Temperature Control of a Solar Furnace

M. Berenguel, E.F. Camacho, F.J. García-Martín, and F.R. Rubio
For the last twenty years, solar energy has been used for a wide range of applications. One of the most promising fields for solar energy is that of solar furnaces for material testing and treatment. A solar furnace is a high concentrating facility made up of a collector system with tracking (usually with a varying number of flat-faceted heliostats) and a static parabolic concentrating system, at the focal spot of which a high percentage of solar energy (collected by the collector system) is concentrated within a small area. One attenuator (shutter) can be used between the collector system and the concentrator to control the amount of energy used for heating the samples placed at the focal spot. Within the test zone a test table, movable in three dimensions, is placed in the area of the focal spot. An excellent description and overview of different solar furnaces can be found in [1].

Tests in a solar furnace usually aim at improving the mechanical properties, such as hardness and wear resistance, of different samples (steel, cast-iron, ceramic composites such as alumina, etc.) by means of heating the samples and studying the many different temperature patterns. The study of physical-thermal properties of materials at high temperatures can be made with innovative treatments impossible to carry out using conventional heating processes, thereby improving the results of industrial material treatments, such as laser surface tempering, in the case of materials which have to work under very severe conditions.

From the control viewpoint, the solar furnace is a system which presents various interesting characteristics which make for a difficult control problem:

- The characteristics of the samples are quite different depending on their nature (steel, alumina, etc.). Obtaining a fixed parameter controller which allows different samples to be controlled becomes a difficult task.
- The dynamic characteristics of each sample greatly depend on the temperature and introduce high nonlinearity in the control system, which makes the behavior of the controlled system change with the operating conditions.
- The control specifications are quite severe (rate of temperature increase, rate of temperature decrease, variable step changes, etc.) and have to be achieved with small errors.
- The system suffers from strong disturbances caused by solar radiation variations (slow variations due to the daily cycle or fast and strong variations due to passing clouds), which make the exact reproduction of the conditions of a determined test impossible.
- Limitations exist in the maximum temperature achievable by the materials and different constraints (nonlinearities) in the actuator (amplitude, slew rate, etc.).

This paper shows the results obtained in the application of PI controllers to a solar furnace. Both fixed and adaptive versions of the controllers have been developed, incorporating feedforward action, anti-windup and slew rate constraint handling mechanisms. The paper is organized as follows: a brief description of the solar furnace is given, followed by the description of a dynamic model of the system for control purposes. The development and implementation of feedback and feedforward control schemes is then presented followed by the study and implementation of an adaptive control scheme. Finally, some conclusions are given.

Brief Description of the System
The Plataforma Solar de Almería (PSA) Solar Furnace is mainly devoted to material treatment. Samples of different kinds have been quenched or sintered at its high flux focal spot, improving the hardening properties and wear resistance of such materials. Many research institutions have carried out various test campaigns on metallic and ceramic samples [2]. The PSA solar furnace mainly consists of:

- Four heliostats which reflect the sunlight onto the concentrator disk, each having a reflecting area of 53.61 m², autonomous computer controlled sun tracking mechanism and 90% reflectivity. This system operates independently of the temperature control system in such a way that the heliostat movement is autonomously controlled by a computer that calculates the heliostat positions, which depend on the geographical latitude and longitude, the sun trajectory, the mirror characteristics, etc. Different solar furnaces are in operation in various places [1] using a computer to control the heliostat movements (e.g. [3]) in an open loop fashion. This paper introduces a scheme to control the temperature profile of the samples by the adjustment of a shutter position.
- A computer controlled louvered shutter (control system) formed by 30 panels which regulates the incoming light onto the concentrator (energy flux entering the furnace), with a total dimension of 11.3 m x 11.2 m and 15896 positions between 0° (open) and 55° (closed).
- A collector which concentrates the incoming sunlight onto a test table and consists of 89 spherical sandwich type facets (0.91 m x 1.21 m) with a total reflecting area of 98.5 m², reflectivity 94%, focal length 7.06 m, focal height 6.09 m, concentration (peak) 3000 MW/m², peak power 60 kW and focus size 22 cm.
- A test table where the samples are placed, mobile on three axes with dimensions of 0.7 m x 0.6 m and a displacement path of x=0.86 m, y=0.6 m and z=0.5 m. The movement of the test table is performed by manually acting on six cursors (x↑, x↓, y←, y→, x←, x→) placed onto the operation board that activate the corresponding step motor of the positioning system of the table to allow displacement in the three dimensions of space to position the samples before starting the tests.

Fig. 1(a) is a schematic of the furnace, in which the solar radiation concentration mechanism is shown. Fig. 1(b) shows an outer view of the PSA solar furnace. It can be seen how four heliostats concentrate solar radiation onto the shutter, which controls the fraction of beam radiation (which goes into the fur-

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nace for material testing purposes). Fig. 2 shows how the solar furnace operates inside. The fraction of the solar radiation collected by the heliostats is incident on a static parabolic receiver to concentrate the radiation onto a small surface. The sample is situated at the focal point and the mobile table serves to position it to collect maximum energy before starting the tests. Once the sample has been placed within the focus (on which solar radiation is concentrated), the table stands at a fixed position.

The variability of the input energy provided by the sun (due to its daily cycle and the presence of passing clouds) and the different temperature profiles needed to perform the tests justify the need for some "degree of freedom" in the installation in order to control the input energy to the system. As can be inferred from the previous comments, neither the positioning system of the heliostats nor the movable table are useful for controlling the temperature of the samples (the function of the autonomous heliostat positioning system is to provide the maximum amount of concentrated solar energy and that of the table is to place the sample within the focus before each test). So, from the temperature control viewpoint, the input signal to the system is the aperture of the shutter and the output signal is the temperature measured by a thermocouple welded to the side or the back of the samples. When the task of controlling the temperature of the sample is manually performed by a skilled operator, efficiency and actual results depend on human capabilities. The development of an automatic control system for these kinds of plants presents many advantages, such as the simplification of the operation with the whole system, as the operator has to perform many tasks before and during the operation and the achievement of adequate results for different kinds of samples and for different operating specifications.

**Dynamical Models of the System**

As a first step in the development of an automatic control scheme for the solar furnace, a simplified model of the system was obtained for control design purposes. In this case, a model was obtained from first principles and compared to input/output data measured in the system. In what follows, a simplified energy balance is introduced. For the sake of clarity, the dependence on time of different variables has not been explicitly written. Fig. 3(a) shows a schematic diagram of the energy balance (conservation principle), which is given by: \( \dot{E} = P_e - P_d - P_r = dE / dt \), where \( E \) is the thermal energy of the sample, \( P_e \) is the input power that the sample receives (this term takes into account the incident flux attenuation due to mirror reflectivity, shutter aperture, etc.), \( P_r \) are radiation losses, and \( P_d \) convection losses. The following paragraphs show the mathematical expressions of the different terms of the energy balance.

**Input Thermal Power**

The heliostats reflect a fraction \( I_r = \rho \) of the direct solar radiation \( I \) coming from the sun (\( \rho \) being the mirror reflectivity). The shutter aperture limits the reflected solar radiation going through it. The attenuation which the incident flux suffers is equal to the percentage of the total area of the panels (blind) which is open. The shutter opening is performed by using an AC motor which rotates the axle to which the panels are linked between \( 0^\circ \) (fully open) and \( 55^\circ \) (fully closed). The variable given by the control program is the aperture percentage. As can be seen in Fig. 3(b) the relationship between the aperture angle \( \alpha \) and the aperture \( A \) is \( A = L(\sin \alpha_0 - \sin \alpha) \), where \( L \) is the length of the panel, \( \alpha_0 \) is the angle in which the shutter is completely closed (zero aperture), and \( \alpha \) is the angle which indicates the aperture percentage. The encoders are designed such that the control signal to the motor which moves the shutter is the percentage of rotated angle \( U \) with respect to \( \alpha_0 \), that is, \( \alpha = (1 - U / 100) \alpha_0 \). Thus the aperture \( A \) related to the control sig-
nal $U$ is given by $A = 1 - \frac{\sin((1 - U/100)\alpha_a)}{\sin\alpha_a}$, where $U$ is the input to the system. This conversion introduces a nonlinearity, as the attenuation of the input flux does not linearly vary with the input, but follows a sinusoidal relationship. The power density behind the shutter is:

$$I_p = I, A = I_p S_c(1 - \frac{\sin((1 - U/100)\alpha_a)}{\sin\alpha_a})$$

This power density is collected by the concentrator in proportion to its surface $S_c$ and is projected towards the focus with different losses due to its reflectivity $p_c$. The power obtained at the concentrator output is:

$$P = I, S_c p_c = I S_c p_c(1 - \frac{\sin((1 - U/100)\alpha_a)}{\sin\alpha_a})$$

The energy received by the sample depends upon its surface ($S_c$). Due to the flux distribution at the focus of the system, 90% of the power is concentrated within a circumference with a diameter of about 20 cm. Supposing that the energy flux is uniformly distributed within the focus (this is obviously an approximation, as reality the distribution is of gaussian type), the input power is:

$$P_c = \frac{\rho_c S_c}{S_{(90\%)}}(1 - \sin\alpha_0)$$

$S_{(90\%)}$ and $\alpha_0$ being the focus area and absorption capacity of the sample, respectively.

**Radiation and Convection Thermal Losses**

The radiation losses depend on the emissivity of the sample $\alpha_c$, which is a parameter that determines the capacity of the sample to radiate energy. The irradiated power is $P_i = \alpha_c S_c(T^4 - T_e^4)$, where $\sigma = 1.379 \times 10^{-8}$ $\text{J K}^{-4}$ is the Stephan-Boltzmann constant, $T_e$ is the environmental temperature, and $T$ is the temperature (supposedly uniform) of the sample given in Kelvin degrees. As can be seen, the previous relationship is of nonlinear nature.

Convection losses depend linearly on the sample temperature and on a constant $\alpha_c$ which indicates the capacity of the sample to interchange heat with the air. This constant depends on the position of the sample and on the properties of the air: temperature, viscosity, etc. The power lost by convection mechanisms can be approximated by $P_c = \alpha_c S_c(T - T_e)$.

**Energy Balance**

As has been previously pointed out, the energy balance is given by: $P_i - P_c = dE / dt$, where $E = mC_pT$, $m$ being the

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**Fig. 3.** (a) Schematic of the energy balance, (b) shutter aperture.
mass of the sample, \( C \), the specific heat, and \( T \) the temperature in Kelvin degrees). By substituting each one of the terms:

\[
\frac{\rho \cdot \rho \cdot S}{S_{(100\%\sin \alpha)}} \cdot IS \cdot \alpha_s \cdot \sin \alpha_s \cdot \sin [(1 - U / 100) \alpha_o]
\]

\[-\alpha_s \cdot \sigma_s \cdot (T_s^4 - T_o^4) - \alpha_s \cdot S_s \cdot (T - T_o) = \frac{d(mC_s \cdot T)}{dt}.
\]

(1)

At the equilibrium point \((U_o, T_o)\) the energy variation in time is null. If a small perturbation around the equilibrium point is produced \((U = U_o + u \text{ and } T = T_o + \xi)\), a linearized model of the system which reproduces the behavior of the system around a determined operating point can be obtained and some consequences can also be interpreted. Notice that all parameters which determine the thermal characteristics of a body depend on the temperature. Nevertheless, if small deviations from the equilibrium point are supposed, constant values of the parameters can be used. In reality, this is another focus of nonlinearities in the system as, depending on the operating point, different values of these parameters are obtained. By merging equation (1) and that which can easily be obtained for the equilibrium point and by linearizing both the sinusoidal term and all those terms with high powers, the following relationship can be obtained:

\[
\frac{\rho \cdot \rho \cdot S}{S_{(100\%\sin \alpha)}} \cdot IS \cdot \alpha_s \cdot \cos[(1 - U_o / 100) \alpha_o] \cdot u
\]

\[-4\alpha_s \cdot \sigma_s \cdot T_o^4 \cdot \xi - \alpha_s \cdot S_s \cdot \xi \cdot mC_s \cdot \frac{d\xi}{dt}.
\]

(2)

The fraction in the first term in equation (2) contains characteristic parameters of the system, independently of the type of material. By a few calculations, this term can be embedded in a constant \( K = (\rho \cdot \rho \cdot S \cdot \alpha_s) / (100 S_{(100\%\sin \alpha)}) = 24.95 \) for this system so that, if null initial conditions are supposed and the Laplace Transform is applied to this linearized model \((u(t) \rightarrow U(s); \xi(t) \rightarrow T(s))\), the following transfer function can be obtained:

\[
T(s) = \frac{K \cdot IS \cdot \alpha_s \cdot \cos((1 - U_o / 100) \alpha_o)}{mC_s + 4\alpha_s \cdot \sigma_s \cdot T_o^4 + \alpha_s \cdot S_s},
\]

(3)

which represents a first order model \( T(s) / U(s) = K / (1 + \tau s) \), where:

\[
K = \frac{K_o \cdot \alpha_s \cdot \cos((1 - U_o / 100) \alpha_o)}{4\alpha_s \cdot T_o^4 + \alpha_s}
\]

and \( \tau = \frac{mC_s}{4\alpha_s \cdot T_o^4 + \alpha_s} \).

(4)

From this simplified model, some simple but important conclusions can be drawn:

- The gain of the system depends proportionally on the solar radiation, and the linearized system time constant is independent of it.
- The variation in the gain of the system with the cosine of a term involving the initial aperture angle and the equilibrium operating point aperture models the shutter nonlinearity so that, the higher the aperture of the shutter the higher the system gain.
- Both the system gain and the characteristic time constant depend inversely on the cube of the temperature. Also, samples with large emissivity and convection loss rate values (high capacity of the material to lose energy) have lower values of the system gain and time constant than those samples with low emissivity and convection loss rate values.
- The value of the area of the sample exposed to the concentrated solar radiation does not influence the value of the gain of the simplified model. Nevertheless, the value of the time constant is influenced by the area of the sample, so that (for samples of the same material), the larger the area of the sample the smaller the corresponding time constant.
- Those samples with high specific heat lead to an increase in the time constant of the system.
- The ambient temperature does not influence the linearized transfer function of the system.
- Notice that all these conclusions are valid under the assumptions made to obtain the linearized model. As indicative values, Table 1 shows typical gain and time constant ranges estimated using data from different tests performed on different kind of samples under several temperature conditions (as is commented at the end of the section).

Another aspect relevant to the modeling of the system involves the shutter activating mechanism (AC motor), which introduces two nonlinearities: one of saturation type—minimum (0%) and maximum (100%) aperture—and the other of slew rate type, as the aperture rate response of the shutter is fixed at 5% per

<table>
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<tr>
<th>Table 1. Example of off-line estimated parameters</th>
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<tr>
<td>Zone A (200°C-400°C)</td>
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<td>Small steel sample</td>
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<td>A 316-L steel</td>
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<td>White zirconia</td>
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<td>Silicon carbide</td>
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second, lasting 20 seconds opening from 0% to 100%. These nonlinearities hardly influence the behavior of the different control schemes, as will be seen in the section devoted to simulation studies.

As it is well known, the existence of saturation nonlinearities within control loops incorporating integral action can cause the integral term to achieve undesired values, producing long-lasting oscillations when set point changes are performed (if adequate anti-windup mechanisms are not included). The effect of the slow rate constraints is also harmful from the control viewpoint, as the limitation of the speed of response can also lead to undesired performance of the controlled system.

It is difficult to validate these types of models, as the thermodynamic characteristics of the materials tested vary with the temperature, and quite often information including tables with these characteristics (specific heat, emissivity, absorption coefficient, etc.) is not provided for as wide a range of temperatures as that covered in these types of applications. Different simplified approaches using input/output data from manual tests have been used to validate these models. These approaches have been based on open loop step and PRBS (pseudo random binary sequence) tests used to obtain input/output data for model validation purposes.

Step tests are useful to validate first order models (usually done with the reaction-curve method), as it is simple to estimate

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Fig. 4. Step tests for model validation.
Table 2. Estimated model parameters for a steel sample

<table>
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<tr>
<th>Heating-up Steps</th>
<th>“Cooling”-Down Steps</th>
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<tr>
<td>mean temp. $T_o$</td>
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Gain and characteristic time constant of the system by inspection of the response of the system. They are also useful for studying the variation of the system characteristic parameters under operating conditions, such as changes in working temperature conditions, solar radiation, etc. For example, Fig. 4 shows open loop step tests performed with a small steel sample. A zoom of several zones of the plot has been included showing the real response that obtained by using first order models with the estimated parameters shown in Table 2. These characteristic parameters have been obtained for different operating conditions (given by mean temperature $T_o$ in Celsius degrees, mean shutter aperture $U_o$ and mean direct solar radiation $I_o$) by identifying each of the steps responses shown in Fig. 4. This table provides information for model validation purposes (notice that these values are subject to errors as they have been estimated from input/output data). As can be seen, slightly different dynamic behavior is obtained when heating the samples than in the case of “cooling” them. The values of both the estimated steady state gain and characteristic time constant decrease as temperature increases, and for a similar value of the temperature conditions, the value of the static gain increases as the solar radiation augments. The static gain should also increase as the shutter aperture augments, but the corresponding temperature increase counteracts this effect. These conclusions are in accordance with those obtained from the energy balance.

More comments can be made on model validation. The inverse of the time constant can be written as (see (4)):

$$\frac{1}{\tau} = a_1 T_o + a_2,$$

(5)

with $a_1 = 4\alpha_x S_x / m C_x$ and $a_2 = \alpha_x S_x / m C_x$. If the coefficients $\alpha_x$, $\alpha_t$, and $C_x$ are considered to be constant (this is a reasonable assumption for small temperature ranges), the coefficients $a_1$ and $a_2$ can be computed by a linear regression algorithm using the data given in Table 2. Fig. 5 shows the plot of the values of the identified time constants (inverse of expression (5)). The deviations observed are due to noise and the dependence of coefficients $\alpha_x$, $\alpha_t$, and mainly $C_x$ on temperature (which was neglected) and are small enough to justify the assumptions made to obtain the simplified model.

As has been mentioned, other types of tests performed for model validation purposes are PRBS ones in order to obtain input/output data with enough dynamic information for model parameter identification purposes. For example, Fig. 6 shows one of these tests around 750°C (also including the response obtained with the identified model). A standard least-squares identification method was used in order to obtain the values of the parameters of the model. For example, in the case shown in this example, supposing a first-order model structure, the values of the identified parameters were: $K = 25^\circC/\%$ and $\tau = 38$ s.

Simple Feedforward and Feedback Control Schemes

Many different temperature profiles are required for a wide class of tests [2] covering melting experiences, production of a super alloy wear resistant coating for high temperature applications, etc. The “ideal” specifications for operation in these kinds of plants can be translated into classical control specifications as follows:

- The steady state error for a ramp input should be as small as possible, as temperature profiles of this type (or more complex ones) are frequently requested.
- A fast settling time after a step in the reference temperature is desirable. The required settling time (less than 1-3 minutes) is approximately that obtained by a very skilled opera.
tor and of the same order of the characteristic time constant of metal samples.

- A minimal overshoot for the closed loop system is desirable. This requirement comes from the fact that it is sometimes necessary to work at temperatures close to melting point, and so overshoots or other types of oscillatory responses would destroy the sample.

A sampling time of 3 seconds has been used for control purposes, and relevant signals are stored every second by the data acquisition system running in the central control computer.

Feedforward Control

As has been demonstrated in other types of solar plants [4]–[6], the use of feedforward controllers is fundamental for systems subjected to measurable disturbances (as is the case of direct solar radiation). These feedforward controllers can be used in classical feedback loops as a complementary control action to reject disturbances acting on the system. Two types of configurations have commonly been used for solar processes: parallel and series (Fig. 7). The main advantages and drawbacks are discussed in [4] and [6].

The most important disturbance acting on the system is the solar radiation, which cannot be manipulated and continuously changes during the operation due to the daily cycle and to the presence of passing clouds. The direct solar radiation is measured by using a pyrheliometer and this measurement can be used to cancel, or at least diminish, the effect that changes in this variable produce in the value of the temperature of the sample.

The continuous system transfer function can be written as:

\[ G(s) = \frac{K}{1 + Ts} \]

where the solar radiation proportionally affects the linearized system gain. In order to achieve control results independent of the value of the solar radiation, it is desirable to have a constant value in this variable.

From the studies performed above, it can be seen that if a block with a transfer function \( G_p(s) = \frac{1}{I_{oi}} \) is placed in the forward path (series feedforward controller in Fig. 7), the resulting global transfer function is theoretically “independent” of the solar radiation values, having a gain constant (if the supposition of the operation around an operating point is fulfilled) corresponding to a solar radiation level (input energy) equal to \( I_{oi} \). In this way, the series feedforward controller is simply a variable gain only dependent on the solar radiation. The value of \( I_{oi} \) has been taken close to the mean value of the solar radiation during different tests and is equal to 900 W/m². This is an approximation valid both for steady state and transient conditions, as the transfer function which relates the changes in the sample temperature to changes in solar radiation has theoretically the same characteristic polynomial as the system transfer function (when considering the linear operation and without nonlinearities introduced by the actuator). This is due to the fact that a decrease in the solar radiation level has the same effect on the output temperature as a diminishment in the shutter aperture. Notice that all these considerations are based on several simplifications made when obtaining an approximated transfer function of the system.

Fixed PI Controllers With Anti-Windup Action

As is usual in the development of automatic control systems [7], [8], the first step in the design is to try to implement classical PID control schemes (widely used in many processes). As the plant can be approximated as a first order system and taking into account the system specifications, the decision was made to tune and implement a PI controller. The usual PI transfer function is given by \( G_p(s) = K_p[1 + 1/(Ts)] \). As has been mentioned, the actuator has amplitude constraints which can be accounted for in classical control schemes by including anti-windup mechanisms [9]. The anti-windup mechanism can easily be understood by looking at Fig. 8, where the system includes a new feedback loop injecting the signal generated by the difference between the controller output and the real input to the plant. This difference is introduced into an integrator with integral constant \( T_i \) and is added to the controller output. The signal through the new loop is zero if the control signal is not saturated, but if the actuator is saturated at its maximum value, then \( v(t) = u(t) \) and the signal injected to the new loop is negative, subtracting a certain amount from the accumulated error. In the case of a saturation at the minimum the effect is the opposite.

![Fig. 5. Real and approximated relationships between \( T_o \) and \( T_c \).](image)

*Fig. 5. Real and approximated relationships between \( T_o \) and \( T_c \).*
In many control problems, the existence of an actuator constraint of the slew rate type is not accounted for during the design step and the obtained controller is detuned when implemented to obtain a generally robust and well-damped performance. As the system is modeled as a first order one, a common solution in the control of these kinds of systems to obtain fast responses from simple root locus analysis is to use low integral times and high gain controllers. When implementation issues are taken into account, this is not always an adequate solution, as the output of the controller must be realistic and take the constraints into account. For example, Fig. 9 shows a simulation performed using SIMULINK [10] in which it can be seen how the behavior of a controlled system deteriorates with the existence of constraints. Both graphics correspond to the response to a step change of 500°C in the reference temperature for a first order system with a gain equal to 50 and a time constant of 100 seconds (notice that these values belong to the set of characteristic gains and time constants shown in Table 1 for different kinds of samples at different temperatures). In both cases, the same PI ($K_p = 0.5$ and $T_i = 50$ seconds) has been used. In the first graph (a), in which an ideal actuator is presumed, quite a fast response can be obtained with a percentage overshoot of 2.7%. In the second graph (b), the constraints in the actuator (amplitude and slew rate) have been taken into account, obtaining an unacceptable response with a percentage overshoot of 57.96%.

Designing a PI controller for a first order system without taking into account the actuator constraints is a simple task. From the root locus analysis viewpoint, and supposing the characteristic time constant of the controlled system to be at a determined location, two cases can be considered, depending on the position of the PI controller zero (depending on the value of $T_i$).

In case a ($T_i > \tau$), for low gains, the expected type of response is an overdamped one (two real poles), but the closed loop system dynamics are quite slow. For intermediate gains, two complex poles are obtained and so oscillations are produced in the closed loop response, which, in general, are not desirable. For high gains, two real poles are again obtained, but the zero of the controller is closer to the origin so that the output of the closed loop response could surpass the reference after a step set point change. As can be seen, it seems to be impossible to completely fulfill all the specifications. As a trade-off, the controller can be designed for this last situation (the controller zero is closer to the origin than real closed loop poles). From a simple analysis of the closed loop transfer function, the condition to obtain real closed loop poles is that

$$T_i \geq \frac{4\pi K_p}{(K_p + 1)^2} \quad \text{with} \quad T_i \leq \tau.$$  

An approach is adopted to express the limitations in the design of the controller imposed by the actuator nonlinearities. As this device moves at a rate of five units per second, the idea is to limit the dynamics of the input signal to the actuator at the design stage of the algorithm in such a way that the rate of variation of this signal does not exceed that of the shutter. In this sense, the PI controller can be designed so as to incorporate low-pass action according to the actuator limitations in such a way that all frequencies higher than a determined cutoff frequency $\omega_c$ are attenuated at least in 20 dB (that is, the bandwidth...
of the PI controller is limited at the design stage). The worst case input signal for the actuator is one sinusoidal signal with amplitude equal to 100 and with a maximum slope equal to 5. Thus, if a sinusoidal signal 100 sin(wo t) is introduced in the actuator input, the derivative of this signal int = 0 gives the maximum rate variation which has to be limited to 5, leading to a value w_o = 1/20 rad/s. This approximation introduces another criterion for the PI design.

The analytical expression of the module of the frequency response of a PI controller is given by

\[ |C(jw)| = K_p \sqrt{T_i w^2 + 1}. \]

For \( w = w_o \), the gain of the PI controller must be less or equal to 20 dB. By performing a few operations, another relationship between \( T_i \) and \( K_p \) can be obtained:

\[ T_i \geq \frac{20K_p}{\sqrt{0.01 - K_p^2}}. \]  

(7)

In this way, two inequalities, (6) and (7), relating \( T_i \) and \( K_p \), are obtained. The set of possible PI parameters which fulfill both inequalities is represented in Fig. 10. The upper curve represents (6), that is, the curve delimits the region over which the closed loop poles are real poles. For a proportional gain less than 1/ \( K \), the poles are on the right side of the zero. For upper gains, the poles are placed on the left side of the controller zero. One point belonging to this curve corresponds to a PI controller which produces a critically damped closed loop system (with respect to the situation of the closed loop poles). The lower curve is given by equation (7) and represents the limitation in the controller bandwidth to adjust the controller dynamics to the shutter constraints. The region within which the controller parameters must be situ-
ated (shadowed in Fig. 10) is below the line $T_c = \tau$ and above the
lines representing equations (6) and (7).

One possible approach for obtaining two relationships be-
 tween the system model parameters and the controller pa-
 rameters is to select the point $C$ given by the intersection of these last
curves (notice that this is the less conservative approach, not ac-
 counting for unmodeled dynamics/modeling errors), leading to
the minimum integral time within the possible range. The param-
eters corresponding to this point can be found by solving the fol-
lowing equality:

$$
\frac{4\tau KK_p}{(KK_p + 1)^2} = \frac{20 K_p}{\sqrt{0.01 - K_p^2}}
$$

Both iterative methods and approximations can be used to
solve it. If an analytical solution is convenient (for instance to be
used in adaptive control schemes) an approximated upper bound
on the curve representing equation (7) can be found in such a way
that the solution is given by a quadratic function. It can be dem-
 onstrated [11] that an upper bound of the function on the right
side of equation (8) is given by $2K_p/(0.01 - K_p^2)$, that is,
$T_c \geq 2K_p/(0.01 - K_p^2)$ fulfills equation (7). In this way, the con-
troller parameters can be found by solving the equality:

$$
\frac{4\tau KK_p}{(KK_p + 1)^2} = \frac{2 K_p}{0.01 - K_p^2}
$$

which leads to the solution:

<table>
<thead>
<tr>
<th>Point</th>
<th>$K_p$</th>
<th>$T_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$1/K$</td>
<td>$\tau$</td>
</tr>
<tr>
<td>B</td>
<td>$\frac{\tan^{-1}(\sqrt{400 + \tau^2})}{2}$</td>
<td>$\tau$</td>
</tr>
<tr>
<td>C</td>
<td>$\frac{\sqrt{(3.125 + 0.06K_p^2) - K_p}}{K_p(2\tau)}$</td>
<td>$\frac{4\tau KK_p}{(KK_p + 1)^2}$</td>
</tr>
</tbody>
</table>

Following this design method, for the example of a system with
$K = 50$ and $\tau = 100$ s. (remember that these are representative pa-
rameters for different samples at different temperature condi-
tions), the controller parameters are given by $K_p = 0.085$ and
$T_c = 61.64$ s. By applying this controller to the system under
simulation, the results shown in Fig. 11(b) are obtained, where the
assumption of both an ideal and a constrained actuator has been
made, providing similar results (as was to be expected from the
design), with an overshoot of 6.82% and a settling time of 259 s (the
open loop system settling time in this case is of about 350 s).

Another possibility in this case is to select an interior point of
the shadowed region represented in Fig. 10. For conservative de-
sign purposed (to implicitly account for modeling errors-
process/model mismatch), an interior point of the shadowed re-
 gion in Fig. 10 can be chosen as follows: $K_p$ located half way be-
tween the values of the proportional gain constant of points $A$
and $B$ in Fig. 10; $T_c$ given by the value of the integral time con-
stant of point $A$ minus one third of the difference between the
values of the integral time constant of point $A$ and that of point $C$
in Fig. 10. So, the following formulae can be used:

$$
K_p = \frac{1}{2} \left[ \frac{1}{K} + \sqrt{\frac{0.01\tau^2}{400 + \tau^2}} \right]
\text{ and } T_c = \frac{1}{3} \left[ 2\tau + \frac{4\tau KK_p}{(KK_p + 1)^2} \right]
$$

Again, for the example of a system with $K = 50$ and $\tau = 100$ s,
the controller parameters given by this conservative approxima-
tion are $K_p = 0.059$ and $T_c = 91.87$ s.

The second design possibility given by root locus analysis
(CASE B) introduces the controller zero between the origin and
the system pole ($T_c \geq \tau$). This seems to be a poor solution as the
closed loop system pole is slower than the open loop one, al-
though the existence of a closed loop zero near the origin makes
the closed loop dynamics fast enough to fulfill the settling time
requirements. From the actuator constraint viewpoint, the same
considerations made in previous paragraphs can be made here,
and controller parameters can easily be found [11]. Neverthe-
less, this second approach is more sensitive to modeling errors,
as changes in system gain lead to pronounced changes in set-
ting time.

### Plant Results With Fixed PI Controllers

The control algorithm previously developed (PI control in-
cluding series feedforward control, anti-windup mechanism, and
designed to cope with slew rate constraints) has been imple-
mented at the real plant and different results are shown in this
section. The tests were performed under very different solar radia-
tion conditions and with samples of different materials. Only
tests corresponding to the less conservative approach of CASE A
are presented in this section (other approaches will be shown in
the following sections).

As a first example, Fig. 12 shows the results obtained in a
test with a sample made of silicon carbide. The representative
test was performed on July 30, 1996, and consisted of a set of
steps with an amplitude of 50°C. The objective of this test was
the calibration of the infrared camera. As can be seen, the be-
Fig. 11. Simulation with the PI controller.

Fig. 12. Test with the PI controller, 30 July 96.
behavior obtained in this case is highly dependent on the operating point, having different responses as the set point temperature increases (diminishing overshoot and increasing the rise time), leading to unacceptable performance (this being one of the reasons why an adaptive control approach has been implemented, as shown in the next section). As the temperature increases, the gain and time constant of the system diminishes producing a slower controlled system. Notice that the properties of the samples (specific heat, emissivity, etc.) are also influenced by operation at high temperatures.

Other representative tests were performed by using a white zirconia sample, which has different dynamic characteristics to metal or silicon carbide samples. The results of this test, performed on November 7, 1996, are shown in Fig. 13. The set point temperature profile consisted of two ramps with different slopes. As can be seen, the tracking characteristics of the closed loop system were adequate below 1200°C. Nevertheless, at higher temperatures, the tracking error increased, mainly due to the plant nonlinearities, as a higher shutter aperture is needed as the set point temperature increases.

In conclusion, the use of a well-tuned PI controller (including feedforward action, anti-windup and slew rate constraint handling mechanisms) provides adequate results (from the plant staff viewpoint) for a wide range of tests. Nevertheless, two main drawbacks can be identified:

• The controller must be tuned for each type of sample whose dynamic parameters (characteristic gain and time constant) have to be a priori estimated.

• When using a fixed parameter controller, the controlled system set point tracking capabilities are only acceptable within a small operating range of the whole test.

These drawbacks justify the inclusion of other kinds of control approaches, such as adaptive control, dealt with in the next section.

Adaptive Control

An adaptive control scheme seems to be a possible solution to solve the problem of plants with different types of dynamics. Adaptive control has previously been used in other kinds of solar plants [5], [6]. This control technique provides a framework in which the controller parameters are adapted to the diverse operating conditions and different plant dynamics. The control scheme implemented consists of a self-tuning controller [12] in which the parameters of a simplified model of the plant are identified on-line. From these parameters, the controller parameters are changed according to an adaptation mechanism that relates controller parameter changes to system parameter changes. The adaptive controller also incorporates feedforward action, anti-windup mechanism, slew rate actuator constraints handling and identifier data prefiltering. The control scheme is shown in Fig. 14.

Different problems arise when using adaptive control in solar plants [6], the main ones being:

• The system excitation is usually poor as the identification is performed in a closed loop configuration and the input signals to the plant have few frequency components.

• The existence of two time scales (one for closed loop system dynamics and the other for identified parameter dynamics) is not always assured, mainly when coping with slow processes.

Fig. 13. Test with the PI controller (white zirconia sample used), 07Nov96.

To account for these problems, different variations to classical adaptive control schemes have been introduced. As previously mentioned, the main advantages of using a series feedforward action [4], [6] are both the compensation for solar radiation variations and the preservation of the validity of simple SISO system models of the plant used for estimation purposes (considering the feedforward controller as a part of the estimated plant). This is valid if the actuator dynamics are linear (or, with static nonlinearities, of saturation type). Nevertheless, in this case, due to the slew rate constraints, if the feedforward controller is included as a part of the estimated plant, problems can arise in the estimation algorithm as the input signal to the identifier may not correspond to the real input to the system. To cope with this problem, the input signal to the identifier loop is the real plant input $u(t)$ and different filters can be introduced in the identification loop (scale filters $F_1$ and $F_2$ in Fig. 14). Notice that one possibility is to make $F_1=1$ and to multiply the output signal of the plant by the same filter used for feedforward control before entering the identifier ($F_2=I_{off}/I_{ref}$). In this sense, if solar radiation augments, the output of the plant (introduced into the identifier) is scaled (diminished) by a factor which theoretically makes the values entering the identifier independent of the solar radiation variations. Another possibility is to make $F_2=1$ and to multiply $u(t)$ by the inverse of the feedforward filter ($F_1=I_{ref}/I_{off}$). Notice that the feedforward action can also include the inverse of
the nonlinearity introduced by the conversion from aperture angle to aperture percentage represented in Fig. 3. Scale filters \( F_1 \) and \( F_2 \) can additionally include a first order lowpass filter to introduce smoother signals within the identifier not affected by the noisy natural changes in solar radiation.

The models used for estimation purposes are of first order type and the controller is the PI developed in the previous section. At each sampling time, the adaptive control strategy consists of estimating the linear model parameters using input-output data from the process, adjusting the PI controller.

Fig. 14. Adaptive control scheme.

Fig. 15. Tests with the adaptive PI controller.
parameters, calculating the control signal, and supervising the correct behavior of the controlled system. The parametric identification algorithm used is the least squares one with a fixed forgetting factor, which has to identify only two parameters as the delay of this plant is negligible (the model of the plant is a first order one in discrete time: \( G(z) = \frac{bz^{-1}}{1-az^{-1}} \), where \( z^{-1} \) is the backward shift operator, \( a = \exp(-T/\tau) \) and \( b = K(1-a) \), \( T \) being the sampling time, \( \tau \) the open loop system characteristic time constant, and \( K \) the open loop system static gain). The control laws obtained in the previous section have been used as an adaptation mechanism, as they relate plant parameters to PI controller parameters.

Finally, three basic supervisory mechanisms have been implemented to overcome the mentioned drawbacks of adaptive control schemes. The first one is based on limiting the maximum and minimum values of the estimated parameters, thus avoiding a wrong identification leading to dangerous behavior of the controlled system. The values of the possible range of variation of the identified parameters have been obtained from a dynamic study of the plant and from experience in operating with different types of materials (see Table 1). The second mechanism consists of filtering the obtained estimated system parameters using a first order lowpass filter with a cutoff frequency such that the variation of the estimated parameters is guaranteed to be slower than the plant dynamics (to assure the existence of two time scales). In this sense, the pole of the filter can be placed in the upper limit of the allowed range introduced by the first supervisory mechanism. Finally, the third supervisory mechanism consist of stopping the identifier in cases in which the dynamic information entering the identifier is poor for identification purposes, as sometimes happens when using slow ramps as inputs to the system.

**Experimental Results**

Several tests have been performed by using the adaptive control algorithm for three kinds of materials: A316-L steel (high gains and small time constants), white zirconia (low gains and high time constants) and a small steel sample (low gains and low time constants). In all cases, the characteristics of the materials change with temperature and solar radiation levels.

The first two tests shown in this section were performed by using the case A less conservative design approach (minimum integral time), which does not account for modeling errors. Fig. 15(a) represents a test with the white zirconia sample in which both the evolution of the main variables of the test (temperature, direct solar radiation and shutter aperture) and the evolution of the estimated parameters of a first order model of the plant are shown.

Filtering the estimated parameters avoids the induction of sudden changes in the controller parameters after a step change in the reference temperature. The filtered estimated values converge to adequate values after a transient which depends on the filter used, as can be seen in Fig. 15(a)—the initial values of the parameters differ considerably from the real ones. In the same figure it can be seen that the trend of the estimated parameter approaches that expected of the dynamical study of the plant, as both the gain and fundamental time constant of the system decrease as the temperature of the sample augments and augment as the temperature decreases.

Undesirable initial transients due to a wrong initial estimation of parameters can be avoided by using a conservative fixed PI controller during the transient whereby the estimated parameters approximate the appropriate ranges, by initially introducing a sequence of set point changes to excite the system in order to provide the identifier with dynamic information for identification purposes, or by using some kind of open loop auto-tuning capability [11]. As the estimated parameters achieve the adequate values, the overshoot obtained after a step response decreases (34% at 500°C and between 13% and 24% in the rest of the test). The rise times are between 31 and 40 seconds, which constitutes quite good behavior.

Other similar tests have been performed with an A316-L steel sample, obtaining adequate results which lead to the same considerations made above. For example, Fig. 15(b) shows the results obtained on February 24, 1997, again using the less conservative design approach. After an initial transient during which identifier excursions occur due to the wrong selection of the initial values of the selected model, the controlled system performance improves, as new dynamical information enters the identifier.

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*Fig. 16. Test with the adaptive PI controller (25Feb97).*
A test performed on February 25, 1997, is shown in Fig. 16 with the same type of sample. The relevance of this test comes from the fact that the solar radiation conditions during this test were such that manual operation under these circumstances was impossible, even for a skilled operator. The good characteristics of set point tracking and disturbance rejection are in part due to the series feedforward action, which compensates for changes in solar radiation within a band of 200 W/m² allowing the output temperature to be maintained within a band of 10°C around the reference.

As can be seen from the previous tests, several of the experimental results exhibit a high degree of overshoot and/or oscillation (notice that one of the control objectives was minimal overshoot). There are several causes which contribute to this undesirable kind of behavior. First of all, the design approach chosen in this case (CASE A, less-conservative approach) leads to a closed loop system quite sensitive to modeling errors, which can produce undesirable behavior, especially when using a small value of the integral time constant in the PI controller (as in this case). Moreover, the effect of the controller zero can also lead to an undesired overshoot, or other aspects such as the use of type B thermocouples, which do not provide for any measurement below 100°C (this fact can produce errors in the integral part of the controller at the starting phase of the operation). From the identification viewpoint, it has been pointed out that the wrong selection of the initial values of the estimated parameters can produce undesirable excursions in the estimated parameters, leading to a deterioration of the performance of the controlled system. In the first of the tests shown with the adaptive controller, results show spikes in parameter estimates due to a wrong selection of the filters in the identifier (Fig. 15(a)). These problems can be avoided by a careful selection of the filters and the supervisory mechanisms (as in the second test, Fig. 15(b)).

In order to improve the results with the adaptive controller, some tests were performed using the more conservative design approach (also explained in the section devoted to the CASE A design approach), in which the adaptation law is given by (9), and by a careful selection of the supervisory mechanisms. Fig. 17 shows the results obtained with this approach with a small steel sample. Several set point changes were produced at the beginning of the operation to provide the identifier with dynamic information so that it was able to “detect” the kind of sample and parameters of the supervisory mechanisms could be adequately fixed. Notice that another possibility to characterize the samples at the beginning of the tests is to perform a classical open loop autotuning process. As can be seen in Fig. 17, the behavior of the controlled system was quite acceptable, showing similar response characteristics under different operating conditions, with rise times of about forty seconds and small overshoot (of less than 5°C, except in one of the steps). The evolution of the estimated parameters is also shown in the figure. It can be seen how the evolution is that expected from the studies performed in previous sections, and spikes have been avoided in the identified parameters.

**Conclusions**

An application of an automatic control strategy to a solar plant for material treatment has been shown. Since these kinds of plants are manually operated by skilled operators, the development of an automatic control strategy aimed at achieving adequate results...
throughout the wide range of operating conditions, under which these plants operate, represents an important improvement towards facilitating operation and obtaining desired performance. The control scheme presented is based on a PI controller which incorporates feedforward compensation, an anti-windup mechanism and actuator slew rate constraint handling, both in fixed and self-tuning configurations. It has been developed and applied to the control of a solar furnace for samples of different materials under extreme temperature profiles. Different plant results have been shown and both advantages and drawbacks of the scheme have been commented on.

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