 8, and to observe the difference in the expected behaviour the outlet field temperature of the previous simulation has been represented too, as variable T_out_PTC_field_CoolerAtHour8. From hour 3 to hour 6.25 the operation mode is (4) and it can be observed how the evolution of the system is slower when the cooler is activated previously under the same solar radiation conditions. The rest of inputs vary in the same way as the initial simulation. As consequence, it can be observed that

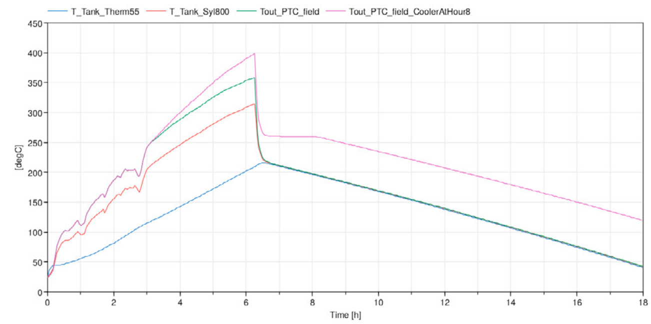

Fig. 6. Simulation results of a typical operation day under solar radiation conditions in Fig. 4 and the air cooler activated at 100% at hour 3. In the lower the next representative temperatures are shown: T_Tank_Therm55 as the mean temperature in the storage tank T-1; T_Tank_Syl800 as the mean temperature of the primary circuit buffer tank T-2; T_out_PTC_field as the outlet temperature of the solar field and hotest in the whole facility; and T_out_PTC_field_CoolerAtHour8 the outlet field temperature of the previous simulation when the air cooler was activated at hour 8.

the cooling of the facility can be controlled if the cooler is properly actuated regarding it is placed in the secondary circuit.

Fig. 7 show simulation results of the same experiment than in Fig. 6 but with the activation of the bypass system for storage tank T-1 at hour 10. The complete sequence of events is:

(1) The plant begins the operation at hour 0, with the solar field unfocused and both pumps working in nominal flow conditions. This is mode (2) that is operative until time 0.1 hour, when solar field is commanded to sun tracking.
(2) Since hour 0.1 to hour 3 the tank storage T-1 is being charged in the secondary circuit with the solar power received by the solar field in the primary circuit. In this time interval the air cooler is deactivated so the plant is operating in mode (2). At hour 3 the air cooler is activated at 100%.
(3) Since hour 3 to hour 6.25 the solar field is receiving sun radiation in the primary circuit while the air cooler is dissipating energy in the secondary circuit. The storage tank T-1 goes on charging at lower velocity that when air cooler was deactivated. This is operation mode (4). At hour 6.25 the solar field is unfocused and the air cooler keeps working at 100%.
(4) Since hour 6.25 to hour 10 the air cooler is cooling down the whole facility including the storage tank T-1. This is a combination of operation modes (5)-(6). In Fig. 7 it can be observed the cooling down velocity of the facility in absence of input solar power. At hour 10 the bypass system for the storage tank T-1 is activated, canceling both inlet/outlet mass flow rates.
(5) Since hour 10 to the end of the experiment at hour 13.5 the storage tank T-1 is isolated from the secondary circuit and the air cooler keeps on working at 100% resulting in a higher velocity cooling down of the whole facility. This interval corresponds to oper-

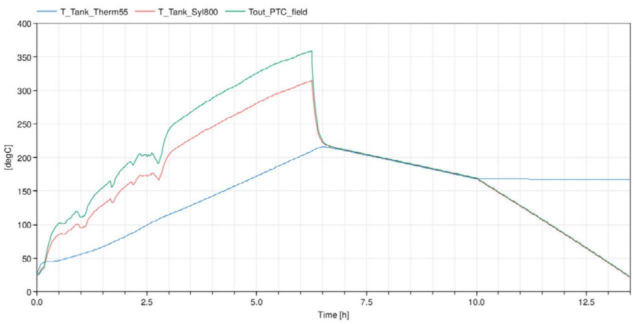

Fig. 7. Simulation results of a typical operation day under solar radiation conditions in Fig. 4 and under the same conditions than Fig. 6. Additionally the storage tank T-1 bypass system is activated at hour 10.

ation mode (6). The tank T-1 maintains the stored energy estimated by Eq. (9) with minimum losses due to the conduction-convection and radiation to the environment. The rest of the facility -except storage tank T-1- finishes the experiment in the same conditions (ambient temperature) from the beginning, letting the TCP-100 to begin a new experiment when solar radiation is available again.

5. CONCLUSION

This paper presents the new TCP-100 research facility for Modelling and Control activities at Plataforma Solar de Almería (CIEMAT). This new research facility replaced the 32 years old ACUREX facility that helped to reach so many advances in Automatic Control to the research community. A set of dynamic models first principles based for system level simulation have been developed and implemented in the Dymola tool, aiming at simplicity. The models have not been validated yet with experimental data and the parameter selection is based on providers' data sheets and in the engineering design project documentation. This approach let us to present results from experiment simulations that show the expected results of a typical operation day in which the system is operated passing through different operating modes. In all presented cases the facility is ready to be operated from initial conditions after finishing the experiment.

Future works will cover the validation of the models with experimental data obtained with real experiments in the TCP-100 plant, and when necessary, the extension of the models complexity.

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