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Use of an Energy Balance around the Mill Sump to Estimate Mill Discharge Density

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A method of estimating the percent solids in the discharge from a grinding mill is described and tested on both pilot and industrial scale. It involves the use of energy and mass balances around the mill discharge sump, requiring measurements of the flowrate and density from the sump together with temperatures of all streams flowing to and from the sump. Accurate estimates of the dynamic variation of mill discharge percent solids are made available, provided that occasional manual sampling of the stream is done to cope with drift in instrumentation. The use of a computer in this application was essential; the various advantages associated with its use are discussed. It is anticipated that this estimate of discharge density can be controlled at a set point by manipulation of the water fed to the mill, resulting in significant decreases in specific power consumption and media consumption.

Introduction

The multivariable control of grinding mills has received a lot of attention. While it has been well established[1] that the percentage of solids or viscosity of the slurry has a substantial effect on milling efficiency, few reports have appeared in the literature of attempts to measure these properties of the slurry and to use them in control schemes. This is presumably because of the difficulty of obtaining a continuous representative sample of the mill discharge stream, which for grate discharge semi-autogenous mills contains a very wide size distribution (all material less than the maximum hole size in the grate, which may be 20 mm) together with wood chips, bits of wire and iron ball chips and remnants. Thus in many installations no attempt to measure mill discharge rheology is made, and feed water rate is ratioed to feed solids rate in an attempt to maintain slurry properties constant. However, this will not work for run-of-mine mills because the feed material contains a widely varying amount of fine (i.e < grate size) material, which is the component which makes an immediate contribution to the percent solids in the mill; the coarser fractions in the feed have a relatively long residence time in the mill, and only make a contribution to slurry density when they are broken down into the fine size range.

Montini and Moys[2] have shown that the economic impact of accurate control of slurry density in the mill can be quite significant. On a large 2,5 MW semi-autogenous mill 5% reductions in power and steel costs alone result in savings of approximately R200 000 p.a., while if improved milling efficiency and increased circuit stability can be used to improve the product quality and hence increase gold recovery by, for example, 0,5%, than increased revenue on a mill treating 100 t/h of an ore containing 8 g/t will be R800 000 p.a. at a gold price of R800/t. This provides a significant motivation for developing techniques for measuring and controlling the percent solids in the discharge from a mill. Moys and Montini[2,3] have reported a method which uses a conductivity probe inside the feed end of the mill for obtaining estimates of slurry viscosity; in this paper use of an energy balance around the mill discharge sump will be described.

If a measurement of the density and volumetric flowrate of the slurry flowing from the sump is available, then the flowrate of solids in this stream can be calculated. At steady-state this will be equal to the solids flowrate from the mill. It remains therefore to obtain an estimate of the water flowrate (or the total flowrate) from the mill, before an estimate of the percent solids in this stream can be made. This is provided by an energy balance around the sump, requiring measurements of the temperatures of all streams entering or leaving the sump.

Authors Da Souza and Tshabalala[4] performed the first series of experiments on a small pilot plant while they were final-year undergraduate Chemical Engineering students at the University of the Witwatersrand. Giddy[5] took the work further on an industrial-scale plant at Anglo American Corporation's Western Deep Level plant.

Mathematical modelling

The experimental equipment used in the pilot investigation is illustrated in Figure 2 while the industrial-scale operation is illustrated in Figure 8. Rigorous mathematical modelling of the dynamic behaviour of these systems is complex, requiring the description of the behaviour of the sump of variable volume, and the time delays suffered slurry in the pipe and pump before it reaches the point where the density and temperatures are measured. This modelling was done by De Souza and Tshabalala (op.cit.), but will not be presented here because it can be shown that certain simplifying assumptions can be made to render the model more tractable but nevertheless adequate for the purpose being discussed.

Giddy[5] describes thé circuit of a large autogenous mill (L=9 m; D=4,5 m) which is typical of a mill where this technique may be applied. The sump has a maximum volume of 7,3 m^3, with an average value of approximately 5 m^3, while the volume of the pipe and pump chamber between the sump discharge and the point of measurement of slurry density is approximately 2,0 m^3. The hold-up of slurry in the mill is assumed to be 30% of the volume of the load, which in turn occupies 45% of the volume of the mill. These assumptions produce a slurry hold-up of 19,3 m^3 for this mill. If the mill is processing 100 t/h at 200% circulating load, and the mill discharge contains 75% solids, then the mill discharge rate is 213 m^3/h, yielding an average slurry residence time in the mill, τ_{mill} = 19,3 x 3600/213 = 326s. This slurry is then diluted to 40% solids, so that the flowrate through the sump is 563 m^3/h. Residence time τ_{sump} in the sump and τ_{pipe} in the discharge pipe are therefore 32s and 13s respectively.

It is tempting to assume that τ_{sump} and τ_{pipe} are negligible in comparison to τ_{mill}. However, since the mill does not behave as a perfect mixer, but also contains an element of plugflow behaviour, it cannot be assumed that the density of the mill discharge will be subject to the damping characteristic of a perfect mixer. It was decided therefore to neglect τ_{pipe}, thereby eliminating the element of the system which is difficult to model, while developing the model for the variable-volume sump. This model is relatively simple and can be further simplified if this is justified.

The model is developed with reference to Figure 1. It is convenient to assume that the mill discharge slurry F_M (kg/s) containing a mass fraction x_m of solids and the sump water F_S (kg/s) mix at a point before entering the sump, to produce an intermediate stream F_i as shown. This stream then enters a perfectly mixed sump in which level h is allowed to vary. The properties (flowrate, density and tempera-

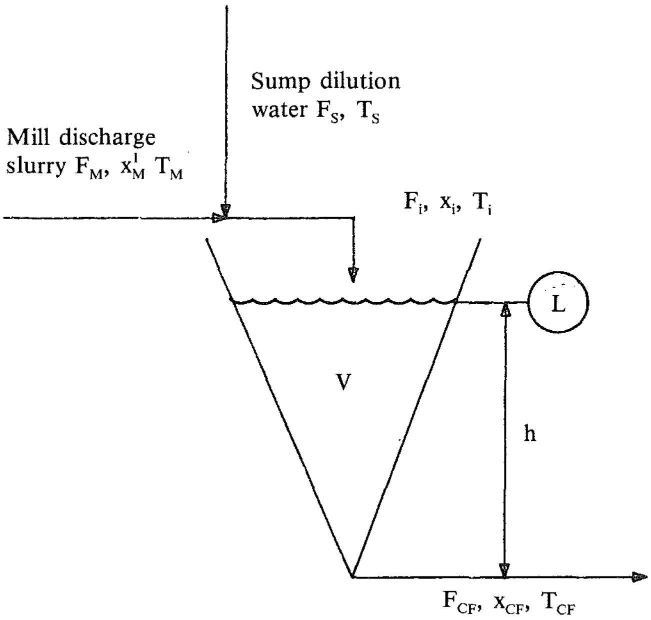

FIGURE 1. Schematic diagram of mill discharge sump

ture) of the discharge from the sump are assumed to be measured close to the sump.

All measurement lags associated with the instrumentation are ignored. Inspection of the data gathered in this project reveals that all instruments could respond adequately to sudden changes in the measured variables.

In order to simplify notation in the analysis below the symbol ψ is used to represent the average heat capacity of slurry with mass fraction of solids x :

$$\psi = xC_s + (1 - x)C_w \tag{1}$$

where C_s and C_w are the heat capacities for solid and water respectively.

Mixing point

Total mass balance:

$$F_S + F_M = F_i \tag{2}$$

Solid mass balance:

$$x_M F_M = x_i F_i \tag{3}$$

Energy balance:

$$F_S C_w T_S + F_M \psi_M T_M = F_i \psi_i T_i \tag{4}$$

If it is assumed that the volume of the sump can be neglected, then the above equations complete the description of the system, with F_i, x_i and T_i replaced by F_{CF}, x_{CF} and T_{CF}.

Sump

Total mass balance:

$$F_i = F_{CF} + \frac{d}{dt}(V\rho_{CF}) \tag{5}$$

Solids mass balance:

$$F_i x_i = F_{CF} x_{CF} + \frac{d}{dt}(x_{CF}\rho_{CF}V) \tag{6}$$

Energy balance:

$$F_i \psi_i T_i = F_{CF}\psi_{CF}T_{CF} + \frac{d}{dt}(V\rho_{CF}\psi_{CF}T_{CF}) + W_s - q \tag{7}$$

where W_s is the pump shaft work (required if T_{CF} is measured downstream of the pump), and q is a rate of energy loss from the system by evaporation from the sump, and conduction and convection from the sump and pump walls. It is shown below that q is small and can be assigned a constant value; W_s is also small and fairly constant, and was ignored. All terms on the right hand side of these equations can be evaluated from the available measurements h, Q_{CF}, ρ_{CF} and T_{CF} using the following elementary formulae:

$$x_{CF} = \left[\frac{1}{\rho_{CF}}\right] / \left[\frac{1}{\rho_s}\right] \tag{8}$$

where ρ_s = solid density, and

$$F_{CF} = Q_{CF}\rho_{CF}$$

The derivatives in (5) - (7) are evaluated numerically, using known relationships between sump volume and sump height. For example, the sump used for the pilot investigation was an inverted cone, and its volume is related to h by

$$V = 0,53 \times 10^{-3} h^3 \ m^3 \tag{9}$$

where h is the height of the slurry surface above the apex of the cone.

Equations (5), (6) and (7) can thus be used to provide estimates of F_i, x_i and T_i; equations (2), (3) and (4) can then be used to solve for

$$F_s = \frac{F_i \ \psi_i (T_i - T_M)}{C_w \ (T_s - T_M)} \tag{10}$$

and

$$x_M = \frac{x_i F_i}{F_i - F_s} \qquad (11)$$

Pilot experimental work

De Souza and Tshabalala (op.cit.) performed this work on the small pilot system illustrated in Figure 2. To simplify experimental work most of the experiments were performed using water only. This demonstrated that the input flowrates could indeed be estimated from an energy balance across the sump, and provided measurements of q, the energy lost from the system under a wide range of conditions. Tests were then performed using slurry to confirm the validity of the method for estimating mill discharge percent solids.

Experimental equipment

Controllers in closed loop with accurate flowmeters and pneumatic control valves were used for controlling the rates F_S and F_M to the system. Instead of using a mill to heat F_M for the water-only experiments, a stirred tank with a 0-10 kW heater was used to heat F_S (it is immaterial whether F_M or F_S is the warm stream). The level in the sump was controlled using a variable speed pump. Exceptionally accurate measurements of F_{CF} (and ρ_{CF} where necessary) were provided by a Micromotion mass flowmeter cum densitometer. Temperature measurements were taken at several locations in the discharge line from the sump in order to provide data for deciding on the best location for measuring T_{CF}. It was found that the temperature measurements close to the sump were unreliable (presumably because of inadequate mixing in the sump), while T_{ap} ('after pump') was affected by the oversized pump used (in some cases temperature rises of

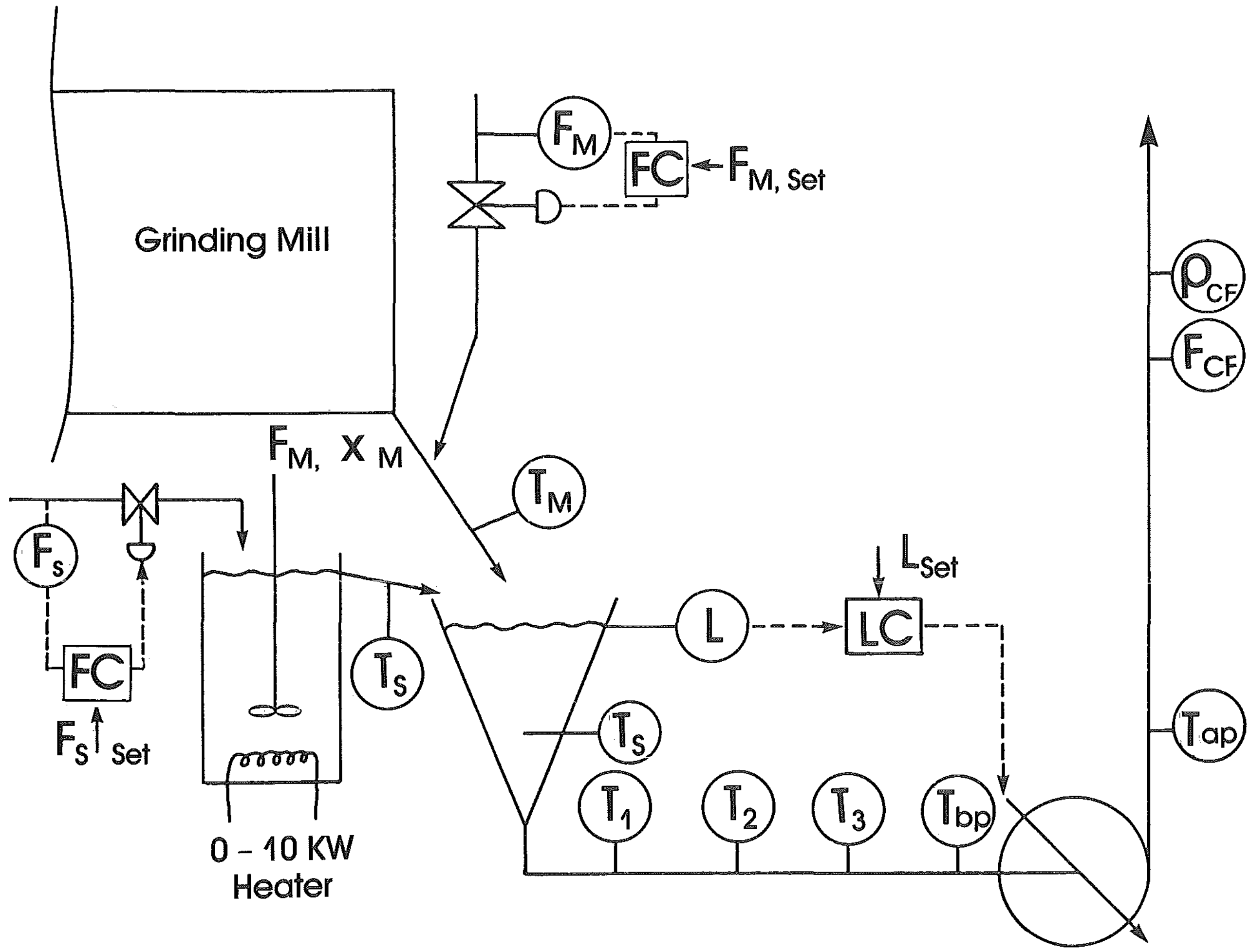

FIGURE 2. Pilot experimental equipment, showing flow and level controls and locations of temperature, flow and density measurements

0,4°C across the pump were observed). Best results were obtained with T_{bp} ('before pump') located at the inlet to the pump and about 20 pipe diameters from the discharge from the sump.

Precision thermistors (10 kΩ at 25°C) inserted in copper jackets of diameter 5 mm were used to measure temperatures. An elementary electronic circuit was used to excite the probes with a 80 μA current, providing a ± 1 volt signal linear with temperature in the 10-50°C range.

All signals were interfaced to a Hewlett Packard 2240A real-time interface controlled by a HP9816 desk-top computer. The A/D conversion was performed with 12 bit resolution providing 0,024% accuracy (e.g. resolution for the temperature measurements was 0,01°C). Flowrate and density signals were linear, while the Steinhart and Hart[7] equation was used to relate temperature to resistance for the thermistors:

$$T(°K) = \{a + b \log R + c (\log R)^3\}^{-1}$$

where a, b and c are constants which are estimated from three measurements of R at known temperatures in the range of interest. This yielded temperature measurements with an accuracy of ± 0,05°C.

The computer was programmed to collect data continuously and to store 5s averages of all variables on disk for subsequent processing.

Water-only tests

25 experiments with F_S varying between 2 and 10 kg/min and F_M varying between 1 and 3 kg/min were performed. The system was allowed to come to steady-state under one set of conditions, then one of the variables was stepped up or down to a new value.

Analysis of steady-state results

Steady-state results were analysed to obtain an estimate of q, the energy loss from the system. Since both inlet flows to the plant were measured as well as the variables discussed above, it was possible to calculate q using equation (7) with W_s = 0. It was found that in all cases q was not large enough to cause a temperature change of more than 0.15°C in T_{CF} which is small (approximately 1% of the temperature changes observed in the experiments), and that q could not be correlated with any variable or combination of variables (e.g. it would be expected that q would be correlated with $F_{CF}(T_{CF} - T_{ambient})$, for example). The conclusion is that very little energy is lost from the system, and that the q-values measured above vary randomly because they are largely a result of random errors in the measurements used to calculate them.

q was thus given an average value of 0,07 kW and equation (10) was used to obtain estimates of F_S for all the steady-state experiments performed. These estimates are compared with the measured values of F_S in Figure 3. It is clear that accurate estimates of F_S can be obtained by the method.

Dynamic response of the system

During the changes from each steady-state mentioned above, the dynamic response of the system was measured. Equations (2) - (11) were solved at each measurement interval (using the measurements obtained during the last two measurement intervals to calculate

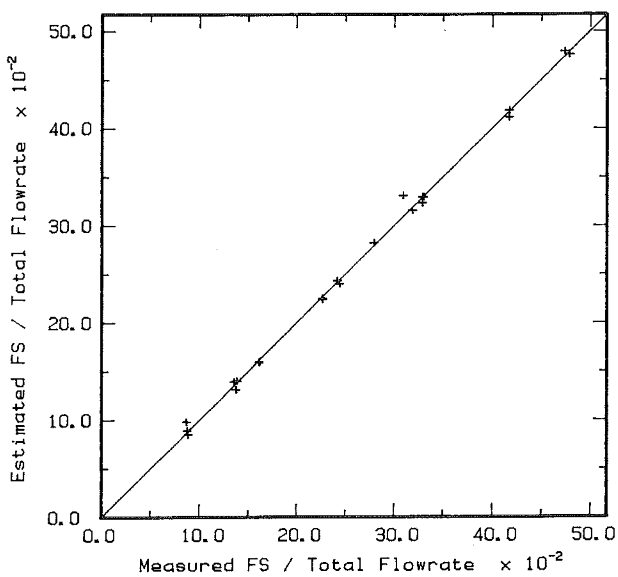

FIGURE 3. Assessment of the ability of the method for estimating the steady-state distribution of inlet flowrates

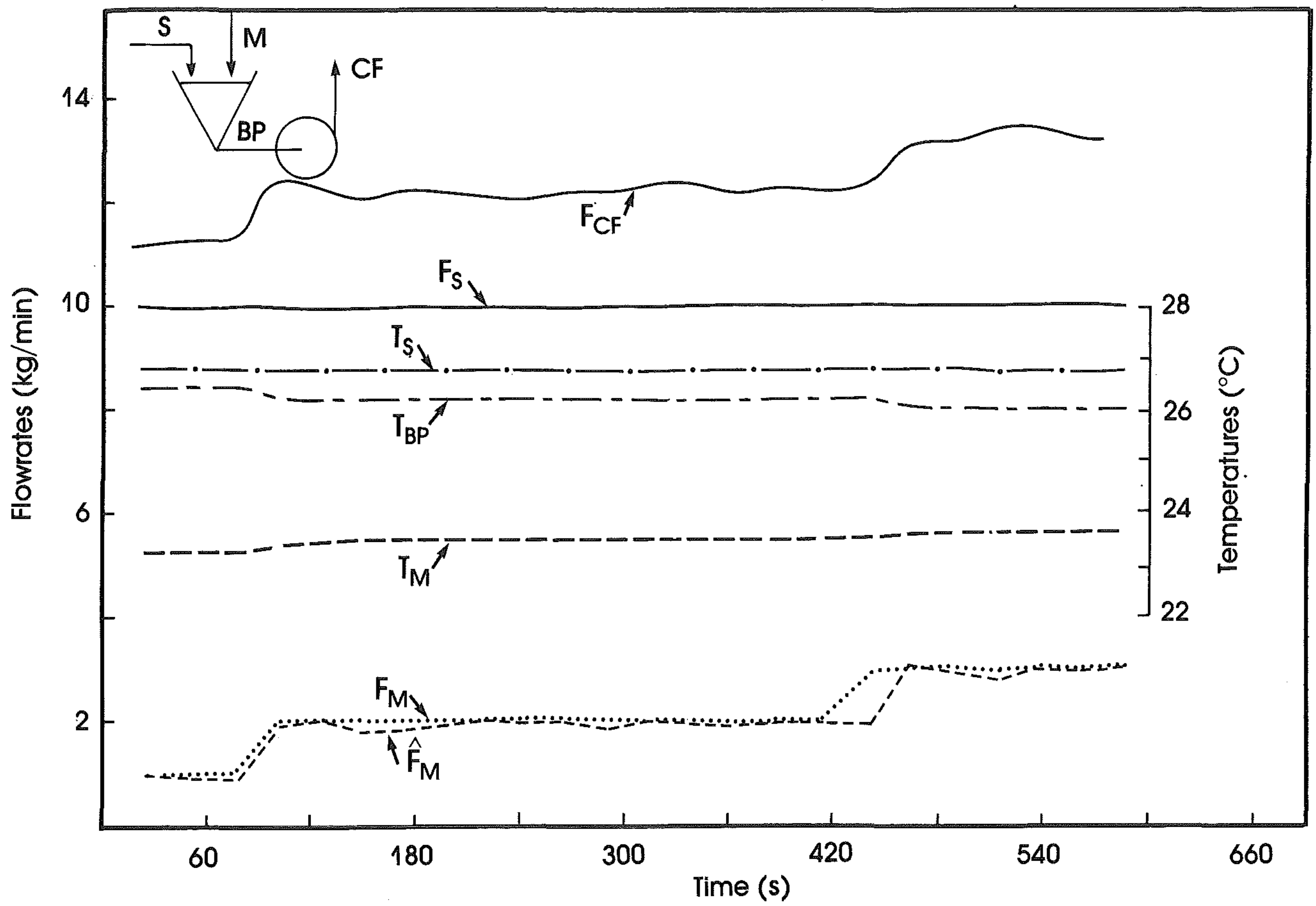

FIGURE 4. Assessment of the unsteady-state response of the method to changes in input flowrate F_M

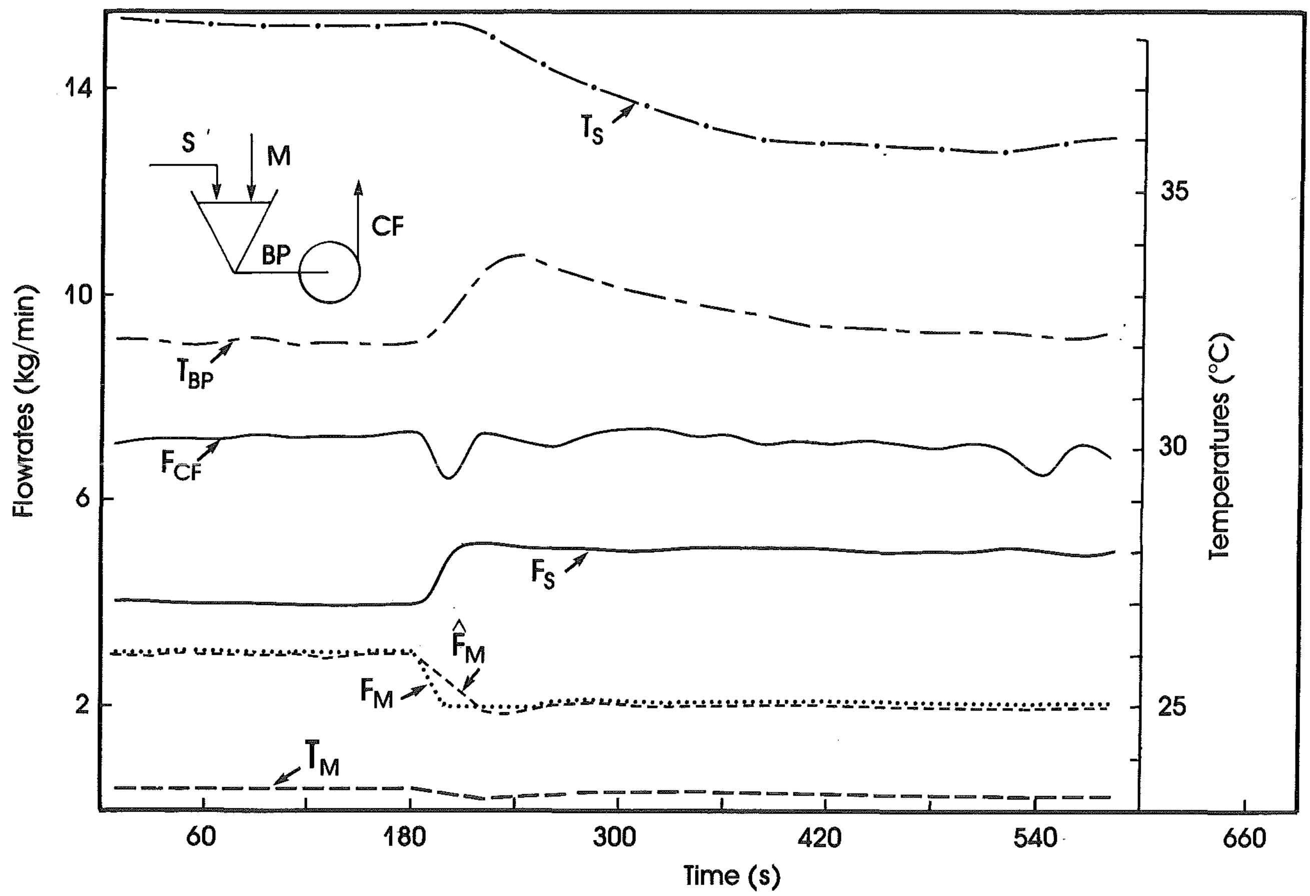

FIGURE 5. Assessment of the unsteady-state response of the method to changes in both input flowrates F_M and F_S

numerical derivatives where required) in order to obtain estimates of F_M, denoted $\hat{F}_M$. These are compared with the measured values of F_M in two situations:

(i) F_M was increased from 1 to 2 kg/min at time 80s and then to 3 kg/min at time 410s, while F_S was held constant at 10 kg/min (illustrated in Figure 4);

(ii) F_m was decreased from 3 to 2 kg/min at time 180s while F_S was simultaneously increased from 4 to 5 kg/min, so that the total flowrate through the system remained constant (illustrated in Figure 5).

Note that in case (i) the temperature difference between the warm and cool stream was only approximately 3°C, because in this run only 2 kw was being added to F_S. In spite of this, F_M is tracked fairly accurately by its estimate. The unsteady behaviour of Q_{CF} is a result of the use of the variable speed pump to control the level in the sump. In case (ii) 10 kw was being added to F_M, resulting in a large temperature difference between the two streams; F_M is more accurately tracked by its estimate in both the unsteady-state and when the system had settled down to a new steady state, in spite of the wide variations in most of the variables involved in the estimation process.

Tests with slurry

A pilot grinding mill described elsewhere[2] was used to produce slurries of nominal mill discharge percent solids of 60, 65 and 70 percent. Ten runs were performed in which total flowrate through the mill and mill speed were varied (the values of these variables are of no relevence to the subject of this paper). Data collected in these tests allowed the following assessments to be made.

Steady-state tests

Samples of the mill discharge stream were taken at steady-state, allowing accurate measurements of x_M to be made. Using an average value for q of 0,11 kw, estimates of x_M were made. These are compared with the

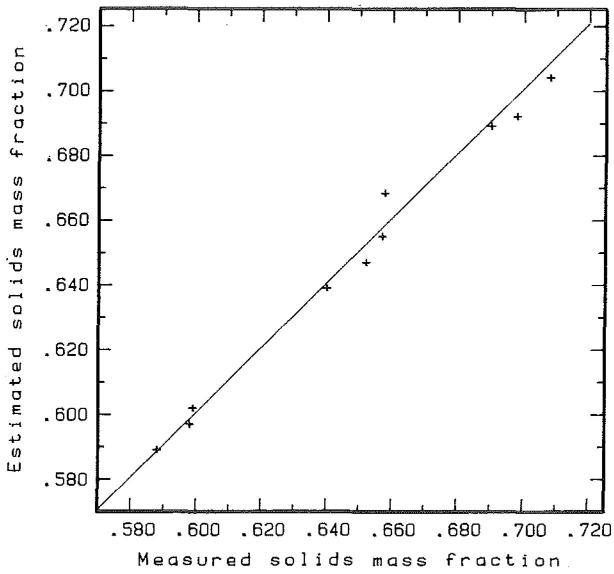

FIGURE 6. Assessment of the ability of the method for estimating the steady-state solids mass fraction in the mill discharge

measurements in Figure 6, revealing a maximum error in x_M of 0,009.

Dynamic response

During the tests described above the apparent viscosity μ of the mill discharge stream was measured. This was correlated with the fractional solids content of this stream by the following equation (based on the Mooney[8] equation)

$$x_{M,\mu} = \frac{1}{2,45/\ln \mu + 1,056} \pm .02$$

using the steady-state measurements of μ and x_M obtained in the ten experiments described above. $x_{M,\mu}$ is compared with $\hat{x}_M$ obtained from the energy balance in Figure 7. Other variables plotted are the fractional solids content into the feed of the mill and x_{CF}. Note the close correspondence between the two estimates of x_M in spite of large changes in sump behaviour (as evidenced by the behaviour of x_{CF}). Some high-frequency noise is superimposed on the $\hat{x}_M$ signal, almost certainly a consequence of the simp lifying assumptions made in the modelling of the system.

Industrial scale experimental work

All experimentation was performed on the No. 1 run-of mine mill at the No. 3 Western

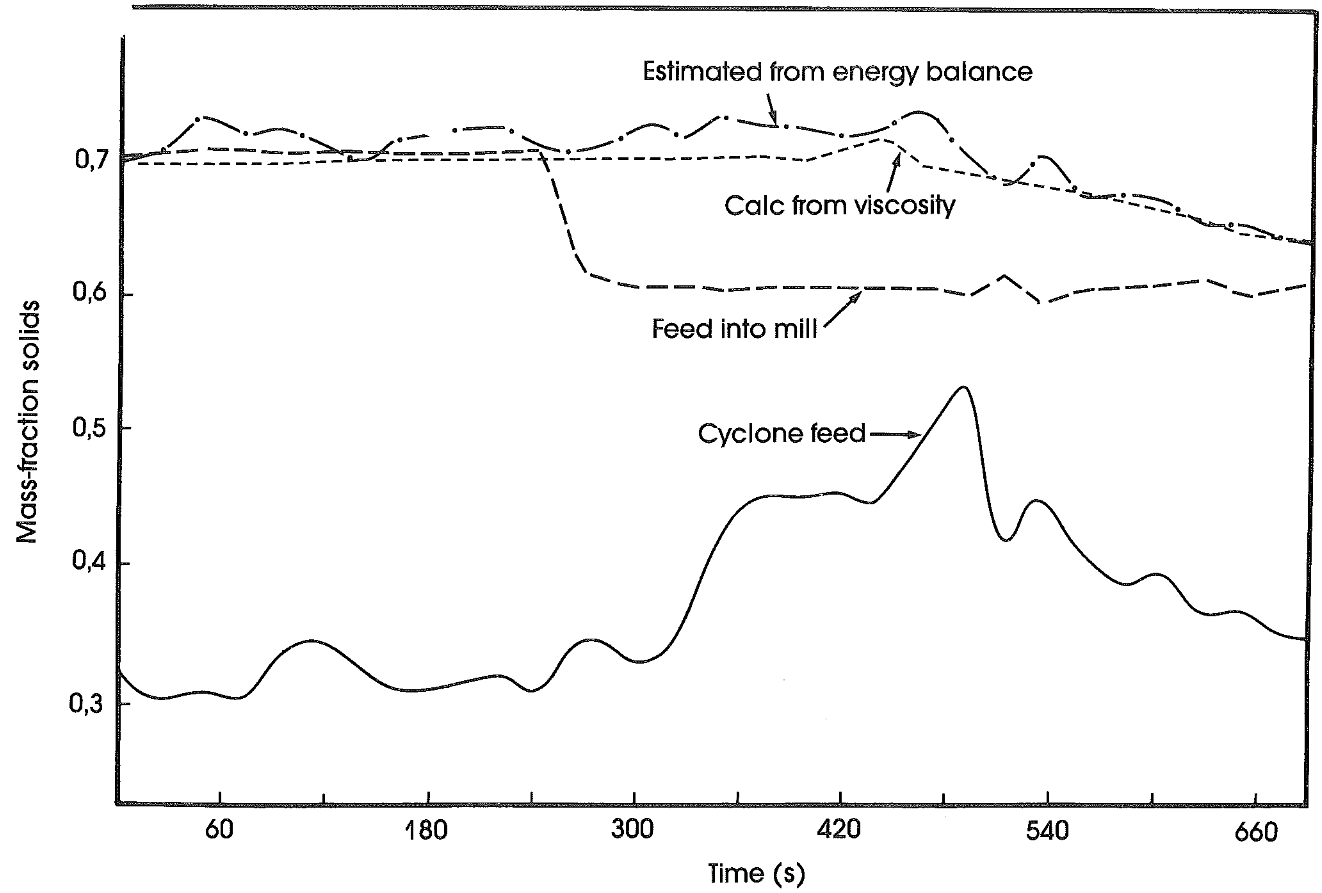

FIGURE 7. Assessment of the unsteady-state response of the method to changes in mass fraction of solids in the mill discharge

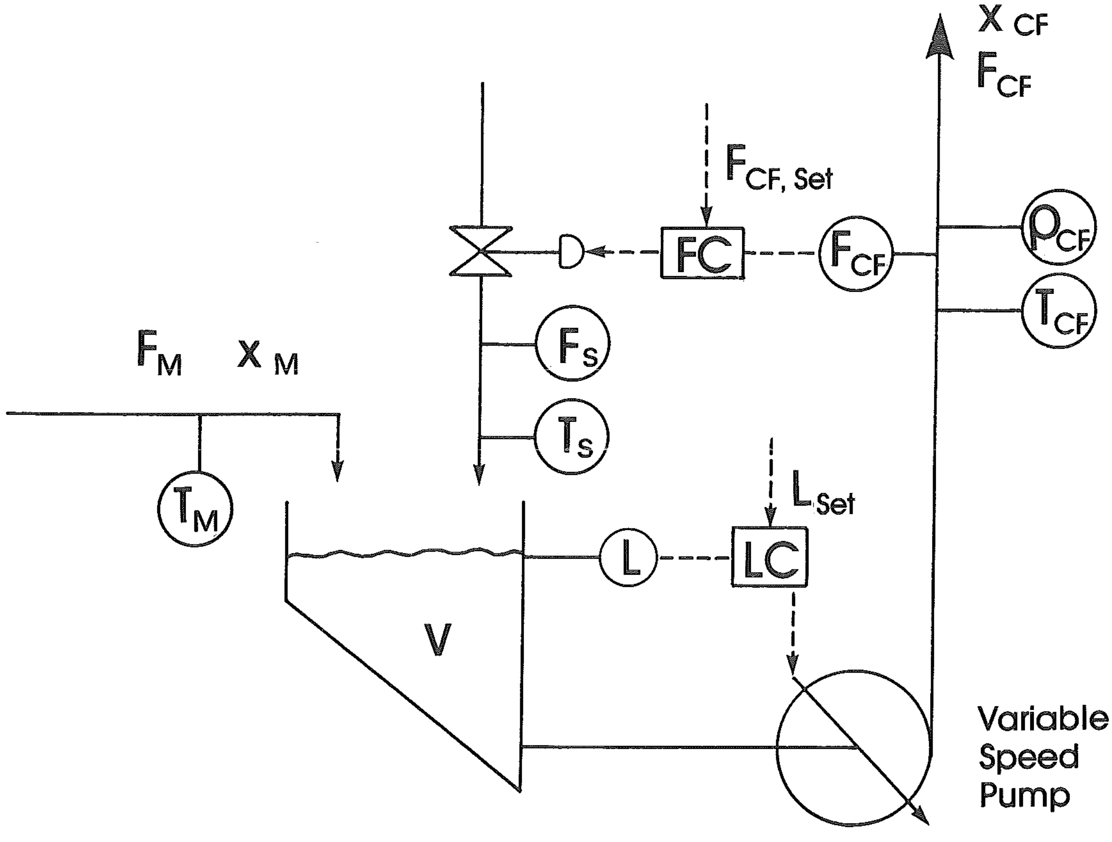

FIGURE 8. Schematic of the industrial scale plant, showing all controls and measurements

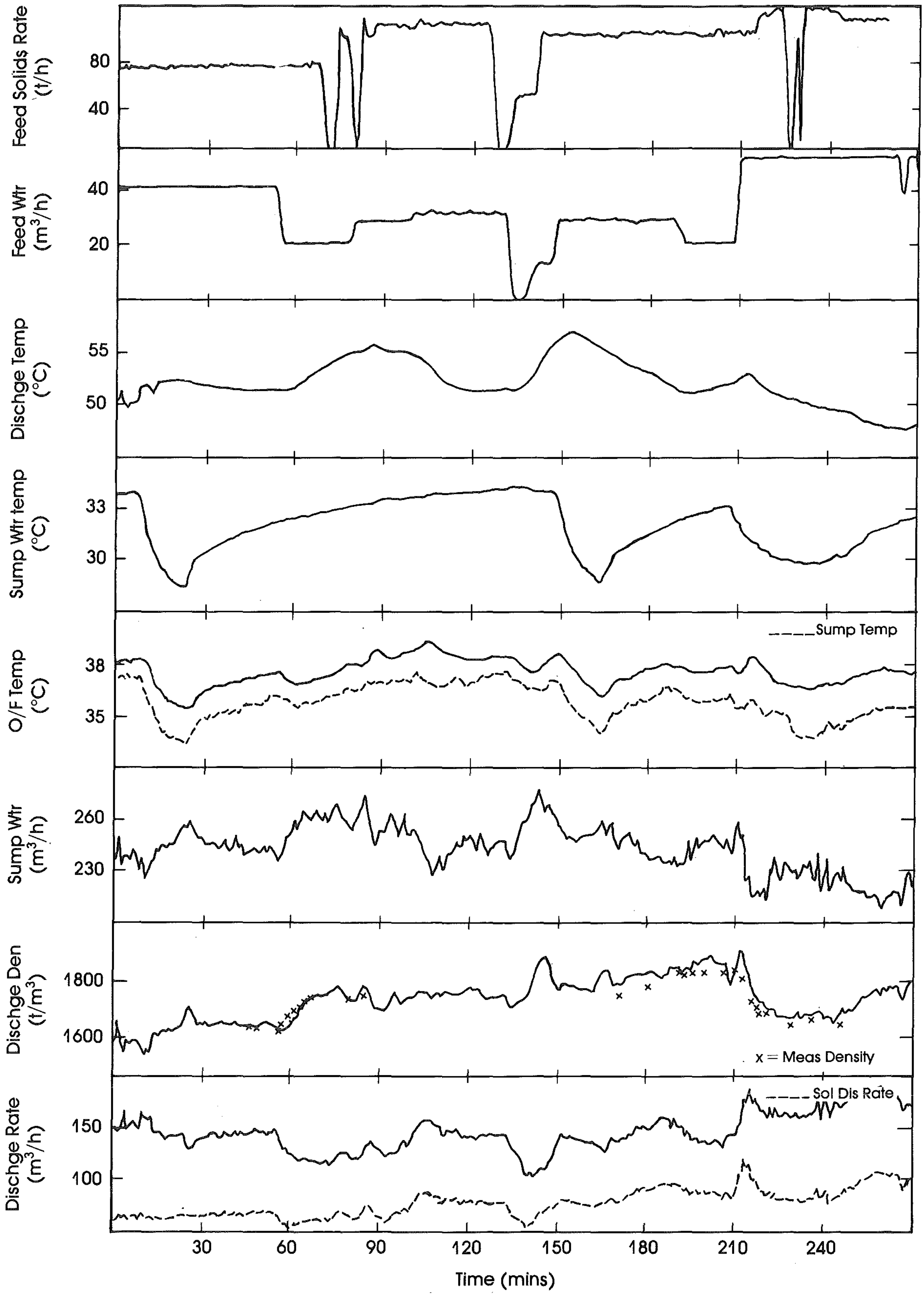

FIGURE 9. Dynamic response of the milling circuit to changes in feed solids and water rates

Deep Levels Gold Plant. The circuit is a conventional one closed with a single-stage hydrocyclone classifier. The relevent section of the plant is illustrated in Figure 8. A variable speed pump is used to control the level in the sump, while cyclone feedrate is controlled by manipulating the sump water rate. Temperature measurements were performed using Pt RTDs for which the suppliers claimed similar accuracy to that provided by the thermistors. While T_M and T_S were measured as close to the sump as possible, T_{CF} was measured in the cyclone overflow stream; this placed a time delay of approximately 20s on this measurement in addition to the dynamic lag characteristic of the sump. In this work the sump and pump + pipe lags were ignored, i.e. only equations (2) - (4) were used to describe the system. Energy losses to the environment and the energy input by the two-stage pump were ignored, making a large contribution to the inaccuracies of the system discussed below.

Signal lines for temperature measurements as well as existing measurements (solids and water feedrates, sump water rate, cyclone feedrate and density) were interfaced to a HP3421 real-time interface (providing 5-digit accuracy) controlled by a HP85 portable computer. One-minute averages of all data collected were stored on tape for subsequent processing.

A detailed discussion of all data collected on this plant is beyond the scope of this paper. Data collected during one run are shown in Figure 9. In this run solids feedrate was maintained constant at 75 or 105 t/h, except for disturbances caused by blockages of the feed mechanism which are of relatively short duration. Feed water was varied over a wide range, and manual density samples of the mill discharge were made at intervals as indicated on Figure 9 by the points plotted on the 'DISCHARGE DEN' graph. The following points are worth noting: (i) It was necessary to reduce the estimate of discharge density produced by the energy balance by 12% in order to produce the correspondence between it and the manual measurements shown in Figure 9. This offset results from errors in the measurements (it is very difficult to obtain accurate calibrations of equipment on plants of this scale; in some cases the manufacturers calibrations were used) and from the simplifying assumptions made in modelling the system (especially ignoring W_S and q). Once this correction was made, however, good correspondence between the two measurements of density was obtained. The correction varied over an 8%-12% range from day to day, implying that occasional samples of the mill discharge density would have to be taken to calibrate the density estimate.

(ii) The density estimate lags the manual measurements by approximately 2 minutes (e.g. at times 62 and 220 minutes), this being a consequence of the dynamic lags in the system.

(iii) The rather unusual behaviour of the sump water temperature resulted from intermittent topping up of the water-holding tanks in the plant with colder water. This did not affect the accuracy of the technique in any observable way.

(iv) The step changes in feed water rate at times 60 and 217 minutes produce predictable responses in the density estimate, which could be modelled as a transportation lag in series with a first order mixer.

Detailed analysis of this kind of data provides insight into the behaviour of the mill under various conditions, and of course provides a rational basis for tuning mill control systems.

Discussion

This project is an excellent illustration of a situation in which a computer is not only a useful, accurate and informative tool to use in the solution of the problem, but is in fact the only tool that could have been used. Five measurements have been acquired by the computer and a sixth has been derived from them using equations based on established thermodynamic principles. While several simplifying assumptions were made to simplify the analysis of the system and hence the development of the technique, it is worth pointing out that it was not essential that these assumptions be made. For example, it is possible to model the flow through the system more accurately, to measure the shaft work input by the pump, and perhaps to correlate the energy lost from the system to the environment with measurements of ambient temperature. The computer places no limit on the user's ability to take into account all those variables which have a significant effect on the application and to neglect those which do not.

Further work is at present being done at the Western Deep Levels mill. It has been extended (to cope with problems such as the periodic injection of floor washings into the mill circuit) and incorporated into the existing peak-seeking control scheme used to control the mill. This peak-seeking control scheme was developed by using a ladder-logic programming technique. Substantial difficulties have arisen because of the out-of-date operating system used. The technique will be implemented on a Siemens system on a new mill which provides several advantages, and will therefore facilitate the full exploitation of this measurement in mill control techniques.

Conclusions

The financial implications of accurate control of slurry rheology in grinding mills are significant, implying payback periods on a successful investment of less than a year. It is, however, controlled on few mills at present presumably because of measurement difficulties. A method of estimating the percent solids in the discharge from a grinding mill is described and tested on both pilot and industrial scale. It involves the use of energy and mass balances around the mill discharge sump, requiring measurements of the flowrate and density from the sump together with temperatures of all streams flowing to and from the sump. The major advantage of this technique is that it avoids the problem of obtaining a representative sample of the mill discharge slurry for density analysis. It was shown on the pilot plant that minimal energy is lost from the system to the environment, and that accurate estimates of the dynamic variation of mill discharge percent solids are made available if an average value of this energy loss was used. On the industrial plant the energy input from the pump was ignored, resulting in a fairly large offset in the percent solids estimate. An accurate reflection of the dynamic behaviour of the percent solids is obtained provided that occasional manual sampling of the stream is done to cope with drift in instrumentation. The use of a computer in this application was essential; the various advantages associated with its use are discussed.

Acknowledgements

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