Preprints, 4th IFAC Conference on
Advances in Proportional-Integral-Derivative Control
Almería, Spain | June 12-14, 2024

Modeling and control scheme of the absorption machine of a solar cooling plant. ⋆

M.G. Satué * **J.D. Álvarez** ** **M. Castilla** ** **F.R. Rubio** *
M.G. Ortega *

* *Systems Engineering and Automation Department, University of Seville, 41092 Seville, Spain (e-mail: {mgarrido16,rubio,mortega}@us.es)*
** *Department of Computer Engineering, Automation and Robotics, CIESOL—ceiA3, University of Almería, 04120 Almería, Spain (e-mail: {jhervas,mcastilla}@ual.es)*

Abstract: The article presents the modeling of an absorption machine and a low level control system necessary to ultimately control the cooling power demanded by air conditioning systems. The modeling of the components has been implemented in Simulink in order to obtain a simulator of an absorption-machine-based cooling plant for controller design purposes. In the simulator, the proposed refrigeration system presents control loops to maintain the output variables of the flow rates and temperatures in established references. Finally, the results of the simulation are presented, which show the behavior of the absorption machine system and support the good performance of the proposed low level control system.

Keywords: solar cooling, absorption machine

1. INTRODUCTION

Electrical consumption related to cooling demand has increased in recent year and will continue to grow in countries with emerging economies. This increase in energy demand will have a significant impact in greenhouse effect and global warming (Satué et al., 2022). The measures taken to counter climate change involve an important push towards the use of renewable energies and technologies with greater energy efficiency. In this context, absorption-machine-based cooling plants represent a potential solution, because they can be fed by thermal energy provided by power solar plants.

Solar absorption systems are considered one of the most applicable methods to harness solar energy for cooling, especially in regions with a large amount of solar radiation (Noforesti et al., 2021). The solar absorption cycle based on lithium bromide ($\mathrm{BrLi-H_2O}$) is one of the most used systems in solar cooling plants.

The use of solar energy for cooling has the great advantage that the greatest demand for cold occurs when solar irradiation is greater. The two main components of a solar cooling plant are the solar collectors (Dobriyal et al., 2020) and the absorption machine, so the efficiency of the system depends on the coupling between both components (Bermejo et al., 2010). This type of plant usually meets the cooling demand partially, as they strongly depend on weather conditions. Therefore, efficient energy storage systems and/or conventional refrigeration machines are necessary to satisfy the rest of the demand.

There are works in the literature related to modeling, simulation and control of solar absorption plants. Many of them focus their objectives on improving the operation and performance of the solar field which, together with the absorption machine, make up the main components of a cold installation. In Camacho et al. (2019) a non-linear model predictive controller is proposed to regulate the outlet temperature of the solar field. Pataro et al. (2022) propose a hybrid nonlinear predictive control for a solar thermal installation with the objective of improving the plant's operating performance. Ortiz et al. (2022) define a split range controller capable of manipulating both the flow and defocus of a Fresnel solar collector to supply water to the High Temperature Generator (HTG) of the absorption machine at the appropriate temperature. Álvarez et al. (2014) present a hybrid control algorithm to achieve a desired inlet temperature in the absorption machine. And in Witheephanich et al. (2014), the control problem maintains the leaving water temperature of the solar field at a specific set point through changes in the flow rate of the pump that regulates the entry of water into the solar field. On the other hand, other works such as in Rathod et al. (2019) and also in Camacho et al. (2019), design a control algorithm to optimally manage the plant configuration.

This article focuses on the modelling and low level control of an absorption machine that will be the basis of a future

---

⋆ This work has been carried out within the framework of the project "Optimal Station Control based on Solar Energy with Storage for Electric Vehicle Charging (CONSOLVE)". Grant PID2020-115561RB-C32 funded by MCIN/AEI/10.13039/501100011033 and by "ERDF A way of making Europe".

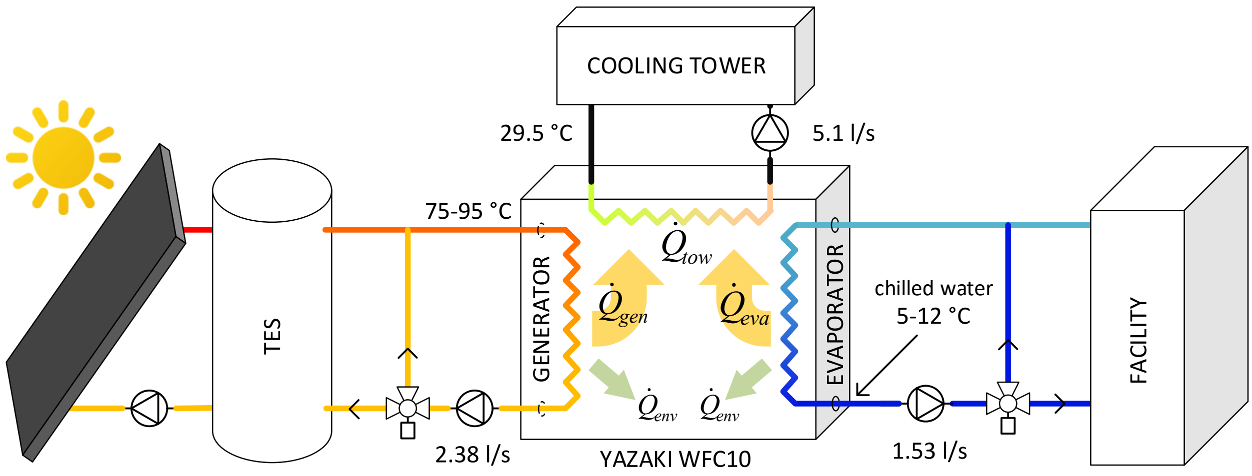

Fig. 1. Diagram of the solar cooling plant using an absorption cycle.

hierarchical control to satisfy the cooling demand of a chilled water consuming installation for air conditioning, by controlling the thermal power supplied by the machine at the top level control layer. The model of the plant includes an absorption machine, a cooling tower and the corresponding circuits that allow flow recirculation from a TES to the generator and from the facility to the evaporator of the machine. The rest of the necessary components needed to make up the solar plant (solar collectors, thermal energy storage (TES) and the cool demanding facility) are not includded in the plant model just to stress the control more than could be achieved under more realistic solar plant operating conditions.

The rest of the article is organized as follows: Section 2 presents a description of the system, while Section 3 presents its modeling. Section 4 describes the control structure proposed in this work and Section 5 presents the simulation results. Finally, in Section 6 the main conclusions of the article are drawn.

2. DESCRIPTION OF THE SYSTEM

The system subject of this work is based on the solar cooling plant located on the roof of the laboratory building of the Escuela Técnica Superior de Ingeniería of the University of Seville. The main equipment that makes up the solar absorption plant are: a set of flat plate solar collectors, a storage tank and an absorption machine. Figure 1 depicts the scheme of the plant. The water heated by the collector field passes through the accumulator, which is capable of storing enough energy to allow an adequate cooling power supply. The Yazaki absorption machine model WFC10 has a nominal cooling power of 35 kW. It works with a hot water flow rate to the generator of 2.38 l/s at a temperature between 75 and 95°C, and produces a chilled water flow rate of 1.67 l/s between 7 and 12°C. This machine is a single stage model, uses water as a coolant and a solution of lithium bromide and water ($\mathrm{BrLi - H_2O}$) as an absorbent. Its *coefficient of performance* or COP, that is, the ratio between the thermal power absorbed in the evaporator and the generator, is 0.7 for nominal conditions. The facility imposes the demand for cooling power that must be satisfied by the refrigeration plant. The load of the installation is time-variable depending on the level of occupancy and the outside temperature, among other factors.

3. MODEL OF THE SYSTEM

The system to be considered in this article is made up of an absorption machine, which supplies chilled water for air conditioning to a facility through a pipe circuit with the possibility of partial bypassing through a three-way valve. On the other hand, the absorption machine is supplied with hot water by an energy reservoir (which is in turn fed by the solar field on the other outlet) also through a piping system with the possibility of partial bypassing through another three-way valve. Figure 2 shows the diagram of the considered system. Regarding the notation used in the following sections, the superscripts i, o and ref associated with variables denote *input*, *output* and *reference*, respectively.

3.1 Absorption machine

From an external description point of view, the absorption machine consists of three circuits through which heat exchanges take place: a generator, an evaporator and a cooling circuit. Hot water (between 75 °C and 95 °C) is introduced through the generator at a specific constant flow rate. This water usually comes from an energy reservoir, typically powered by solar energy. The purpose of the evaporator circuit is to cool the water coming from an installation, thus supplying cold water (at approximately 8 °C) to the installation's air-conditioning system. Finally, the cooling circuit is fed with water from a cooling tower, which is supposed to be able to provide cold water (around 29.5 °C) to cool the machine.

Generator:

Applying a power balance to the generator the following equation is obtained:

$$C_{gen}\frac{dT^{o}_{gen}}{dt} = \dot{m}_{gen}\,C_p\,(T^{i}_{gen} - T^{o}_{gen}) - \dot{Q}^{gen}_{env} - \dot{Q}_{gen} \quad (1)$$

where T^{i}_{gen} and T^{o}_{gen} are the inlet and outlet temperatures of the water in the generator, respectively, and $\dot{Q}_{env}$

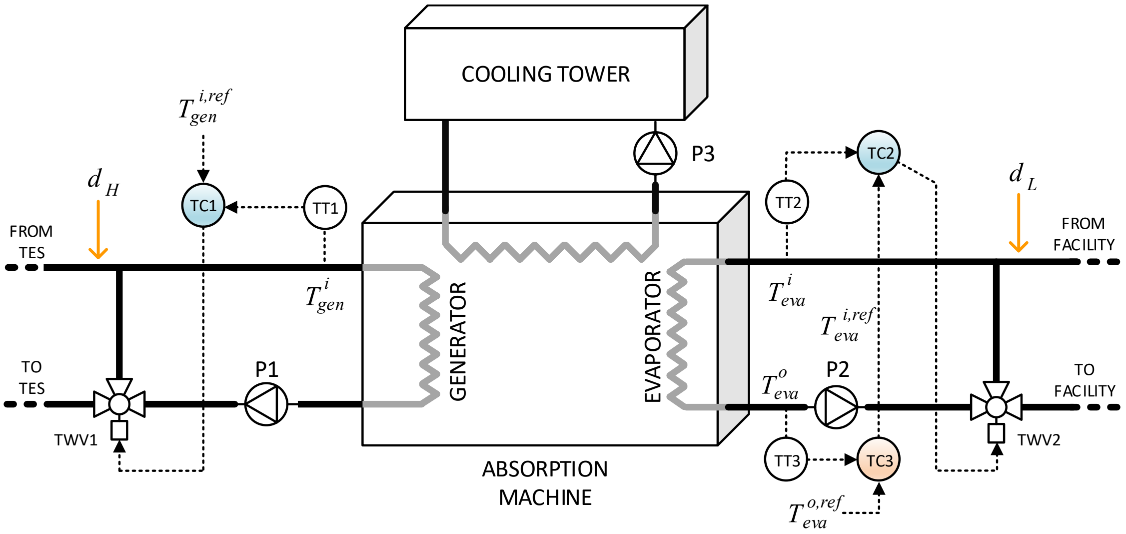

Fig. 2. Process diagram of the absorption-machine-based cooling plant.

account for the losses to the environment of the generator. This term is modeled according to the equation 2 in which $\overline{T}_{gen}$ is the average temperature of the water inside the generator.

$$\dot{Q}_{env}^{gen} = (\overline{T}_{gen} - T_{env})\, UA_{gen} \tag{2}$$

The rest of the terms of equation 1 are explained below:

- C_{gen}: thermal capacity of the generator (J/K)
- C_p: specific heat capacity of water (J/kgK)
- $\dot{m}_{gen}$: mass flow through the generator (kg/s)
- T_{env}: environment temperature (K)
- UA_{gen}: global heat loss coefficient to the environment of the generator (W/K)

The constant C_{gen} has been adjusted taking into account the residence time of the water in this circuit at nominal flow.

Evaporator:

Applying a power balance in the evaporator, the following differential equation is obtained:

$$C_{eva}\frac{dT_{eva}^{o}}{dt} = \dot{m}_{eva}\, C_p\, (T_{eva}^{i} - T_{eva}^{o}) - \dot{Q}_{env}^{eva} - \dot{Q}_{eva} \tag{3}$$

where T_{eva}^{o} is the temperature of chilled water at the outlet of the evaporator, T_{eva}^{i} is the temperature of the water at the inlet of the evaporator, C_{eva} is the thermal capacity of the evaporator, $\dot{Q}_{env}^{eva}$ are the losses to the environment and $\dot{Q}_{eva}$ is the cooling power of the absorption machine. Again, the constant C_{eva} has been adjusted taking into account the residence time of the water in this circuit at nominal flow.

The term of losses to the environment is modeled as follows:

$$\dot{Q}_{env}^{eva} = k_{eva}\, \dot{m}_{eva}\, C_p\, (\overline{T}_{eva} - T_{env}) \tag{4}$$

where k_{eva} is the loss coefficient and $\overline{T}_{eva}$ is the average temperature of the water inside the evaporator.

Cooling circuit:

Applying a power balance to the cooling tower, the following equation is obtained:

$$\dot{Q}_{tow} = \dot{m}_{tow}\, C_p\, (T_{tow}^{i} - T_{tow}^{o}) \tag{5}$$

where T_{tow}^{i} and T_{tow}^{o} are the cooling tower water inlet and outlet temperatures, respectively, and $\dot{Q}_{tow}$ is the thermal power transferred to the cooling system (see equation 6).

$$\dot{Q}_{tow} = \dot{Q}_{gen} + \dot{Q}_{eva} \tag{6}$$

Internal energy balance and COP modelling:

A static model of the absorption machine will be used to model the energy balance between the three circuits of the machine. It is based on the data provided by the manufacturer, namely, the cooling thermal power and COP for several combinations of the evaporator outlet water temperature, the generator inlet water temperature, and the temperature of the cooling water returning from the cooling tower. The the cooling thermal power and COP values are interpolated from the data provided by the manufacturer based on the three variables mentioned above. Figure 3 shows the operating curves used in this work. For simplicity, only data corresponding to a cooling water temperature of 29.5 °C are presented.

3.2 Rest of the system

The rest of the system consists of a cooling tower and a series of pipes, three-way valves and pumps that will allow regulating flows. The cooling tower will be considered to be capable of providing cooling water at around 29.5ºC. The three way valves $TWV1$ and $TWV2$ (see Figure 2) have a fixed slew-rate of $1/120\ \mathrm{s}^{-1}$ and a non-linear relationship between the opening ratio, β, and the flow ratio, α, as shown in Figure 4. The opening ratio is the ratio of recirculation from the outlet stream to the inlet stream of the generator/evaporator. A ratio of recirculation of one means that all the water from a outlet is bypassed to the inlet. The rest of the three way valve's model consist in a static thermal power balance and a mass flow balance.

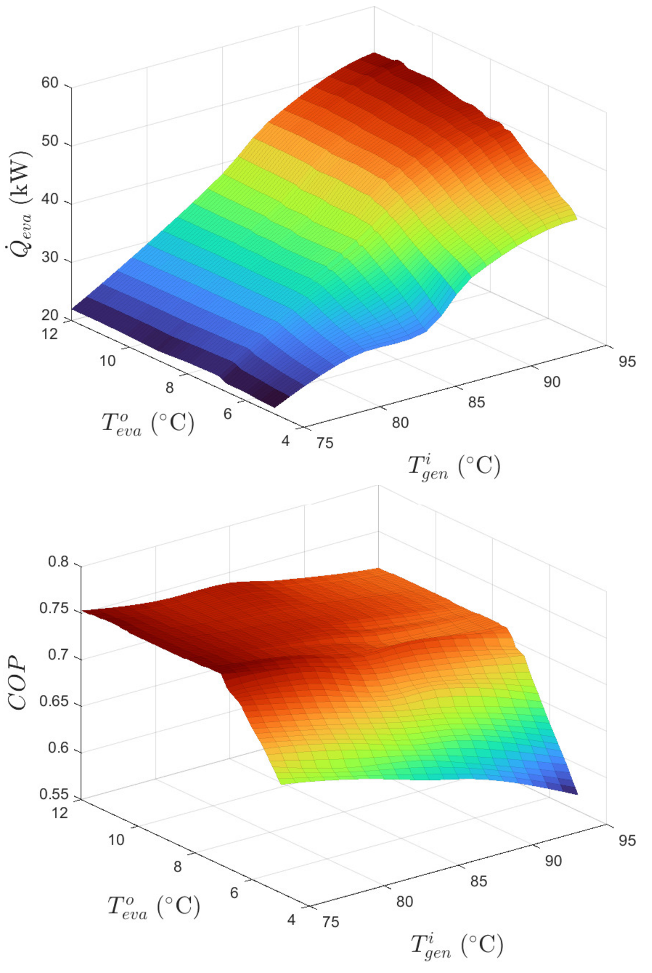

Fig. 3. Absorption machine operating curves for a temperature of water returning from the cooling tower equal to 29.5 °C

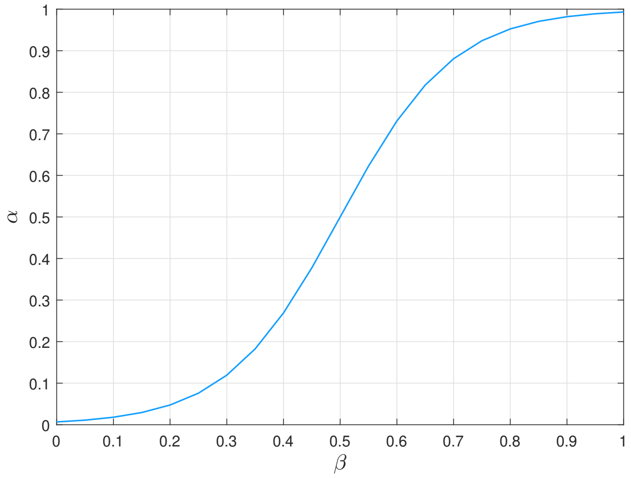

Fig. 4. Relation between the opening ratio, β, and the flow recirculation ratio, α, of the three-way valves.

4. CONTROL SYSTEM STRUCTURE

At the lowest level, the speed of pumps $P1$, $P2$ and $P3$ are adjusted to guarantee nominal flow rates in the supply circuits to the absorption machine: 2.38 l/s for the generator circuit, 5.1 l/s for the cooling tower, and 1.67 l/s for the evaporator. These controllers have not been included in the process diagram depicted in Figure 2.

Once the nominal flow rates of the machine are guaranteed, the following lower level controllers will be responsible for controlling the inlet temperatures to the circuits of the generator, $T1$, and the evaporator, $T2$, and the outlet temperature of the evaporator, $T3$, of the absorption machine. It is assumed that the control of the inlet temperature to the cooling circuit of the machine is done by the cooling tower itself. The control will be carried out by adjusting the corresponding recirculation ratios through the three-way valves $TWV1$ and $TWV2$ using PI controllers $TC1$ and $TC2$ in Figure 2. Notice that by setting the temperatures at the generator inlet and the evaporator outlet, it is possible to ultimately control the cooling power provided by the machine.

Figure 5 shows the control loops used, where the symbol $\sum$ is used to represent the plant, that is, the absorption machine and the recirculating circuits with the three way valves. The generator inlet's temperature uses a regular feedback loop in which the process variable $T1 = T^i_{gen}$ is controlled via the manipulable variable β^{ref}_{gen} (as stated in Section 3.2, the three way valves have a fixed slew rate). A cascade controller is used to keep the temperature of the evaporator outlet at the desired reference. The outer controller $TC3$ computes the reference $T^{i,ref}_{eva}$ for the inner controller $TC2$ and later acts on the manipulated variable β^{ref}_{eva}.

The references $T^{i,ref}_{gen}$ and $T^{o,ref}_{eva}$ for the two PI controllers would be computed by a higher layer in the control hierarchy.

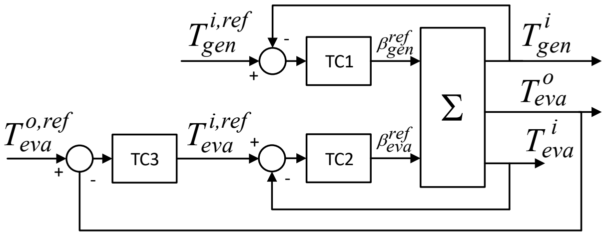

Fig. 5. Control system block diagram.

5. SIMULATION RESULTS

Three different scenarios have been simulated. The first one consist of a series of simulations to show the two-way coupling existing between the generator and the evaporator of the absorption machine. Figure 6 shows the result of a simulation in which nor the inlet nor the oulet temperature of the evaporator are controlled, while the generator's inlet temperature is subjected to an abrupt change. It can be seen that the conditions on the evaporator side of the machine change due to the modification inducted in the generator side at minute 60 of the simulation. Figure 7 shows the result of a simulation in which the inlet temperature of the generator is not controlled, while the outlet temperature of the evaporator is subjected to an abrupt change at minute 60 of the simulation. It can be seen that the change of the conditions in the evaporator side also have an effect on the generator side.

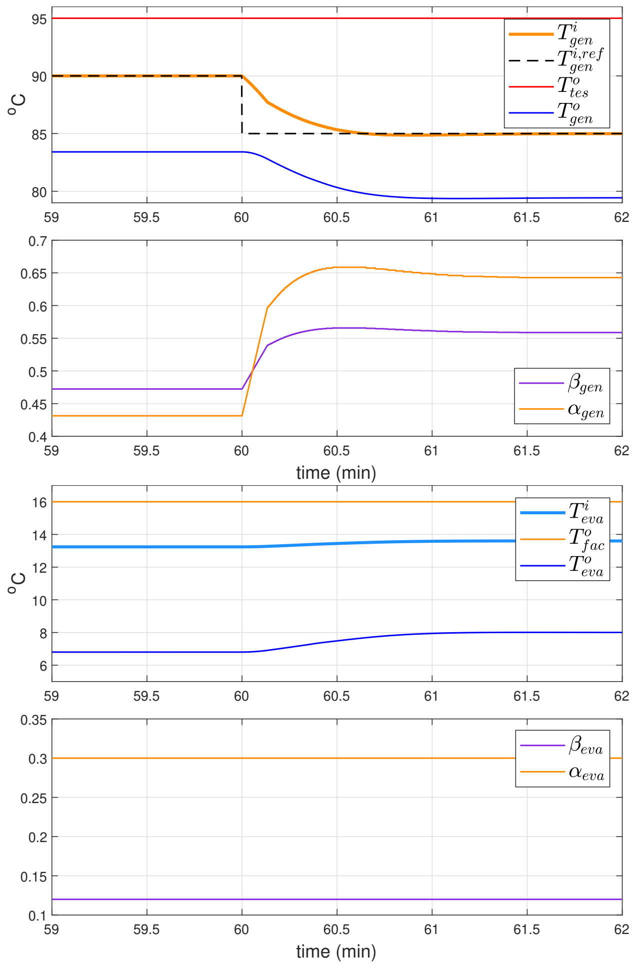

Fig. 6. Simulation to show the coupling between generator and evaporator.

The second scenario consist of a simulation in which all the controllers are operative and step-like changes are given to the references of the inlet temperature of the generator and the outlet temperature of the evaporator, $T_{gen}^{i,ref}$ and $T_{eva}^{o,ref}$ respectively. Figure 8 shows the results. The generator inlet temperature's reference changes from 90 to 88 °C at minute 60, leads to a evaporator's inlet reference adaptation in order to keep the evaporator's outlet temperature at the specified set point. At minute 70 the evaporator outlet temperature's reference changes from 8 to 6 °C, causing an adaptation of the actuated variable β_{gen} to maintain the temperature at the inlet of the generator at the set-point.

The last scenario is setup to show the rejection of disturbances. Two possible sources of disturbance have been considered: a temperature disturbance at the outlet of the TES, T_{tes}^{o}, and a temperature disturbance at the outlet of the facility, T_{fac}^{o} (d_H and d_L in Figure 2 respectively). Figure 9 shows the result of a simulation in which the two disturbances are applied. The disturbance at the TES is introduced at minute 60 and the disturbance at the facility at minute 70. Both are rejected successfully within a reasonable period of time.

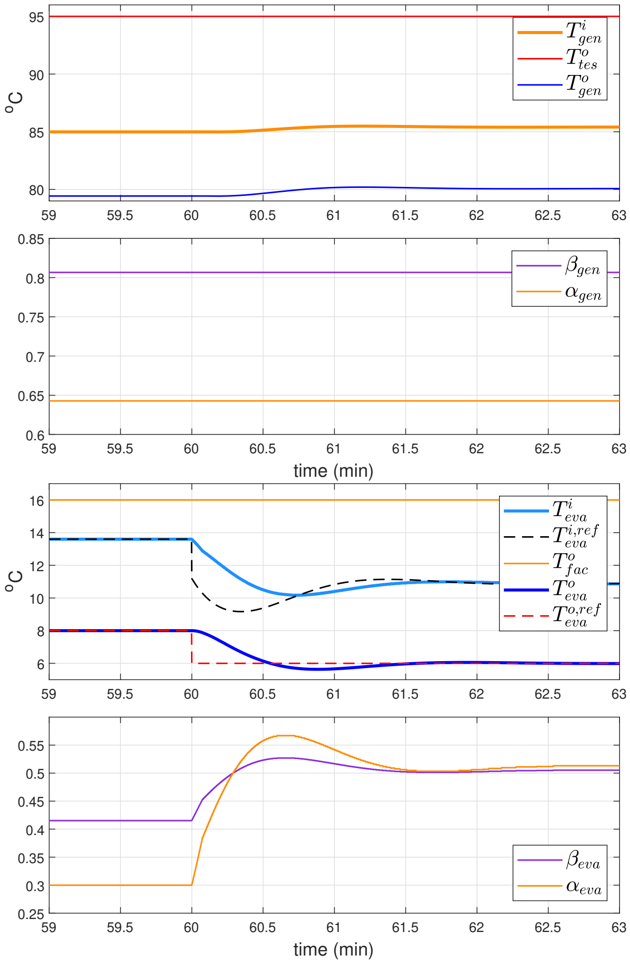

Fig. 7. Simulation to show the coupling between evaporator and generator.

6. CONCLUSION

The proposed low-level control system responds adequately under operating conditions far more unfavourable than those expected during normal operation of a solar cooling plant. In normal plant operation, the controllers would reject constant but mild disturbances due to the solar cycle. In addition, this control scheme will allow future work to include a higher control layer in the hierarchy which will be responsible for generating the temperature references for the low-level controllers TC1 and TC3, and which will allow the instantaneous cooling power provided to meet a time-varying demand to be specified.

ACKNOWLEDGEMENTS

This work has been carried out within the framework of the project "Optimal Station Control based on Solar Energy with Storage for Electric Vehicle Charging (CONSOLVE)". Grant PID2020-115561RB-C32 funded by MCIN/AEI/10.13039/501100011033 and by "ERDF A way of making Europe".

REFERENCES

Álvarez, J.D., Pasamontes, M., Guzmán, J.L., and Camacho, E.F. (2014). A practical hybrid predictive control

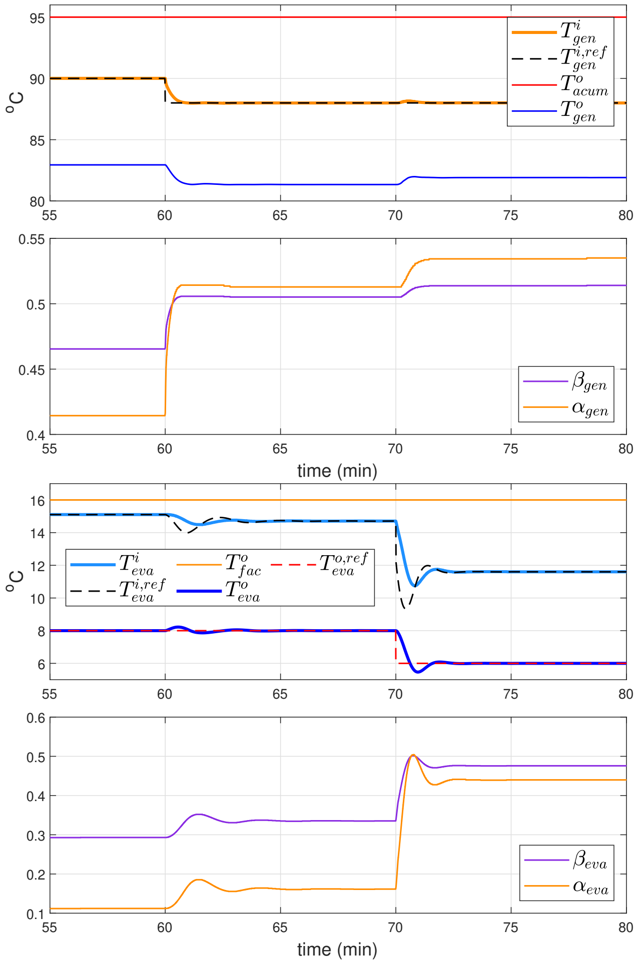

Fig. 8. Control results for set-point changes.

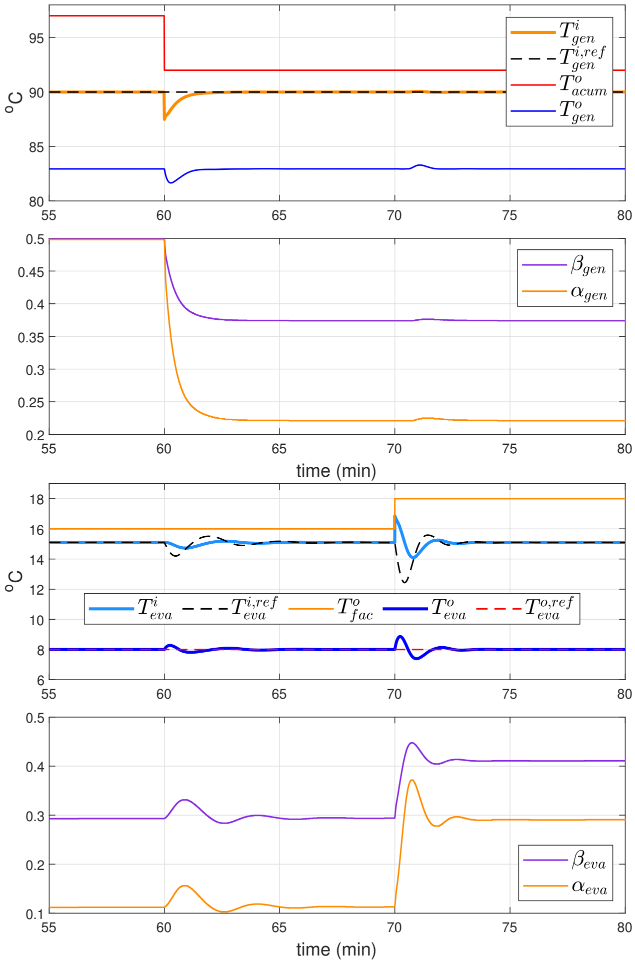

Fig. 9. Control results for disturbance rejection.

algorithm for a low-temperature thermosolar plant. *Optimal Control Applications and Methods*, 37, 508–520. doi:10.1002/oca.2139.

Bermejo, P., Pino, F.J., and Rosa, F. (2010). Solar absorption cooling plant in Seville. *Solar Energy*, 84, 1503–1512. doi:10.1016/j.solener.2010.05.012.

Camacho, E.F., Gallego, A.J., Escaño, J.M., and Sánchez, A.J. (2019). Hybrid nonlinear MPC of a solar cooling plant. *Optimal Control of Hybrid Systems and Renewable Energies*, 12 (14), 2723. doi:10.3390/en12142723.

Dobriyal, R., Negi, P., Sengar, N., and Singh, D.B. (2020). A brief review on solar flat plate collector by incorporating the effect of nanofluid. *Materials today: Proceedings*, 21, 1653–1658. doi:10.1016/j.matpr.2019.11.294.

Noforesti, S., Ahmadzadehtalatapeh, M., and Motlagh, V.G. (2021). The application of solar integrated absorption cooling system to improve the air quality and reduce the energy consumption of the air conditioning systems in buildings - a full year model simulation. *Energy and Buildings*, 274, 112420. doi:10.1016/j.enbuild.2022.112420.

Ortiz, D.M., Sánchez, A.J., Gallego, A.J., de Andrade, G.A., Normey-Rico, J.E., Bordons, C., and Camacho, E.F. (2022). Split-range control for improved operation of solar absorption cooling plants. *Renewable Energy*, 192, 361–372. doi:10.1016/j.renene.2022.04.064.

Pataro, I.M.L., Gil, J.D., Costa, V.A.D., Guzmán, J.L., and Berenguel, M. (2022). A nonlinear control approach for hybrid solar thermal plants based on operational conditions. *Renewable Energy*, 183, 114–129. doi:10.1016/j.renene.2021.10.057.

Rathod, N., Bella, A.L., Puleo, R.G.S., Rossetti, A.R., and Sandroni, C. (2019). Modelling and predictive control of a solar cooling plant with flexible configuration. *Journal of Process Control*, 76, 74–86. doi:10.1016/j.jprocont.2019.01.009.

Satué, M.G., Arahal, M.R., Acedo, L.F., and Ortega, M.G. (2022). Economic versus energetic model predictive control of a cold production plant with thermal energy storage. *Applied Thermal Engineering*, 210, 118309. doi:10.1016/j.applthermaleng.2022.118309.

Witheephanich, L., Escaño, J.M., and Bordons, C. (2014). Control strategies of a solar cooling plant with fresnel collector: A case of study. *Optimal Control Applications and Methods*, 37, 508–520. doi:10.1002/oca.2139.