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Control Strategies in a Thermal Oil – Molten Salt Heat Exchanger

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Abstract. This paper presents a preliminary control scheme for a molten salt – thermal oil heat exchanger. This controller regulates the molten salt mass flow rate to reach and maintain the desired thermal oil temperature at the outlet of the heat exchanger. The controller architecture has been tested using an object-oriented heat exchanger model that has been validated with data from a molten salt testing facility located at CIEMAT-PSA. Different simulations are presented with three different goals: i) to analyze the controller response in the presence of disturbances, ii) to demonstrate the benefits of designing a setpoint generator and iii) to show the controller potential against electricity price variations.

INTRODUCTION

Thermal energy storage (TES), which allows energy dispatch, is a widely used resource in concentrating solar power plants. The two-tank indirect storage configuration with molten salt as storage medium is the option most commonly used in parabolic trough commercial power plants [1], [19], despite the cost that this configuration involves. Recent research works deal with simulation studies using thermocline TES systems instead of two tanks in order to reduce costs [4], however results show that the estimated annual electricity yield is lower than that one obtained from the two-tank configuration.

From the operating point of view, published results from commercial plants with two-tank indirect storage reveal that the steam turbine load is reduced in discharge mode [2] but also that the transition to discharge mode can produce high overshoots in the steam turbine power [3, 17, 18]. One way to increase the economic benefits in existing facilities is to study the actual operating strategies and improve them by using reliable dynamic models and suitable control strategies. Computing optimal setpoints in the solar field could lead to a considerable increase in the electricity production [6] but, if the objective is to follow the demand, a higher control layer is the most suitable way to predict future outputs, calculate optimal operating actions and manage the storage system properly. As proposed in [5], thermo-economic optimizations using a physical system of the power plant can be included to handle the storage system taking into account electricity price information. But it is clear that, in order to assure continuous production, the discharging operation should be in accordance with a low-level control strategy in the heat exchanger. This component, as one of the most expensive in this kind of plants, should be studied in depth. It is a key element whose operation should be clearly defined [1] and whose control strategy strongly affects the performance of the system. In [7] two PI controllers are implemented and tested in simulation to maintain the molten salt temperature for charging and discharging modes and transient responses are evaluated using as case study a 50 MW_e power plant. Nevertheless, as it is pointed out in that work, further studies on advanced controllers should be carried out to maintain the desired thermal conditions in the power cycle.

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This work presents a preliminary control scheme to follow the desired thermal oil temperature at the outlet of the heat exchanger at a pilot scale using the molten salt mass flow rate as the control variable and with the objective of transferring the acquired knowledge to commercial plants.

The present paper is organized as follows, the case study is presented in the next section in which the molten salt testing facility at CIEMAT-PSA is described, section 3 outlines the model used to simulate the heat exchanger behavior and the parametric curves that have been obtained to simulate a power block (PB) and determine realistic disturbances at the heat exchanger thermal oil inlet temperature, section 4 presents the control architecture that is composed of a PI controller with feedforward action, section 5 shows simulation results for three different examples to achieve the goals mentioned above and finally, section 6 summarizes the main conclusions and ongoing work.

CASE STUDY

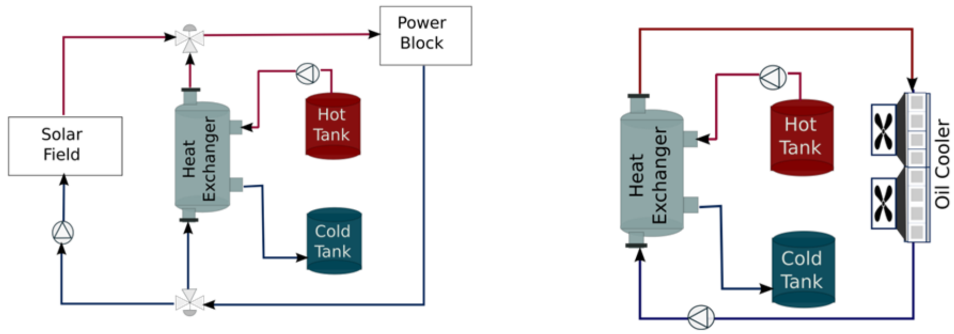
The case study is focused in control strategies to be applied to the heat exchanger of parabolic trough solar thermal power plants (oil as heat transfer medium) with two-tank indirect storage (molten salt as storage medium).

For this objective, the multipurpose molten salt testing facility located at Plataforma Solar de Almería (PSA) has been used as reference. The principal components of the molten salt testing facility (see Fig. 1) are: two molten salt tanks, a CO_2 - molten salt heat exchanger (connected to a parabolic trough collector loop where the gas can be heated), a thermal oil - molten salt heat exchanger, an oil heater, molten salt and oil air coolers and an expansion tank. For further details consult [9, 10]. Its main use is to evaluate and control the heat exchange between molten salt and different kinds of heat transfer fluids that can be used in solar thermal power plants, i.e. thermal oil and pressurized gases.

FIGURE 1. Molten salt testing facility at CIEMAT-PSA.

The thermal oil - molten salt heat exchanger included in this testing facility has been used as pilot plant to evaluate control strategies at a pilot scale which can be adapted for large scale commercial plants with the two-tank indirect storage configuration and molten salt as storage medium. This heat exchanger is composed of two counter-flow multi-pass shell-and-tube units, with the molten salt in the shell side and the thermal oil in the tube side.

The evaluation of the control strategies is focused on the heat exchanger operation called “discharge mode” (see Fig. 2a) either for solar irradiance absence operation or coupled with the solar field. The PSA pilot plant is completely equipped to test this operating mode by the use of an oil-cooler designed to cool down the thermal oil from 380 ºC to 270 ºC (see Fig. 2b). Due to the difficulties that commercial plants present to test control strategies, this molten salt facility is an excellent system to design, develop and evaluate control algorithms that can be later adapted to large scale systems.



(a) (b)

FIGURE 2. Two-tank indirect storage configuration: (a) discharge mode in commercial plants; (b) discharge mode at PSA pilot plant.

SYSTEM MODEL

As a first step, controllers can be evaluated in simulation using a heat exchanger model [5] developed following the same design as the heat exchanger installed at the molten salt testing facility. To define realistic boundary conditions, a model of a steam power cycle has been included to simulate disturbances that could affect the heat exchanger control. Table 1 describes the nomenclature used.

TABLE 1. Nomenclature

Variable	Description	Units	
c_p	specific heat capacity	J/(kg·K)	
$\dot{m}$	mass flow rate	kg/s	
T	temperature	ºC	
Subscript	**Description**	**Subscript**	**Description**
HX	heat exchanger	out	outlet
in	inlet	PB	power block
ms	molten salt	ref	setpoint
oil	thermal oil	SF	solar field

Heat Exchanger Model

The heat exchanger model used in this work is a one-dimensional dynamic model developed following an object-oriented methodology based on first principles. The language used is Modelica [11] and the Modelica tool used for its implementation is Dymola [12]. The model inputs are the inlet shell-side and tube-side temperatures and mass flow rates and, in order to close the hydraulic circuits, the outlet shell-side and tube-side pressures. A complete description of this model can be found in [8].

Power Block Simulator

To define boundary conditions in the heat exchanger, the model of a steam power cycle has been developed to estimate thermal oil temperature at the outlet of the power block (which corresponds to the heat exchanger oil inlet temperature in discharge mode). The same methodology as that one shown in [16] has been followed, considering a simpler reheat Rankine power cycle without feedwater heaters. Since the oil flow in the molten salt testing facility is in the range [0.6, 10] m^3/h, a small steam turbine of 168 kW_e is considered. This resulting power block simulator is used to include disturbances at the thermal oil inlet temperature of the heat exchanger which could be produced by changes in the oil flow, oil inlet temperature and load in the steam cycle.

The power block, which includes an oil-water/steam heat exchanger train (preheater, steam generator and superheater), a steam turbine and a cooling system, has been modeled at steady state using the *Engineering Equation Solver* software tool [13]. The efficiency considered for the heat transferred between thermal oil and water/steam has been 95% (which has been considered in power block models of parabolic trough solar thermal power plants with TES obtaining good results [17]). This model has been evaluated at different operating conditions with respect to the thermal oil at the inlet of the heat exchanger train and turbine load. Figure 3 shows the steady-state values obtained with the model and the parametric curves calculated (grey lines) using the MATLAB Curve Fitting Toolbox™. Table 2 summarizes the parametric curves details with the R-squared coefficient (R).

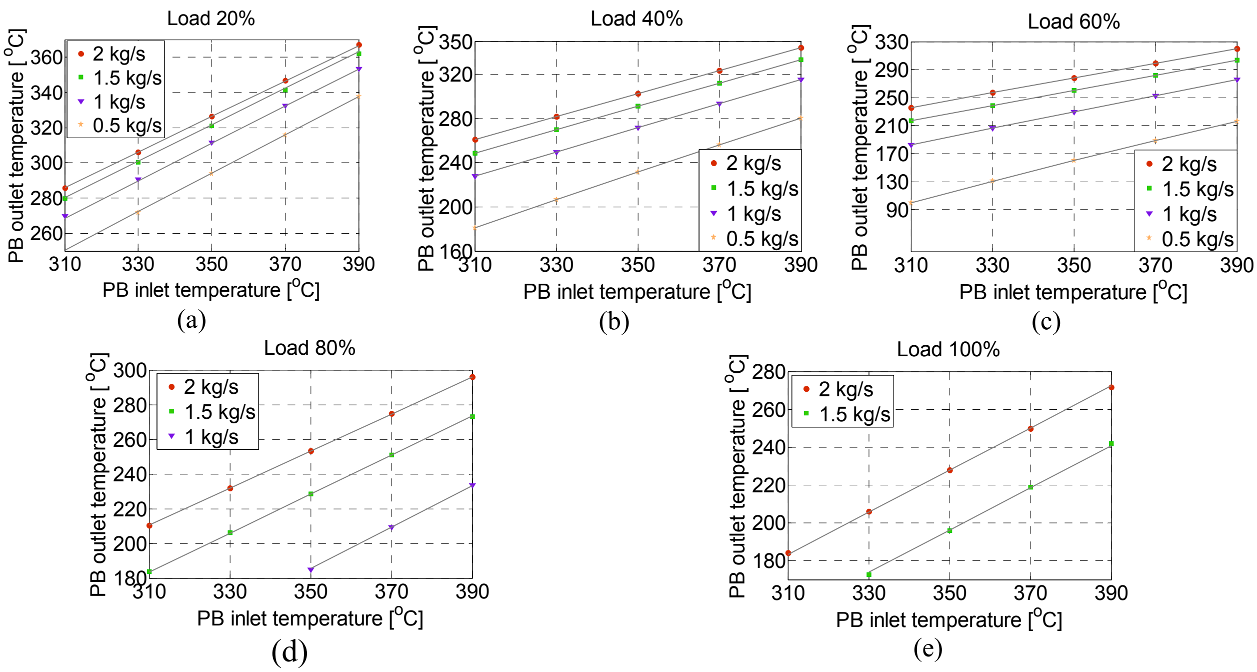


FIGURE 3. Parametric curves obtained from a power block model: oil outlet temperature vs. oil inlet temperature for different oil mass flow rates and turbine loads.

Notice that for cases 20%, 80% and 100% (Fig. 3a, 3d, 3e) the approximated polynomials are function of the mass flow rate and one curve is obtained for each case. In the other cases, 40% and 60% (Fig. 3b, 3c), one polynomial has been fitted for each mass flow rate considered.

TABLE 2. Power block simulator parametric curves,

$$T_{out,PB} = p_0 + p_1 \cdot T_{in,PB} + p_2 \cdot \dot{m}_{PB} + p_3 \cdot T_{in,PB} \cdot \dot{m}_{PB} + p_4 \cdot \dot{m}_{PB}^{\ 2}$$

load (%)	$\dot{m}_{PB}$ (kg/s)	p_0	p_1	p_2	p_3	p_4	R
20	*	-128.6	1.169	71.28	-0.0545	-12.32	0.9996
40	2	-59.75	1.035	-	-	-	1
	1.5	-78.14	1.055	-	-	-	1
	1	-112.5	1.098	-	-	-	1
	0.5	-203.2	1.241	-	-	-	1
60	2	-90.82	1.054	-	-	-	1
	1.5	-119.6	1.085	-	-	-	1
	1	-176.6	1.16	-	-	-	1
	0.5	-349.2	1.453	-	-	-	1
80	*	-407.2	1.273	219.4	-0.1215	36.38	0.9999
100	*	-288.7	1.114	63.39	-	-	0.9995

$T_{in,PB}$ and $T_{out,PB}$ measured in ºC and $\dot{m}_{PB}$ in kg/s
*valid for the range [0.5,2] kg/s

HEAT EXCHANGER CONTROL

The study of the heat exchanger control has two main purposes; to maintain the system within safety operating conditions and to improve the productivity through the operation in optimal points. The first step towards the optimization of the operating strategy is to guarantee the setpoint tracking despite operating conditions and disturbances. To reach this objective, considering discharge mode, a typical PI (proportional-integral) controller with anti-windup function and a feedforward controller working in parallel configuration [14] have been proposed in order to reach and maintain the outlet temperature of the heat exchanger at the tube side (oil circuit) with the molten salt mass flow rate as the control variable (see Fig. 4).

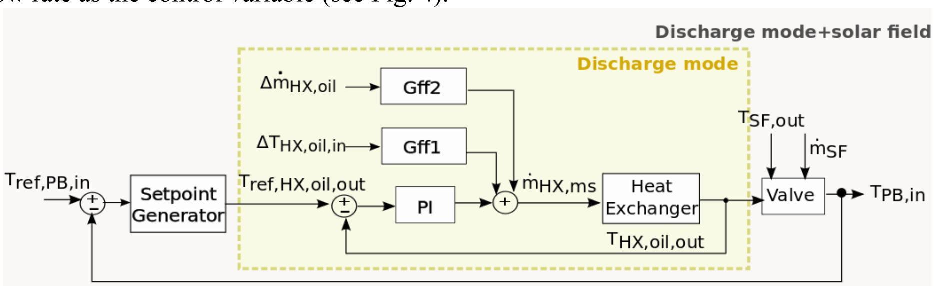


FIGURE 4. Heat exchanger molten salt – thermal oil controller scheme.

The feedforward actions, G_{ff1} and G_{ff2}, used to compensate in advance those disturbances affecting the controlled variable, have been calculated from first order models obtained in simulation:

$$G_{ff1}(s) = \frac{\Delta \dot{m}_{ff1,HX,ms}}{\Delta T_{HX,oil,in}} = \frac{-111.2s - 0.2}{10023s + 18.7} \tag{1}$$

$$G_{ff2}(s) = \frac{\Delta \dot{m}_{ff2,HX,ms}}{\Delta \dot{m}_{HX,oil}} = \frac{10214s + 18.37}{3440s + 18.7} \tag{2}$$

When the TES discharge mode is combined with the solar field, the heat exchanger oil outlet temperature setpoint can be calculated from a steady-state balance in the three-way valve in which the thermal oil coming from the solar field is mixed with the thermal oil at the outlet of the heat exchanger:

$$T_{ref,HX,oil,out} = \frac{T_{ref,PB,in} \cdot c_{p,PB,in} \cdot \dot{m}_{PB} - T_{SF,out} \cdot c_{p,SF,out} \cdot \dot{m}_{SF}}{c_{p,HX,oil,out} \cdot \dot{m}_{HX,oil}} \tag{3}$$

Since $c_{p,HX,oil,out}$ depends on the temperature $T_{ref,HX,oil,out}$, this setpoint generator requires an iterative process. For the first iteration, we can consider $c_{p,PB,in} \approx c_{p,HX,oil,out} \approx c_{p,SF,out}$ and eliminate the specific heat capacity from the equation. In addition, to compensate model mismatches, the steady-state balance can be combined with a PI controller.

SIMULATION RESULTS

In this section, three simulation examples are described: transition between TES discharge mode+solar field to TES discharge mode, setpoint changes and electricity price changes. The simulation environment has been MATLAB and its toolbox Simulink. To include the heat exchanger model, the library called Dymola Block has been used. This library allows importing Dymola models in Simulink as S-functions. The parametric curves for the power block simulator have been implemented in a MATLAB function. Linear interpolations between curves are considered to evaluate the PB outlet temperature. In addition, to include the dynamic behavior of the molten salt pump with the mass flow rate controller, a first-order model has been considered with static gain 1 and time constant 10 s. These values have been calculated from experimental data of the PSA facility. The PI parameters has been tuned using the AMIGO tuning rules [14] (proportional gain K_p=0.1 kg/(s·ºC), integral time T_i=400 s) and the tracking time for the anti-windup has been stablished to T_t=20 s. The molten salt mass flow rate is limited between 0.5 kg/s and 4 kg/s, such as the operating range at the PSA facility.

Transition to TES Discharge Mode

Although this mode cannot be reproduced in the PSA pilot plant, the transition to TES discharge mode when the solar field is being stopped is an operation that should be studied to maximize the use of solar energy while avoiding hard disturbances at the inlet of the power block. In order to simulate this transition, a temperature controller has been assumed in the solar field, so that, in absence of other disturbances, the thermal oil mass flow rate follows the solar irradiance curve. Figure 5 shows an example of this transition with the PB setpoint established to 360 ºC. When solar irradiance is lower than 600 W/m^2, molten salt starts to be discharged from the hot tank and thermal oil flows from the power block to the heat exchanger. Initially, heat exchanger outlet temperatures are considered as the temperatures at the cold side (see Fig. 5b), the heat exchanger oil outlet temperature is 300 ºC which causes a temperature fall at the inlet of the power block of 11.5 ºC (Fig. 5a). With the aim of maintaining an oil mass flow rate of 2 kg/s in the power block, the thermal oil mass flow rate in the heat exchanger (Fig. 5b) varies depending on the solar field mass flow rate (Fig. 5a) until this mass flow rate reaches 0.5 kg/s, which is considered the minimum, and the solar field is defocused. Notice how the controller varies the molten salt mass flow rate to reach the desired oil temperature (Fig. 5b). Initially, this molten salt mass flow rate is saturated at the maximum value to heat up the heat exchanger and the oil inlet temperature to the power block reaches 360 ºC in 144 s after the heat exchanger start-up but it needs 50 minutes to reach steady-state conditions. When solar field mass flow rate drops from 0.5 kg/s to 0 kg/s, thermal oil mass flow rate shows a step change from 1.5 kg/s to 2 kg/s which affects the feedforward action and causes a sudden change in the molten salt mass flow rate.

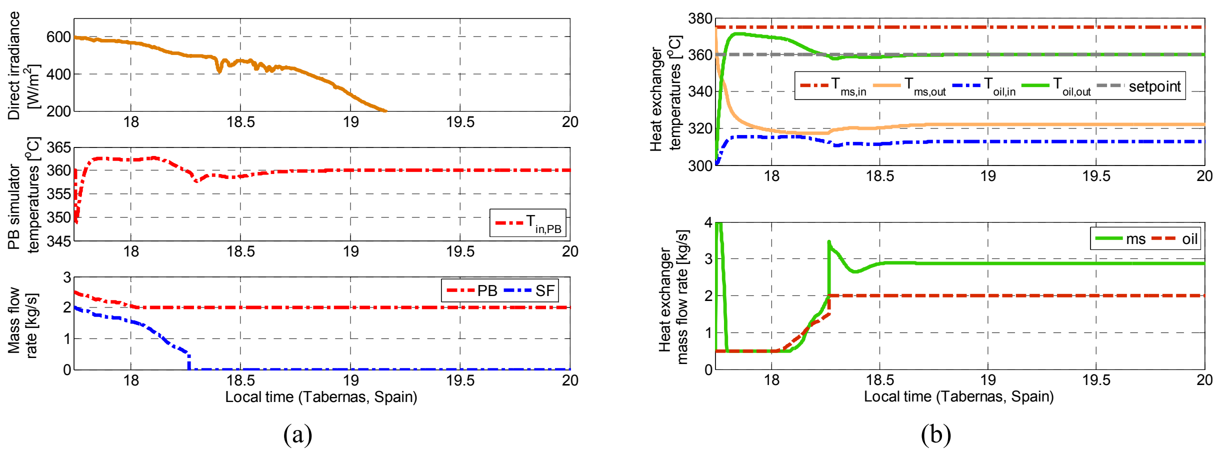


FIGURE 5. Heat exchanger control simulation. Transition to discharge mode.

Setpoint Change

Another situation that can be analyzed is the improvements obtained if the heat exchanger oil outlet temperature setpoint is modified. Consider the case in which the system is in discharge mode (without solar field), the turbine is working at partial load, 60%, the molten salt inlet temperature is 375 ºC (Fig. 6a) and the setpoint is established to 360 ºC (Fig. 6b). Under these conditions the temperature of the molten salt at the outlet of the heat exchanger is 312 ºC (Fig. 6a), but if the sepoint is decreased to 355 ºC, the molten salt mass flow rate is reduced and the temperature of the molten salt at the outlet of the heat exchanger decreases to 293.1 ºC. Notice that this setpoint decrease has two benefits; a reduction of the electricity consumption related to the molten salt pump and a reduction in the thermal energy consumed from the storage system. Nevertheless, if the turbine load is increased up to 70%, the molten salt temperature goes below 290 ºC (which is considered the minimum value for the cold tank). This new situation forces to increase again the setpoint of the thermal oil in the heat exchanger.

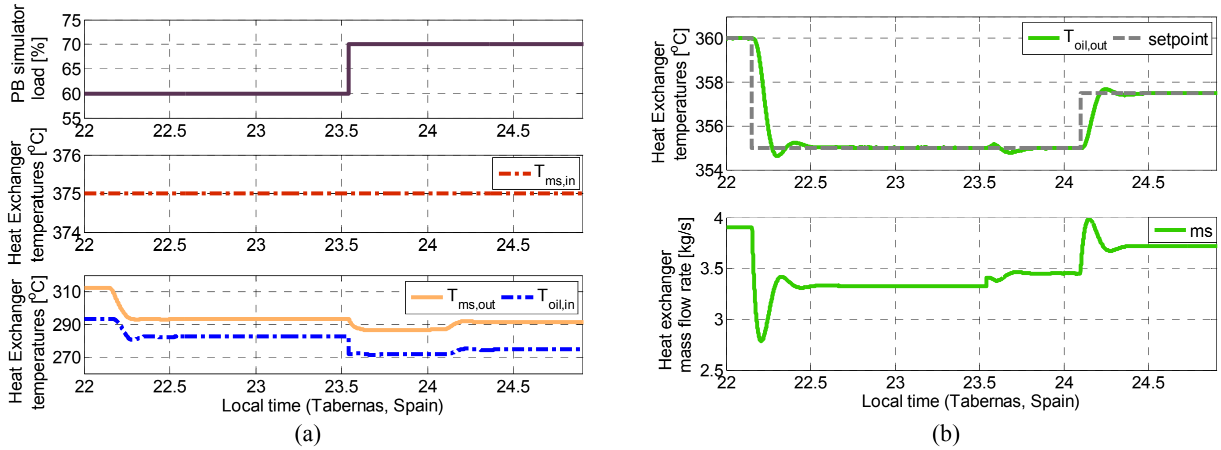


FIGURE 6. Heat exchanger control simulation. Setpoint changes.

Electricity Price Changes

This third example shows the case in which the turbine load changes according to the electricity Spanish market for the 30th and 31st of June 2015 [15] (Fig. 7a), the setpoint changes to maintain the cold molten salt temperature between 290 ºC and 300 ºC and the heat exchanger controller is used to maintain the desired temperature setpoint. In this case the system is in discharge mode (without solar field). Assuming that an economic controller predicts the optimal steam turbine load as a function of the electricity price[1], the heat exchanger controller regulates the molten salt mass flow rate to maintain the different setpoints applied (Fig, 7b) obtaining overshoots lower than 1 ºC except for the setpoint change at 01:00 in which the overshoot is of 2 ºC. This example shows that, due to the non-linear nature of the system, the proposed linear controller causes different responses depending on the operating conditions. A robustness analysis should be performed to determine if the PI parameters should be tuned to obtain a more conservative behavior or a gain-scheduling controller should be considered instead of the proposed PI.

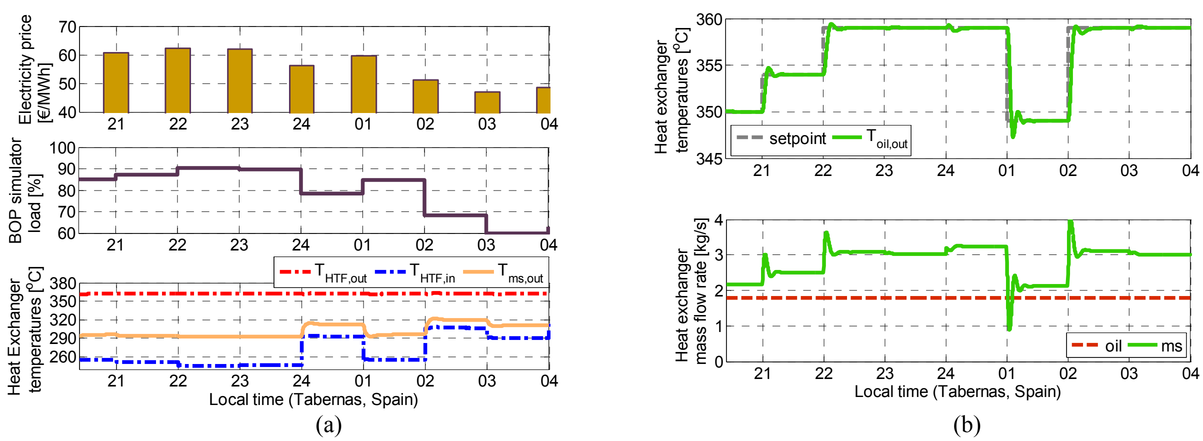


FIGURE 7. Heat exchanger control simulation. Electricity price changes.

CONCLUSIONS

This paper is the first study towards a complete control design for a thermal oil – molten salt heat exchanger with the same design as one installed at CIEMAT-PSA test facilities. A typical control structure widely used in solar fields has been proposed to maintain the heat exchanger thermal oil outlet temperature using the molten salt mass flow rate as the control variable. Simulation results show the response of the controller despite step disturbances at

[1] The economic control layer is out of the scope of this paper. Load changes are performed according to the electricity price as an example to observe the heat exchanger controller when oil inlet temperature disturbances and setpoint changes occur at the same time.

the thermal oil inlet temperature, setpoint changes and at startup. Future works will include control tests in the PSA heat exchanger. Although the dynamic of the heat exchanger in the pilot plant considered is faster and mass flow rate operating conditions are quite lower than those in commercial plants, these real tests are the base for analyzing the system behavior and reduce the control design phase.

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