Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

HYBRID PREDICTIVE CONTROL OF A SOLAR AIR CONDITIONING PLANT

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Abstract: This paper presents a hybrid controller for a solar air conditioning plant, located at the University of Seville, Spain, and used as a benchmark for the HYCON NoE of the EU. The plant uses two sources of energy: solar and gas, plus a set of accumulation tanks and an absorption tower to provide conditioned air to an university building. The hybrid control is based on a model predictive control strategy developed with the objective of operating the air conditioning system using the smaller amount of energy from gas. A novel approach incorporating an internal model with embedded logic control is used to transform the hybrid problem in a continuous-nonlinear one. Simulation results are presented, showing promising results.

1. INTRODUCTION

The efficient use of renewable energy is receiving increased attention, both by the scientific community and by the society. An air conditioning system that uses solar energy presents an appealing characteristic based on its power performance, because the demand of refrigeration occurs when the climatic conditions are more favourable to feed the system, that is, when it is shiny. But, at the same time, it has the difficulty of requiring the simultaneous use of other sources of energy to cope with changing whether conditions. This paper presents a control system for a solar air conditioning plant. This plant uses two sources of energy: solar and gas, plus a set of accumulation tanks and an absorption tower to provide conditioned air to a university building. The aims of the control system are to operate properly the refrigeration system, and to optimize the natural gas consumption. Due to the nature of the process, a hybrid control has been developed, based on a model predictive control (MPC) strategy mixing control and economic aims. A novel approach incorporating an internal model with embedded logic control and the concept of virtual control variables is presented. This approach allows transforming the hybrid problem into a reduced order nonlinear model predictive control (NMPC) one that can be solved with continuous optimization methods.

Being used as a benchmark of the EU Network of Excellence HYCON, the solar plant has received attention from other researches. Main contributions are found in (Zambrano *et al.*, 2007) and (Ding *et el.*, 2007). They provide different approaches to the problem, the former based on a hierarchical architecture with mix integer optimization and the second relying on a rule based controller.

2. THE SOLAR PLANT

The solar refrigeration plant is located in the flat roof of the lab building of the Seville Engineering School in southern Spain. The purpose of the installation is to provide cooling to the air conditioning system of a laboratory placed in the building. It consists of three main sections: the one related to the refrigeration system, an absorption machine and the energy supply subsystem. A schematic of the energy subsystem and the absorption machine can be seen in Fig.1.

The absorption machine, with a nominal power of 35kW, is a process unit able to cool a flow of water using another stream at a higher temperature by means of a complex procedure involving two circuits, the generator, linked to the hot flow, and the evaporative one, linked to the chilled stream. This flow feeds the refrigeration system, which has several elements, including heat exchangers, a refrigeration tower and a heat pump that can be used to simulate an external heat load.

The energy supply subsystem must provide a hot stream to the absorption machine above 75 ºC, and is composed of three main elements: i) Four fields of solar collectors, with a total surface of 151.2 m^2 and a nominal power of 53 kW. ii) A gas heater able to provide 68 kW, which operates with its own control system: a relay set to switch the gas on/off in the range [86, 94] ºC. iii) A set of two thermally isolated accumulation tanks, with a total capacity of 5 m^3. They operate in parallel and are always full of water, so that no real mass accumulation takes place on them, but energy can be stored in them for later use as hot water. They can receive a flow of water from the output of the generator or from the

978-1-1234-7890-2/08/$20.00 © 2008 IFAC **10.3182/20080706-5-KR-1001.2579**

solar collectors. Its output can be sent to the solar collectors to the absorption machine or be maintained closed.

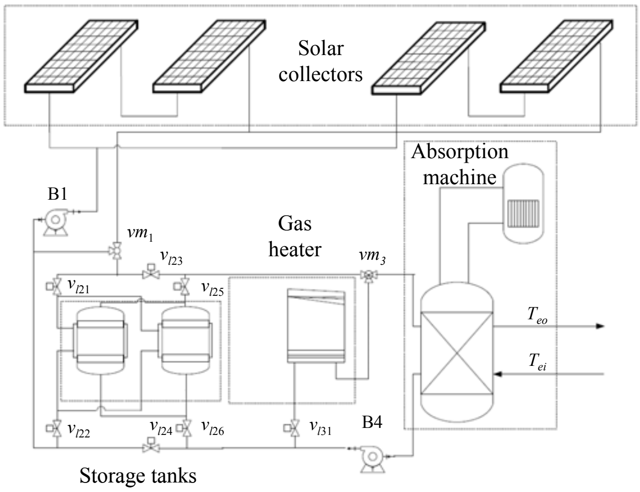

Fig. 1. A schematic of the solar plant with the on/off valves and continuous actuators: speed of the *B1* pump and position of the three way valve vm_3.

The three energy elements can operate independently or cooperate in supplying energy to the absorption machine according to the position of a set of on/off valves and a complex network of pipes. Two pumps, *B4* and *B1*, are used to circulate the water through the pipe system. *B1,* being a variable speed one, is used as a continuous manipulated variable. Also, a second continuous manipulated variable, a three way control valve, vm_3, can be operated in order to change the fraction of flow to the absorption machine that comes through the gas heater. The on/off valve vm_1 can be used to isolate the solar panels when is at 100%, while positioned at 0% connect them to the circuit. Other valves perform similar operations with other elements and are also manipulated variables of binary nature.

The variable structure of the plant makes the control problem a hybrid one, with both, continuous and on/off decision variables, and different process units in operation along time according to the mode of functioning.

2.1 Modelling

A hybrid dynamic model of the process was provided by the University of Seville (Zambrano *et al.*, 2006). It combines models for the process units with the ones of the hydraulic interconnections organized in a set of 11 modes of operation that corresponded to sensible combinations of the on/off elements of the plant. The list of modes are given next. In the following, if a valve is not mentioned, it is assumed to be closed:

Mode 1: Recirculation. With vm_1 position at 100%, and acting on *B1,* the water can operate in closed loop through the solar collectors, without interaction with the rest of the plant.

Mode 2: Storing hot water. With v_{l21}, v_{l22} open and vm_1 at 0%, and acting on *B1*, the accumulation tanks can be loaded with hot water from the solar collectors.

Mode 3: Absorption machine operated with water from the solar collectors. With valves v_{l23}, v_{l24} open, vm_1 at 0% and *B4* on, the water from the solar collectors will flow to the absorption machine.

Mode 4: Absorption machine operated from the solar collectors and the gas heater. With valves v_{l23}, v_{l24}, v_{l31} open, vm_1 at 0% and *B4* on, the water from the solar collectors and through the gas heater will flow to the absorption machine.

Mode 5: Absorption machine operated from the gas heater. With valve v_{l31} open, and *B4* on, the water through the gas heater will flow to the absorption machine.

Mode 6: Absorption machine operated from the accumulation tanks and the gas heater. With valves v_{l25}, v_{l26} and v_{l31} open, and *B4* on, the water from the accumulation tanks and through the gas heater will flow to the absorption machine.

Mode 7: Absorption machine operated from the accumulation tanks. With valves v_{l25}, v_{l26} open, and *B4* on, the water from the accumulation tanks will flow to the absorption machine.

Mode 8: Absorption machine operated from the gas heater and accumulation tanks been loaded from the solar collectors. With valves vm_1, v_{l21}, v_{l22} , v_{l31} open, and *B4*, *B1* on, the water through the gas heater will flow to the absorption machine and the water from the solar collectors will store energy in the accumulation tanks simultaneously.

Mode 9: Corresponds to modes 1 and 5 simultaneously. Water is re-circulated in the solar collectors while the absorption machine is fed from the gas heater. It corresponds to valves v_{l31}, vm_1 open and *B4*, *B1* on.

Mode 10: The solar collectors feed the absorption machine and load the accumulation tanks simultaneously. With valves vm_1, v_{l21}, v_{l22} , v_{l23} open, and *B1*, *B4* on, the water from the solar collectors will flow to the accumulation tanks and to the absorption machine.

Mode 11: The solar collectors and the gas heater feed the absorption machine and the accumulation tanks are loaded from the solar collectors simultaneously. With valves vm_1, v_{l21}, v_{l22} , v_{l23}, v_{l31} open, and *B1*, *B4* on, the water from the solar collectors will flow to the accumulation tanks and to the absorption machine and the gas heater will feed the absorption machine too.

The model was compared against experimental data collected on site and, as a result, significant deviations were detected on two components: the solar panels and some flows under certain modes of operation. Hence, new models were developed to fit the plant dynamics

The models that describe the behaviour of the absorption machine, solar panels, gas heater and the accumulation tanks are formulated through mass and energy balances plus domain specific equations. For example, in the solar panels, the proposed model includes two energy balances, one for each component: black plate and copper water tubes. The first one takes into account the solar radiation and the heat flow to the water, considering a transfer coefficient proportional to the water flow, as well as the losses to the atmosphere. The second one considers the overall energy balance carried by the water, incorporating a transport delay related to the speed of liquid in the tubes, that is, to the flow of liquid:

$$\begin{cases} C_{ps}\dfrac{dT_p}{dt} = I_G A_{sc} - q_{sc} C_{pw} A_t (T_p - T_{sco}) - U_{ps} A_{sc} (T_p - T_{amb}) \\ C_{wc}\dfrac{dT_{sco}}{dt} = q_{sc} C_w (T_{sci}(t - t_{delay}) - T_{sco}) + q_{sc} C_{pw} A_t (T_p - T_{sco}) \\ t_{delay} = \dfrac{V_{sc}}{q_{sc}} \end{cases} \tag{1}$$

where, T_p is the black plate temperature assumed uniform (ºC), T_{sco} is the water temperature at the output of the solar collectors (ºC), T_{sci} is the water temperature at the input of the solar collectors (ºC), T_{amb} is the ambient temperature (ºC), I_G is the solar radiation (W/m^2), A_{sc} is the surface of the solar collectors (m^2), A_t is the inner surface of the tubes inside the solar collectors (m^2), q_{sc} is the flow of water through the solar collectors (l/s), C_{ps} is the heat capacity of the black plate (J/ºC), C_{wc} is the heat capacity of the water inside the tubes (J/ºC), $q_{sc}C_{pw}$ is the heat transfer coefficient between the black plate and the water (W/m^{2}ºC), U_{ps} is the heat transfer coefficient between the black plate and the ambient (W/m^{2}ºC), V_t is the volume of the tubes inside the solar collectors (*l*), C_w is the specific heat of the water (J/lºC), t_{delay} is a transport delay (*s*).

The value of T_{sci}, the water temperature at the input of the solar collectors, will depend on the mode of operation:

$$T_{sci} = \begin{cases} T_{sco} & (Mode = 1) \\ T_{tsc} & (Mode = 2,8,9) \\ T_{go} & (Mode = 3,4) \\ T_{amb} & (Other) \end{cases} \tag{2}$$

where, T_{tsc} is the temperature of the water flowing from the tanks to the solar collectors and T_{go} is the output temperature of the absorption machine.

3. THE HYBRID CONTROLLER

The aims of the control system are maintaining the chilled water temperature close to its set point and the input temperature of the generator within its operating range in spite of possible disturbances. As decision variables, one have the values of the two continuous manipulated ones: the speed of the pump v_{B1} and the opening of the three way valve vm_3, as well as the choices on what energy sources to use at every time instant, that is, the mode of operation, which can be implemented by means of a set of on/off valves. The purpose is to accomplish the control aims using as less gas as possible in the gas heater and leaving the accumulation tanks at the end of the day with a temperature as high as possible in order to facilitate the operation of the following day. In addition, some other constraints have to be fulfilled, like the security ones on the maximum temperature allowed in the solar panels, 100 ºC. In the current conditions of operation, both temperature targets, chilled water and input to the generator, are equivalent and we will consider as the only target keeping the input temperature of the generator of the absorption machine T_{gi} within a operation range [76 – 95] ºC and as close as possible to a set point, with minimum consumption of gas. This led to the minimization of the cost function:

$$J = \int_0^{t_p} \left[(T_{gi} - T_{ref})^2 + \beta (q_{gh}(T_{gwo} - T_{gwi}))^2 \right] dt\,, \tag{3}$$

where the second term is proportional to the increment of energy in the flow through the gas heater, that is, the gas used on it, β being a weighting factor used as a tuning parameter.

MPC offers a useful framework for solving problems of optimal decisions in real time under a set of constraints, as the ones we are dealing with. So, a MPC approach was chosen for developing the hybrid controller, taking advantage of the available model. In order to define the kind of MPC controller that could be used in this problem, two important aspects were considered *i*) The hybrid nature of the decisions to be taken, and *ii*) The constraints imposed by the real time implementation of the controller. Regarding the first one, integer variables representing either the state of the on/off valves or the modes of operation could be taken as additional decision variables, such as they appear in the model. In this case the optimization problem associated to the controller that must be solved every sampling time would be one of Mixed Integer Nonlinear Programming (MINLP) type. Due to the large computation times expected, it is doubtful that this approach could be used in a real time framework. Two alternatives are presented next.

3.1 Embedded Logic Control

In order to reduce the integer degrees of freedom of the problem in a sound way, facilitating a real time solution, an "Embedded Logic" approach was developed incorporating physical insight into the decision procedure and formulating an internal model that combined pre-defined operating policies and process dynamics with a parameterization that avoids the use of integer variables.

The first step is to define a "rational" operating policy. It will fix the modes of operation, that is, the on/off variables, as a function of the current states of plant and external inputs. This was done using physical knowledge and the help of the simulation and implemented as a set of rules. The next step is incorporating this policy into the internal model of the controller (Prada *et al.,* 2007). So, when computing predictions, the changes of modes of operation will take place automatically along the prediction horizon, according to the state of the process at every time instant and the value of the manipulated variables and disturbances (solar radiation). In this way, only the continuous manipulated variables, that is, the speed of the pump v_{B1} and the opening of the three way valve $vm3$, appear as free decision variables. Optimization of the cost function (3) is performed every sampling time in relation to these continuous variables along a control horizon using an adequate parameterization (within each mode of operation along the prediction horizon) and considering explicitly the constraints on inputs and outputs. Once the optimal continuous variables have been computed, its value, besides the one of the solar radiation and the state of the plant can be fed to the logic that defines the operating policy in order to deduce the mode of operation that must be applied in the current time instant. Formulated in this way, the hybrid MPC controller, while considering explicitly the structural changes associated to the uses of different sources of energy, must solve only a nonlinear programming (NLP) optimization problem each sampling time, instead of the more complex one of the MINLP type that appears when the on/off valves are taken as independent decision variables. This fact, even if it is suboptimal, makes it more suitable for on-line real-time implementation. The method used in the optimization is a Sequential Quadratic programming (SQP) from the NAG library.

The internal model is formulated and implemented in continuous time in the EcosimPro environment (EA Int.,1999), a state-of-the-art simulation language. The computation of the cost function (3) is done by integration of the model along a prediction horizon, as in Fig.2. Events taking place along the prediction horizon are treated rigorously with the discontinuity handling capabilities of EcosimPro. Observe that the fact that the model incorporates structural changes does not necessarily imply that the cost function (3) is a discontinuous one.

Nevertheless, tests performed in simulation with this controller, using one minute sampling time, proved that, being a feasible approach, the optimizer got stuck in local minimums and did not always give the expected performance. An alternative optimization algorithm, the Differential Evolution (DE) one, that is supposed to give global optimums and that do not required to compute gradients, proved to be too slow to be applied in real time. This led us to reformulate the problem putting more physical knowledge into the decision making process.

3.2 Virtual manipulated variable

In order to maintain the key variable T_{gi} (temperature at the input of the absorption machine) within its operating range. The main physical concept used in the reformulation is how much energy is added to the corresponding flow, irrespective of the source it comes from. In fact, it is possible to obtain the same temperature with different sources of energy and different values of the manipulated variables: the speed of the pump v_{B1} and the opening of the three way valve vm_3, which contributes to the local minimums referred to previously. In order to control T_{gi}, the key decision is how much to increase or decrease the energy given to the current q_g, which could be represented by a single continuous decision variable $u(t)$. More precisely, $u(t)$ represents the degree (in an arbitrary scale between maximum cooling and maximum heating) of heating that can be supplied to the current q_g . This variable does not match any of the physical actuators of the plant, hence, we have denoted it as a "virtual" manipulated variable.

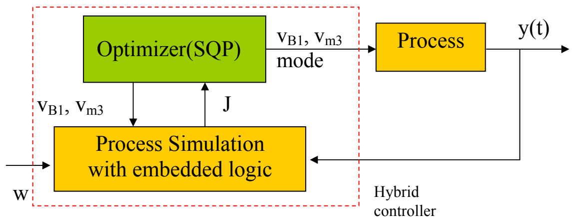

Fig.2. Sequential approach to dynamic optimization

3.3 The embedded operating policy

The range of operation of the virtual variable u can be decomposed in three regions, namely: heating the plant with the gas heater, operating without the gas heater and cooling the plant, according to the energy required for the plant. Arbitrarily, we have assigned the value 0 to maximum cooling and the value 4 to maximum heating. Increasing the value of u means that we need to supply more energy to the plant and decreasing values of u means that we need to decrease the energy been supplied to the plant.

The embedded logic controller is reformulated maintaining the internal continuous model, with an associated operating policy, but this policy only indicates which is the most adequate mode of operation for heating or cooling the plant as a function of the current state, the external input (solar radiation) and the value of the virtual variable $u(t)$. Additionally, an adequate parameterization of the continuous control actions provide the value of the actuators v_{B1} and vm_3 as a function of the selected mode and the value of $u(t)$. The logic behind is that in order to increase or decrease the supply of energy to the absorption machine, there is a corresponding mode of operation and changes of the actuators.

The rules of operation have been developed for each of these regions, combining it with the value of the solar radiation: The experiments in the plant indicated that bellow 500 W/m^2 the operation of the solar collectors is not feasible, while above this value it is always possible to collect useful energy.

Within every region, it makes sense to use a certain subset of the modes of operation according to some rules related to the state of the plant and the demand of energy. For instance, if the sun radiation is above 500 W/m^2, the temperature of the solar collectors is bellow 85ºC and the value of u is high (that is, we require a substantial increase in the energy supplied to the plant) the plant should operate in mode 4, because this mode mixes the solar collectors and the gas heater. Within a region and a mode of operation, increasing or decreasing u, that is, increasing or decreasing the supply of energy to the plant, can have a direct translation as a change in the manipulated variables, the speed of the pump v_{B1} and the opening of the three way valve vm_3, in a continuous way. For instance, increasing v_{BI} will increase the heat transfer coefficient of the solar panels and, so, the amount of solar energy transferred to the water. In the same way, vm_3 will change the flow through the gas heater and the energy collected by this flow. In Reference to the previous example of mode 4, it seems adequate to use a value v_{BI} = 100% in order to collect as much energy as possible from the sun and modulate the power from the gas heater with a change in vm_3 function of u as in Fig.3. For each value of u, combined with other variables, the mode of operation and the value of the continuous manipulated variables are provided. The relation between $u(t)$ and the manipulated variables has been chosen as linear, this not means that we claim linearity between energy and these variables, but it is only a convenient parameterization. A detailed view of the operation rules can be seen in Fig.3.

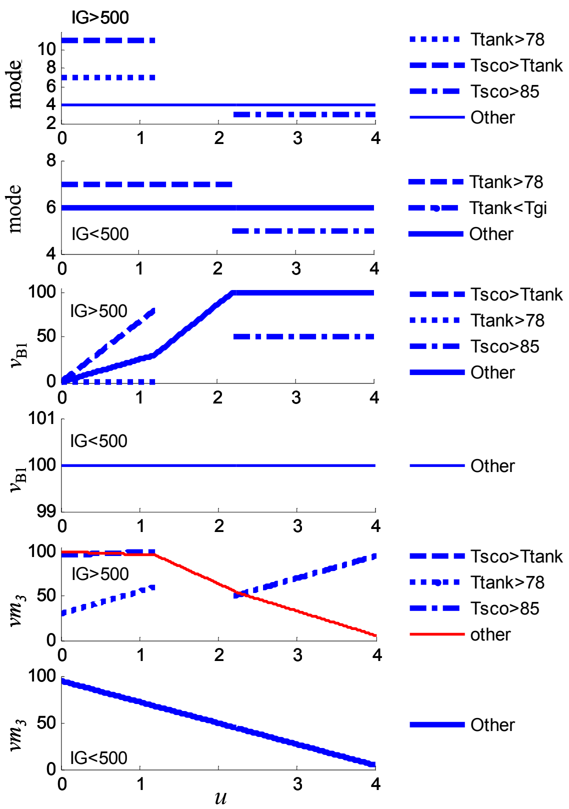

Fig.3. Embedded logic control rules of operation. Graphical format

3.3 Controller implementation

The hybrid controller was built with these elements according to the current NMPC practice. The optimization is performed every sampling time in relation to $u(t)$, with the cost function (3) modified accordingly:

$$J = \int_0^{t_p} \left[\left(T_{gi} - ref\right)^2 + \beta u^2 \right] dt \, , \tag{4}$$

under the constraints imposed by the dynamic model, the operating policy and the allowable range of u and the one of the process outputs. A sequential approach as in Fig.2 is used for the optimization. The internal model with the embedded logic provides predictions of the process outputs (and the associated cost function), as functions of the current state and the future values of the virtual decision variable u with a suitable parameterization. The computations were made integrating the model along a prediction horizon of 15 minutes. Due to that the component T_p (temperature of the black plate of the solar collectors) of the vector of states is not measurable, a Receding Horizon Estimator (RHE) is used to estimate its value every sampling time, providing suitable starting values to the integration of the model. (Alessandri *et al*., 2003).

Note that the use of rules is only a way to eliminate the integer decisions in a sensible way. The controller remains with the MPC architecture and cannot be classified only as a rule base controller. Problems linked to possible discontinuities in the gradients (Galán *et el*., 1999). are limited to the borders of the two internal regions of $u(t)$ and can be avoided, but a discussion is out by space limits. The dynamic optimization problem minimizing (4) under the constraints imposed by the model with the embedded logic, and other explicit constraints related to the allowable range of the variables, is solved in order to compute the value of u. The rules of Fig.3 can then be used to compute the values of the modes and manipulated variables. The procedure is repeated every sampling time using a receding horizon strategy.

4. SIMULATION RESULTS

Tests in simulation were performed in the EcosimPro environment. The tests used the radiation data given by University of Sevilla that corresponded to two days of operation. Fig. 4 presents the results obtained when using the hybrid controller along the first day. The graphics cover only the time during the controller was in operation, from 11h up to 17h every day, plus a short time at the end after switching off. Initial temperatures of the accumulation tanks were 70ºC. The upper graphic (a) shows the input and output (dotted) temperatures to the generator of the absorption machine. The red lines are the allowable range for T_{gi} and its set point. In (b) we can see the time evolution of the input and output chilled water temperatures, also with ranges and set point. Graphic (c) present the input and output temperatures of the gas heater and, finally, (d) gives the solar radiation. Notice that, as it was mentioned previously, it is not possible to exert real control on the chilled water temperature. After start up, the input temperature to the absorption machine is always within range and close to the set point while input and output temperatures of the gas heater are equal most of the time indicating no gas consumption. Virtual variable, manipulated variables and mode of operation are given in Fig.5. Similar results for the second day, where the solar radiation was disturbed more frequently by some clouds, are presented in Fig.6. As we can see, the controller maintains a good control of the plant in spite of the disturbances. The consumption of gas for the two days appears in Fig.7. As it can be seen, except for the start-up phase, or cloudy times, the consumption is very low according to the aim of the controller. End of day temperatures of the accumulation tanks were 85ºC.

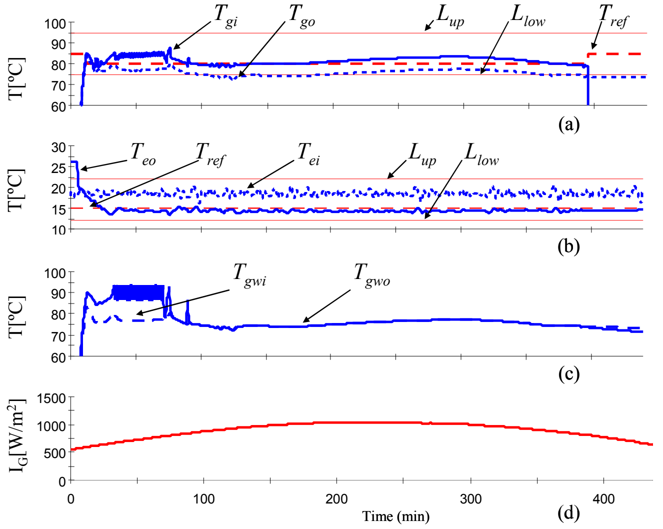

Fig. 4. Simulation results in the first day

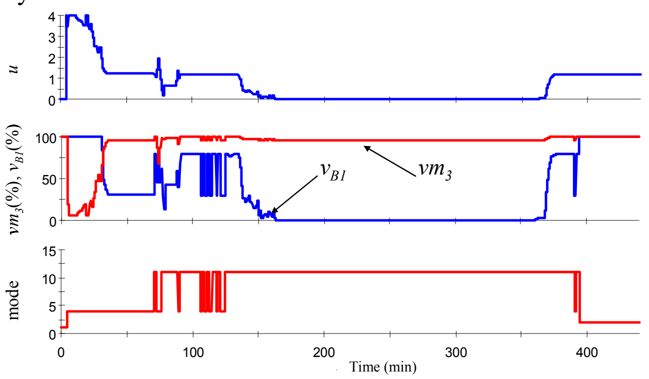

Fig. 5. Manipulated variables for first day

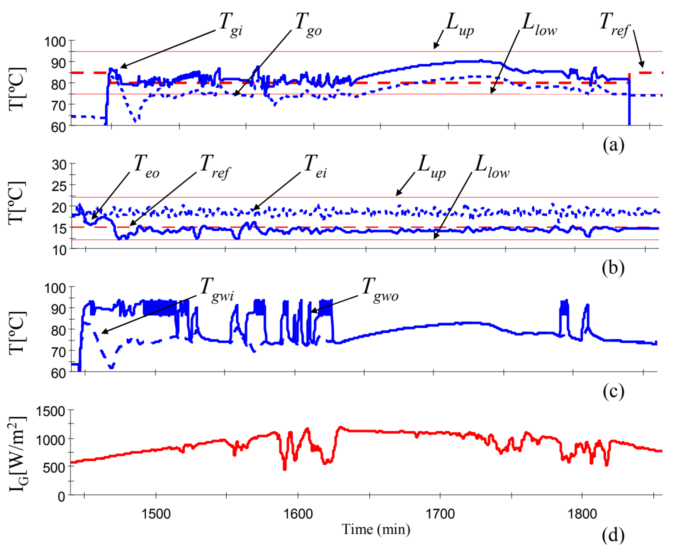

Fig. 6.Simulation results for the second day.

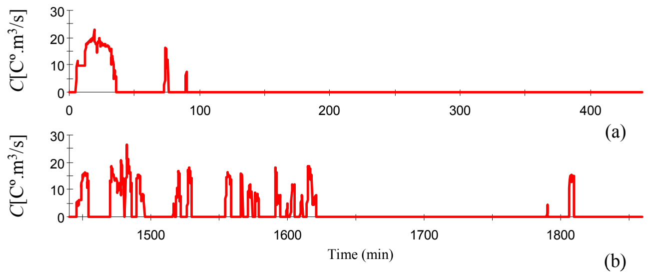

Fig.7. Gas consumption in a) the first day, b) the second day.

5. CONCLUSIONS

An approach for controlling a solar plant has been presented. The aim was to formulate a controller able to deal with the hybrid nature of the process and the control decisions, able to be implemented in real time at a reasonable cost. The controller was developed within the framework of MPC combining physical insight with rigorous mathematical formulation. Notice nevertheless that the proposed embedded logic control posses the problem in such a way that other more simple controllers, such as a PID, could be used to compute the virtual control u, taking advantage of the remaining elements of the controller, but in this case no optimality is obtained.

REFERENCES

Alessandri, A., M. Baglietto, G. Battistelli (2003). Recending-Horizon Estimation for Discrete-Time Linear Systems. In: *IEEE Transactions on Automatic control*, Vol. 48, No. 3.

Barton, P.I., C. K. Lee, M. Yunt (2006). Optimization of Hybrid Systems. In: *Computersand Chemical Engineering*, 30, 1576-1589.

Boggs, P.T., J.W. Tolle (1995). Sequential Quadratic programming. In: *Acta Numerica*. (Arieh Iserles), 1-55, University of Cambridge.

Ding, H., C. Sonntag, S. Engell, and O. Stursberg (2007). Hybrid Supervisory Control of a Solar Air Conditioning Plant. *In: Proc. European Control Conference*, Kos, Greece, pp. 5516-5521

EA Int (1999). EcosimPro User Manual. Available from: www.ecosimpro.com (accessed 25 july 2007).

Galán, S., F. William and P. I. Barton (1999), Parametric sensitivy finctions for hybrid discret/continuous systems. In: Applied Numerical Mathematics, volume 31, issues 1, pp.17-47.

Prada, C., S. Cristea, J. J. Rosano (2007), Optimal start-up of an evaporation station. In: *8th Int. Symp. on Dynamics and Control of Process Systems, DYCOPS07, IFAC*, Cancún, Mexico, Vol.3 pp.115-120.

Zambrano, D., C. Bordons, W. García, E. F. Camacho (2006). A Solar Cooling Plant: A Benchmark For Hybrid Systems Control. In: *2nd IFAC Conference on Analysis and Design of Hybrid Systems*. Alghero, Italy.

Zambrano, D., W. García, E. F. Camacho (2007). A Heuristic Predictive Logic Controller Applied to Hybrid Solar Air Conditioning Plant. In: *Hybrid Systems: Computation and Control 2007*. Pisa, Italy.