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Optimal operation of a combined cooling system ⋆

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Abstract: The effectiveness of Concentrated Solar Power (CSP) plants is significantly influenced by the temperatures at which steam condensation occurs. The existing cooling systems, whether wet (water-cooled) or dry (air-cooled), involve trade-offs. Wet cooling enhances performance but raises concerns due to substantial water usage, particularly in water-scarce regions where CSP plants are often located. On the other hand, dry cooling conserves water but at the cost of reduced efficiency, especially during high ambient temperatures that coincide with peak electricity demand. A possible compromise solution involves a combined cooling system that integrates both wet and dry methods, providing flexibility for overall reduced water consumption and enhanced efficiency.
The incorporation of such systems into CSP plants is thus of great interest, owed to the potential adaptability of its operation to changing conditions. In order to make this optimally and feasible, a suitable control system needs to be developed. In this work we present the first implementation, in a real pilot plant, of a two-layer hierarchical control strategy, where the upper layer solves a multi-objective optimization problem for conflicting water and electricity consumptions, and a regulatory PID-based control layer adapts the system operation to the generated optimal references.

Keywords: Process control applications, Optimization, Hierarchical control, Solar energy

1. INTRODUCTION

Concentrated Solar Power (CSP) plants use mirrors to concentrate the sun's energy to generate electricity. This technology currently represents a minor part of renewable energy generation: only approximately 5 GW are installed globally. However, the potential for growth is significant given the capability of CSP to provide renewable electricity when needed (thanks to its in-built thermal energy storage), unlike other renewable technologies that are dependent on the availability of the energy source. Another aspect to consider is the ability of these plants to respond to peaks in demand and continue production even in the absence of sunlight, replacing fossil fuel alternatives in managing the grid. According to the International Energy Agency (IEA, 2014) forecasts, CSP has an important potential in the mid to long term, ranging from the 986 TWh by 2030 up to 4186 TWh by 2050, meaning that CSP is forecasted to account for 11 % of global electricity production and 4 % in the case of Europe.

The need to reduce water consumption in these processes (mainly power block cooling) is becoming increasingly evident, especially since they have a wider field of application in areas with significant water scarcity. Added to this is the high price of water, which can be up to 10 €/m^3 in such areas (including transportation costs), ultimately calling into question the profitability of this type of application and its sustainability.

Currently, there are two main cooling methods in CSP plants: wet or dry. Wet cooling by evaporative cooling Tower (WCT) is the most common method in CSP plants, since it allows higher efficiencies (as it is based on the wet bulb temperature). However, their main problem is the need for constant resupply of the evaporated water. An example of the large water consumption in wet-cooled CSP plants is the plant located in the Mojave Desert, California, with a consumption of approximately 3 m^3/MWh (Damerau et al., 2011), making it environmentally unsustainable. Dry Cooling systems (DC) are based on dry bulb temperature and have hardly any water consumption (between 0.30 and 0.34 m^3/MWh Bourillot (1983)). The most widespread DC systems are based on the use of air cooled condensers (ACC), although there are several dry cooling methods, such as "Air Cooler Heat Exchangers (ACHE)". Despite the low water consumption, the main problem of dry cooling systems compared to wet cooling systems is the high investment costs and the significant reduction in electricity production due to the higher condensing temperatures required in the power block (up to 10 % reduction in power output).

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There are different types of innovative cooling systems that can reduce water consumption: those that integrate dry and wet cooling systems in the same cooling device, which are called hybrid cooling systems (Rezaei et al., 2010; Asvapoositkul and Kuansathan, 2014; Hu et al., 2018) and those that combine a dry and a wet cooling system, which are called combined cooling systems. The latter are presented as the most suitable option since their flexible operation enables adaptability depending on environment conditions, allowing the best operating strategies to be selected to achieve a compromise solution between water and electricity consumption. The most common type found in the literature is that which considers an air-cooled condenser (ACC) in parallel with a WCT (Barigozzi et al., 2011, 2014). In this case, the turbine outlet steam is condensed through the ACC and/or through a surface condenser coupled to the WCT. Another configuration, recently proposed in the literature (Palenzuela et al., 2022a) is the combination of a wet and a dry cooling tower (ACHE type), both sharing a surface condenser. In this case, the steam is condensed through the surface condenser and the cooling water at the outlet (at higher temperature) is cooled either through the WCT or through the DC, or different combinations of both.

This potential adaptability can only be realized if a suitable control system is set in place. In this work we present the development and implementation of a complete control solution in an experimental pilot plant, it is a two-layer hierarchical control architecture that, on-line, evaluates and selects the optimal operation strategy, given some operation conditions and selection criteria, and regulates the pilot system inputs to achieve it.

2. COMBINED COOLING SYSTEM

The combined cooling pilot plant at the Plataforma Solar de Almería (see Fig.1) consists in three circuits: cooling, exchange and heating circuits. In the cooling circuit, water circulating inside the tube bundle of a Surface Condenser (SC, whose thermal power at nominal conditions is 80 kW_{th}) is cooled through a WCT and/or a DC (type ACHE), both with a thermal power at design conditions of 204 kW_{th} . Valves 1 and 2 (V_1, V_2) allow the operation in different configurations: only DC (V_1=V_2=II), only WCT (V_2=I), in series (V_1=I, V_2=II), in parallel with different aperture percentages (V_1=II, V_2 between I and II) or parallel-series with different aperture percentages (V_1 and V_2 between I and II). In the exchange circuit, a saturated steam generator with 80 kW_{th} of thermal power at nominal conditions, generates steam at different pressures (ranging between 82 and 200 mbar), that is in turn condensed through the Surface Condenser, transferring its latent heat to the cooling water that is thus heated. Finally, in the heating circuit, a 300 kW_{th} static solar field provides the thermal energy required by the steam generator using hot water as the heat transfer fluid. A more detailed description can be found in (Palenzuela et al., 2022a).

3. CONTROL PROBLEM DESCRIPTION

The cooling system has to satisfy one primary goal, condensate all incoming saturated vapor into saturated liquid, i.e. meeting the cooling requirements. In order to achieve this, it makes use of two resources: electricity and water. The nature of this process makes it so that both resources have conflicting trends, so it is fundamentally a multi-objective optimization problem. There is no single optimal solution but a collection of good solutions (the Pareto front region, Gendreau and Potvin (2010)) with trade-offs among the considered objectives: reducing the electricity consumption necessarily comes at the expense of increased water usage, and viceversa.

From the results obtained in (Palenzuela et al., 2022b), it was concluded that the most suitable configuration depends on the operating and ambient conditions, so the control system (see Fig. 2) is tasked with finding out the best operation strategy, on-line during operation, that satisfies the cooling requirements. It is a two layer system where in the upper layer, a multi-objetive optimization is performed, obtaining a range of optimal operation points, the Pareto front. In order to choose from the range of optimal strategies, the criteria established was to minimize the electricity consumption while keeping the water consumption below a defined limit. The decision variables obtained are then the setpoints of a regulatory PID control layer (lower layer), in charge of manipulating the system actuators.

4. MODELING

The model of the combined cooling system (see Figure 3) consists on the combination of the models of its main components: dry cooler, wet cooling tower, surface condenser, pump, three-way valves and the different mixing of fluids that take place.

There are mainly two types of models, on the one hand FOPDT transfer functions have been used to model the dynamic relation between the control variables or actuators and the controlled variables. On the other hand a combination of first principle and black-box modeling approaches was used to evaluate the behavior of the system in steady state conditions. This allows to, given some operating conditions, have the ability to predict the cooling capabilities of the combined system and the associated consumptions depending on the chosen operation strategy.

4.1 FOPDT models

The dynamic transfer functions were determined experimentally by means of open-loop tests involving step changes in the actuators. The reaction curve method was employed to extract the parameters of the FOPDT transfer functions. Table 1 presents the transfer functions corresponding to the mean operating range of each control variable, with y representing the controlled variables, u the control variables, K the static gain, τ the time constant and d the time delay. This was done for the DC and WCT, the SC pump and both three-way valves V_1 and V_2.

4.2 Steady state models

Dry cooler The model of the DC (see Fig. 3 - *DC*) is a black-box model based on a multi-layer non-recurrent Artificial Neural Network (ANN). The output of the model is the temperature of the cooling water leaving the DC, Hybridized cooler Paper Optimization v2 Res300.png Hybridized cooler Paper Optimization v2 Res300.bb

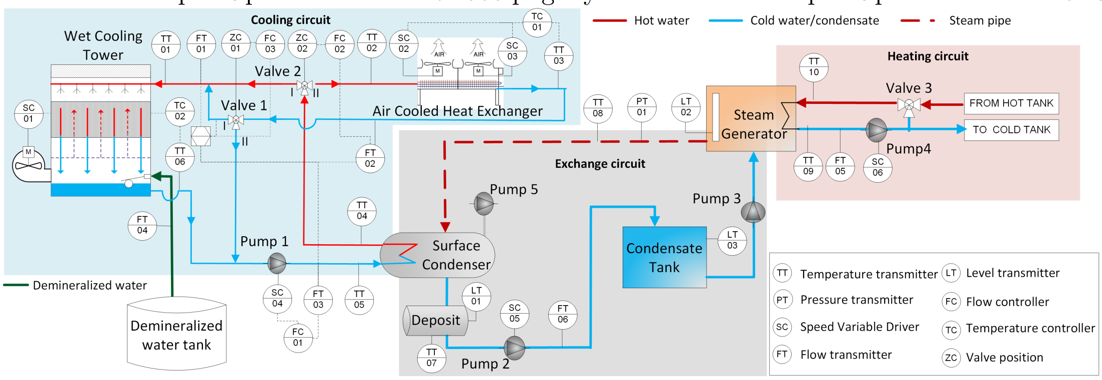

Fig. 1. Layout of the combined cooling pilot plant at PSA

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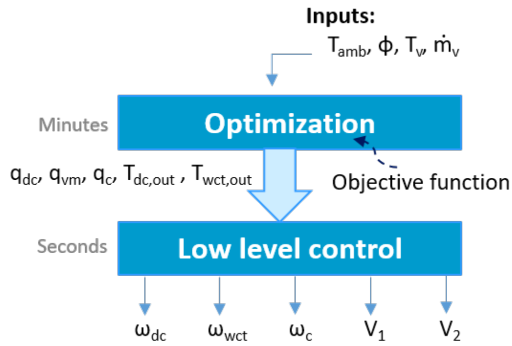

Fig. 2. Control structure

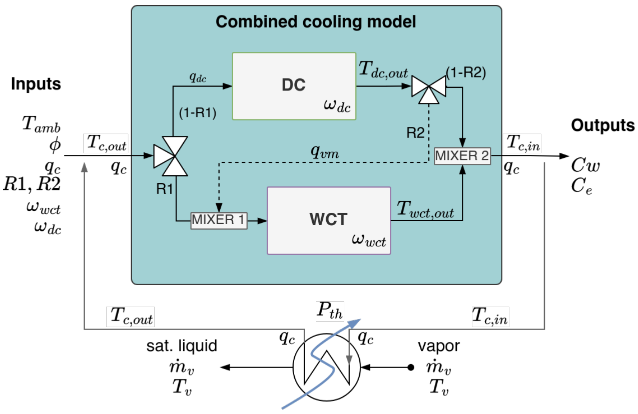

Fig. 3. Complete system model diagram

Table 1. Transfer functions experimentally obtained

System	y	u	K	τ (s)	d (s)
DC	$T_{dc,out}$	ω_{dc}	-0.16 ° C/%	47.7	26.7
WCT	$T_{wct,out}$	ω_{wct}	-0.12 ° C/%	49.6	34.4
Pump 1	q_c	ω_c	0.25 m^3/(h·%)	2	1
Valve 2	q_{dc}	V_2	-3.1 m^3/(h·%)	2	1
Valve 1	q_{vm}	V_1	0.99 m^3/(h·%)	5	1

$T_{dc,out}$ and the input variables are: the cooling water flow rate circulating through the DC (q_{dc}), the cooling water temperature at the inlet of the DC ($T_{dc,in}$), the fans frequency (ω_{dc}) and the ambient temperature (T_{amb}). Another output variable is the electrical consumption, $C_{dc,e}$, that has been modeled by a parametric adjustment from experimental data that relate this variable ω_{dc}.

Wet cooling tower The model of the WCT (see Fig. 3 - *DC*) is also based on ANN, same type of the DC. In this case, the output variables are: the cooling water temperature at the outlet of the WCT, $T_{wct,out}$, and the water consumption due to evaporation and drift losses, C_w. The input variables are: the cooling water flow rate circulating through the WCT (q_{wct}), the cooling water temperature at the inlet of the WCT ($T_{wct,in}$), the fan frequency (ω_{wct}) the ambient temperature (T_{amb}) and the relative humidity (ϕ). As in the case of the DC, the electrical consumption, $C_{wct,e}$, has been modeled by a parametric adjustment with experimental data that relate this variable with ω_{wct}.

Surface condenser The surface condenser (see Figure 3 - *SC*) was modeled by applying an energy balance, where it is assumed that all the vapor that enters the condenser (at saturated conditions), leaves it as saturated liquid, so the outlet temperature from the cooling water can be estimated as:

$$T_{c,out} = T_{c,in} + \frac{\dot{m}_v \lambda_{sat,v}(T_v)}{\dot{m}_c c_p(T_{c,in}, P_c)}\,, \qquad (1)$$

where $T_{c,in}$ and $T_{c,out}$, are the cooling water inlet and outlet temperatures, respectively, $\dot{m}_c$, the cooling water mass flow rate, T_v, vapour temperature and $\dot{m}_v$ its mass flow rate. Finally $\lambda_{sat,v}$, is the phase change enthalpy of the saturated vapour and c_p, the specific heat.

As mentioned above, the complete system model (combined cooling + surface condenser) is obtained by combining the above component models. The resulting system exhibits a highly non-linear response to changes in its inputs, as well as discontinuities resulting from the activation or deactivation of individual components (DC and WCT).

5. CONTROL

5.1 Low-level control layer

It is a regulatory layer with five control loops, (see Table 2). The aim of this layer consists on tracking the setpoints calculated by the upper layer for the five controlled variables and maintaining them near steady state conditions around these references, even in the presence of disturbances such as variations in temperature or flow rate.

Classical feedback loops with PI controllers have been used in this regulatory layer, which were tuned using the improved SIMC technique Skogestad and Grimholt (2012) according to the models presented in Table 1 and considering a close-loop time constant between 1 and 1.4 times the constant time of the systems, depending on the PI controller. Table 2 summarizes the proportional gain, K_p, and the integral time, T_i, for each control loop. The ideal configuration of the PI controller has been implemented, $C(s) = K_p(1 + 1/(T_i s))$, including anti-windup mechanism and sample time of 1 s.

5.2 Optimization layer

The aim of the optimization is to satisfy the operation requirements, thus guaranteeing the cooling thermal power needed according to the ambient conditions (ambient temperature and humidity) and resources restrictions (water).

The cost function to evaluate the performance of the system is described in Eqs. (2),(3):

$$\min_u J(C_w, C_e) = f(T_{amb}, \phi, q_c, R_1, R_2, \omega_{dc}, \omega_{wct}), \quad (2)$$

$$s.t. \, C_w \le C_{w,max}, u_{min} \le u \le u_{max}, \quad (3)$$

where, as shown in Fig. 3, C_w and C_e are the water and electricity consumptions, respectively; u represents the inputs: R_1 is the ratio of q_c that, in parallel, goes towards the WCT, while R_2 the ratio of q_{dc} that, in series, circulates through the WCT. Finally, ω_{dc} and ω_{wct} are the fan speed of each component. When a feasible solution is found, the optimal setpoints are calculated and given to the regulatory layer [1] ($T^*_{dc,out}$, $T^*_{wct,out}$, q^*_c, q^*_{dc}, q^*_{vm}).

The problem is solved by means of a Genetic algorithm (GA) which has been implemented employing MATLAB's *gamultiobj* (MATLAB (2023)) with a variant of NSGA-II (Deb, 2011)), that prioritizes elitism by favoring individuals with superior fitness while also valuing diversity, thus striking a balance between exploration and exploitation. The iterative process continues until a predefined running time elapses, established in 900 seconds for the first iteration, and 300 seconds in the subsequent since they are initialized with prior solutions.

Tuning of algorithm parameters has been done systematically by selecting three case studies and evaluating 4 different parameters: population size, elite set size ratio, crossover fraction and tournament size ratio (Grygar and Fabricius, 2019).

6. RESULTS

The experimental results from the application of the proposed methodology are shown in Fig. 6. The first group of three figures contains information relevant to the optimization layer, while the ten remaining figures represent the control layer. The optimization layer is

[1] The superscript * indicates a decision variable from the optimization layer, a setpoint for the low-level control layer

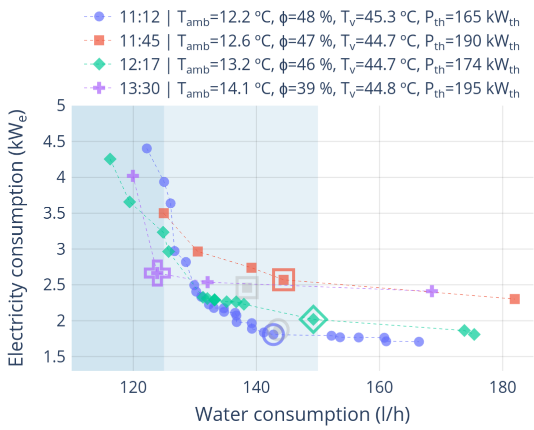

Fig. 4. Pareto fronts with the selected optimum highlighted

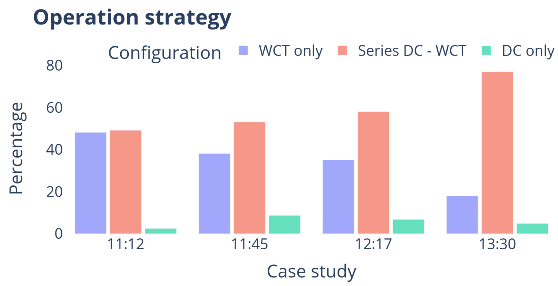

Fig. 5. Operation configurations obtained

evaluated 11 times by calculating the mean of the last 300 samples (5 minutes) with the condition that the system is stable (mainly cooling requirements). Every time the optimization layer is processed, updated optimal setpoints are generated for the control layer.

In general, solid lines represent the experimental values recorded with the data acquisition system, a dash-dotted line (−·−) indicates a variable from the optimization layer, either a given input (e.g. T_{amb}) or internal evaluations (e.g. C_e). In the case of the control layer plots, the optimizer outputs are the setpoints for the control layer and they are represented with a dashed line (−−).

The objective of the test was to validate experimentally the hierarchical control scheme given real operating conditions, so an evaluation of the optimization layer is performed every time the environment variables (Fig.6 - *Environment* - T_{amb}, ϕ) drift significantly, and/or when the cooling requirements were changed. Thermal power requirements (Fig.6 - *Cooling requirements* - P_{th}) vary depending on the vapour temperature (T_v) and/or vapour mass flow rate ($\dot{m}_v$). For each optimization a prediction of the expected consumptions to be obtained, after a transitory period, is shown in terms of electricity (C_e) and water (C_w) together with the experimentally obtained values (Fig.6 - *Costs*).

The estimated pareto front is shown in Fig. 4 for 4 of the 11 cases evaluated, where the solution chosen for each case is highlighted. Additionally, optimal solutions (obtained given a large computation time) are highlighted in gray for the first two case studies, the first matches since it was

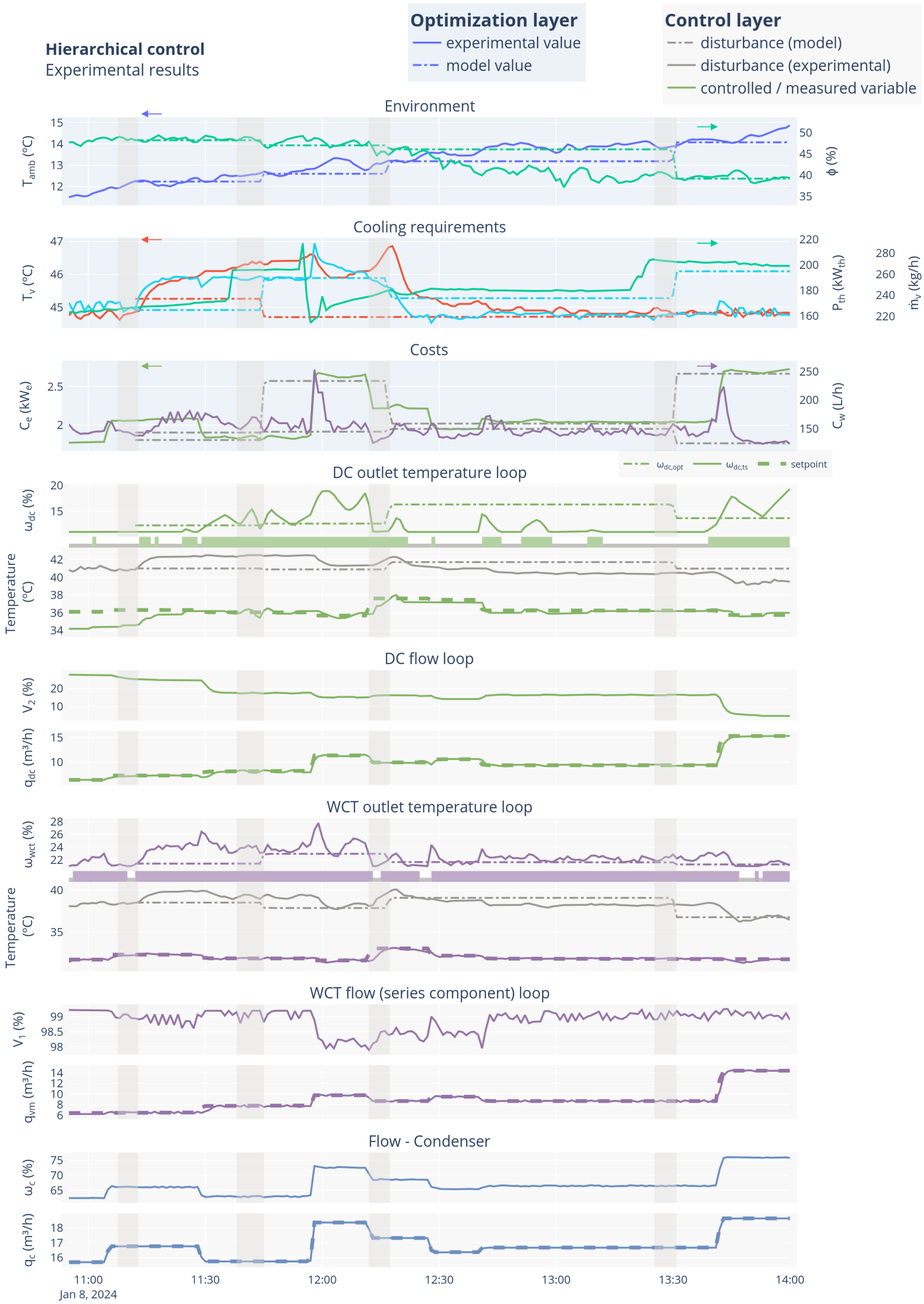

Fig. 6. Experimental results of proposed methodology

Table 2. Low-level control loops

Controller	Control signal variable	Control signal P&ID	Controlled signal variable	Controlled signal P&ID	K_p	T_i (s)
TC-01	ω_{dc}	SC-02, SC-03	$T_{dc,out}$	TT-03	-4.5 %/°C	56.6
TC-02	ω_{wct}	SC-01	$T_{wct,out}$	TT-06	-5.9 %/°C	61.1
FC-01	ω_c	SC-04	q_c	FT-06	2.3 %$\cdot(h\cdot\mathrm{m}^3)$	2.5
FC-02	V_2	ZC-02	q_{dc}	FT-02	-0.2 %$\cdot h\cdot\mathrm{m}^{-3}$	2.3
FC-03	V_1	ZC-01	q_{vm}	f(FT-01,FT-02, FT-03)	0.7 %$\cdot h\cdot\mathrm{m}^{-3}$	5.0

initialized with prior solutions, while the second was given the same time but without initialization, thus providing a small but noticeable sub-optimal solution.

As shown in Fig. 6, during this test, the ambient conditions did not change significantly, thermal power requirements started at a value of 165 kW for the first considered evaluation (at 11:12), raised to 190 kW for the second one (11:45), returned to a value of 174 kW half an hour later (12:17), and maintained there for a long period. Finally, after about an hour (13:30) cooling conditions were kept low (160 kW). The selection criteria was the same for all runs, except for the last one, where the maximum water consumption constraint was reduced from 150 to 125 l/h.

Analyzing how the operation strategy is modified to adapt to the changing conditions or selection criteria (Fig. 5), it can be seen that for the first evaluation (11:12) the strategy is a mix of parallel and series operation. This configuration is maintained when increasing the thermal load (11:45), but with an increase in the cooling flow (q_c). Later, when returning to the first evaluation cooling requirements and not significant changes in the environmental conditions (12:17), as expected the chosen solution yields very similar configuration and consumptions. Finally, when increasing the restriction in water consumption (13:30), the optimal strategy shifts towards only series operation while increasing the cooling flow.

From the qualitative analysis of the results five main takeaways can be summarized:

(1) The Dry cooler and Wet cooling tower models were validated and produced accurate predictions within the uncertainty limits. However the condenser model is a simple energy balance and, as it can be observed in Fig. 6 - *Temperature DC*, there is a significant difference between the expected condenser outlet temperature ($T_{c,out} = T_{dc,in}$) and the experimental value. This is a clear area for improvement.
(2) The optimization function is executed manually, at established time periods or when cooling requirements change. The next implementation step should automatize this procedure with the aim of reevaluating the optimization layer every time one of the process variables changes significantly.
(3) Although FOPDT models have been used for nonlinear systems (pump and valves), the low-level control requirements of this system are positively satisfied with a PID-based control system, reaching the established setpoints in a reasonable time. In the case of DC system, the control variable shows some oscillations due to the severe non-linearities of the system. Next versions will include a Gain Scheduling PID controller to improve the low-level control response.
(4) If the GA of the optimization layer is provided with prior solutions of similar operating conditions, the results obtained are significantly better. This advantage could be extended by building a database over time.

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