15th Triennial World Congress, Barcelona, Spain

CONTROL OF A CERAMIC TILES COOLING PROCESS BASED ON WATER SPRAYING

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Abstract: The control of the surface temperature of ceramic tiles in a real industrial production line is developed. The process consists of a transportation band that carries the hot tiles through a water sprayer whose objective is to reduce its temperature. The regulation of the quantity of water deposed (and hence evaporated) per tile allows to control the output surface temperature. This quantity is regulated by changing two variables: the velocity of the transportation band and the flow of the sprayer. First, the experimental identification of the process model is carried out. Then, a static control based on the measurement of the input temperature is proposed and tested in the plant. Finally, an adaptive control based on the measurement of the input and output temperatures is developed and also tested in the plant, showing a much better performance.

Keywords: Tile temperature control, water spraying, industrial adaptive control.

1. INTRODUCTION

On the ceramic tiles production lines there is commonly a water sprayer after the dryer and just before the glazer. The objective of this sprayer is to reduce the temperature of the tiles (by evaporation) to adequate levels for the glazer to work well. An inadequate temperature may produce defects that lead to the rejection of the produced tile. Too high temperatures produce a kind of surface defects called ”punctures”, while too low temperatures produce surface defects called ”pools”. Nowadays, almost all the ceramic plants have a fixed water sprayer, that can only be changed manually by the operator. The only automatic regulation system that is used on some plants consists of an extra sprayer that can be switch on or off by an electrovalve depending on the input temperature.

The measurements obtained in a real plant under normal production show that the temperatures are highly time varying. As a consequence, a fixed sprayer (or a discrete sprayer switch) leads to very important fluctuations on the temperature of the tiles that enter the glazer.

This paper is concerned with the study of the automatic control of the surface temperature by continuously changing the mass of water deposed (and hence evaporated) per tile. The objective is to maintain the input temperature at the glazer as uniform as possible in order to reduce the percentage of defects associated to temperature variations.

There are few works in the literature about the water spraying evaporative cooling. One directly related to ceramics is (Abu-Zaid and Atreya, 1994), where the transient cooling of ceramic

[1] This work was supported by the Generalitat Valenciana under project GV00-142-11 and by the Fundació Caixa Castelló-Bancaixa under project P1.1A2000-19. This work was possible thanks to the collaboration of TAU Cerámica.

solids by water drops evaporation is studied theoretically. Other application that is interesting due to its similarity with the proposed problem is the cooling by water spraying in steel continuous casting process (see (Bending *et al.*, 1995)). Nevertheless the conditions and the temperature ranges are very different to the case studied. There are also other theoretical studies about the evaporative cooling models, as (Halasz, 1998) or (diMarco and Tinker, 1996), but the complexity of the process and the particularities of the case studied makes more suitable the direct experimental identification.

The paper deals with the solution of the industrial control problem based on standard well known techniques for identification ((Ljung, 1999), (Nelles, 2001)) and for the control algorithms ((Åström and Wittenmark, 1995), (Isermann, 1991)).

The layout of the paper is as follows: in section 2 the process to be controlled and the experimental setup (sensing and actuating procedures) are described. In section 3 the process identification is carried out. Section 4 describes the feedforward open loop control strategy and experiments. In section 5 the adaptive control is developed and tested, and finally in section 6 the conclusions are summarized.

2. PROCESS DESCRIPTION AND EXPERIMENTAL SETUP

The industrial process is shown in figure 1, including the implemented control system. It consists of a tiles transportation band with a clean water sprayer that creates a flat water curtain perpendicular to the band. When one tile passes through the water curtain a given quantity of water is deposed on its surface. Due to the high temperature of the tile the water evaporates extracting a given quantity of heat and hence reducing the surface temperature. The quantity of water deposed per tile depends on the velocity of the tile and on the flow of the water nozzle. The nozzle is situated inside a steel cabinet. The input and output temperature sensors are located outside this cabinet, and hence they are separated from the nozzle position (around 2 m away).

The water sprayer is situated on the ceramic tile production line between the dryer and the glazer processes. The dryer works in such a way that the output temperatures of the tiles (that are the input temperatures for the process to be controlled) have important variations with time. On one hand there are important differences from one tile to the next, due to their different position inside the dryer, and on the other hand there are slower changes on the average temperature along time.

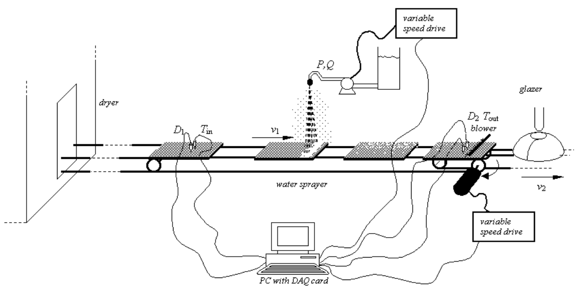

Fig. 1. Process and implemented control system

In figure 2 the temperatures before and after the water sprayer in a normal operation are shown when the quantity of water per tile is fixed (i.e. no control implemented). The output temperature has a very important variation following the pattern of the input temperature. The objective of the control system studied in this paper is to minimize the variation of that output temperature, i.e. to maintain it as uniform as possible, by means of applying a different mass of water on each tile.

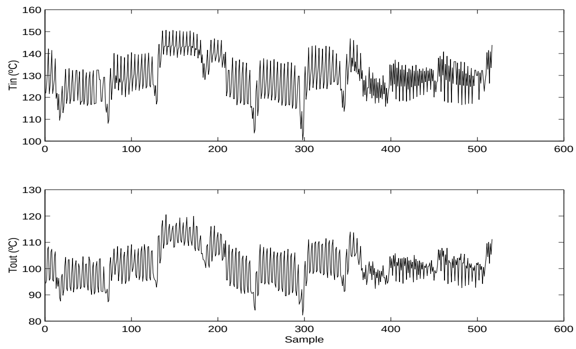

Fig. 2. Input and output tile temperatures with non controlled sprayer

The experimental setup of the implemented control system is shown in figure 1. In order to measure the input and output temperatures two infrared non contact sensors are used, one before the nozzle and the other one after it (with a sufficient separation that guarantees the evaporation of all the water before reaching the output sensor). Two optical proximity sensors detect the presence of the tiles and allow the synchronization of the temperature measurements. The equivalent temperature of a tile is calculated as the average of several measurements taken after the settling time of the sensor. This settling time is around 300 ms, hence the tile should be at least $0.4\, v_{max}\ m$ long (where v_{max} is the maximum velocity that will be applied) in order to be able to take measurements. The velocity of the band is changed by means of a variable speed drive, while the water flow is varied by a high pressure piston pump driven by a variable speed drive and AC motor. The volumetric nature of the pump implies that the flow is proportional to its rotation speed. The control algorithm is implemented on a industrial computer with a data acquisition card that receives the analog and digital signals and produces the analog outputs for the variable speed drives. The settling time for the water flow with this system is approximately 200 ms, while the settling time for the velocity is also about 200 ms. Hence, for applying a uniform mass of water over the whole tile surface the distance between tiles should be at least of $0.2\, v_{max}\, m$.

In order to apply the correct mass of water to a given tile it is necessary to know the exact instant when it passes under the nozzle. This is accomplished simply by integrating the velocity of the tile with time (the exact distance between the proximity sensor and the nozzle is known). This idea is also used to relate the output temperature measurements to input temperatures and mass of water applied to a given tile.

The process variables are defined as:

- $T_{in}(k)$. Average input temperature of tile number k.
- $T_{out}(k)$. Average output temperature of tile number k.
- $Q(k)$. Flow of water while tile number k is passing under the nozzle.
- $v(k)$. Velocity of tile number k passing under the nozzle.
- $u(k) = \frac{Q(k)}{v(k)}$. Control action. This variable is proportional to the mass of water deposed on tile k.

The mass deposed per tile depends on the water flow and the velocity of the tile. Therefore, there are two redundant actuation signals. Nevertheless, besides the usual maximum and minimum saturation limits of the actuators, the velocity change from one tile to the next is limited because consecutive tiles may approach leading to failures and line stops in some processes down the line. Due to the important temperature changes between consecutive tiles, this signal is not suitable for tile to tile control. As a consequence, the water flow will be used for this purpose. Once the control algorithm determines the control action, the velocity and the water flow are obtained according to the following algorithm: if the flow can be changed to produce the desired control action with the present velocity, leave the velocity unchanged. If this is not possible due to the limited span in the flow regulation, change the flow as much as possible and then obtain the velocity (limiting its change to the maximum permitted due to tile separation problems). In this way, if the water flow saturates, the velocity changes in order to avoid that saturation for the next tiles. This leads to the use of the maximum span in the regulation of the water mass per tile.

3. PROCESS IDENTIFICATION

Once the sensing and actuating devices and procedures have been defined, a model of the process must be obtained in order to design the control algorithm.

The complexity of the thermal process makes unsuitable a theoretical identification, hence an experimental identification is proposed. For this purpose a different mass of water is applied to every tile, storing the input and output temperatures. In figure 3 the exciting control input ($\frac{q}{v}$) and the measured temperatures are shown. The

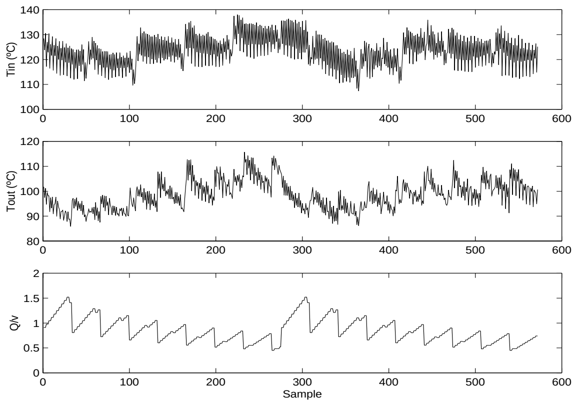

Fig. 3. Control input and temperatures on the identification experiment

objective of the identification experiment is to obtain a static function relating the input and output temperatures to the control action as:

$$T_{out}(k) = f\left(T_{in}(k), u(k)\right) = f(T_{in}(k), \frac{Q(k)}{v(k)})$$

In a first place, a linear function was fitted by least squares leading to

$$\begin{aligned} T_{out}(k) &= a + bT_{in}(k) + cu(k) \\ &= 44.8 + 0.548T_{in}(k) - 16.3u(k) \end{aligned} \quad (1)$$

In figure 4 the residues of the estimated function are plotted with respect the control input, the sample (number of tile) and the input temperature. It is clearly shown that the residues with respect to the control input are not white noise (the deterministic pattern is evident). In order to improve the model, an adequate nonlinear function must be found. The easiest approach (see (Nelles, 2001)) is to increase the degree of the polynomial. Adding a quadratic term of the control action and applying least squares one obtains

$$\begin{aligned} T_{out}(k) &= a + bT_{in}(k) + cu(k) + du(k)^2 \\ &= 58.8 + 0.531T_{in}(k) - 44u(k) + 14.9u(k)^2 \end{aligned}$$

The residues are now much more independent, but the function has 4 parameters instead of 3.

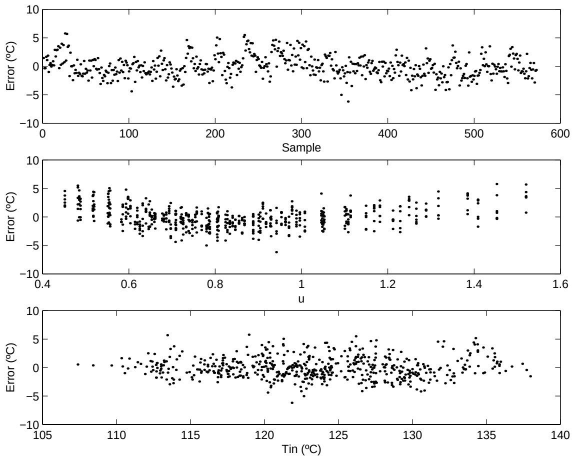

Fig. 4. Residues of the identification experiment with respect k, u and T_{in}. Linear model.

The standard deviation of the error is 1.56^oC. In order to reach a similar error behavior but without increasing the number of parameters, several nonlinear transformations on the variable $u(k)$ were tried. The result was the following non linear (but linearly parameterized) function with 3 parameters (also fitted by least squares)

$$\begin{aligned} T_{out}(k) &= a + bT_{in}(k) + c\frac{1}{u(k)} \\ &= 18.38 + 0.531T_{in}(k) + 11.5\frac{1}{u(k)} \end{aligned} \quad (2)$$

The low number of parameters was especially important for the implementation of a robust adaptive control (as will be shown in next sections). In figure 5 the residues of the estimated surface are plotted against the input temperature, the number of samples and the inverse of the control action. In the figure the low correlation of the error with those variables is shown. The standard deviation is now 1.54^oC. This implies that there are important stochastic effects that can not be compensated (i.e. a limitation on the achievable performance). Other non linear functions were tried leading to a slightly lower error variance, but the increase in complexity (and hence the loss of robustness) did not compensate the accuracy improvement of the estimation.

4. OPEN LOOP FEEDFORWARD CONTROL

The easiest control strategy for compensating the measurable disturbance (T_{in}) is an open loop feedforward control. The benefit of the open loop strategy is that only one temperature sensor has to be used. The controller (as the process model) is static and simply obtains the control action required for a given input temperature and a desired output temperature by inverting the identified model (2):

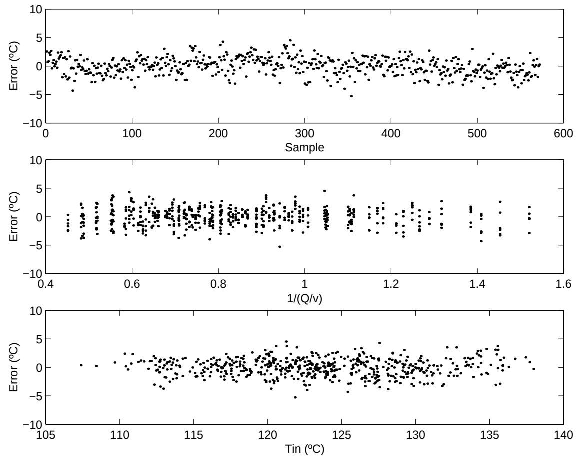

Fig. 5. Residues of the identification experiment with respect k, $\frac{1}{u}$ and T_{in}. Nonlinear model

$$\begin{aligned} u(k) &= \frac{c}{T_{out,ref} - a - bT_{in}(k)} \\ &= \frac{11.5}{T_{out,ref} - 18.38 - 0.531T_{in}(k)} \end{aligned} \quad (3)$$

The above controller was tested on the plant one day after the identification experiment. In figure 6 the input, output and reference temperatures are shown, together with the control action (flow over velocity). The standard deviation of the output temperature has been greatly reduced with respect the non controlled system (3^oC with respect 7^oC). Nevertheless, the output temperature has an average error of about 10^oC. This error reflects an important change in the process and concludes that an open loop fixed feedforward controller is not sufficient. In figure 7 the evolution of the water flow and the velocity are shown. The velocity changes slowly to maintain the span of the flow as centered as possible, while the flow changes rapidly from one tile to the other to control the final temperature.

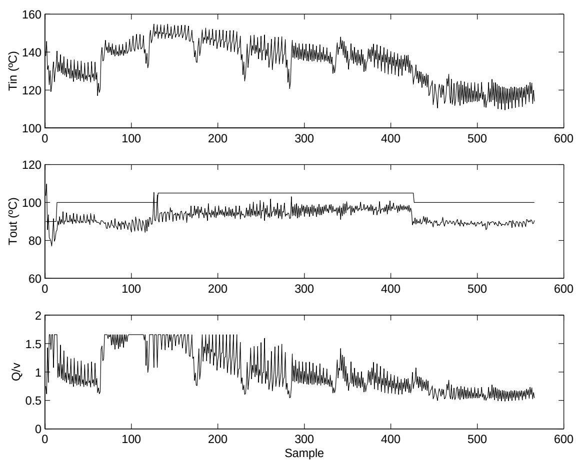

Fig. 6. Input, output and reference temperatures and control action. Fixed controller.

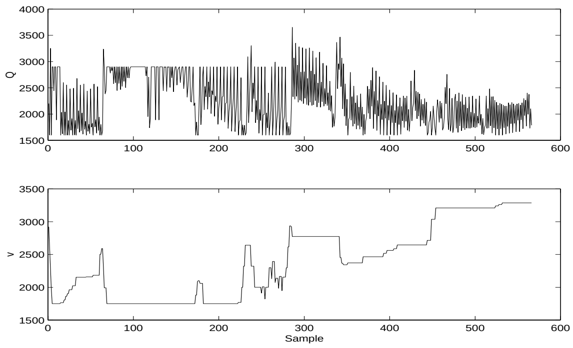

Fig. 7. Flow and velocity variations. Fixed controller.

5. FEEDFORWARD ADAPTIVE CONTROL

The problem of the fixed feedforward control strategy is that changes in the process lead to an important deviation from the desired output temperature, as shown in the previous experiment. The process varies with time due to changes in the dryer, in the composition and humidity of tiles, ambient temperature, nozzle wear, and so on.

The average dc error of the open loop controller could be eliminated by adding an integral feedback term (such a PI controller). Nevertheless the resulting variance would be about 3^o C, that is much larger than that of the identified model error.

In order to improve the performance, the process model should be updated continuously, leading to an adaptive control scheme. The online identification algorithm is a standard RLS algorithm (see (Ljung, 1999)) that estimates the parameters a, b and c from equation (2) based on the input temperature, the inverse of the control action and the output temperature. The parameter and regression vectors are

$$\theta = [a \;\; b \;\; c]^T$$

$$\psi_k = \begin{bmatrix} 1 & T_{in}(k) & \dfrac{1}{u(k)} \end{bmatrix}^T$$

The controller will be the same open loop feedforward controller, except that the parameters are updated online by the RLS algorithm. The choice of the forgetting factor is a compromise between rapid identification of fast process changes and the adequate filtering of the very important disturbances. After some simulations, a value of $\lambda = 0.995$ was chosen for testing the adaptive controller on the plant. In figure 8 the input, output and reference temperatures as well as the control action obtained in the plant experiment are shown. After the initial transient necessary to identify the correct process parameters, the average error is approximately zero, clearly improving the behavior of the fixed controller. The standard deviation is also lower to that obtained with the fixed controller (about 2.2^oC). In fact it could be even lower because the control action saturates quite frequently in this experiment due to very high input temperatures. If the data between tile numbers 50 and 180 are considered (after the RLS initial transient and before the high control saturation interval) the standard deviation is about 1.5^oC, that is, similar to the off line identified model error.

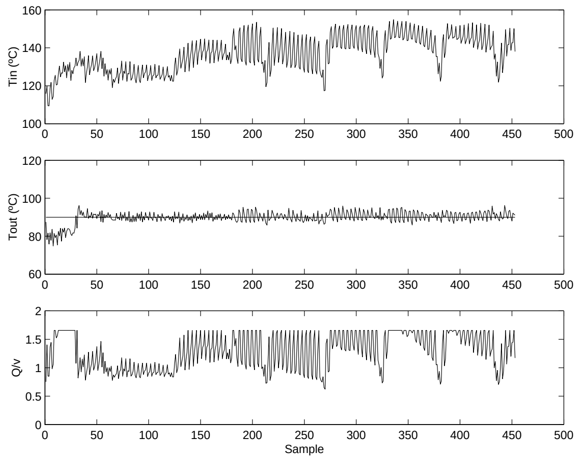

Fig. 8. Input, output and reference temperatures and control action. Adaptive controller.

In figure 9 the evolution of the estimated parameters with time is shown. During the initial transient (first 30 samples where the prediction error is high) the process parameters converge to values near $\theta \approx [24 \;\; 0.4 \;\; 11]^T$, that are similar but slightly different from the ones obtained on the off line identification. When the prediction error converges to an independent signal of zero mean (since sample number 40 approximately), the parameters suffer a quite fast and significative change, converging around the values $\theta \approx [-8 \;\; 0.6 \;\; 19]^T$. This is due to the lack of excitation when the process is perfectly controlled. In this case the output temperature remains approximately constant at $T_{out} \approx 90^oC$. This means that there is not enough information to identify the surface $T_{out} = a + bT_{in} + c\frac{1}{u}$, but only the intersection of this surface with the plane $T_{out} = 90^oC$. As a consequence, the identification algorithm may converge to any surface whose intersection with $T_{out} = 90$ is the same as that of the true surface. In fact, the previous parameters ($[-8 \;\; 0.6 \;\; 19]^T$) define one of those possible surfaces. It is obvious that in this case the "true" parameters of the process are not obtained. However, the model is still adequate for control purposes because the predicted output temperature is the correct one. The only concern is the possibility of a wind up of the variance-covariance matrix due to this lack of excitation. In figure 10 the evolution of the trace of this matrix is shown. Since tile number 90 till tile number 180 the trace increases, but not dramatically. Since tile number 180 till the end of the experiment, due to the saturation of the actuator, the error is no longer an independent signal of zero mean, and hence, the algorithm has enough information to identify the "true" process model (in fact, the parameters converge again to values near the initially identified ones). This leads to the stabilization of the trace (that stops increasing). During normal production, however, there could be long periods of time without saturation and the trace could then grow leading to numerical problems. Therefore, for a long term implementation, a trace control strategy should be implemented (see (Åström and Wittenmark, 1995) for some alternatives).

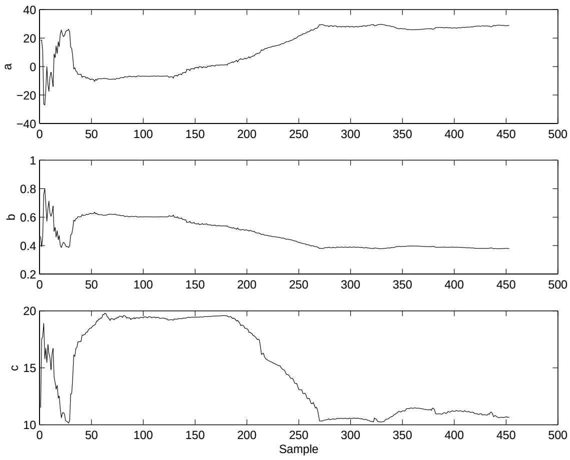

Fig. 9. Model parameters. Adaptive controller.

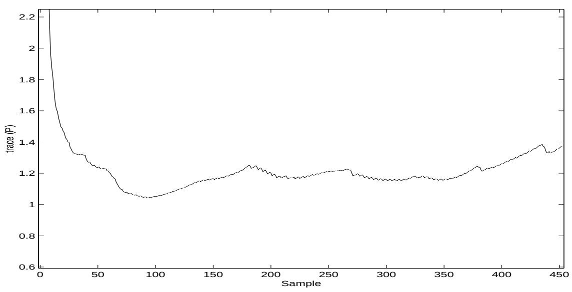

Fig. 10. Trace of the variance-covariance matrix.

The proposed control scheme does not use an explicit feedback term. However, the feedback is implicit on the RLS online identification. The addition of an explicit feedback PI term was tested in simulations, but the performance was not improved. The reason is that the main control problem is the rejection of the input temperature disturbance, that is a measurable signal that suffer important changes from one tile to the next. The feedback can only compensate for the slow variations, but this is already done by the online RLS algorithm. The feedback could be interesting if no adaptation is used. In this case, the feedback term would compensate for variations of the process model parameters related to the control action, leading to null mean error. The drawback is that the changes on the parameter related to the input temperature are not detected, and hence, the variance of the error is not minimized, leading to a worse performance.

6. CONCLUSIONS

In this paper, the control of the surface temperature of tiles by means of variable water spraying has been studied.

First, the experimental setup has been described, including the sensing and actuating procedure.

An experimental identification has been carried out, leading to a very simple nonlinear static model that relates the mass of water deposed per tile to the input and output temperatures.

A fixed open loop feedforward control has been defined and tested in the plant. The controller used in the experiment was defined with the model identified one day before. The performance was very poor (an error about 10^{o}C in average and standard deviation about 3^{o} C), due to significant changes in the process.

To overcome this drawback, an adaptive feedforward control was designed and tested in the plant. The performance was very good, with a null average error and approaching the error standard deviation of the process model (about 1.5^{o} C).

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