AUTOMATIC CONTROL OF DENSITY AND VISCOSITY IN CONTINUOUS MILLS

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ABSTRACT

The study analyses the problem of on-line measurement of slip density and viscosity at the continuous mill exit. Density is measured with a flow meter based on the Coriolis effect, while viscosity is measured with a sensor based on the vibrating probe principle. The viscosity measurement entails particular difficulty because ceramic suspensions have shear thinning behaviour and are, to a greater or lesser extent, thixotropic; therefore, apparent viscosity depends on the shear rate and even on the preliminary stirring state of the suspension. Even in an ideal situation, this means that the value measured by a vibrant probe differs from that obtained with the Ford glass. Despite these difficulties it has been found that values can be obtained, by means of proper calibration, which are comparable to those found with a Ford cup.

A further difficulty to be addressed was the internal soiling of the sensors, which led to fictitious variations of density and viscosity. The industrial monitoring of the operation of these sensors has shown that they can reliably be used in industrial measurement, although certain precautions need to be taken.

In addition, the control loop has been closed which regulates density, for automatic modification of the water flow feed into the mill. The study shows this control provides significant reduction of the oscillations and drifts in density.

1. INTRODUCTION

At the present time milling technology features widespread use of continuous mills. In these mills, mill feed and discharge occur continuously. The mill instruments allow measuring the solids weight and volumetric flow of the water and deflocculant. In regard to the characteristics of the product (suspension), the most important variables are density, viscosity and oversize. These variables are measured manually at regular intervals by an operator, while manual adjustment also occurs of the clay mass flow, and water and deflocculant volume flow settings. The fact that manual action is so important in a continuous process may be considered surprising.

A previous paper demonstrated the technical possibility of automatically controlling density and viscosity[1], with the evident improvement in process control that this could mean; however, one of the basic problems involved the selection of the most appropriate industrial sensor to perform this measurement. Selecting the most appropriate sensor involves compromising between various features, such as accuracy, reliability, robustness, low maintenance, and stability over long periods of time. Although much progress has been made in the selection of the most appropriate sensors[2], no solution has yet been found that could be considered sufficiently reliable for industrial use.

In this study it has been attempted to select and fine-tune sensors and measuring methodologies that allow determining, reliably and continuously, the density and viscosity of a suspension. This would enable implementing control loops of both variables, although in the present phase of the work, only density control has been completed.

2. DESCRIPTION OF THE MEASUREMENT AND CONTROL SYSTEM

2.1. GENERAL DESCRIPTION

Figure 1 depicts the industrial arrangement used in conducting this work, which includes sensors for measuring slip density and viscosity. When the slip exits the mill it is discharged on a sieve (9) to eliminate very coarse particles, and subsequently conveyed by pipes to the storage tanks. At a point in the pipes close to the discharge zone of the mill, a bypass is fitted which leads a small quantity of slip to the density (1) and viscosity (8) sensors, positioned in series, and then on to the storage tank.

In addition, a cleaning system was incorporated that introduced water through a timer-controlled valve (2). This automatic system served to avoid or reduce internal soiling of the sensors.

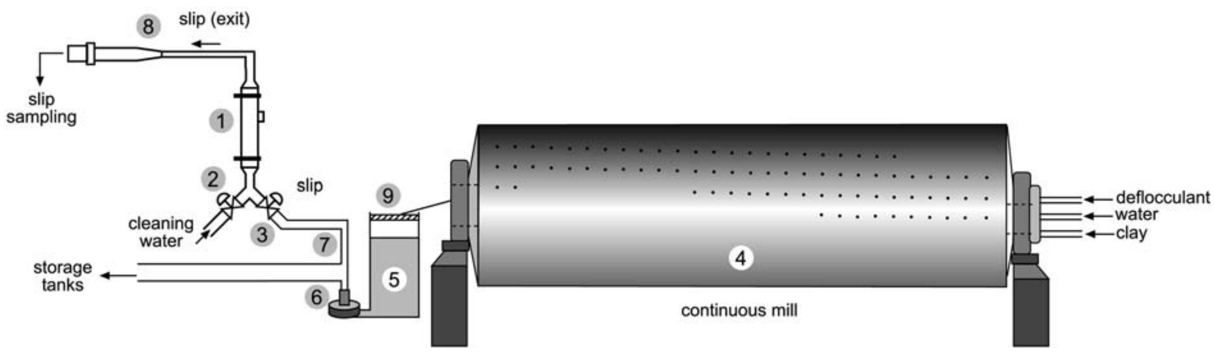

Figure 1. Industrial setup of the densimeter–viscometer arrangement

Description of the elements:

1. Densimeter–flow meter with Coriolis effect
2. Cleaning water injection valve
3. Slip sampling valve
4. Continuous mill
5. Slip collection hopper
6. Slip-conveying pumps
7. Slip pipe
8. Viscometer
9. Sieve

Figure 2. Graph recorder.

For data logging, a recorder was installed, without paper, which was able to store data numerically or graphically (figure 2), in order to monitor the main properties of the slip on-line: density, viscosity, flow rate and temperature.

2.2. DENSITY MEASUREMENT AND CONTROL

2.2.1. Sensor operation

Density was measured with a flow meter–densimeter supplied by the firm Krohne (figure 3), based on the Coriolis principle, which allows measuring the density and mass flow of any moving fluid. The sensor consists of a straight tube that vibrates at resonance frequency. When slip flows through the tube, the resonance frequency varies; this variation is related to the density of the fluid. The most important characteristics are detailed below:

- Straight smooth measuring tube
- No narrowing of the passage section
- Low pressure drop

- Easy to clean
- High measuring accuracy: 2 kg/m^3

Figure 3. Flow meter–densimeter used in the study

2.2.2. Density control loop

If the raw materials (essentially clay and water) proportioning were perfect, strict control of these would assure consistent density of the suspension at the mill outlet. However this control is not perfect, due to swings in clay moisture, errors in weighing of the clay or in the water flow measurement, etc. This makes it necessary to measure slip density at the mill exit, in order to correct possible deviations.

In most industrial installations, as mentioned previously, an operator regularly (generally every hour) measures density and appropriately adjusts the setting for the water or clay feed into the mill. This method poses a number of problems:

- Information is only available hourly. Instant information is unavailable.
- Slip density and viscosity may both vary at the mill outlet. It would be preferable to use a high number of measurements, averaging these suitably, than use a point measurement.

Process automation serves to measure density on-line and use this information for automatic control of the water input in order to hold density at the prefixed setting.

The density control system needs to coexist without interfering with the system in the mill; the latter is not to be replaced, since this would involve technical difficulties that could only be addressed by the mill manufacturer. Therefore, a system was designed in which most of the water feed into the mill was regulated by the mill control system (determined by the relevant composition batch formula), while the density control system acted by just adjusting a small amount of additional water, 'control water' at the mill entrance. Figure 4 shows a block diagram of the control system.

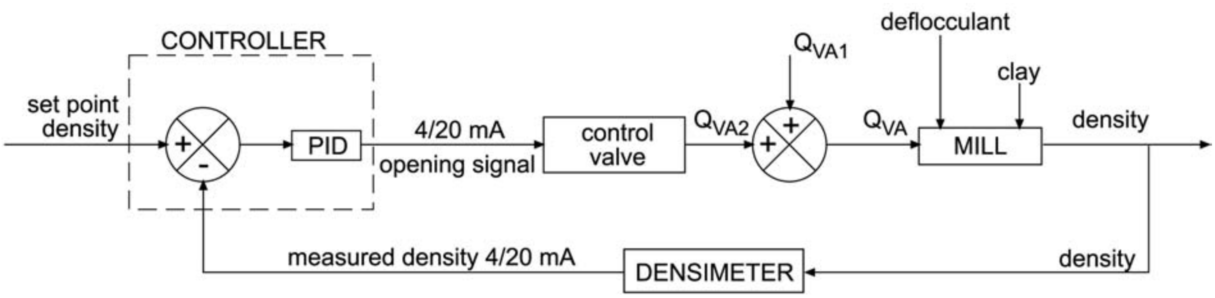

Figure 4. Block diagram of the density control system.

where:

Q_{VA1}: Main water flow. The value is constant and is determined by the batch formula.

Q_{VA2}: Water flow used for control. Regulated by the density controller.

Q_{VA}: Total water flow introduced into the mill.

Figure 5. Detail of water and deflocculant feed to the mill

An intake for a small bypass was fitted in the main recycled water feed to the mill, which routed approximately 10% of the feed through the valve regulated by the density controller. This valve made the fine adjustment of the water introduced in the milling cycle. Figure 5 shows a detail of the water and deflocculant feed, together with the control valve regulated by the density controller. The items in this figure are:

1. Main recycled water feed to the mill. Constant flow rate
2. Deflocculant feed
3. Recycled water feed regulated by the control valve
4. Control valve

2.3. VISCOSITY MEASUREMENT

The industrial determination of ceramic suspension viscosity is complex, largely because of the nature of the property to be measured[2].

We tested several types of sensors for measuring viscosity, like those based on a tuning fork, which allow measuring density and viscosity simultaneously. However, problems of probe soiling were detected, also reported by other researchers[3], so there appeared to be no simple solution. It was finally decided to try a viscometer with a vibrating probe, supplied by Hydramotion (figure 6). The operating principle is based on the torsion generated in a submerged cylinder. This torsion, of microscopic amplitude, generates shear waves that dissipate energy in a magnitude that depends on the viscosity of the medium; therefore, accurate measurement of the dissipated energy enables establishing the viscosity of the fluid in which the probe is immersed.

Figure 6. Viscometer used

3. RESULTS AND DISCUSSION

3.1. DENSITY MEASUREMENT AND CONTROL

3.1.1. Sensor calibration

In order to perform any control it is necessary to have accurate and reliable measurement of the variable to be controlled, which involves selecting an appropriate sensor and establishing its operating conditions.

A first study was made, in the laboratory, to verify the factors that could affect the proper operation of the instrument. Industrial tests were then conducted, which made it clear that the main difficulty in measuring density with the industrial sensor was sensor soiling. The soiling caused slow drifts of the signal; this meant that the values provided by the sensor were completely erroneous after a few days.

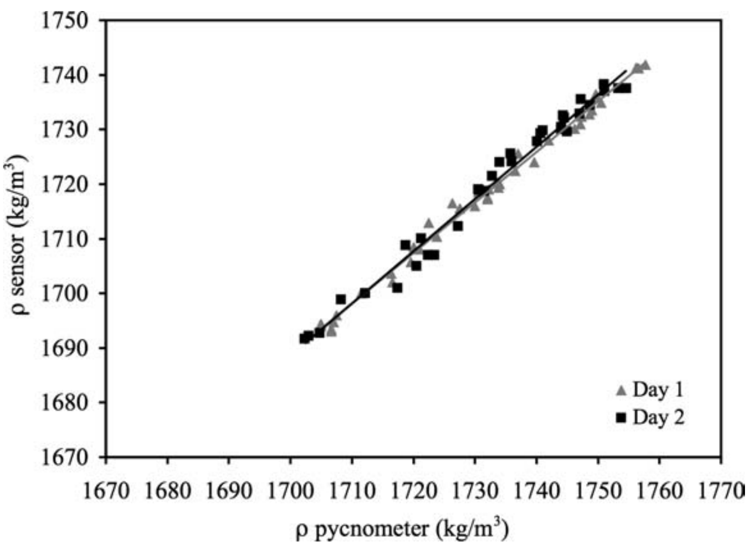

Figure 7. Industrial calibration of the density sensor.

To solve the soiling problems, a cleaning system was designed, consisting of the periodic injection of a joint stream of water and slip at high pressure. This allowed using the abrasive power of the suspended solids, since the use of water by itself as a cleaning fluid was found to be insufficiently effective. The selection of the most appropriate conditions for cleaning required compromising between several factors: frequent cleaning favoured having the sensor in good condition; however, it meant a high cost in water and, in addition, during cleaning a correct density reading became unavailable.

With the foregoing automatic cleaning system the sensor measured correctly for at least one week. After this period mechanical cleaning of the pipe with a brush was needed to remove any possible deposits that had not be eliminated with the automatic cleaning system.

The cleaning system set out above, together with the implementation of the density measurement and control described in section 2.2, has been the subject of a patent application by the Instituto de Tecnología Cerámica (ITC).

Sensor calibration was performed by comparing the manual measurements made with a pycnometer with those supplied by the densimeter. Figure 7 shows the results obtained, which evidence the excellent correlation between the density measurements by the sensor and those determined by the pycnometer. In addition, as was to be expected, the calibration was maintained over time (figure 7 displays two calibrations made on different days).

3.1.2. Automatic density control

After proper operation of the densimeter had been verified, we proceeded to monitor density in normal mill operating conditions.

Figure 8 plots the evolution of density over a period of 12 hours in which there was no automatic control. The density set point was 1725 kg/m^3, with control limits of ± 5 kg/m^3. When the density exceeded these limits during a certain time, the operator made a correction in the water flow feed.

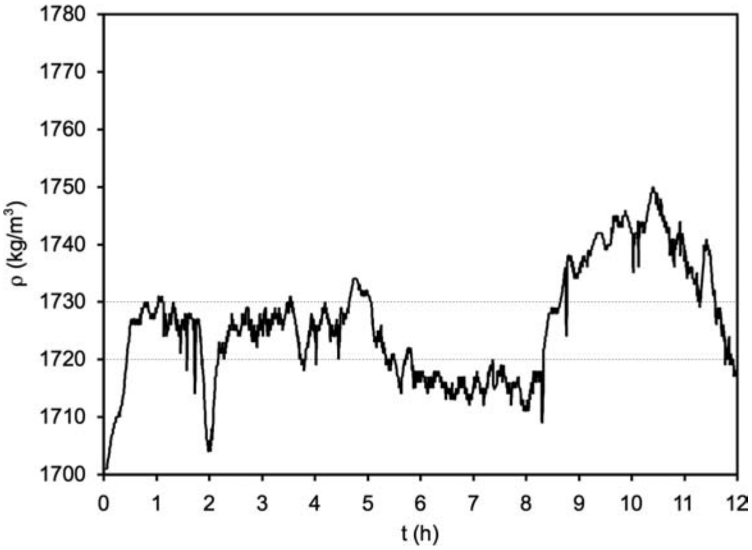

Figure 8. Evolution of density without the automatic control system.

It can be observed that, in the beginning, the density swings around the control range limits. After 5 hours, density decreases below the lower limit, and then increases again after 8 hours. Correction of this increase in density does not commence until 2 hours after detection. The graph clearly evidences one of the main problems of manual control: the time it takes to react to a deviation is quite long.

For comparative purposes figure 9 shows an example of the automatic control system, in which the evolution of density and valve opening have been plotted. An identical setting density and control limits were used to those in figure 8. It can be observed that in this case, though density oscillates, it stays near the control limits, by appropriate adjustment of the valve opening.

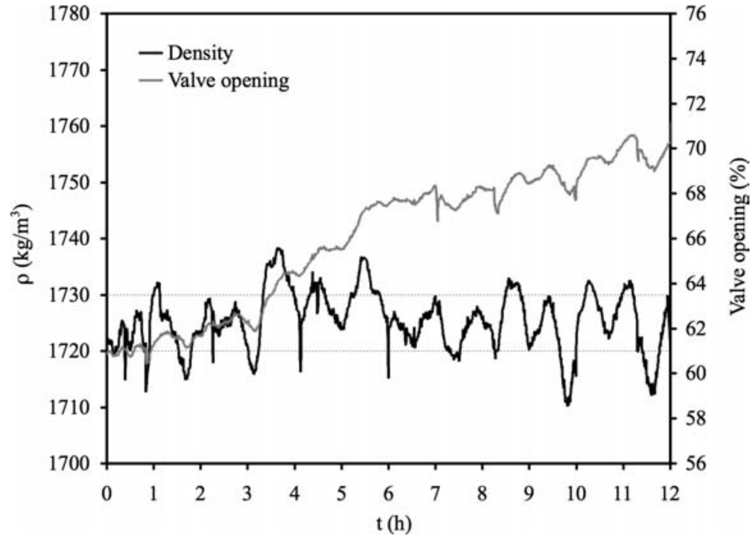

Figure 9. Evolution of density with automatic control

Valve operation is also noteworthy. During the three first hours density swings around the setting without the control valve displaying important movements, but from then on there is a progressive increase in the valve opening up to 70%, which is approximately equivalent to an increase of 400-500 l/h water throughout this period of time. Without this automatic correction, the density would foreseeably have increased progressively, overstepping the set control limits and possibly causing mill operating problems.

With automatic control, the density correction is smoother. In manual control, the operator abruptly increases (or reduces) the flow, whereas in automatic control, valve opening is more progressive, as it is governed by a PID controller.

However, the controller is unable to eliminate the fluctuations that are observed in a period of 1 hour, in figure 9. There are certain occasions when these fluctuations have been observed with manual control; it is, therefore, not a problem stemming from the presence of the automatic density control system. In any case, these fluctuations are not important, owing to their small amplitude and because their effect is minimised in the spray drying tank.

Automatic density control is also effective when there are short breaks in the water or solids feed to the mill. When these breaks occur, density increases or decreases rapidly. In such cases, automatic control minimises the swings in density.

As figure 10 shows, after 5 hours the solid feed in the system was interrupted. The control system responds quickly, closing the water input valve and restoring density to near the setting value.

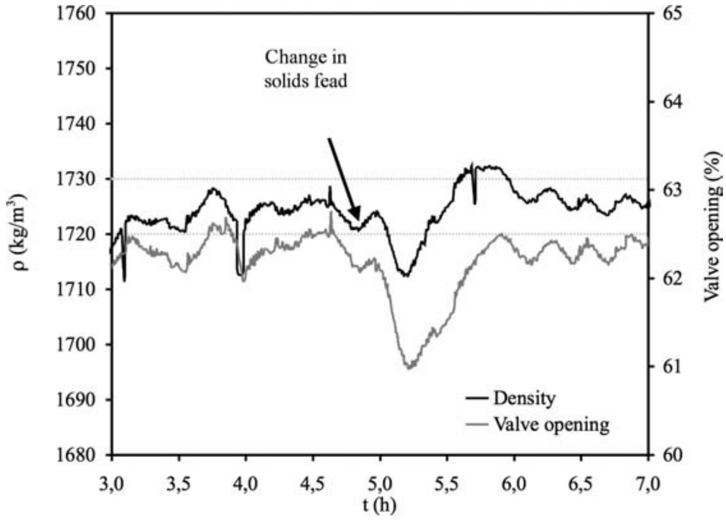

Figure 10. System reaction to a disturbance.

The fluctuations that occur at the mill entrance (breaks in the feed, partial clogging of the water valves as a result of using recycled water, etc.) could be controlled better by using a feedforward system combined with the applied feedback control scheme[4]. In a feedforward system, the information on the fluctuations in the feed would allow correcting the water input before a variation in density occurred. However, using a combined feedforward-feedback control scheme would have complicated the control system greatly.

In order to verify the effectiveness of the control system, an operation was performed in which the automatic control system was switched off. Figure 11 shows how the automatic system was running from 11:00 to 14:30 hours. At 14:30 the control system was switched off; the valve position remained fixed and it was verified that slip density diminished progressively. At 17:00 hours a manual correction took place of the amount of water that was fed into the mill, which caused significant density swings.

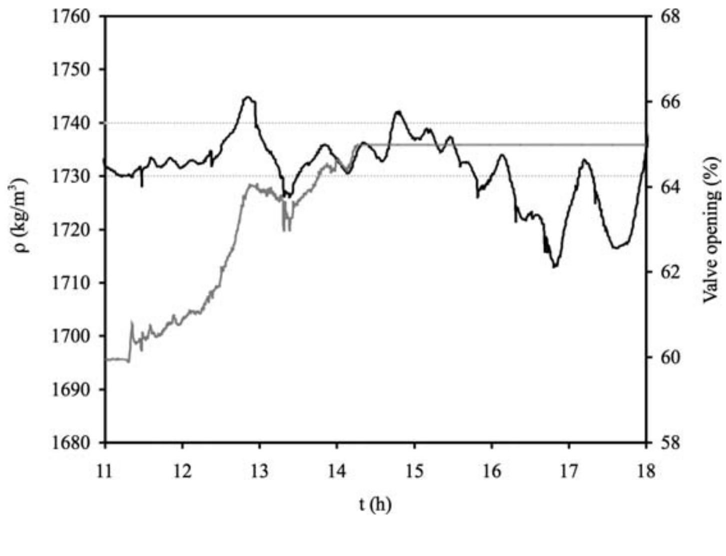

Figure 11. Effect of switching off the automatic control system

Anomalous situations occasionally appear that the control system cannot solve; in these cases a series of safety alarms are triggered. The first goes off when the slip density is outside the control limits, and the system switches over to manual control. The second monitors the water flow, and is triggered when this decreases considerably or is interrupted (for example, due to an obstruction in the valve).

Analysis of the stability of the automatic control over long periods of time confirmed the advantages of on-line slip density control as opposed to the usual procedure used in milling plants.

Being able to control density within a narrow range enabled optimising the milling process, making it possible to work at slightly higher densities (about 30 kg/m^3) and, in particular, having a variable on which it was possible to act directly (with the automatic control system the setting can be modified directly, whereas it was previously necessary to modify the water flow rate).

3.2. VISCOSITY MEASUREMENT

To calibrate the viscosity sensor the percentages of deflocculant and water were modified, thus yielding slips with different viscosity. Figure 12 shows the sensor reading as a function of viscosity, determined as the time required to drain a no. 4 Ford cup. A linear relation is found between both variables, confirming that the sensor is sufficiently accurate to measure viscosity. In addition, the measurements were highly reproducible (figure 12 displays the calibrations made on two different days).

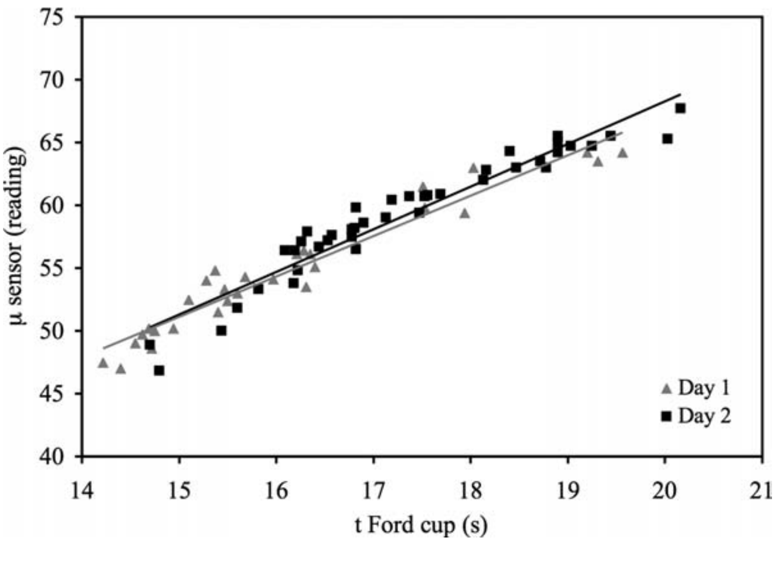

Figure 12. Calibration of the viscosity sensor.

The greatest problem with the viscosity sensor, just as with the density sensor, was the formation of a thin film around the vibrating probe (soiling). Figure 13 displays the effect of such soiling on the calibration straight line: a practically parallel displacement occurs. A sensor that is not perfectly clean will produce a higher viscosity reading than the actual viscosity.

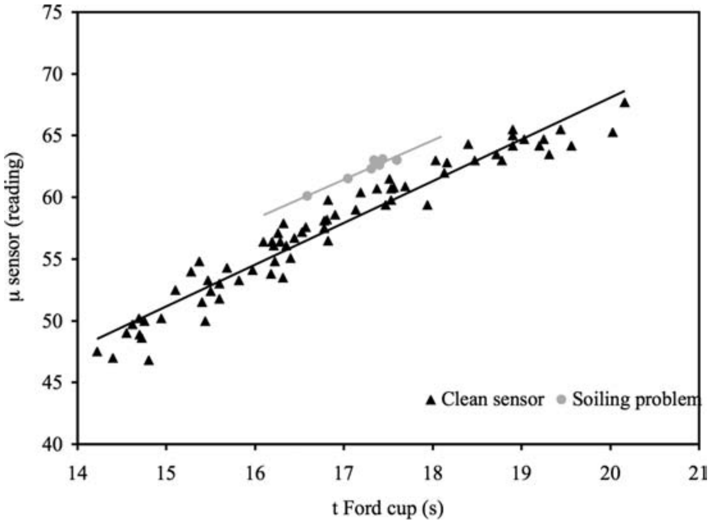

Figure 13. Effect of soiling on the sensor reading.

The solution to the soiling problem of the viscometer was very complicated, and required designing a special cylinder–conical (pocket) measurement chamber in which the viscometer was axially set. The slip was made to circulate through the annular section between the viscometer and the chamber wall. Trials were conducted to determine the most appropriate orientation (horizontal, vertical or sloped), as well as the direction of slip movement and the cleanness conditions (duration and frequency of the cleaning cycles with slip diluted with water).

Under the most favourable conditions it was unnecessary to perform mechanical cleaning for 30 hours (which is the continuous operating time of the mill).

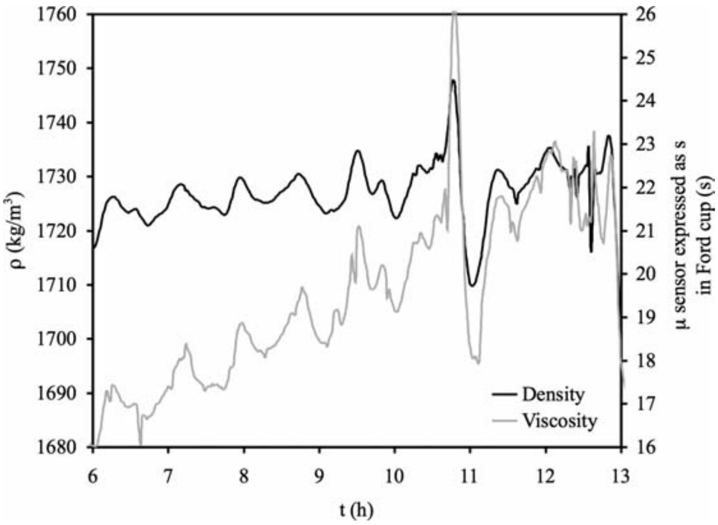

Figure 14. Effect of progressive soiling of the viscosity sensor.

Figure 14 shows the effect of viscometer soiling. In this graph density and viscosity have been plotted as a function of time. It can be observed that viscosity increases progressively, whereas density remains practically constant. The measurement of viscosity in a Ford cup showed that the evolution of viscosity in figure 14 was not real, but was caused by sensor soiling.

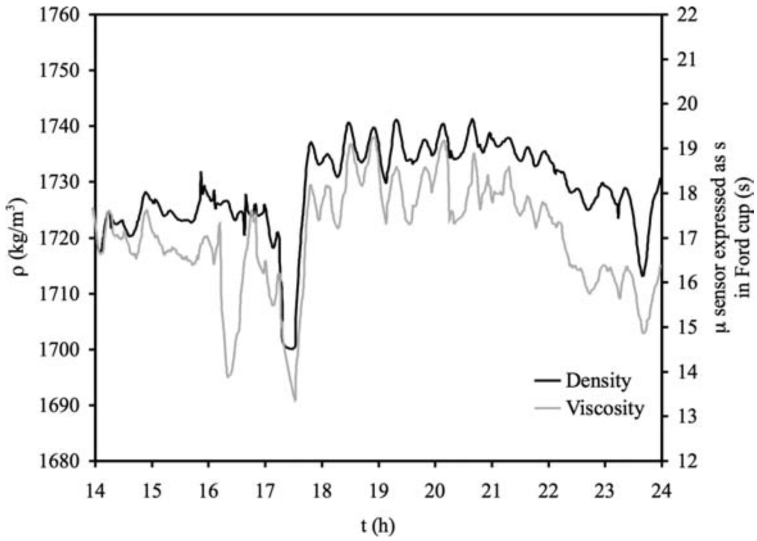

Figure 15. Monitoring of density and viscosity.

The new cleaning system provided results like those shown in figure 15. In the period recorded in this graph no modifications occurred in the mill feed, so that there was a great parallelism between density and viscosity. It may be stated that the variations in viscosity are directly related to those of density, provided feed conditions are not modified.

Obviously, if the deflocculant percentage, the type of clay (e.g. more or less plastic) or the type of water (clean or recycled) changes, the above parallelism is lost.

4. CONCLUSIONS

- Using a flow meter–densimeter based on a Coriolis effect the slip density at the mill outlet can be measured. In order to obtain a reliable measurement it is necessary to use a cleaning system that eliminates the deposit created by the slip in the sensor.
- A control system has bee fine-tuned, based on the value supplied by the densimeter, which acts on the water feed flow into the mill, with a view to keeping suspension density constant. This system has effectively stabilised suspension density at the mill exit.
- The automatic density control has enabled increasing the slip working density slightly, and makes mill control easier, as the value of the density setting can directly be modified.
- A viscometer with a vibrating probe has been tested for the measurement of viscosity. With an appropriate measurement chamber and cleaning system, it is possible to obtain reliable viscosity readings for a period of 30 hours.
- The positive results obtained with the viscosity sensor allow addressing automatic viscosity control of the slip at the mill exit, in a similar way to that of the density control set out in this study.

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