CONTROL AND AUTOMATION IN THE CERAMIC INDUSTRY. EVOLUTION AND PERSPECTIVES.

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ABSTRACT

The last 30 years have witnessed a tremendous transformation of the ceramic tile production process with the incorporation of technology that has in some cases been quite revolutionary. This technology is still in a state of incipient automation, albeit with great possibilities for development which, if realised, will enable increasing the flexibility and productivity of the manufacturing facilities, and the quality and performance of the end product, thus enhancing company competitiveness.

The present paper analyses the current possibilities of automating the ceramic tile manufacturing process stages, describing the different measurement systems and the state of the art in each case. The advantages and disadvantages of the proposed control systems are analysed, highlighting the features that could help outline the 'production plant of the future'. The last part of the paper presents the results of a recently developed automatic control system of porcelain tile bulk density.

1 INTRODUCTION

Maturity in technological processes is evidenced by an increasing interest in matters relating to control and instrumentation. Certain studies indicate that the ceramic tile sector has reached high degrees of automation, in comparison with the sanitary ware or tableware branches [1]. The incorporation of control in the ceramic industry has advanced according to a series of phases, which have often evolved in parallel fashion, and have not all developed to the same extent in every production stage.

In the traditional chemical industry, process control is further advanced than in the ceramic industry. This is partly because the ceramic sector works with solids, and the level of knowledge in unit operations involving solids has progressed far less than in fluids. The second point that makes automatic control difficult stems from the structural nature of the ceramic product, which causes its required end characteristics to be multiple and complex, unlike what happens in most chemical processes in which the most important feature is usually the chemical composition; in the case of ceramic tiles the end product must meet a number of requirements that range from purely technical characteristics (low porosity, wear resistance, etc.) to aesthetic qualities (gloss, design, etc.), often restricting the implementation of control systems. Finally another aspect that makes automation difficult in this type of industry is the wide variety of products (models) that the same company needs to make at present.

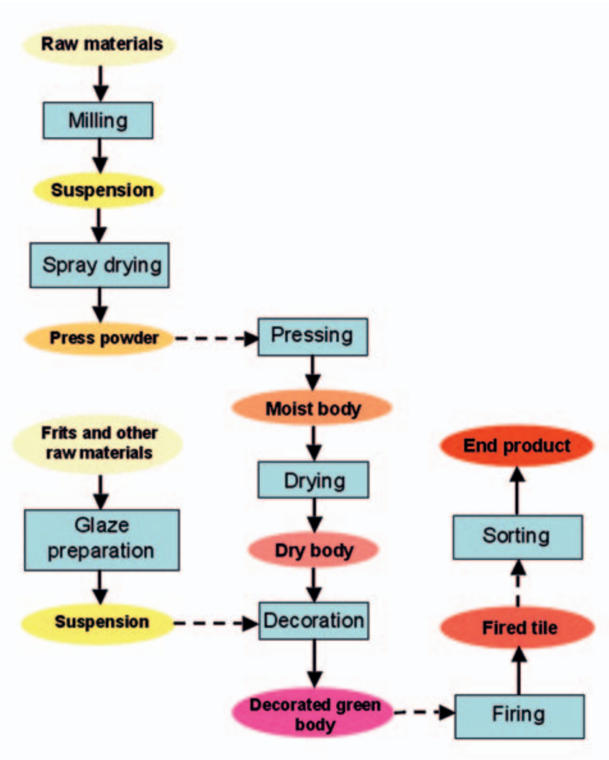

Figure 1. Manufacturing process of pressed and glazed ceramic tiles by single firing, using the wet method.

The fact that the ceramic materials production process requires performance of different consecutive basic operations (milling, spray drying, pressing, etc.) on the materials until obtaining the end product (Figure 1) has caused the introduction of automatic control to be gradual, and this has been undertaken according to process stages; this modular character of the process means that the characteristics of the material resulting from the series of operations in a stage, although not necessarily determinant for the end product, are of extraordinary importance since they define the material's behaviour in the following stage. The material resulting from a given stage – sometimes referred to as a product – is in fact a semi-processed raw material that will be used in a subsequent process stage (for example spray-dried powder), or an intermediate product, which will subsequently be transformed (for example, a pressed tile body).

With a view to quantifying the implementation of control in the ceramic industry, certain 'levels of automation' may be defined (Figure 2). At the bottom level there is purely manual control and at the top there is comprehensive automatic control, which would encompass all the production stages and their interactions.

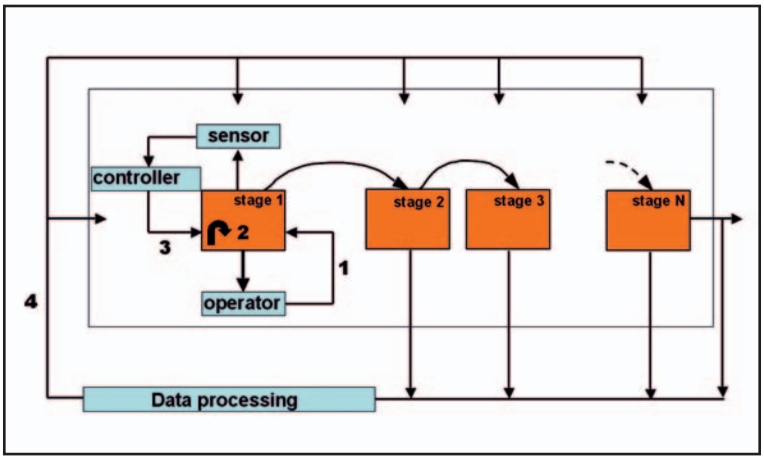

Figure 2. Levels of automation

1.1. LEVEL 1: MANUAL CONTROL

The first *control level* could be termed *manual*. An operator measures one or more variables and, depending on product specifications (settings), modifies manually a series of variables. Examples of this type of action are found in most of the companies that make spray-dried powder, in which control of powder moisture content is made by manual measurement with an infrared balance, then acting on the burner setting temperature or on some other variable.

1.2. LEVEL 2: AUTOMATIC CONTROL OF THE MACHINE VARIABLES

The complexity of many modern machines (dryers, presses, kilns, etc.) causes a certain control to exist in all of these. This control involves *machine variables,* as opposed to *product variables,* which are the characteristics of the material being processed. This control level is found in innumerable facilities; for example, the press, in which the machine variable that is controlled is pressing pressure, whereas the product variables that are regulated are the bulk density and thickness of the piece.

The control levels are not associated with machines, as one might be led to imagine, but to sets of input and output variables. Thus, in the spray dryer, the pair of variables *gas temperature/spray-dried powder moisture* is manually controlled *(level 1)* at most companies, whereas the pair of variables *gas temperature/burner gas valve position* is a clear example of machine variables control *(level 2)*.

The use of relatively simple control systems, such as PID controllers or PLC programmable logic controllers, is characteristic of this level. The dizzying advances in computer science in the two last decades have led many machines of a certain complexity to be equipped with computers. However, it is a little discouraging that, in spite of the potential that these devices have, in most cases they are just used as mere data recorders, when they could have a much more active role.

1.3. LEVEL 3: AUTOMATIC CONTROL OF PRODUCT VARIABLES

At the third level of control lies the regulation of *product variables.* This third level involves at least two different areas of knowledge: that of materials and processes, and that of instrumentation.

The knowledge of the materials and processes involved in the manufacture of frits and ceramic tiles is sufficiently advanced to implement a control system in most cases. This is partly because in order to carry out the control it is sufficient to have a model of inputs/outputs, which relates the modifications that take place in an output variable as a result of the changes in an input variable. General techniques such as design of experiments or the empirical identification of parameters can allow obtaining the necessary knowledge to implement automatic control.

The greatest difficulties in automatic control lie, in almost every case, in having the appropriate sensor to make the measurement or in defining the variables on which to act *(handled variables)*. The selection of a new sensor is usually a complex process, since it must work with sufficient accuracy and robustness in a field for which, in all likelihood, it was not originally designed. Typical cases are the infrared moisture-measuring devices, designed originally for moisture measurement of tobacco leaves; radio frequency-based measuring devices, used in the wood and gypsum industry; or density sensors by bubbling, applied in the mining industry.

In the simplest cases, such control can be carried out with PID controllers or programmable logic controllers; however, as the equations that govern the processes are more complicated, it is necessary to use computers. In other industrial sectors, computers are used for feedforward systems, predictive control, expert systems or for dynamic simulation [2]. At present the use of models of this type is only found in automatic tile sorting systems. Although studies have been developed for the application of these advanced systems in process control (application of DMC (Dynamic matrix control) models [3] to milling, dynamic simulation applied to tile drying [4], or the implementation of compaction diagrams for tile density control at the press exit [5]), such developments are not very widespread at the present time.

1.4. LEVEL 4: COMPREHENSIVE CONTROL

The different unit operations that make up the ceramic process (milling, spray drying, pressing, etc.) are not independent. The output of one represents the input to the next (Figure 1). Thus, control of the moisture content in press powder conditions the bulk density of the pressed tile bodies, which in turn influences the linear shrinkage of the pieces during firing.

The inadequate execution of any stage in the process not only affects the development of the following stages, but also the characteristics of the semi-processed products (porosity, permeability, etc.) as well as those of the finished products. The ceramic tile manufacturing process is essentially a set of interconnected stages that progressively transform the starting raw materials into the finished product [6]. Automatic control cannot and should not limit itself to individual stages. Comprehensive process control is an approach whose application would allow having information (and not just data) on the process, in order to optimise the manufacture of tiles comprehensively and detect weak points.

In the ceramic industry this fourth level is starting to be tackled, although in an incipient form and involves, particularly, the acquisition of information. There are a growing number of companies that have a centralised system in which the operators introduce process data in each stage, indicating the number of processed pieces and monitoring the pieces throughout the process. Unfortunately certain key aspects have not yet been addressed: thus, for instance, it is virtually impossible to achieve machine intercommunication because the machinery manufacturers use closed communication protocols. The use of closed protocols is a way of assuring exclusiveness: nobody but the manufacturer is able to communicate with the machine or integrate it in a larger network.

Comprehensive control should also envisage comprehensive action; i.e. acquisition and handling of process variables, and not just the acquisition of information related to machine productivity. The technology available today allows taking this step.

2. CONTROL AND AUTOMATION OF THE DIFFERENT PROCESS STAGES

2.1. MILLING

Milling serves to obtain a homogeneous suspension of solids in water with an appropriate particle size distribution (PSD) for conducting the subsequent stages (pressing, drying, etc.), compatible with high solids content and an appropriate viscosity, so that the spray drying operation will be optimum [7].

The particle size of the solids in the suspension conditions the behaviour of the piece during processing (compactness, permeability, etc.) and determines some of the parameters of the finished tile (end size, porosity, etc.). The measurement of particle size distribution is complex and expensive, which is why, on an industrial level, the close relation is used that exists, for a given material and type of mill, between PSD and the quantity of coarse particles of the solid for different milling times. In fact, wet milling mainly reduces the size of the coarse particles, narrowing the PSD, which is why the measurement of the oversize (as such sieving is colloquially known) enables controlling the milling operation by means of a simple test.

Suspension density largely determines the energy efficiency of the spray-drying stage and must, therefore, be as high as possible. However, for a given composition, when density is increased, viscosity also rises; high viscosities make it difficult to empty the mill, and can lead to malfunctions (formation of crusts and agglomerates), diminishing the sieving speed and adversely influencing spray drying. For these reasons, in the milling stage it is attempted to achieve the highest possible suspension density, keeping a constant viscosity that enables processing the suspension.

In milling it is necessary to distinguish between milling in continuous mills and batch milling in Alsing-type mills. Automation is much easier in the former than in the latter; therefore, in this section the discussion will focus on continuous mills.

The machine variables (solids, water and deflocculant flow rates) are measured automatically. In terms of the differentiation in control levels outlined in the introduction, one could consider continuous milling to be at *level 2*. In the last five years important efforts have been devoted to implementing automatic suspension density and viscosity control, leaving aside oversize control [8, 9]. The idea of automatic control in continuous mills consists of on-line measurement of density and viscosity, which are currently measured manually, and acting on the water and deflocculant flow rates (Figure 3).

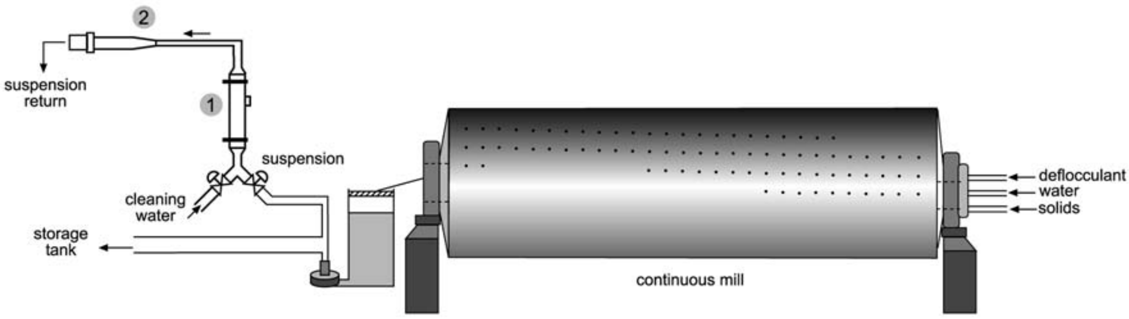

Figure 3. Scheme of the arrangement of the measuring elements in an industrial continuous mill. 1: Densimeter/flow meter; 2: Viscometer.

The main difficulty in automatic control of this operation is the selection of reliable density and viscosity measurement elements, given the harsh industrial operating conditions. At present, the industrial measurement of suspension density can be considered solved by the use of Coriolis-effect densimeters (Figure 4).

The future tendency for control in this stage would involve design of an advanced control system that measured density, viscosity and even oversize. However, the difficulties are numerous: interaction between the density and viscosity control loops, fine-tuning of a viscosity sensor, etc. The incorporation of the oversize, although technically possible, poses certain difficulties whose solution is not foreseen in the short term. The control system, necessarily, should be smart enough to manage the interaction between all the variables, which is not possible just by using PID controllers.

Figure 4. Coriolis-effect densimeter

2.2. SPRAY DRYING

Spray drying of the suspension obtained by milling is the most widespread granulation procedure in the ceramic tile sector in Spain and Italy for obtaining the press powder. There are two key variables in press powder: moisture content and granule size distribution.

Moisture, together with maximum compaction pressure, determines the bulk density of the body which, as we shall see below, is one of the most important variables in the entire production process. The quantitative relation between density, pressing pressure and moisture is set out in the well-known compaction diagram [10].

Granule size distribution (GSD) determines the flowability of the powder, which affects its behaviour, fundamentally in filling the press die [11, 12]. Appropriate flowability of the powder leads to homogeneous filling of the press die and uniform distribution of the bulk density of the compacted body; if bulk density is uniform, the behaviour of the body during processing will also be uniform and more importantly, end product geometry will be appropriate.

Studies conducted by ITC [13, 14] have meant an important advance in the control of the pair of variables *gas setting temperature/spray-dried powder moisture*. At present many companies use infrared measuring devices next to a spray-dried powder sampler to monitor powder moisture content; however, fewer companies use this signal to complete the control loop, and not only *measure* but also *control* moisture (Figure 5).

Granule size distribution could be measured automatically; however, there are two factors that make it difficult to control this variable: the high cost of the sensors and the fact that with present spray dryer design and, in particular, nozzle design, granule size distribution cannot be readily modified.

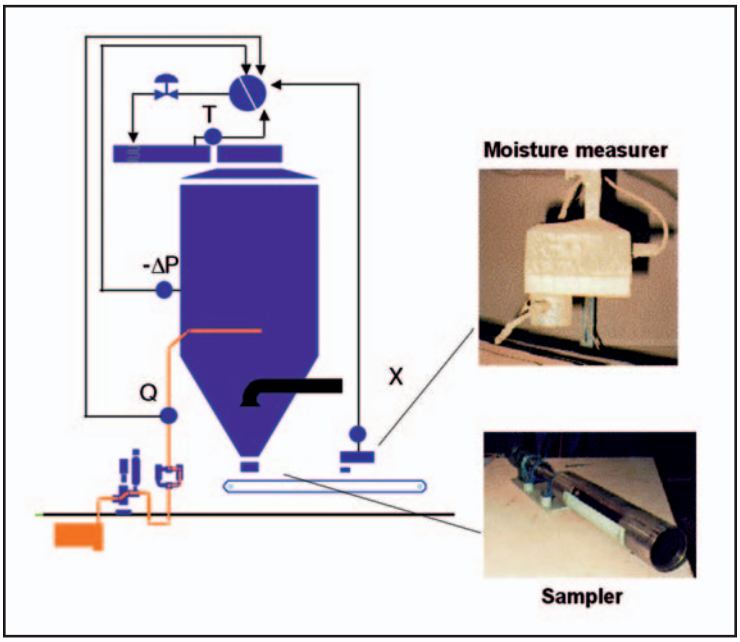

Figure 5. Automatic control of powder granulate moisture content at the spray dryer exit

2.3. PRESSING

The most important process variable related to the characteristics of the pressed body is its bulk density, both in terms of its mean value in a given piece and between pieces, as well as its distribution within a given piece.

Bulk density influences tile behaviour during the stages subsequent to pressing and conditions some of the most important characteristics of the end product. Bulk density is the macroscopic variable that reflects the porous structure of the body, which is why it determines, for a given composition, the body's gas permeability, mechanical strength, sintering process, elastic modulus, etc. Inadequate bulk density can lead to cracks in drying, breakage in the glazing line, black coring, lack of dimensional stability (calibres and/or departures from rectangularity) or lack of planarity in the end product or inappropriate final porosity [10, 11, 12, 15].

Homogeneity in bulk density distribution has improved greatly in recent years with the use of hydraulic punches; although the lack of uniformity has not altogether disappeared, the main concern at present is the difference in bulk density between tiles.

The bulk density measurement is currently made in a manual or semiautomatic way, by means of the mercury displacement method. Studies have been undertaken [16] to attempt to replace this test, given its discontinuous, manual, destructive and harmful character; however, no satisfactory solution has been found to date to enable using this as an industrial control. At the moment the use of ultrasounds is being tested for this application, with very promising results [17]. The Instituto de Tecnología Cerámica has also developed and patented a device that measures bulk density by X-ray absorption (Figure 6). In the tests conducted on a laboratory scale sufficient accuracy has been obtained to use it as a control system [18].

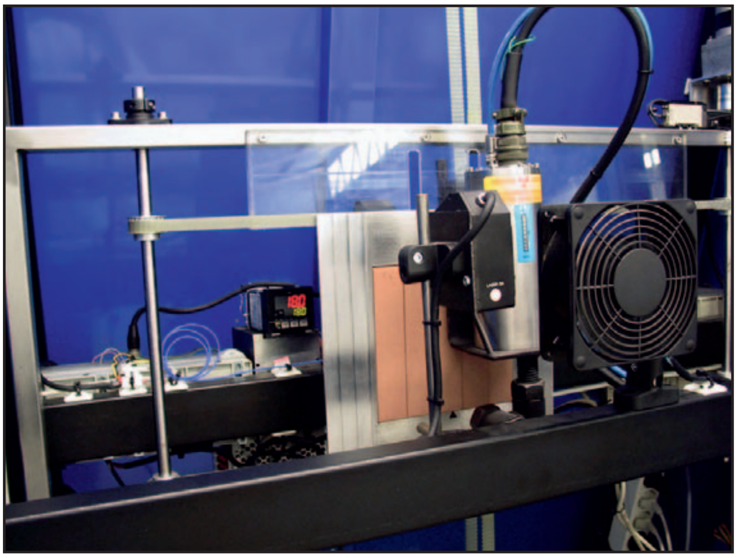

Figure 6. Bulk density measurement of the tile bodies by radiological inspection

On-line measurement of bulk density using ultrasound sensors [19] has been attempted, without yet achieving the required accuracy in the experiments done to allow tackling automatic control. Fitting strain-gauge sensors in the press punch to measure the pressure distribution on the bodies during compaction, together with the use of infrared sensors to determine the pressing dust moisture content, has been another attempt to obtain on-line measurement of the bulk density distribution [20]; however the mechanical complexity of the system has prevented its industrial application as a control system.

An alternative way of tackling the problem consists of using a feedforward control strategy. Feedforward control is based on measuring the variable that causes the disturbance, and not the variable to be controlled, as occurs in feedback control. The main disturbance variable is known to be the moisture content of the press powder, which is why measuring this should enable controlling bulk density. Thus, the moisture of the body can be measured with an infrared sensor located at the press exit, modifying pressure according to the moisture variations to keep bulk density constant. This system allows estimating the mean bulk density of the bodies on-line and holding this within the set variation margins, significantly reducing the percentage of calibres, as will be discussed below.

2.4. DRYING

Drying of the ejected compacts serves to reduce their moisture content and provide them with an appropriate temperature for the decoration stage to take place properly.

The process variables to be controlled after drying, in relation to the bodies, are tile temperature and moisture content. High residual moisture in the bodies ($> 0.1\%$) reduces their mechanical strength and makes the decoration operation difficult. Temperature affects the glazing stage: inadequate values can produce defects (pinholes, etc.) or inhomogeneity in the glaze spread on the tile surface.

Both tile temperature and moisture at the dryer exit depend on the temperature distribution and, to a lesser extent, the relative humidity of the gases in the dryer. The information available on the temperature curve in the dryer is very fragmentary, especially in the vertical dryers.

Temperature probes have been developed that are placed in the dryer and contribute information on the temperature curve of the gases or of the tile surface [4]. These probes consist of a data logger with a series of thermocouples and they are used sporadically in dryer diagnostics. Figure 7 shows the gas temperature profile obtained with one of these probes, in three different positions inside the vertical dryer.

The information from the temperature curve in a dryer allows detecting areas in which drying is too slow (with the ensuing loss of efficiency) or too fast (which can originate problems of breakage), and can thus help in designing more rational drying curves.

The temperature at the dryer exit is usually measured by optical pyrometers with a readout in which the worker can see the instant value of the temperature. Therefore, a point reading of the tile temperature is available as the tile passes under the pyrometer. It is impossible, under these conditions, to know the mean temperature of a tile located in given position in the dryer. A software has been developed that enables combining the information of tile mean temperature at the dryer exit with its position in the dryer [21]. Figure 8 depicts the evolution of the mean temperature at the dryer exit of three tiles, which were located in different positions in the dryer.

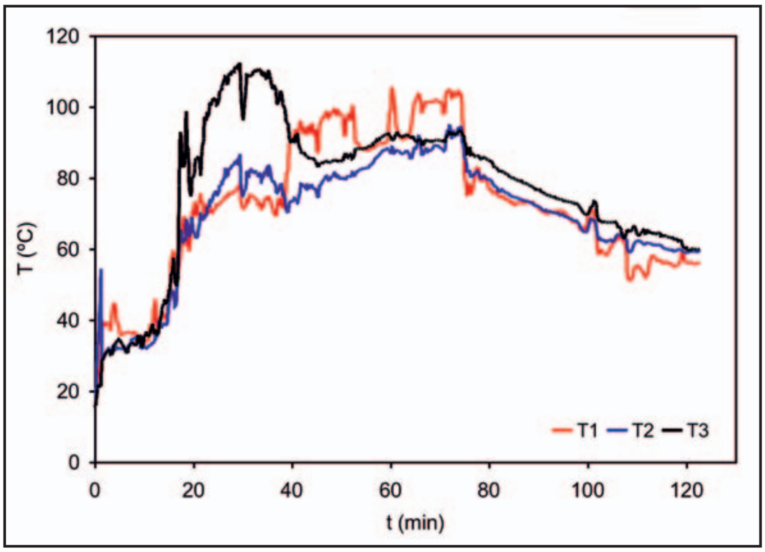

Figure 7. Gas temperature distribution in a vertical dryer during a drying cycle, in different positions

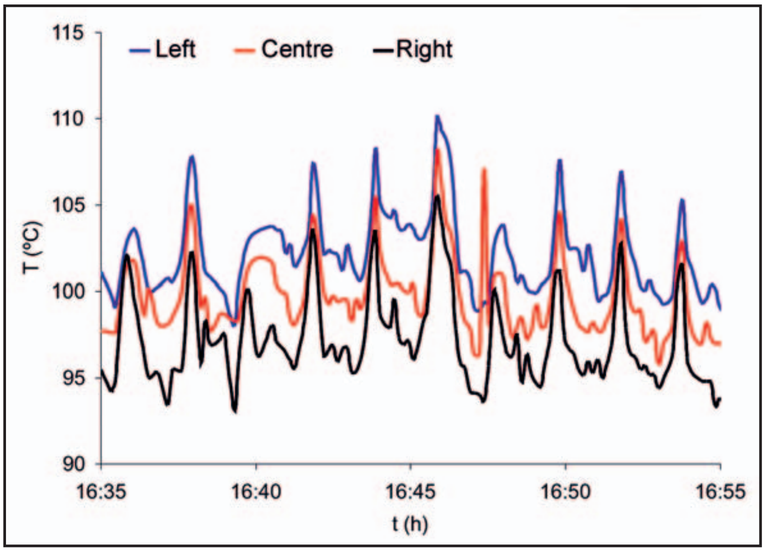

Figure 8. Evolution of the temperature of three tiles, located in different positions, at the dryer exit

The use of this instrumentation is not complicated, particularly in vertical dryers, and it contributes useful information on dryer operation and thermal stability, in both a steady and non-steady state.

The second variable of importance in industrial drying is tile residual moisture. This residual moisture influences tile mechanical strength [22]: greater moisture content means lower mechanical strength and, therefore, a greater likelihood of breakage.

Residual moisture content is usually measured manually from test specimens cut from industrial pieces, which are set on a balance with electric resistances or in an oven. The infrared moisture sensor used in measuring moisture content of the pressing powder and of the ejected compacts (feedforward control of their density) cannot be used in this case, since infrared radiation penetrates very little and only allows determining the moisture in the tile surface. In order to measure the mean moisture it is necessary to use microwave or radio frequency sensors. There is greater experience in the ceramic tile sector with these last sensors; tests have shown that these devices can be used to obtain accurate measurements of tile residual moisture at the dryer exit.

2.5. GLAZING AND DECORATION

This operation is not a single stage, but a set of linked substages. Each of these substages has its own independent variables, although interactions undoubtedly exist between the different substages; thus, for example, the amount of water applied with an airbrush influences the quality of the base glaze application.

Efforts have been made to implement a monitoring system and even control these substages. There have been attempts to control the amount of glaze applied by means of load cells. The results obtained have highlighted the difficulty of making sufficiently accurate measurements of the weight of the pieces before and after each glaze application.

Greater success has been achieved in controlling the amount of glaze applied by the bell [23] (Figure 9). In this case, an electromagnetic flow meter records the glaze flow rate provided by the bell, and corrects deviations by actuating a motorised valve.

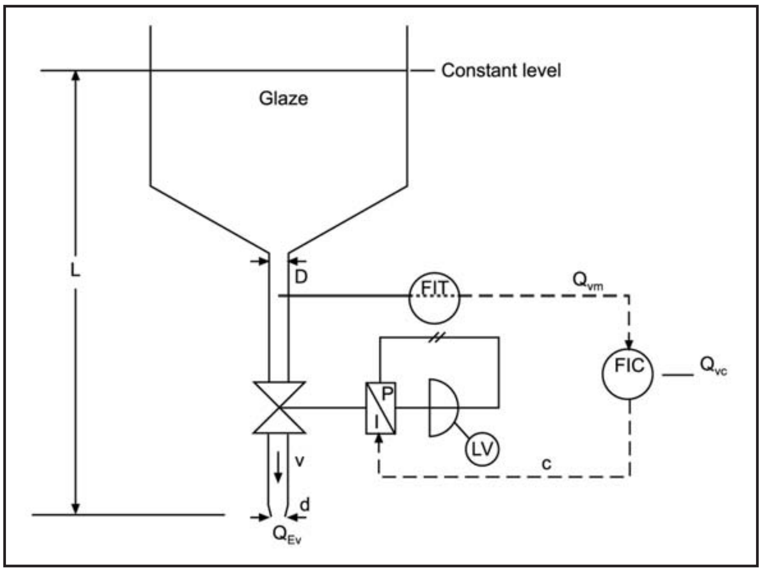

Figure 9. Scheme of the automatic control system of the glaze flow rate at a bell

It was verified that, when the valve was held in the manual position, the variations in flow rate were significant, stemming fundamentally from the variation in glaze viscosity, due, in turn, to changes in density (by evaporation of the water) and in temperature (ambient changes and heating caused by the impeller pump).

Figure 10 shows the distribution curve of flow rates with manual control and with automatic control, in which the signal of the electromagnetic flow meter is used to keep the glaze flow rate constant.

Many of the problems that appear in the glazing line are related to incorrect application of the decoration, which leads to defects that are visible in the glazing line itself.

This idea has caused some companies specialising in automatic visual inspection to study the use of these systems to evaluate the characteristics of the pieces before firing [24].

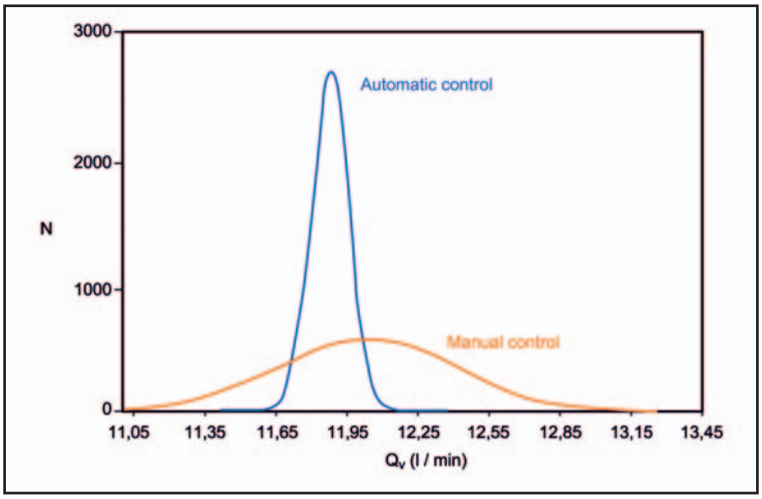

Figure 10. Distribution of glaze volume flow rates with manual and automatic control

The benefits of detecting improperly decorated pieces in the glazing line are obvious: only the properly decorated pieces go on to the following stage (firing); this saves glaze and energy, and increases production and percentage of first quality, etc. However, visual inspection in this process stage faces many difficulties. First, there is the presence of dust and water, which requires protecting all the systems. Secondly, there is the difficulty of detecting defects in green pieces. The technique is promising, but it is still in an early stage.

2.6. FIRING

Firing is one of the most important stages in the ceramic process since it provides the tiles with their final technical and aesthetic characteristics; it is also the thermal stage with the greatest energy consumption. The kiln variables on which it is possible to act and which determine tile characteristics and energy consumption are: temperature distribution, both longitudinally and transverse, pressure and composition of the gases inside the kiln, fundamentally the amount of oxygen. This involves, in terms of control language, a *distributed-parameter* system, in which the complete curves are to be controlled and not just one value of these.

In general, although there have been attempts to control the pressure curve and even the oxygen percentage in the kiln gases [25, 26], only the temperature is measured and controlled on-line throughout the kiln (firing curves). However, this measurement is often insufficient and the temperature differences across the kiln (transverse distribution) are important. Instruments are available that enable measuring the transverse temperature distribution; widely known are for instance the multi-thermocouple roller [27] and the Datapaq temperature probe.

The multi-thermocouple roller looks like a conventional metallic roller, but inside it is fitted with thermocouples (Figure 11) that allow measuring the transverse profile on-line in an area of the kiln, the bottom region (Figure 12). Any change or operation in the kiln (modification of the temperature setting, air pressure, burner nozzle diameter or type, etc.) affects the temperature profile and the system allows analysing this influence immediately. If another area of the kiln is to be studied, the position of the roller just needs to be changed.

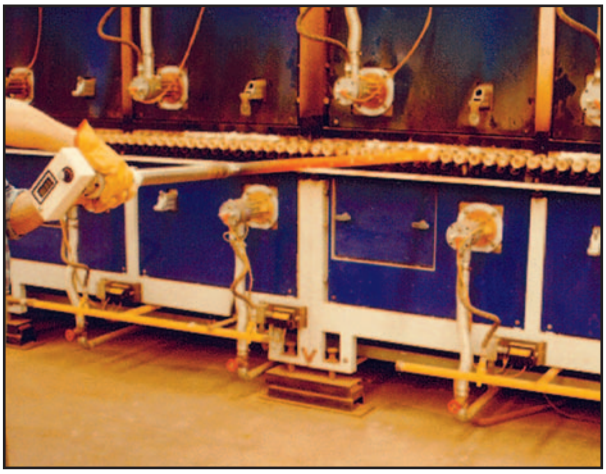

Figure 11. Measurement of transverse temperature gradients with the sensorised roller

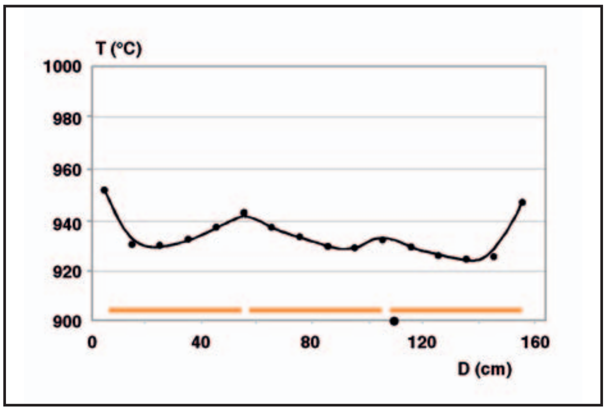

Figure 12. Transverse temperature gradients inside the kiln

The Datapaq probe provides the complete temperature curve, in different positions across the kiln and in given kiln operating conditions. It consists of an electronic device, with appropriate thermal insulation, to which a series of thermocouples are connected, which is set on the tiles. The assembly is put in the kiln and it provides the temperature distribution analogously to the probe used in the dryers, discussed above. Depending on the position of the thermocouples, the temperature at the top or bottom surface of the piece can be recorded. The main disadvantage of the device is the preparation of the measurement, which is laborious, and the difficulty of assuring that the introduction of the probe does not disturb the temperature distribution too much, in particular that no "gap" is created in the kiln.

However, the temperature curves, pressure and oxygen percentage are not variables of the fired product. The variables that should really be controlled are dimensions (calibres and departures from rectangularity), curvatures and visual appearance (shades, surface defects and breakages). The problem in many cases is the on-line measurement of these properties at the kiln exit, due to the high temperatures that the pieces have at this point and/or the fact that some of these properties can change with time (delayed curvatures).

Devices are presently available for on-line measurement of dimensions, and, in principle, it would be possible to have information on tile visual appearance. Studies have also been conducted on the relation between the thermal variables and curvatures [28]. However, although there are technical resources capable of measuring fired tile properties at the kiln exit on-line and, in many cases, the area of the kiln that affects the final characteristics of the product is known, this is not yet controlled automatically. The greatest problem lies in defining the variables on which to act and the *"indirect effects"* of these actions. Thus, for example, the modification of temperature in an area of the kiln in order to correct calibres could affect the shade of the tiles. Curvature control, especially of the irregular curvatures, is even more complex [29, 30, 31].

2.7. SORTING

Sorting is one of the stages that have lately undergone more significant changes from the point of view of automatic control. The arrival of the first automatic classification instruments [32, 33] has led many machinery manufacturers to develop their own classification equipment. Several factors have led to the recent success of this type of equipment: development of fast computers, complex computer programs and high resolution cameras.

The sorting of ceramic tiles is a complex process because a series of appreciations need to be taken into account, particularly aesthetic ones, which are difficult to quantify in mathematical terms for a computer to 'understand'. At the present time, for certain types of models, the errors in automatic classification systems are fewer than those made by sorting personnel who, due to the fatigue caused by this work, cannot discern chromatic defects after a short period of work.

2.8. GENERAL SITUATION

Table 1 provides a synopsis of the situation regarding measurement and automation in the different stages of the ceramic tile manufacturing process. The table shows that the degree of automation is not the same in all the production process stages, as mentioned previously.

In some of these stages, on-line measurement of the variable to be controlled is not yet possible (for example, milling oversize), a preliminary step for tackling automation. In these cases an additional effort in R&D is necessary to find the appropriate sensorial element for measuring and, subsequently, undertaking automatic control of the operation.

In other cases on-line measurement of the variable is already possible, but it has not been possible to hold the setting values automatically; such is the case for example of tile temperature and moisture at the dryer exit. In these cases the effort pending is smaller than in the previous one, since the measurement technology is ready.

Finally, in certain stages, it has been possible to control automatically some of the most interesting variables; this is, for example, the case in spray-drying suspensions, in which the value of the moisture content of the press powder can be controlled automatically. However, in most cases, the degree of implementation of the control systems on an industrial scale is very low, as may be observed in Table 1. An opportunity exists, therefore, for putting in place automatic controls in many of the production process stages. This opportunity should not be missed since, besides contributing information on the process, automatic control will contribute to reducing production costs, increasing end product quality, and enhancing company competitiveness.

Stage	Variable measured	Measurement*	On-line measurement technology	Variable handled	Handling*	Degree of implementation
Milling	suspension density	A	Coriolis-effect sensor	water flow rate	A	Low
	suspension viscosity	A	vibrant sensor	deflocculant flow rate	M	-
	oversize	M	-	several	M	-
Spray drying	suspension flow rate	A	electromagnetic sensor	pump pressure	M	-
	spray-dried powder moisture	A	infrared sensor	burner valve-gas temperature	A	Medium
Pressing	body moisture content	A	infrared sensor	maximum pressure	A	Low
	body bulk density	M	-	maximum pressure	M	-
Drying	body temperature	A	optical pyrometer	gas temperature distribution	M	-
	body moisture content	A	radio frequency sensor	gas temperature-drying cycle	M	-
Glazing	glaze flow rate	A	electromagnetic sensor	valve opening	A	Low
	glaze density	M	-	amount of water	M	-
	glaze viscosity	M	-	amount of water-additives	M	-
Decoration	visual appearance of the decorated piece	A/M **	CCD camera	several	M	-
	several	M	-	several	M	-
Firing	tile dimensions	A	linear CCD	temperature-others	M	-
	tile curvature	A	laser telemeters and ultrasonic	temperature-others	M	-
	visual appearance of the piece	M	-	temperature cycle-burner air	M	-
Sorting	tile dimensions and curvature	A	linear CCD and telemeters	-	A	High
	visual appearance of the piece	A/M ***	CCD cameras	-	A	Medium

(*) A: Automatic; M: Manual (**) automatic inspection in the decoration line is in an early stage of development (***) in some cases automatic sorting is not yet fully reliable

Table 1. State of the art in the measurement and control of product variables in the different ceramic tile manufacturing stages

3 AUTOMATIC CONTROL OF THE PRESSING OPERATION. A REALISATION ALREADY IMPLEMENTED ON AN INDUSTRIAL SCALE

The last section of this paper will analyse in some detail a practical recent example of automatic control of product variables. The case study deals with the automatic bulk density control of the porcelain tile body when the compact is ejected from the press.

In order to achieve this objective it has been necessary to complete each of the following phases: posing the problem, understanding the process, selecting the appropriate instrumentation, verifying the efficiency of the chosen instrumentation, and implementing and validating the control system on an industrial scale.

3.1. POSING THE PROBLEM

3.1.1. Problems associated with the presence of calibres

The most important defect associated with the lack of dimensional stability in ceramic tiles is the presence of calibres, which involve a lack of dimensional stability between different items of the same product lot.

The end product is classified in terms of four features: surface appearance, curvature, shade, and size or calibre. If three classes are assumed for tile surface appearance (first, second and unique type), two for shade and three for size, the total number of classes per model is 13. If to this is added the great variety of models usually made by a company, a situation is reached in which the number of references to be managed is very high.

The existence of calibres reduces profit margins: material that is not of the desired size can sometimes not be readily sold or must be sold at a lower price, while its manufacturing cost is the same as that of the item with the desired size. In addition, the reduction in the number of calibres facilitates finished product handling, reduces the required storage space, diminishes the possibility of claims because of sizes (adversely affecting the company image, besides causing direct additional expenses) and reduces the possibilities of mistakes in preparing orders. Moreover, strict control of dimensions results in savings in rectification abrasives.

3.1.2. Origin of calibres

Previous research [34, 35, 36] has shown that the lack of dimensional stability is due to incorrect unfolding of the pressing and/or firing operation. In the case of porcelain tiles, calibres are fundamentally due to variations in mean dry compactness between the green bodies, since these differences cannot be corrected during firing [5]. Thus, the pressing operation acquires a particular relevance in the case of porcelain tile, though it is also important in floor tiles – evidently much more so than in wall tiles, in which the end size is practically independent of body bulk density.

The moisture of the pressing powder displays fluctuations that can lead to differences in the mean bulk density between the pieces and which can, therefore, originate calibres in the end product.

3.2. UNDERSTANDING THE PROCESS. RELATION BETWEEN VARIABLES

During firing, porcelain tile size decreases, together with apparent porosity. Tile linear shrinkage during firing determines its end size and depends exclusively and linearly on green and dry bulk density of the body. Previous studies [5] have demonstrated that, for the water absorption required of porcelain tile (below 0.01 %), its linear shrinkage is practically independent of peak firing temperature. Therefore, the linear shrinkage of a composition can be estimated from the dry bulk density of the bodies, from the following equation:

Equation 1 $LS = mD_{ap} + n$

where:

LS: linear shrinkage (%)
Dap: dry bulk density of the body (kg/m^3)
m and n: empirical parameters of fit

Equation 1 represents the generalised vitrification diagram of porcelain tile compositions. This diagram enables establishing the target bulk density objective that would yield pieces of a certain size, as well as the maximum margin of admissible variation in dry bulk density in order not to have calibres. Figure 13 plots the experimental results and the calculated values according to equation 1 (solid line), which shows good correlation between the experimental values and the theoretical ones.

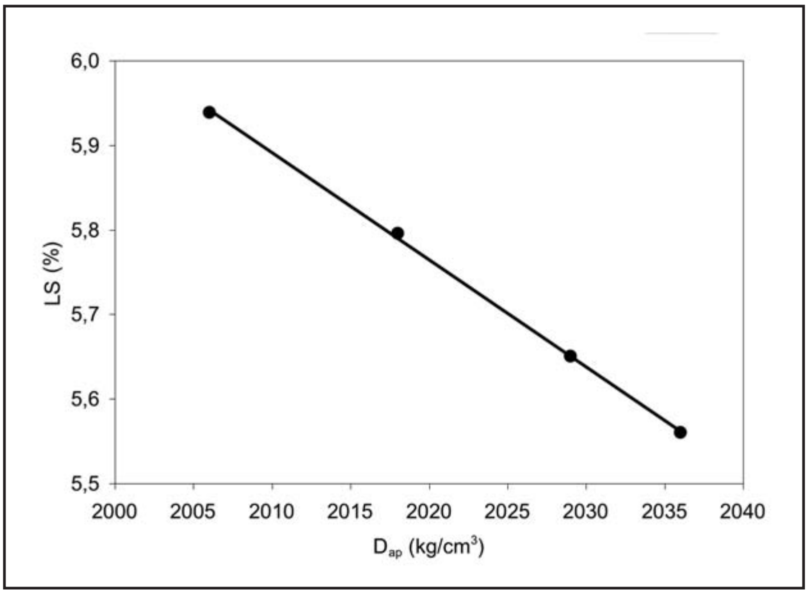

Figure 13. Industrial vitrification diagram of a porcelain tile composition

The second part of the characterisation consists of establishing the relation between pressing pressure, press powder moisture, and the dry bulk density of the formed tiles (compaction diagram). In order to obtain the compaction diagram of a spray-dried powder, cylindrical test specimens are formed in a hydraulic laboratory press under different pressure and moisture conditions. The specimens are dried in a laboratory oven at 110 ºC to constant weight and their bulk density is subsequently determined by mercury displacement.

The experimental results fit an equation of the type:

Equation 2 $D_{ap} = (aH + b) \ln p + cX + d$

where:

D_{ap}: bulk density of the dry test specimens (kg/m^3)
H: spray-dried powder moisture measured on a dry basis (%)
p: maximum pressing pressure (kgf/cm^2)
a, b, c, d: empirical parameters of fit obtained in the laboratory

Figure 14 presents the experimental results and the ones calculated according to Equation 2 (solid lines), which are observed to display good correlation between the experimental values and the theoretical ones.

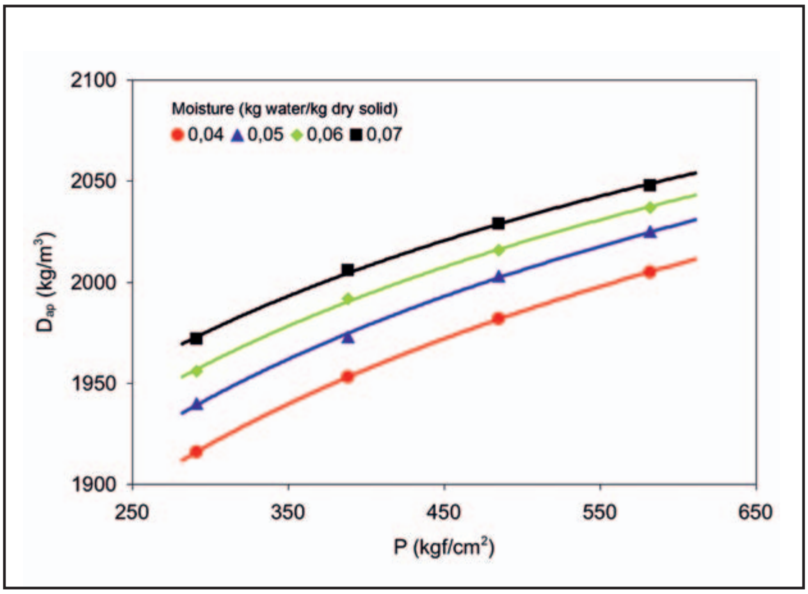

Figure 14. Laboratory compaction diagram of a porcelain tile composition

3.3. SELECTION AND VALIDATION OF THE INSTRUMENTATION USED

The studies have been conducted at a hydraulic press of the type customarily used to form ceramic tile bodies. The on-line measurement of the press powder moisture has been made using a sensor based on infrared radiation absorption by water molecules in a solid [37] (Figure 15).

The equipment has been calibrated under actual operating conditions to establish a relation between the signal provided by the system and the real moisture of the pressed body. The standard deviation of the values estimated from the calibration, for a confidence range of 85% is 0.1%, which is sufficiently accurate to tackle automatic control of the pressing operation.

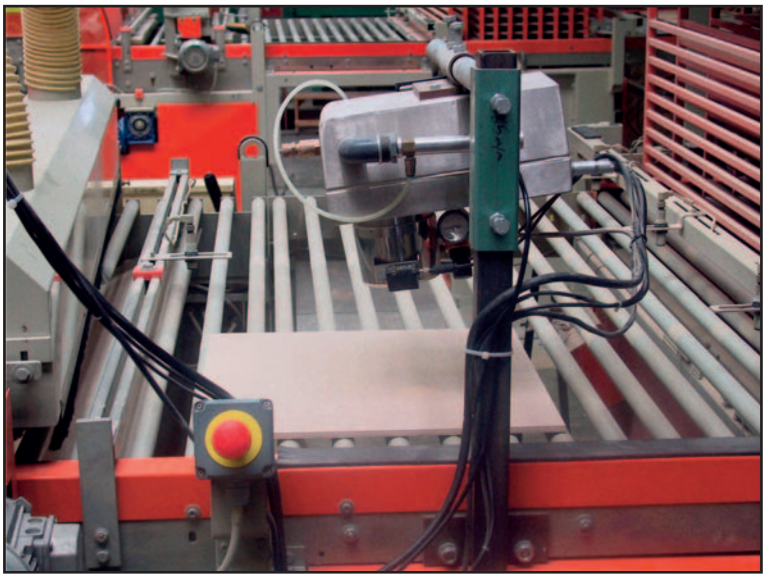

Figure 15. On-line moisture measurement of ejected compacts

Figure 16 presents a block diagram of the feedforward control designed to carry out the automation of the pressing operation. The moisture of the tiles at the press exit (H) is measured by means of an infrared sensor. The measured value (H_m) is sent to the computer, which also has the target density ($D_{ap,target}$). From H_m, $D_{ap,target}$ and the compaction diagram, the computer estimates a maximum setting pressure, which is sent to the press computer.

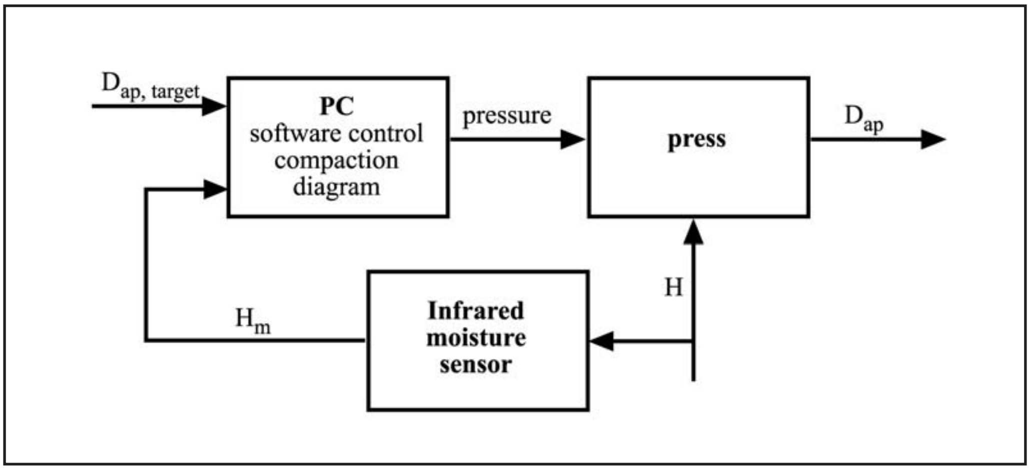

Figure 16 . Block diagram of feedforward control

Figure 17 displays the user interface of the control software. It shows, on the one hand, a group designated *'Datos' (data)* which visualises the moisture of each tile that crosses the sensor *('Humedad' (moisture)*, the maximum pressing pressure measured by the press *('Pres.med.' (meas. press.)*, the bulk density estimated from the industrial compaction diagram *('Dens.Sec.' (dry dens.)*, the target bulk density *('Dens.Obj.' (targ. dens.)* and the estimated pressing pressure calculated by the program *('Pres.est.' (est. press.)* to keep a constant dry bulk density in the ejected compacts.

Figure 17. User interface of the bulk density control application

On the other hand, in the group *'Acción' (action)* there are two buttons for starting and stopping the data-logging system, in addition to a third button for activating or deactivating the automatic control of the pressing operation.

Before implementing the feedforward control system it is necessary to verify the validity of the system for estimating the bulk density of the bodies. For this, the bulk density estimated by the system (D_{ap} estimated) and the value obtained by the mercury displacement method were monitored, considering the latter to be the real value (D_{ap} real) (Figure 18). The error obtained for a range of confidence of 95% was ± 4 kg/m^3 (bars in Figure 19). This accuracy is considered sufficient, since previous studies have demonstrated that the maximum admissible variation in bulk density to avoid calibres in porcelain tile pieces is ±10 kg/m^3.

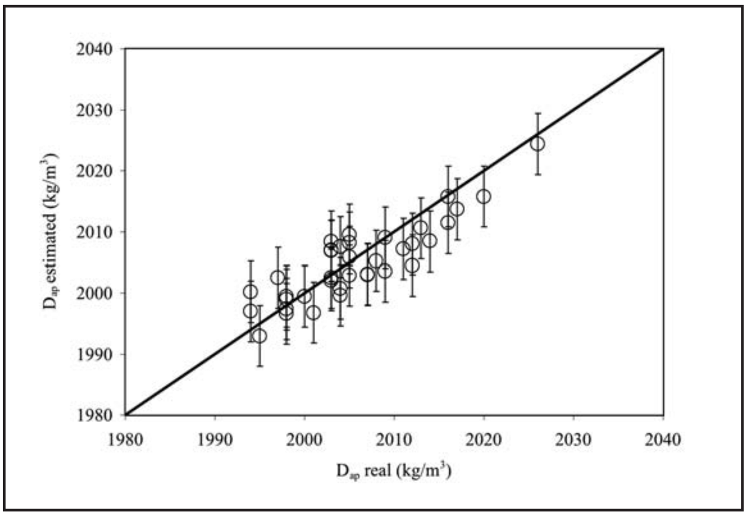

Figure 18. Estimation of the bulk density of the ejected compacts from the industrial compaction diagram

3.4. IMPLEMENTATION ON AN INDUSTRIAL SCALE. VALIDATION OF THE CONTROL SYSTEM.

As indicated previously, the main causes of the variability in density were the changes in spray-dried powder moisture. Figure 19 shows the evolution of moisture in the ejected compacts during 16 h (left axis and blue line). The areas in the graph in which gaps appear correspond to periods of press stoppage. The figure also displays the specification limits (red lines) established from the mean value of the moisture recorded during the analysed period. These limits represent the maximum variation that the body moisture content may reach without calibres appearing, in accordance with the admissible tolerances for the type of product made. In this figure it can be observed that moisture content in the bodies during the period analysed is within the specification limits.

However, the designed control system compensates the variations in moisture content, modifying the maximum pressing pressure and thus holding the bulk density of the body. Figure 19 depicts the evolution of pressing pressure (right axis and brown line), calculated from the moisture content and from Equation 2. It shows how, as moisture decreases, it becomes necessary to raise the pressing pressure.

Figure 20 displays the classification of the tiles made under the pressure and moisture conditions presented in Figure 19. It shows that all the produced tiles have the same calibre and that the size distribution lies around the centre calibre (calibre A), reflecting the efficiency of the designed press control system to hold the mean bulk density of the ejected tile compacts.

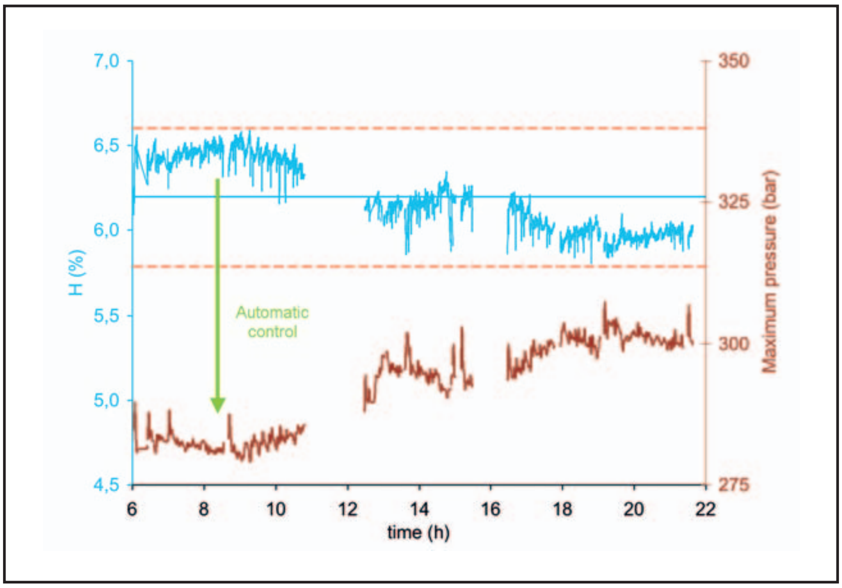

Figure 19. Evolution of moisture content in the ejected tile compacts and of the maximum compaction pressure modified by the control system to hold bulk density

The use of the automatic control system for 6 months improved the percentage of centre calibre by 17% with respect to the usual (manual) control, going from a mean value of 75% to 92%, generally improving the classification of the end product. Indeed, as Figure 21 shows, in which the quality of the classification obtained with and without the automatic control system is compared, significant improvement has occurred. The lots with 3 or more calibres practically disappear, decreasing from 24% to 5%, while the proportion of lots with 95% of the tiles in the desired calibre increases to 65%; operating in the usual way, only 6% of the lots are obtained with this requirement. Finally, note that the proportion of lots with a single calibre has been multiplied by 5, going from the 6 to 30%.

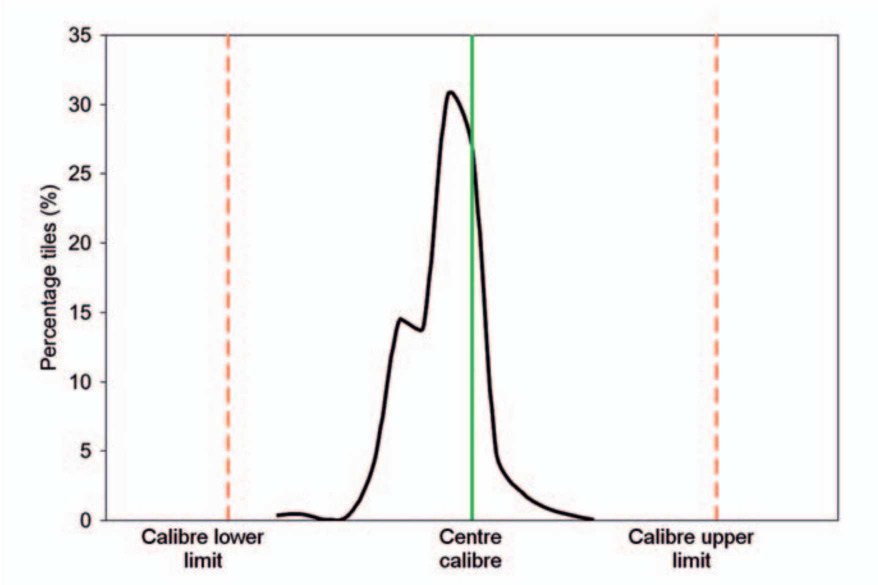

Figure 20. Classification by sizes of the tiles made with the activated automatic control system (3000 m², of nominal size 45 x 67.5 cm).

At the present time the described control system has been running for more than a year at all the presses in which the company makes porcelain tile. In this period, the mean percentage of centre calibre for all the lots fabricated has been 90%, with a slight reduction in the percentage of centre calibre owing to the increase in the number of pieces pressed by a stroke, i.e. when the tile size is smaller.

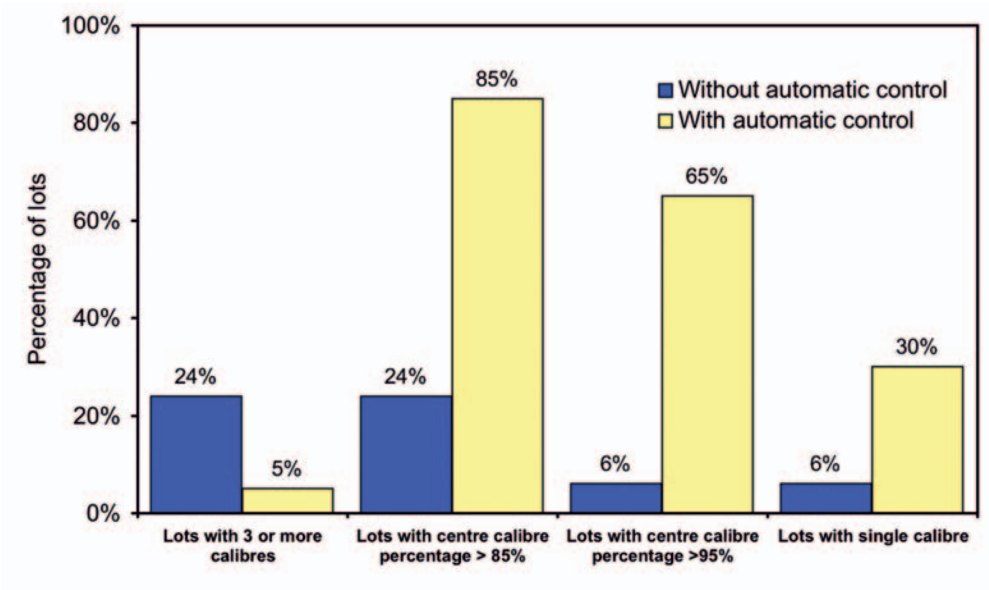

Figure 21. Analysis of the quality of the classifications (porcelain tile of size 45 x 67.5 cm).

The proposed system is being implemented at the presses that make floor and wall tiles for both red and white-body products; the results obtained are currently being evaluated.

Practical experience has demonstrated the efficiency of the bulk density control system by means of moisture measurement and the judicious modification of maximum pressure. This experience is a mature and demonstrable proposal, put forward by ITC to the ceramic sector within the framework of manufacturing process optimisation.

4. ACKNOWLEDGEMENTS

The present paper has sought to provide an overview of the current situation and the future prospects for instrumentation and automatic control in the ceramic tile manufacturing process. Most of the studies mentioned in this paper have been developed by ITC, in collaboration with different companies from the ceramic sector. Therefore, I should like to thank all the ITC staff that have participated directly or indirectly in this work, as well as the companies and Public Bodies whose economic support has made it possible for mere ideas to become useful products for the ceramic tile manufacturers.

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REFERENCES

[1] REH, H.; KROZINGEN, B. Process technology in whitewares. Cfi Ber DKG, 75(10), 7-11 , 1998.

[2] PEÑA DIEZ, J.L. La simulación dinámica en el control de procesos. Ingen. Quím., 348, 139-145 , 1998.

[3] MARLIN, T.E. Process control: Designing processes and control systems for dynamic performance. New York: McGraw-Hill, 1995 pp. 745-773.

[4] JARQUE, J.C. et al. Comportamiento de composiciones cerámicas frente al secado en condiciones industriales. En Qualicer 2002: VII Congreso Mundial de la Calidad del Azulejo y del Pavimento Cerámico. Castellón: Cámara Oficial de Comercio, Industria y Navegación, 2002. Vol.II, pp. PGI365-PGI384.

[5] MALLOL, G. et al. Mejora de la estabilidad dimensional de piezas de gres porcelánico a través de la medida en contínuo de la humedad de los soportes prensados. Cerám. Inf., 311, 117-126, 2004.

[6] AMORÓS, J.L. Vidriados para pavimentos y revestimientos cerámicos. Evolución y perspectivas. En: Qualicer 1992: Actas del II Congreso Mundial de la Calidad del Azulejo y del Pavimento Cerámico. Castellón. Cámara Oficial de Comercio, Industria y Navegación, 1992. pp. 73-103.

[7] BLASCO, A.; ENRIQUE, J.E.; ARRÉBOLA, C. Los defloculantes y su acción en las pastas cerámicas para atomización. Cerám. cristal, 98, 37-41, 1986.

[8] MALLOL, G. et al. Control de la operación de molienda en contínuo. En: Qualicer 2002: Actas del VII Congreso Mundial de la Calidad del Azulejo y del Pavimento Cerámico. Castellón: Cámara Oficial de Comercio, Industria y Navegación, 2002. Vol.I, pp. GI219-GI236.

[9] MOSCHINI, M. et al. Medida en línea de la densidad y viscosidad de la barbotina. En: Qualicer 2004: VIII Congreso mundial de la calidad del azulejo y del pavimento cerámico. Castellón: Cámara oficial de Comercio, Industria y Navegación, 2004. Volumen I, pp. GI67-GI80.

[10] AMORÓS, J.L. Pastas cerámicas para pavimentos de monococción: Influencia de las variables de prensado sobre las propiedades de la pieza en crudo y sobre su comportamiento durante el prensado y la cocción. Valencia: Universidad, 1987, p. 61. [Tesis doctoral]

[11] AMORÓS, J.L. et al. La operación de prensado en la fabricación de pavimento por monococción. I Influencia de la naturaleza del polvo de prensas sobre las propiedades de la pieza en crudo. Bol. Soc. Esp. Ceram. Vidrio, 27(5), 273-282, 1988

[12] AMORÓS, J.L. et al. La operación de prensado de pavimentos por monococción. II Influencia de la naturaleza del polvo de prensas sobre las propiedades de la pieza en cocido. Bol. Soc. Esp. Ceram. Vidrio, 29(3), 151-158, 1990

[13] NEGRE, F. et al. Estudio de la operación de secado por atomización de polvos cerámicos a escala industrial, su control y automatización. Téc. Cerám., 228, 736-744, 1994

[14] JARQUE, J.C. et al. Control automático de la humedad en una instalación de secado por atomización. En: XL Congreso Nacional de la Sociedad Española de Cerámica y Vidrio: Onda, 8-11 de noviembre, 2000: programa y libro de resúmenes. Castellón: SECV, 2000

[15] ESCARDINO, A. et al. Cinética de la oxidación de la materia orgánica en productos cerámicos prensados. En: I Congreso Iberoamericano de Cerámica, Vidrio y Refractarios. Arganda del Rey: Sociedad Española de Cerámica y Vidrio, 1983. pp. 317-329.

[16] ENRIQUE, J.E. et al. Alternativas al método de inmersión en mercurio para la determinación de la densidad aparente de baldosas cerámicas. Téc. Cerám., 250, 18-27, 1997.

[17] CANTAVELLA, V. et al. Uso de la técnica de ultrasonidos para medir la densidad aprente de las baldosas en crudo y optimizar el proceso de prensado. En: Qualicer 2006: IX Congreso Mundial de la Calidad del Azulejo y del Pavimento Cerámico. Castellón: Cámara Oficial de Comercio, Industria y Navegación, 2006. [aceptado]

[18] AMORÓS, J.L. et al. Medida no destructiva de la densidad aparente de piezas en crudo mediante absorción de rayos X. En: Qualicer 2006: IX Congreso Mundial de la Calidad del Azulejo y del Pavimento Cerámico. Castellón: Cámara Oficial de Comercio, Industria y Navegación, 2006. [aceptado]

[19] MARCHETTI, B.; REVEL, G.M. Medida en línea de la densidad en crudo de baldosas cerámicas: análisis de incertidumbre. En: Qualicer 2002: VII Congreso mundial de la calidad del azulejo y del pavimento cerámico. Castellón: Cámara oficial de Comercio, Industria y Navegación, 2002. Vol. I, pp. GI11-GI23.

[20] MALLOL, G. et al. Experimental Study of the determination of dry compaction of ware shaped by unidirectional pressing, in continuous operation and in true time. Tile Brick Int., 8(6), 424 - 438, 1992.

[21] MALLOL, G. et al. Estudio de la operación de secado de los soportes de las baldosas cerámicas en secaderos verticales. En: Qualicer 2002: VII Congreso Mundial de la Calidad del Azulejo y del Pavimento Cerámico. Castellón. Cámara Oficial de Comercio, Industria y Navegación, 2002. Vol.II, pp. PGI329-PGI348.

[22] JARQUE, J.C. Estudio del comportamiento mecánico de soportes cerámicos crudo: Mejora de sus propiedades mecánicas. Universitat Jaume I de Castelló. Castelló, 2001. [Tesis doctoral]

[23] AICE. Dispositivo y método de control automático de aportación de fluidos. ES 2165760, 2003-06-16.

[24] COE, S. The automatic inspection of ceramic tiles between press and kiln. CFI Ceram forum int, 79 (11), E11-E13 , 2002.

[25] MALLOL, G. et al. Optimización de las condiciones de funcionamiento en hornos monoestrato (I). Curva de presiones. Téc. Cerám., 206, 585-593, 1992.

[26] MALLOL, G. et al. Optimización de las condiciones de funcionamiento en hornos monoestrato (II). Caudal de aire de combustión. Téc. Cerám., 218, 716-729, 1993.

[27] MALLOL, G. et al. Optimización de las condiciones de funcionamiento en hornos monoestrato. III Medida de gradientes transversales de temperatura. Téc. Cerám., 227, 653-662, 1994.

[28] JARQUE, J.C. et al. Influencia de las condiciones de operación del horno de rodillos sobre la curvatura de las piezas. Téc. Cerám., 303, 685-687, 2002.

[29] AMORÓS, J.L. et al. Estabilidad dimensional en piezas de monococción porosa. En: Qualicer 1992: II Congreso Mundial de la Calidad del Azulejo y del Pavimento Cerámico. Castellón. Cámara Oficial de Comercio, Industria y Navegación, 1992. pp. 347-376.

[30] CANTAVELLA, V. Simulación de la deformación de baldosas cerámicas durante la cocción. Castelló: Universitat Jaume I, 1998. [Tesis doctoral]

[31] AMORÓS, J.L. et al. Acuerdo esmalte-soporte (I) Causas y factores de los que depende. Téc. Cerám., 178, 582-592, 1989.

[32] MASSEN, R.; FRANZ, T. The quality of automatic tile quality inspection systems. Cfi ber. DKG, 78 (1-2), E15-E17 , 2001.

[33] COE, S. Automatic tile inspection. Int. Ceram., 1, 33, 35, 2000.

[34] ORTS, M.J. Sinterización de piezas de pavimento gresificado. Valencia: Universitat de Valencia, 1991. [Tesis doctoral]

[35] ESCARDINO BENLLOCH, A.; AMORÓS ALBARO, J.L.; ENRIQUE NAVARRO, J.E. Estudio de pastas de gres para pavimentos. Bol. Soc. Esp. Ceram. Vidr., 20(1), 17-24, 1981.

[36] AMORÓS ALBARO, J.L. et al. Control de la compactación durante el proceso de fabricación de pavimentos y revestimientos cerámicos. Téc. Cerám., 118, 1307-1314, 1983.

[37] MALLOL, G. et al. Medida en contínuo de la humedad de los soportes cerámicos prensados. Cerám. Inf., 289, 81-90, 2002.