DEVELOPMENT OF A GLAZING SYSTEM INSENSITIVE TO VARIATIONS IN GLAZE VISCOSITY

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ABSTRACT

This study presents a new glaze feed system for bell application that is insensitive to variations in glaze viscosity. The first part of the paper describes the equations that explain how a glaze feed system behaves with a view to determining why conventional feed systems are sensitive to variations in viscosity.

In the second part, based on the previously analysed theoretical concepts, a prototype glaze feeder has been constructed, for which a patent has been filed [1], whose constructive form makes it insensitive to variations in glaze viscosity. In order to verify the appropriate operation of the developed prototype, its performance has been tested under pilot and industrial conditions.

1. INTRODUCTION

One of the most common defects in the ceramic tile manufacturing process, which has an important adverse affect on end product quality, is the lack of colour uniformity between tiles of the same model. Numerous studies [2][3][4][5] have shown that the origin of this defect lies, on the one hand, in the inconsistency of the physico-chemical properties of the materials used in the decoration process (body, engobes, glazes, inks, etc.) and, on the other hand, in inappropriate processing, basically in regard to the engobe and glaze application, decorating, and firing.

At the present time, bell glaze application systems are widely used in the ceramic tile manufacturing sector. Although the use of curtain or so-called *filera* application systems has increased considerably in recent years, many ceramic tile manufacturers still use bells in engobe and glaze applications, since they cost much less than curtain systems.

Many defects associated with a lack of colour uniformity between tiles stem from changes in the discharge flow rate [6] of conventional glaze feed systems for bell application as a result of viscosity variations in the glaze contained in the stirring and pumping tanks. These variations in viscosity, mainly due to temperature changes in the glaze caused by stirring and fluctuations in ambient temperature, lead to important variations in the quantity of glaze applied on to the ceramic tiles, known as 'grammage', which originates colour differences in the end product. As shown below, viscosity variations cause the discharge flow rate to vary as a result of changes in the mechanical energy losses undergone by the glaze as it traverses the feeder.

Most current glaze feed systems for bell application consist of a metallic pipe inside which the glaze, fed through the top by means of a pumping system, reaches a constant height thanks to an overflow system which may have different constructive forms, depending on the manufacturer. The bottom of this pipe is fitted with a truncated cone mouthpiece that has a valve at the bottom for manual regulation of the glaze flow rate on to the bell, thus allowing adjustment of the glaze quantity applied on to the tiles. Immediately after this valve there is a straight pipe section, with the same diameter as the valve outlet diameter, and at the end of that pipe there is a nozzle with a constant diameter through which the glaze suspension flows on to the bell.

The control method used to correct the variations in the glaze flow rate consists of making regular manual measurements (every half hour, in the best of cases) of the grammage applied on to a metallic control plate that is made to cross the glaze curtain created by the bell, so that when the measured glaze quantity departs from the pre-set values, the operator will adjust the valve to increase or decrease the glaze flow rate. This way of working, given its periodicity, fails to assure application of a consistent quantity of glaze, and leads to defects associated with lack of colour uniformity in the end product.

2. OBJECTIVE

The purpose of the present work has been to develop a new glaze feed system for bell application, which, unlike conventional ones, is insensitive to changes in glaze viscosity, thus assuring application of a consistent quantity of glaze and reduction of the defects associated with viscosity variations.

3. THEORETICAL FOUNDATIONS: MECHANICAL ENERGY BALANCES

In order to explain glaze feed system behaviour when there are variations in viscosity, it is interesting to use mechanical energy balances. Equation 1 represents the complete mechanical energy balance of an incompressible newtonian fluid in the steady state [7], between the input (1) and the output (2) of a generic glaze feed system like the one schematically illustrated in Figure 1.

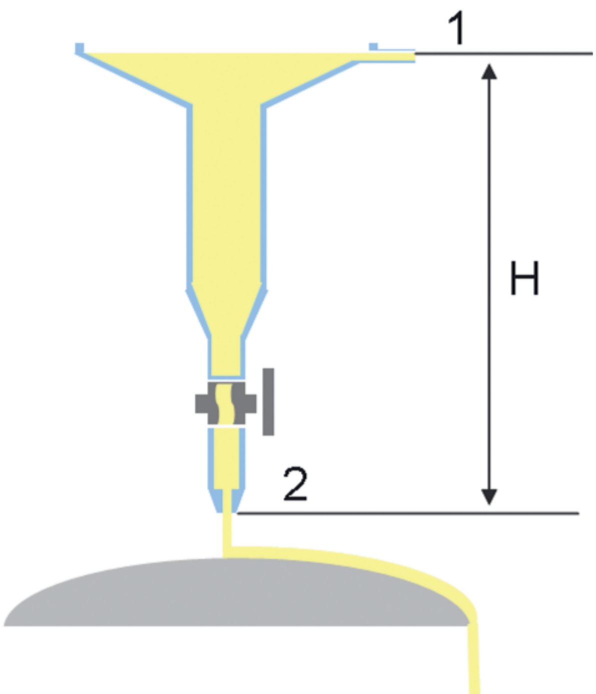

Figure 1. Scheme of a generic glaze feed system to which a mechanical energy balance is applied between points 1 and 2.

$$\frac{v_2^2}{2\alpha_2} - \frac{v_1^2}{2\alpha_1} + g(z_2 - z_1) + \frac{p_2 - p_1}{\rho} + \Delta F = W$$

Equation 1

where:

- v_i : velocity of the fluid in the input section (i=1) or output section (i=2) of the system (m/s)
- z_i: height of the input section (i=1) or output section (i=2) of the system (m)

- g: gravity acceleration (m/s^2)
- p_i: pressure of the fluid in the input section (i=1) or output section (i=2) of the system (N/m^2)
- ρ: density of the liquid or suspension (kg/m^3)
- ΔF: loss of mechanical energy by the fluid owing to friction throughout the entire system (J/kg)
- W: work performed by external forces (J/kg)
- α_i: correction parameter that takes into account velocity variations in the radial direction, allowing the average velocity of the fluid to be used in the calculations (α = 1, turbulent flow, and α = 0,5, laminar flow)

Equation 1 can be transformed into Equation 2, taking into account the simplifications that are described below:

- the velocity at the system input (v_1) is much smaller than the velocity at the system output (v_2), since the system input cross-section is much larger than the output section
- the difference ($z_2 - z_1$) is equal to the height of the column of liquid inside the system with a negative sign (-H)
- the input pressure (p_1) and the output pressure of the system (p_2) are the same and equal to the atmospheric pressure, because the liquid is discharged under ambient conditions and the top of the column of liquid is in direct contact with the atmosphere
- the work performed by external forces is zero, since the liquid flows exclusively under the action of gravity

$$\frac{v_2^2}{2\alpha_2} - gH + \Delta F = 0$$

Equation 2

Equation 2, corresponding to the simplified mechanical energy balance of a generic glaze feed device, relates the liquid discharge velocity to the height of the liquid and the loss of mechanical energy caused by friction.

It was experimentally verified that, for a system with the characteristics of the one being studied, and for the rheological properties of the glazes, the Reynolds number was below 2100 at any point of the system, which indicates that the circulation regime is completely laminar. Taking into account that parameter α_2 acquires a value of 0,5 in laminar flow circulation, the fluid discharge velocity can be calculated using the equation corresponding to the mechanical energy balance, which adopts the form of Equation 3.

$$v_2 = \sqrt{gH - \Delta F}$$

Equation 3

Thus, according to Equation 3, the glaze discharge velocity depends exclusively on the height of the glaze column and on its mechanical energy loss in crossing the supply system.

Equation 4, known as the Poiseuille equation, allows calculation of the irreversible friction losses by a fluid circulating in laminar flow, where μ is fluid viscosity, L pipe length, v fluid velocity, ρ fluid density, and D pipe diameter.

$$\Delta F = \frac{32\mu L v}{\rho D^2}$$

Equation 4

These mechanical energy losses are due to two different factors. On the one hand, to the friction of the fluid against the inner walls of the system it is circulating through. And on the other, to the frictions originated by the system's changes of geometry or modifications of the fluid stream caused by the presence in the pipes of a series of disturbances, such as valves, measurement devices, elbows or other accessories. In accordance with the foregoing, the loss of mechanical energy is calculated as the sum of the friction losses in the straight stretches of the system and of the mechanical energy losses in all the system disturbances, calculated using the so-called equivalent length of the disturbance. The equivalent length of a disturbance is the length of straight section of duct of given diameter that would originate the same charge loss as the disturbance.

Analysis of Equations 3 and 4 shows that if the system's loss of mechanical energy, ΔF, is so low that it may be considered negligible with respect to the product of gravity acceleration by height, gH, the velocity of glaze at the feeder outlet, v_2, will depend solely on column height, H, since Equation 3 would become:

$$v_2 = \sqrt{gH}$$

Equation 5

Therefore, in accordance with Equation 5, the glaze quantity that would be applied using a feed system designed such that the glaze charge loss, ΔF, was very low, would depend exclusively on the height of the overflow, H, and be independent of glaze viscosity.

4. DESCRIPTION OF THE DEVELOPED PROTOTYPE

A glaze feeder prototype was developed on the basis of the physical foundations set out in section 3, whose constructive form minimised the variations in the discharge rate caused by changes in glaze viscosity.

The main restriction to be met in the prototype design was that it should not contain the valve found in most conventional systems, or any other disturbance that might cause high mechanical energy losses and, hence, important variations in the discharge flow rate with viscosity. It was therefore assumed, a priori, that the constructive form with the lowest related mechanical energy losses would be that in which the glaze passage was solely restricted in the nozzle orifice that generates the fluid stream discharged on to the bell. On the basis of this hypothesis, a prototype was built, which is schematically illustrated in Figure 2. The prototype consisted basically of a metal tube, 10 cm in diameter, with an overflow system fitted at the top, which allowed the glaze height to be held constantly at a height of 50 cm. The bottom of the feed tube was equipped with a truncated cone injector system containing a stainless steel nozzle in the centre with rounded edges.

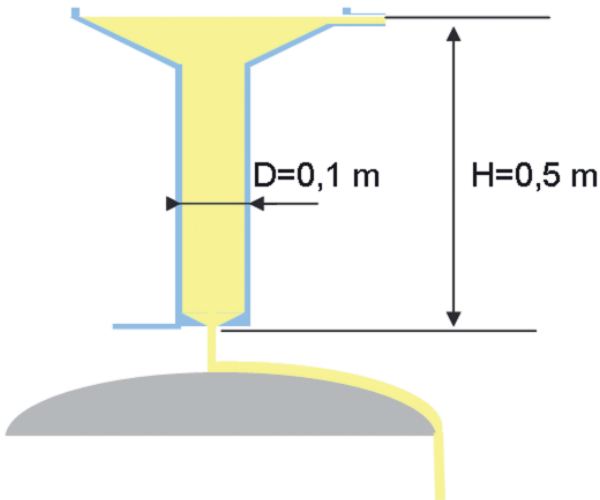

Figure 2. Scheme of the developed feeder prototype.

In order not to lose the versatility of systems that include a valve as flow rate regulator, it was decided to equip the prototype with a system of fast nozzle changeovers, shown in detail in Figure 3. This device has a revolver type of mechanism which, by actuating a side lever, allows the nozzle to be shifted and immediately replaced by another with a different diameter, located in a secondary nozzle holder. This mechanism enables rapid modification of the quantity of glaze fed on to the bell, without stopping the glaze supply to the bell, providing a great advantage with respect to current nozzle changeover systems.

Despite these advantages, the use of nozzles with fixed diameters, without the possibility of having a continuous range of nozzle diameters, does not allow continuous variation of the applied glaze quantity. However, the possibility of modifying glazing line velocity in the desired section enables fine adjustment of the system, which thus supplies the desired glaze quantities at every moment.

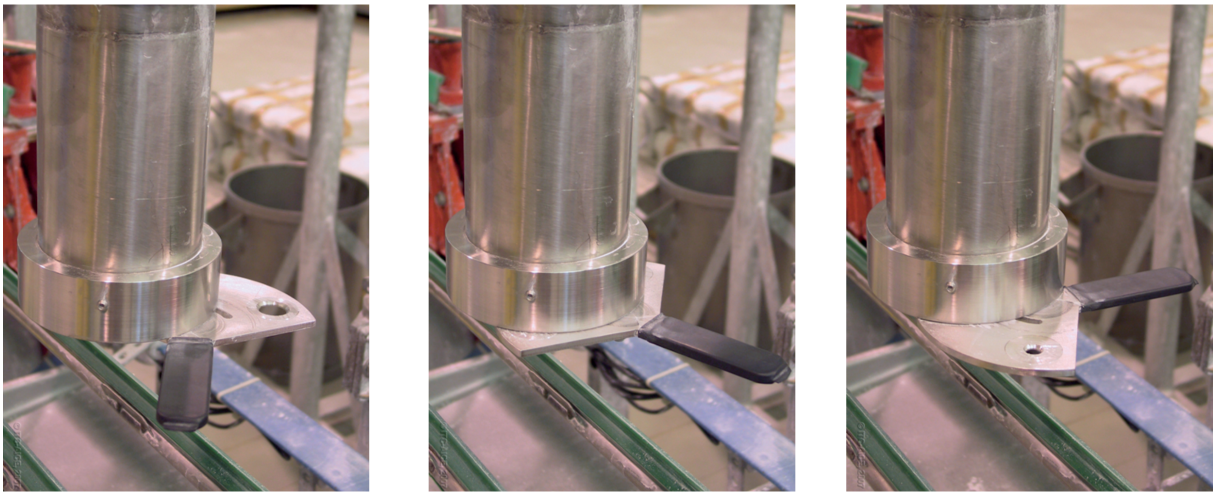

Figure 3. Detail of the rapid nozzle changeover system in its three positions: (from left to right) nozzle 1, closed, and nozzle 2.

5. PILOT PLANT TESTS

Before testing the prototype under industrial conditions, it was decided to run a series of experiments in the pilot plant glazing line at the Instituto de Tecnología Cerámica (ITC), where prototype behaviour was compared with that of a conventional glaze feed system fitted with a diaphragm valve or Saunders valve. For this purpose, both supply systems were arranged serially on the glazing line and were fed with the glaze contained in a single stirring tank, using the same pumping group.

5.1. DESCRIPTION OF THE EXPERIMENTS

The tests consisted of determining how the discharge flow rate of both feed systems was modified as variations occurred in glaze viscosity. Initially, the viscosity variations took place as a result of the increase in glaze temperature caused by continuous glaze stirring. Once a practically steady state had been reached, in which the viscosity changes were very slow, the rheological behaviour of the glaze was further modified by using additives. Viscosity was determined by measuring the outflow time in a Ford cup number 4, which is the measurement method customarily used to control glaze viscosity.

In order to facilitate test performance, the glazing bell was not installed under either of the supply systems. For this reason, the quantity of glaze that would be applied on to a tile of given size was not directly measured either; instead the mass flow rate of the glaze discharged by the feeder was measured. This measurement was made using a plastic receptacle of known dimensions which, circulating on the transport line, travelled under the discharge generated by the feeder, thus collecting a certain quantity of glaze. Since transport line speed was known, the time it took the plastic receptacle to pass under the glaze stream could be determined; the mass flow rate was then calculated as the quotient between the collected quantity of glaze and the receptacle passage time. Glaze density, measured with a pycnometer, then allowed the volumetric flow rate of the discharge to be calculated.

With a view to observing the behaviour of the two systems in their entire working range, the discharge flow rate at every test viscosity was determined of the conventional feeder with three different positions of the Saunders valve (100%, 75%, and 50% aperture) and nozzle of 19 mm, and of the prototype with three different nozzle diameters (12, 11, and 10 mm).

In order to carry out the tests, a glaze suspension with a viscosity of approximately 90 s was used, for which the discharge flow rate in both systems was measured with a 12 mm nozzle and completely open Saunders valve. Then, before the viscosity of the suspension was modified, two more measurements were made in each system using 11 mm and 10 mm nozzles in the prototype and valve closure to 75% and 50% of the aperture in the conventional system. All flow rate points corresponding to a viscosity of 90 were thus obtained. Once the first series of flow rates had been established, the viscosity was allowed to decrease progressively as a result of the increase in temperature. When a viscosity of about 85 s was reached, another series of flow rates were determined, for both the prototype and the feeder, thus obtaining the points corresponding to a viscosity of 85 s. The test was completed by measuring the flow rates at 4 other glaze viscosities.

5.2. RESULTS OBTAINED IN THE PILOT PLANT

For practical purposes, to facilitate the interpretation of the results, the discharge flow rate of the studied supply systems was used to establish the grammage that would be applied on to a 33x33 cm ceramic tile that was glazed with these systems. Although the applied glaze quantities were not experimentally measured, they could be theoretically calculated after verifying experimentally that they were directly proportional to the mass flow rate discharged by the feeder.

The variation of the glaze quantity applied on to a 33x33 cm tile as a function of viscosity, for both studied systems, is shown in Figure 4. It may be observed that, for both systems, the applied glaze quantity decreases practically in linear form when glaze viscosity increases. However, in accordance with the initial hypothesis, the variation of grammage with respect to viscosity is much smaller in the prototype than in the conventional system, independently of the nozzle diameter and valve opening used.

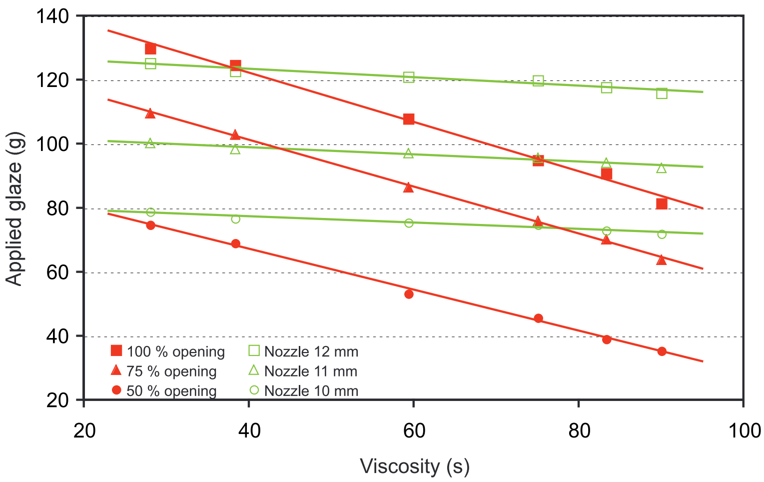

Figure 4. Evolution of the glaze quantity applied on to 33x33 cm tiles as a function of glaze viscosity for the developed prototype (green line and empty points) and for a conventional glaze feed system (red line and solid points).

The slope of the fitted lines in Figure 4 quantifies the change in applied glaze quantity when glaze viscosity varies. Therefore, these slopes indicate how sensitive the studied systems are to variations in viscosity. The slope of each straight line is plotted (Δquantity/Δviscosity) as a function of the glaze quantity that would be applied, in each situation, at the lowest viscosity of all tested viscosities (28 s) in Figure 5. It may be observed that for any grammage value, the variation of the glaze quantity in regard to the modification of viscosity is always larger for the conventional system than for the prototype. In addition, this difference becomes more pronounced when the applied quantity of glaze increases.

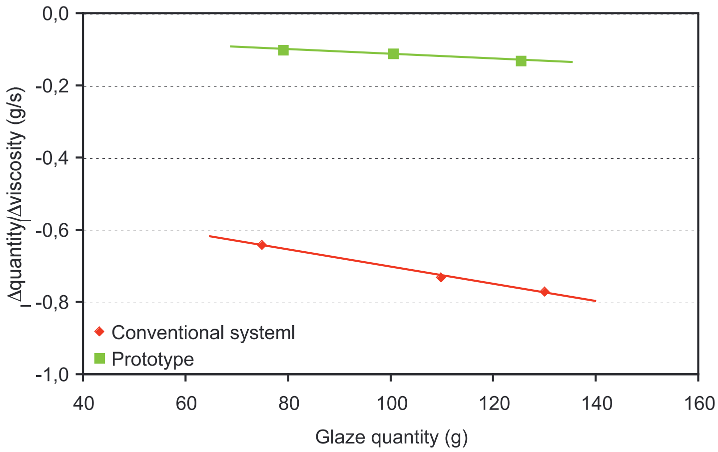

Figure 5. Variation of sensitivity to the changes in viscosity of the feeders studied with the applied quantity of glaze.

Table 1 shows what the variation of the applied glaze quantity would be with a 5 s change in glaze viscosity. For example, if the operation is run at a nominal applied glaze value of 75 g, a change of 5 s in viscosity in the conventional system would cause a change of 3,2 g in the glaze quantity applied on to the piece, whereas in the new system this variation would only be 0,5 g. These results indicate that the new prototype is about 5 times less sensitive to viscosity changes than conventional glaze feed systems that use a Saunders valve as a flow rate regulator.

	Variation of applied glaze quantity (g/tile)	
Nominal applied glaze quantity (g/tile)	**Conventional system**	**Developed prototype**
75	3,2	0,5
100	3,6	0,6
125	3,9	0,7

Table 1. Variation of the glaze quantity applied on to a 33x33 cm tile as a result of a 5 s variation in glaze viscosity.

5.3. VERIFICATION OF THE VALIDITY OF THE ENERGY BALANCES AND OF THE HYPOTHESES MADE TO STUDY THE DEVELOPED PROTOTYPE

In order to verify the validity of Equation 5, experiments were performed in which the glaze discharge rate, v_2, was measured for different glaze heights, H, in the discharge tube. The average value of the glaze discharge rate is plotted as a function of $H^{1/2}$, together with the experimental error in the measurement of the discharge rate, in Figure 6. The figure shows that the experimental results fit quite well a straight line that passes through the origin and has a slope equal to $g^{1/2}$ (3,13 $m^{1/2}/s$). These results corroborate the validity of Equation 5 for studying the behaviour of the proposed feed system, as well as the hypotheses made to obtain it.

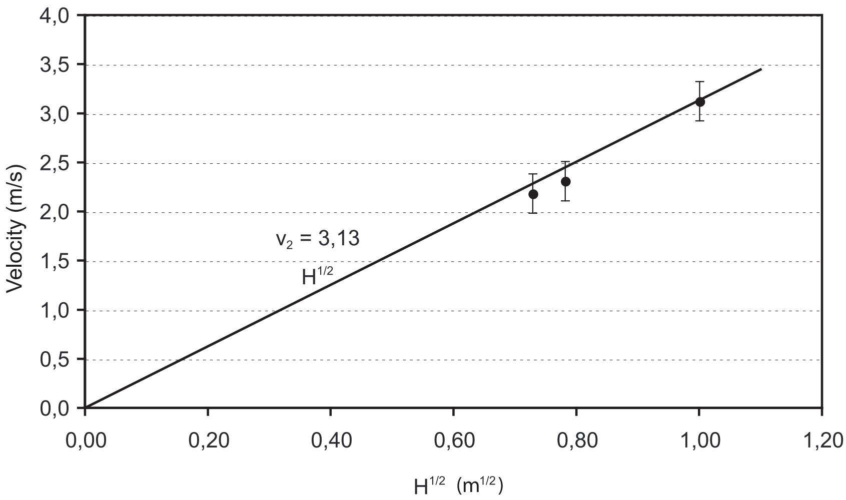

Figure 6. Dependence between glaze discharge rate and glaze height. Fit of the experimental results to Equation 5.

6. TESTS UNDER INDUSTRIAL CONDITIONS

After it was verified in the ITC pilot plant that the developed system provided important advantages in regard to conventional glaze feeders, it was decided to run a series of trials in an industrial glazing line. To do this, the prototype was installed on the bell used for the base glaze applications in this glazing line (see Figure 7), and production was monitored to study how the system performed. For comparative purposes, a conventional glaze feed system fitted with a Saunders valve was also monitored, both systems being supplied with the same glaze.

Monitoring consisted of intermittently measuring the glaze viscosity outflow in seconds from a Ford cup, glaze density with a pycnometer, and the quantity of applied glaze. This last measurement was made with the metal plate used by the line operators to control the glazing operation.

Figure 7. Prototype installed in the industrial glazing line (left) and detail of the rapid nozzle changeover system (right).

Figures 8 and 9 display with squares and on the right axis, the evolution of viscosity in the glaze applied by the two studied systems (the conventional system is shown in Figure 8 and the prototype in Figure 9) for 7 and 6 hours' production, respectively. The same figures depict, with rhombuses and on the left axis, the evolution of the glaze quantity deposited on a control plate during the same period of time. The solid horizontal line represents the nominal glaze quantity to be applied, while the dashed horizontal lines correspond to the control limits outside which defects can appear in the end product.

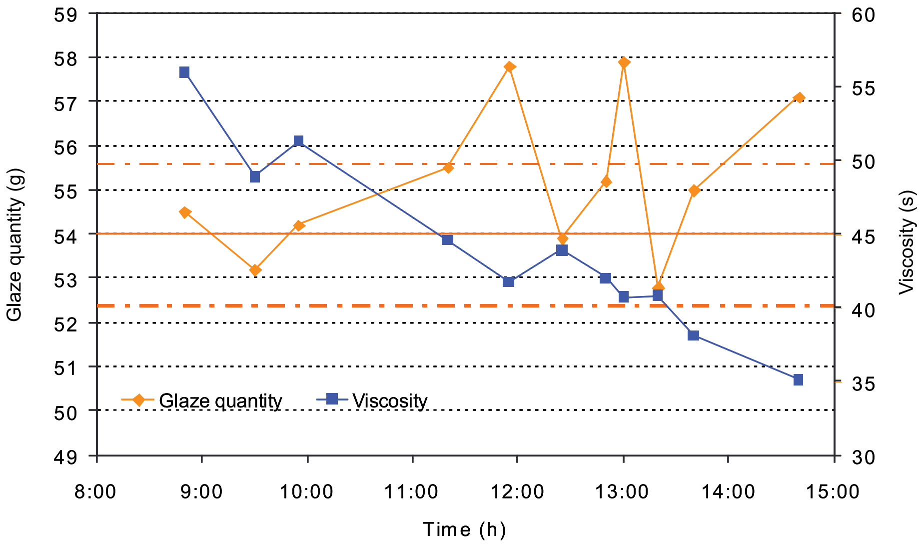

Figure 8. Evolution with time of applied glaze viscosity and quantity using a conventional feed system, under industrial conditions.

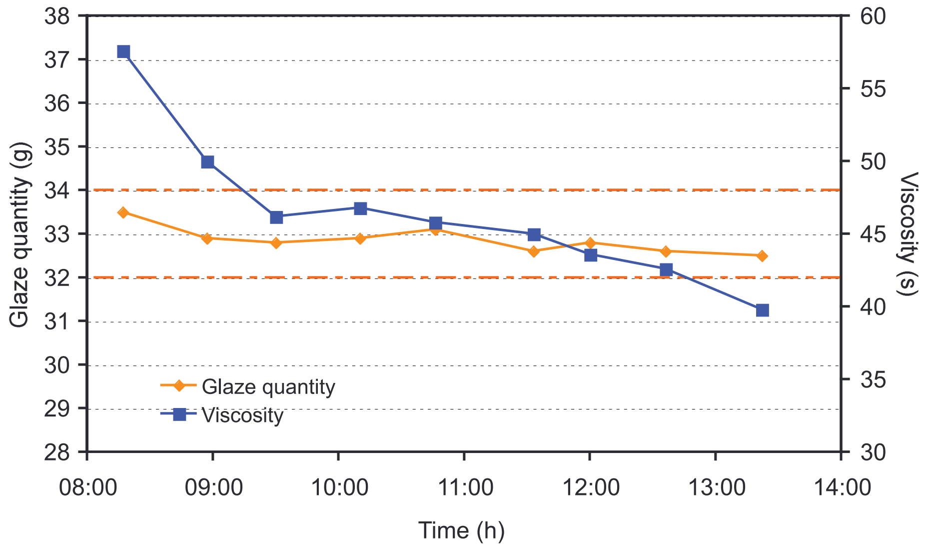

Figure 9. Evolution with time of applied glaze viscosity and quantity using the feed system developed in this study, under industrial conditions.

As Figure 8 shows, when production began in the conventional system, the values of the applied glaze quantity lay within the control limits. However, as glaze viscosity decreased, the applied glaze quantity increased, until it came to lie outside the upper control bound, at about 11:30 hours. At that moment, a line operator manually reduced the Saunders valve opening, causing the applied glaze quantity to return within the control limits. However, since the decrease in viscosity, associated with the increased ambient temperature at midday, did not stop, the applied glaze quantity again quickly crossed the control bounds at 13:00 hours, which made it necessary again manually to adjust the discharge flow rate. Finally, owing to the continuous decrease in viscosity, the glaze quantity again crossed the control bound at about 14:00 hours.

As far as the prototype (Figure 9) is concerned, it may be observed that, unlike what happened with the conventional system (Figure 8), despite a variation in viscosity occurring of about 20 s (similar to that in the experiments with the conventional system), the values of the applied glaze quantity were all within the control limits (dashed horizontal lines), without any type of adjustment (change of nozzle, change of line speed, etc.) being made in the glazing system, and without any type of defect being observed in the end product that might be attributable to the use of the prototype.

The results obtained in the industrial trials demonstrate the advantages of the developed feeder compared with the traditional system. Indeed, at a variation in glaze viscosity of almost 20 s, the designed prototype was able to keep the applied glaze quantity inside the control limits without it being necessary to act on the system. In contrast, with the conventional system, at the same variation in viscosity (20 s), the applied glaze quantity crossed the control limits on three occasions, it being necessary to adjust the output flow rate in order to try to keep the applied glaze quantity inside the control limits.

7 CONCLUSIONS

- Mechanical energy balances have been applied to a glaze feed system and it has been verified that the variation of the applied glaze quantity or grammage, caused by modifications of glaze viscosity that are difficult to control, is directly related to charge losses in the feed system (presence of valves, narrowing, etc.).

- The validity of mechanical energy balances has been verified for the study of the behaviour of the glaze feed systems used in bell applications.

- A new glaze feed system has been designed and built in which the mechanical energy losses of the glaze are minimised, with a view to reducing the system's sensitivity to viscosity changes in the suspension. The pilot plant trials show that the developed system is 5 times less sensitive to viscosity variations than the systems used at the present time.

- It has been verified that the designed prototype works appropriately under industrial conditions, keeping the applied glaze quantity inside the set control limits without there being any need to act on the system, and holding end product quality.

8. ACKNOWLEDGEMENTS

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