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Further developments in the control of levels in flotation columns*

by M.H. Moys†, J. Engelbrecht‡, and N. Terblanche‡

Synopsis

Interface levels in flotation columns are generally measured with the aid of a pressure-sensitive instrument, e.g. a differential-pressure cell. This paper criticizes the use of this type of measurement, and discusses other methods that are claimed to give more accurate measures of interface levels. The paper focuses on the development of methods based on the measurement of conductivity across the froth–slurry interface. These are often sabotaged by variations in the conductivity of the feed slurry, particularly when the pH of the slurry is being controlled, e.g. in sulphide flotation. Methods of improving the accuracy and reliability of this technique are described. The result is a robust, easy-to-maintain level-control scheme that successfully rejects large disturbances in plant operation (including a 5:1 change in slurry conductivity) while controlling levels to an accuracy of ± 4 cm.

Samevatting

Die tussenvlakhoogte in flottasiekolomme word gewoonlik met behulp van 'n druksensitiewe instrument soos 'n differensiaaldruksel gemeet. Hierdie referaat kritiseer die gebruik van hierdie tipe meting en bespreek ander metodes wat na bewering akkurater metings van tussenvlakhoogtes gee. Die referaat spits hom toe op die ontwikkeling van metodes wat op die meting van geleivermoë oor die skuim-floddertussenvlak gebaseer is. Hierdie metodes word dikwels gesaboteer deur variasies in die geleivermoë van die toevoerflodder, veral wanneer die pH van die flodder beheer word, bv. in sulfiedflottasie. Metodes om die akkuratheid en betroubaarheid van hierdie tegniek te verbeter word beskryf. Die resultaat is 'n sterk hoogtebeheerskema wat maklik in stand gehou kan word en wat groot steurings in die aanlegbedryf (insluitende 'n verandering van 5:1 in die flodder se geleivermoë) suksesvol verwerp, terwyl dit die hoogtes met 'n akkuraatheid van ± 4 cm beheer.

INTRODUCTION

For effective operation of a flotation column, the level must be controlled near a pre-specified level, L_{set}, so that it is (a) not so high that the significant mixing that occurs in the froth phase results in a loss in grade, and (b) not too low, resulting in both an excessive residence time of bubbles in the froth phase and a loss of residence time in the pulp phase (both of these effects resulting in a loss of recovery). Yianatos *et al.*[1] recommend a froth depth of approximately 1 m. Current methods for measuring the interface level, L, are reviewed below, and research work aimed at the development of a reliable method of measuring L by the use of conductivity measurements is described.

METHODS FOR MEASURING INTERFACE LEVEL

The method most widely used is that based on the measurement of hydrostatic pressure, P, at a distance between 1,5 and 2 m below the overflow lip. However, P is not an accurate indicator of interface level because it is a strong function of other variables, such as slurry density, hold-up of liquid in the froth, bubble loading, etc. Moys and Finch[2] showed that errors in L exceeding 0,5 m are easily possible when high gas rates, small bubbles, and high bubble loadings occur, particularly when the floatable mineral is dense, e.g. pyrite or galena. Moys and Finch[3] measured an error of 0,4 m in the flotation of galena in a limited test programme at the Polaris Mine, N.W.T., Canada, and the variation of level with pneumatic pressure measurement in pyrite pilot tests performed by Multotec Cyclones (Pty) Ltd (a local supplier of flotation columns) is shown in Fig. 1. This lack of precision means that frequent checks on level must be made by the operator in situations where there is a sight window on the side of the column; in the absence of a sight window, the poor performance of the measurement cannot be checked, and the operator is forced to set the interface level at a conservatively low level to avoid disaster, thereby incurring losses associated with unnecessarily deep froths most of the time.

Accurate measurement of interface levels relies on the measurement of intensive properties of the fluids near the interface (such as density, temperature, or conductivity), rather than an extensive property such as pneumatic pressure, which is a function of the total mass of material above the measurement point. Some of these methods are discussed later.

Techniques based on the measurement of the position of a float at the interface (this is essentially a density technique and is used successfully with conventional flotation), cannot be relied upon since the density of the froth near the froth–slurry interface varies over too wide a range. It is not generally possible to select a density for the float that will apply to all possible conditions.

Huls *et al.*[4] have reviewed the use of multiple-pressure sensors for the estimation of interface level. If two D/P

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† Department of Chemical Engineering, University of the Witwatersrand, Private Bag 3, Wits, 2050 Transvaal.

‡ Multotec Cyclones (Pty) Ltd, P.O. Box 224, Kempton Park, 1620 Transvaal.

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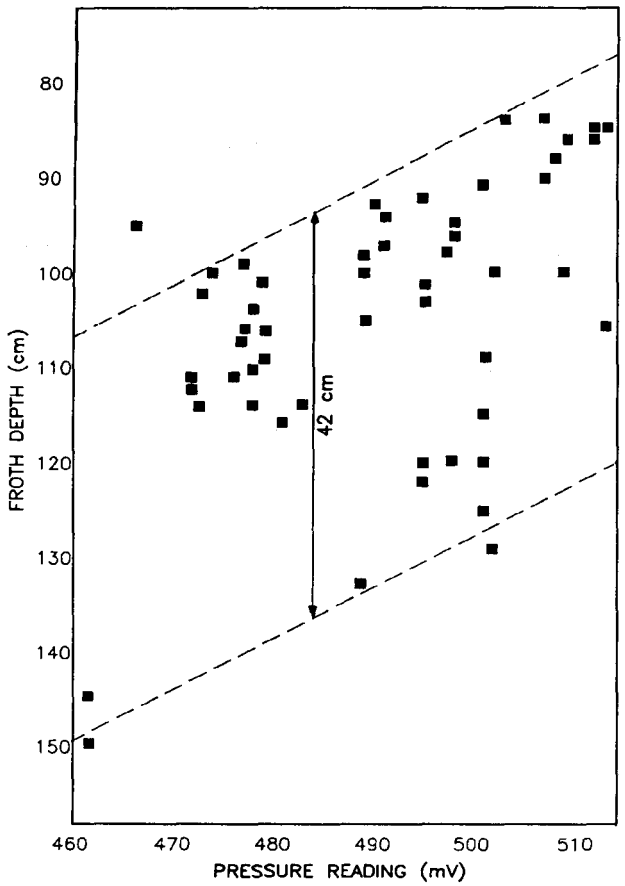

Fig. 1—Variation of true interface level with pneumatic pressure signal

cells are mounted above the interface (to provide an estimate of froth density), and two are mounted below the interface (to provide an estimate of pulp phase density), then accurate estimates of the interface level can be obtained. Expense and inflexibility mitigate against this approach, and Huls *et al.* recommend the use of a conductivity method such as that developed by Gomez *et al.*[5] which is discussed later.

Moys and Finch[2-4] have reported the use of measurements of temperature profiles across the froth–slurry interface. The technique relies on the existence of a significant and reliable temperature differential between the wash water and the feed slurry. Provided that the column is operated under positive bias conditions (i.e. with wash water flowing downwards through the froth phase, so that the froth phase temperature is close to the temperature of the wash water), there is a sharp change in temperature at the interface. Detection of the level at which this change occurs provides an estimate of interface level accurate to ± 7 cm. The method suffers the disadvantage of requiring the intelligent analysis of 10 to 15 temperature measurements, and will be expensive. Other significant advantages to be obtained from such measurements (such as online measurements of froth washing efficiency[6]) may make this technique an attractive option, particularly in an environment where computer-control resources are already available.

The use of conductivity measurements may provide a measurement that is reliable, simple to implement, and cheap. Moys and Finch[2] discussed initial work in this area. The first method involved the use of two parallel, vertical probes that provide a fairly linear correlation between level and conductivity, as shown in Fig. 2. (The conductivity profiles obtained with two short probes are shown in the lower part of the figure.) The second involved measurement of the conductivity between two probes, one above and one below the interface, as shown in Fig. 3. The correlation is non-linear but the simplicity of the design (the two probes can be mounted on a vertical rod passing through the froth phase) makes the exploitation of this approach attractive.

Gomez *et al.*[5] have developed an interface-level sensor that is based on the above principle. They used an IBM-compatible PC to multiplex a conductivity meter to a level-detection probe that consisted of 12 pairs of conductivity probes mounted one above the other on a PVC rod (similar to that illustrated in Fig. 10). This was used to measure the conductivity of the contents of the column at 12 different levels, each separated vertically from the next by 10 cm, spanning the range of levels within which control of the interface level was desired. Detection of the level at which

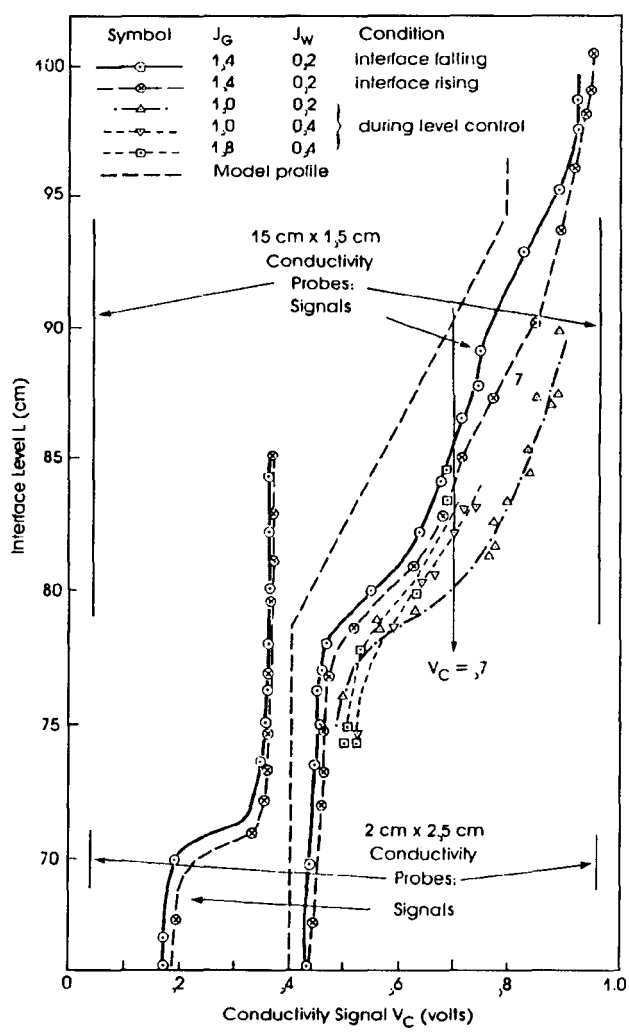

Fig. 2—Response of a conductivity measurement to changes in level by the use of two long parallel probes located across the interface[2] (J_G and J_W are superficial gas and wash-water rates respectively)

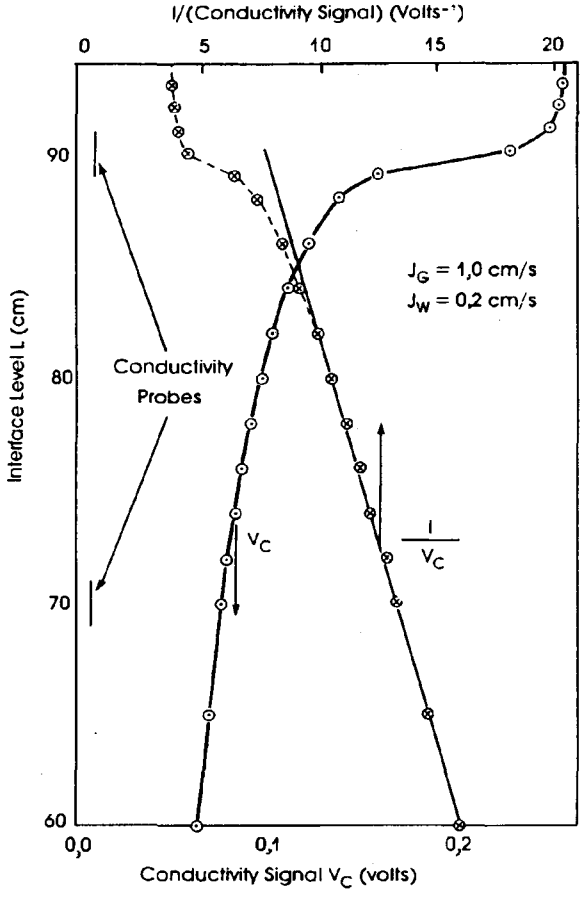

Fig. 3—Response of conductivity measurement to changes in level by the use of two short probes located one above the other and spanning the range in which the control of interface level is desired[2]

a sharp change in conductivity occurred provided a measurement of interface level accurate to within ± 10 cm. This accuracy can be increased by the use of shorter distances between the conductivity probes. Mintek has independently developed and patented[7] a similar instrument.

The work described in this paper was performed in parallel with the work described in the previous paragraph. A technique was developed for the control of level that has worked exceptionally well, relies on the use of off-the-shelf instrumentation, and is cheap and robust.

THEORETICAL DEVELOPMENTS

Variation of Conductivity across the Interface

This is discussed by Moys and Finch[2] in some detail; only the salient points are summarized here.

The conductivity of a gas–liquid dispersion typical of column flotation froths[8] is given by

$$k_{fr} = 0,432\, k_{l,fr}\left[\frac{\epsilon_{l,fr}}{1-\epsilon_{l,fr}}\right], \qquad [1]$$

where $k_{l,fr}$ and $\varepsilon_{l,fr}$ are the conductivity and fractional holdup respectively of the liquid in the froth phase. Typically, $\varepsilon_{l,fr}$ is less than 0,4 at the base of the froth, and drops rapidly to approximately 0,2 at the top of the froth phase; $k_{l,fr}$ will be similar to the conductivity of the slurry, k_{sl}, at the base of the froth but in columns, where washing of the froth phase by the wash water is efficient, it will change rapidly towards the conductivity of the wash water.

In the pulp phase, the conductivity is given by

$$k_{pulp} = k_{sl}\left[\frac{\epsilon_{sl}}{1,55 - 0,55\,\epsilon_{sl}}\right], \qquad [2]$$

where the slurry hold-up, ε_{sl}, is generally greater than 0,7. For $k_{l,fr} = k_{sl}$, $\varepsilon_{l,fr} = 0,4$, and $\varepsilon_{sl} = 0,7$, the ratio between froth and pulp conductivities is 0,48. This corresponds very closely to the ratio observed by Gomez *et al.* (0,35 to 0,50). In cases where $k_{wash} < k_{sl}$, this ratio will be decreased, giving ample variation in k across the interface while, if $k_{wash} > k_{sl}$ (e.g. this can occur in unusual cases where the pH of the wash water must be controlled), the variation of k across the interface will not provide a reliable basis for interface detection.

Conductivity across the Interface

Conduction in fluids between two small probes a significant distance apart is a complex phenomenon. In an infinite uniform medium, the conduction paths follow lines through the medium that constitute the lines of steepest descent in the voltage field set up between the two probes. While most of the current follows a relatively short, direct path between the probes, a significant proportion of it follows much longer paths. The conductivity between the two probes is a strong function of the specific conductivity of the liquid, the distance between the probes and the surface area, and the geometrical arrangement of the probes. The very simple assumption that the current is conducted through two resistances set up by the froth and the pulp provides the following model (formulated in terms of resistances):

$$R_{tot} = \bar{R}_{fr}\,(z_{top} - L) + \bar{R}_{pulp}\,(L - z_{bot}), \qquad [3]$$

where $\bar{R}$ is the resistance per centimetre, L is the interface level, and z_{top} and z_{bot} are the probe positions. This implies a linear relationship between R_{tot} (=$1/k_{tot}$) and L. This is true only for L some distance from the top probe, as shown in Fig. 3, where the inverse of a signal, V_c, from a linear conductivity meter is plotted versus L ($1/V_c$ is proportional to R_{tot}). A more comprehensive model must account for the geometrical design of the sensors, and must in particular account for the different conduction paths followed by the current when the interface level is rising past the probe faces.

Measurement of Conductivity

Some industrial conductivity meters rely on the (simplified) circuit diagram shown in Fig. 4. A high-frequency alternating voltage, E, is applied to a range resistor, R_R connected in series with the conductivity sensor (which has a resistance R_k). The voltage, V, is easily related to R_k:

$$V = E\left[\frac{R_k}{R_R + R_k}\right]. \qquad [4]$$

In the conductivity meters used in this project, this voltage was converted into a 4 to 20 mA signal, i_k, corresponding to a two-decade range on k ($=1/R_k$) and a 0 to 100 per cent gauge reading, q (%), as follows:

i_k (mA)	4	12	20
k (Ω^{-1})	$1/10R_R$	$1/R_R$	$10/R_R$
q (%)	0	50	100.

Thus, the meter output i_k and reading q are strongly and non-linearly related to k; the relationship is such that a 10 per cent change in k results in a large change in i_k or q, approximately independent of the value of k. This means that the signal is sensitive to changes in k over a two-decade range of k, something that could not be achieved with a linear instrument. The design of this instrument lends itself ideally to the purpose of this investigation, as will be revealed below.

EQUIPMENT

Experiments were performed in a square (12 cm by 12 cm) Perspex laboratory column 1,8 m tall. The pilot plant is illustrated in Fig. 5. Two sources of feed material were available. (Only water, not slurry, was used to simplify the experimentation.) One feed source was dosed with hydrochloric acid to raise its conductivity substantially above that in the other source, which was ordinary tap water. Turbine flowmeters provided measurements of these flowrates. Wash water dosed with Dowfroth 250 was added at the top of the column. Gas was added through a canvas sparger; both the wash water and the gas rate were measured using rotameters. Two LTH DCM-1 conductivity meters, a D/P cell for measurement of pressure 1 m below the interface, and an analogue PID controller were available

The true interface level was measured by use of a pointer attached to a string passing round two pulleys, as shown in

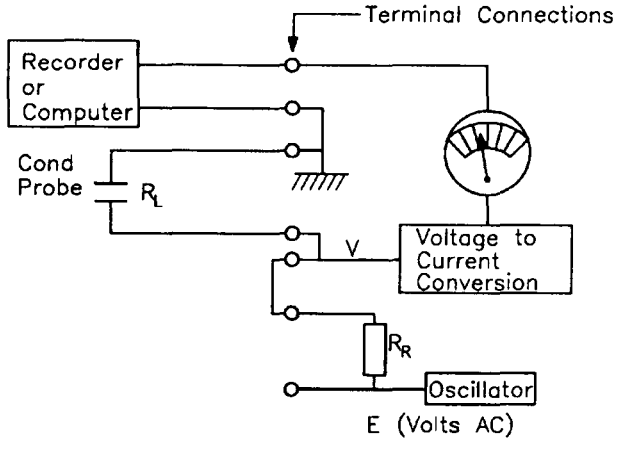

Fig. 4—A simplified circuit for the conductivity meter used in this investigation

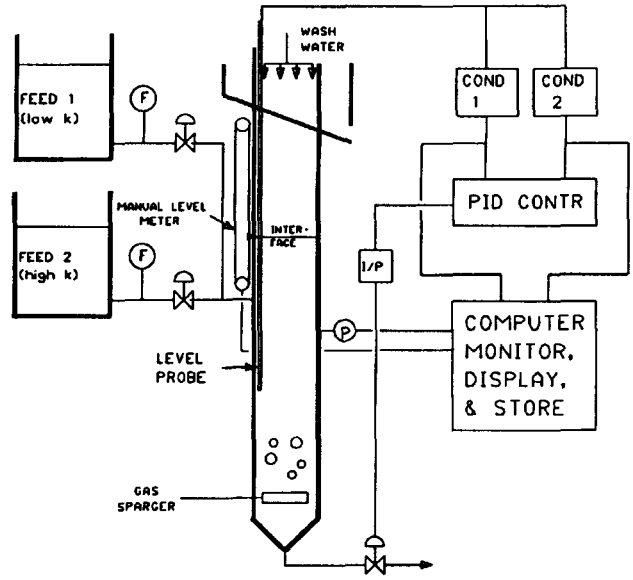

Fig. 5—The pilot flotation-test rig

Fig. 5. One of the pulleys was mounted on a 10-turn potentiometer. The pointer was moved manually to track the interface position, which caused a linear change in the resistance of the potentiometer. This change was converted to a voltage proportional to the interface level. All the measurements were interfaced to an IBM-compatible PC, which was programmed to display, print, and store all the data collected.

EXPERIMENTAL RESULTS AND DISCUSSION

Previous work had shown that a level-control system based on the probe arrangement illustrated in Fig. 3 worked fairly well when coal and fluorite ore were being processed, but failed dismally when applied to pyrite flotation, because the conductivity of the slurry varied widely as a result of the necessity to control the pH of the slurry at a setpoint of 3,8 pH units. As small variations in pH resulted in large variations in conductivity, it was impossible to select a reliable setpoint for the conductivity (i.e. level) controller. It was necessary in this situation to revert to the use of pneumatic measurements for level control. The data given in Fig. 1 were collected during this experimental programme. It was clear that a control scheme was required that would adapt to the variations in slurry conductivity. Several approaches were investigated.

Setpoint Obtained from Measurement of Pulp Conductivity.

Here, two conductivity meters were used. The first was connected to a sensor measuring the conductivity across the interface level; its signal was connected to the measurement input of a PID controller. The second was connected to a sensor approximately 0,6 m below the level sensor. This was used to obtain a measurement of pulp conductivity, which was then passed through a variable resistor to obtain a remote setpoint for the PID controller. The controller was configured to manipulate the tailing flowrate from the column in order to provide control of the interface level, as shown in Fig. 5.

It was found that there was excessive interference between the two conductivity meters; this and other problems were overcome by careful matching of the conductivity meters and modifications to the design of the sensors. The resulting arrangement was used successfully to control the level for a wide range of operating variables (feedrate, gas rate, and wash-water rate), but failed when large changes (e.g. 3:1) in the conductivity of the feed were imposed. Clearly, the use of two meters in this fashion required exactly matched conductivity meters, which mitigated against the production of a robust control system; a simpler approach was needed.

Use of a Modified Single Conductivity Meter

An examination of the circuit diagram for the conductivity meter led to a dramatically simplified solution to the problem. This involved the use of the resistance across the second probe discussed above (used for measuring the pulp conductivity) as the range resistor for the first conductivity meter, as shown in Fig. 6. The governing equation for this meter then becomes

$$V_R = E\left[\frac{\gamma}{\gamma + 1}\right], \quad \text{where} \quad \gamma = \frac{k_L}{k_{s1}}. \qquad [5]$$

This arrangement eliminates problems associated with both unmatched sensors and unmatched meters, and greatly simplifies the design of the control system.

A new sensor was designed as shown in Fig. 7. This contained only three probe surfaces, the centre probe being used to provide the V-signal, rather than the more general probe illustrated in Fig. 6. Existing terminal connections on the conductivity meter were used. The measurement was now a 4 to 20 mA signal denoted i_q (to distinguish it from i_k), which was recorded as a variable q (0 to 100 per cent of span). This signal was connected to the controller, which was given a manual setpoint q_{sp} = 15 to 20 per cent, as shown in Figs. 8 and 9.

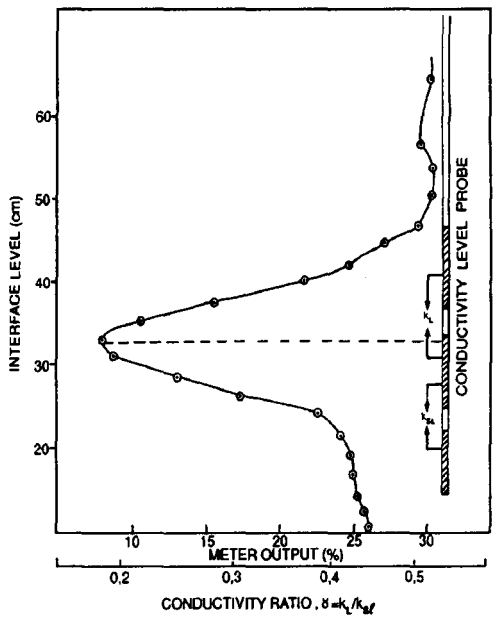

Fig. 7—Variation of relative conductivity, γ, with interface level

To characterize the measurement, the signal, q, was recorded as the interface was allowed to drop over the full height spanned by the level sensor. The variation of interface level, L, with q (and γ) is shown in Fig. 7. Clearly, the sensor design was not symmetrical with respect to the middle probe surface; if this had been the case, then according to equation [5], q = 50 per cent would have been obtained when the sensor was completely submerged (L > 50 cm) because, in this case, the conductivities (γ = 1) between the two probe pairs would have been equal. No adjustments were made so that the necessity for probe matching could be assessed.

The ability of this arrangement to provide adequate control of levels in the face of operating changes is shown in Fig. 8. Clearly, changes in the gas superficial velocity, J_G, provide much more serious disturbances than changes in the superficial velocity of the wash water, J_W. Nevertheless, the control scheme controlled the level near

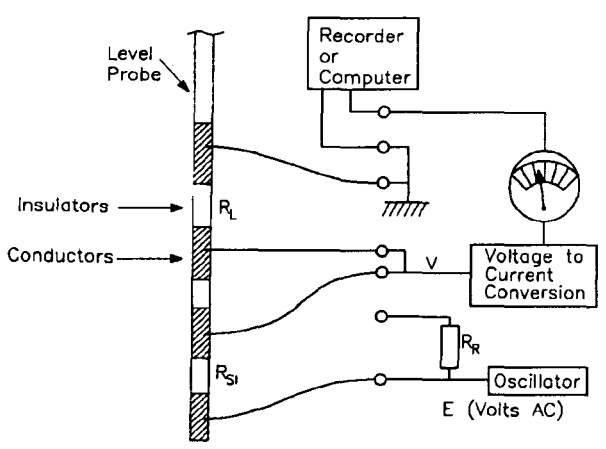

Fig. 6—The conductivity circuit adapted for the measurement of conductivity across the interface relative to the conductivity of the slurry

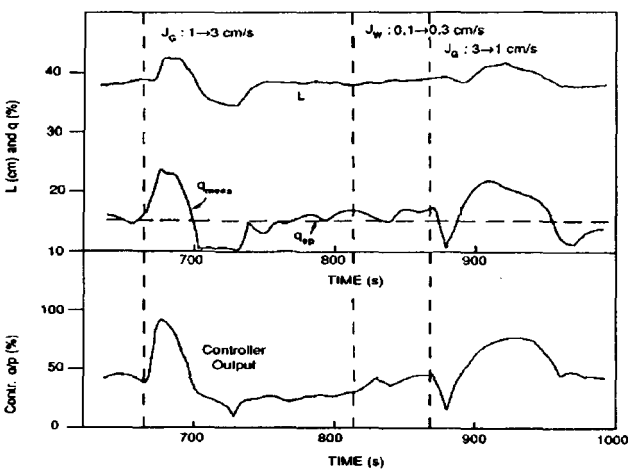

Fig. 8—Level control subject to disturbances in gas rate and wash-water rate

38 cm with maximum deviations of 4 cm.

The effects of a change in setpoint and a major disturbance in feed conductivity are shown in Fig. 9. The setpoint response overshoots slightly but is nevertheless completely satisfactory. The conductivity disturbance produces very little effect on the level, in spite of the fact that the conductivity changed by a factor of approximately 5:1. Extensive tests of various combinations of these disturbances showed that the control scheme was able to control levels successfully in the face of disturbances that are generally much larger than those encountered during the normal operation of flotation columns. In general, the system was able to control the interface under all the conditions in which an observer was able to discern the interface through the transparent wall of the column.

DEVELOPMENT OF AN INDUSTRIAL INSTRUMENT

The development of a robust industrial instrument is often the most exacting task facing the developer of a new instrument. In this case, the process was relatively easy to complete since existing off-the-shelf equipment could be used.

The final arrangement is illustrated in Fig. 10; a design appropriate to a narrow (e.g. 0,5 m diameter) pilot column is shown, together with a design for a probe appropriate to an industrial column. The latter is made of stainless-steel rings mounted on a PVC rod (similar in design to that described by Gomez *et al*.[5].

The level probe for the pilot column consists of many (e.g. 10 to 15) stainless-steel probes passing through the wall of the column, spanning the range of levels at which control may be desired. Each of these sensors is connected to the input of a multi-channel selector (which can be switched locally by the operator, or controlled by a remote signal). Four input lines are connected to the conductivity meter as shown in more detail in Fig. 6. The two lowest probes are used for measuring the resistance of the slurry. The selector switch is used to connect the two probes that span the level at which the interface is desired.

This equipment has given trouble-free service in a wide range of pilot-test programmes performed by the sponsors of this research, Multotec Cyclones (Pty) Ltd, a local supplier of flotation columns. It has been sold to several customers as part of a pilot column, and has been installed and operated successfully in industrial columns in the platinum industry.

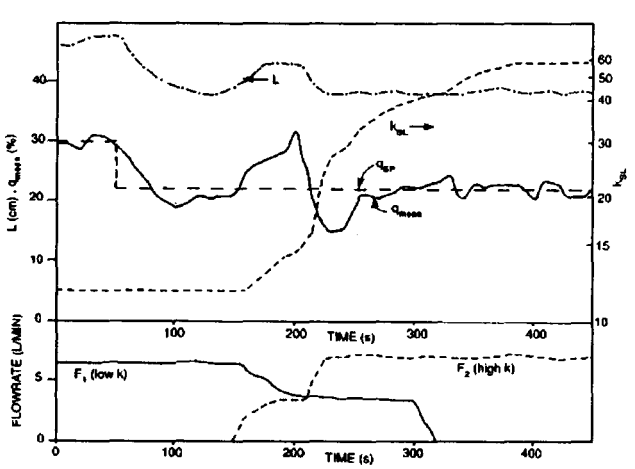

Fig. 9—Level control subject to a large variation in feed conductivity

DISCUSSION

The main disadvantage of this approach to interface-level control is that a measurement of interface level is not produced if the level is either above or below the top pair of electrodes selected (as shown in Fig. 10). In these conditions, the signal merely indicates to the PID controller that the level is 'too high' or 'too low'. If the interface level is between these two electrodes, then an indication of level is given. Since the distance between probes can be chosen to suit the needs of the user, this is not likely to present a serious problem. Very accurate and robust control of level is provided, even if the distance between the probes is fairly small, e.g. 10 cm.

Conventional off-the-shelf instrumentation is used. The key measurement device, the conductivity meter, is necessarily based on a very simple design, and is therefore easy to maintain; a conventional PID controller is used for the control function. The intermediate multiplexing switch is also of the simplest possible design. The combination yields robust and precise control of levels, requiring non-specialist servicing, and is therefore suited to isolated mineral-processing plants. The instrument can, of course, be used for the control of level in conventional flotation cells as well. The device has been patented[9].

ACKNOWLEDGEMENTS

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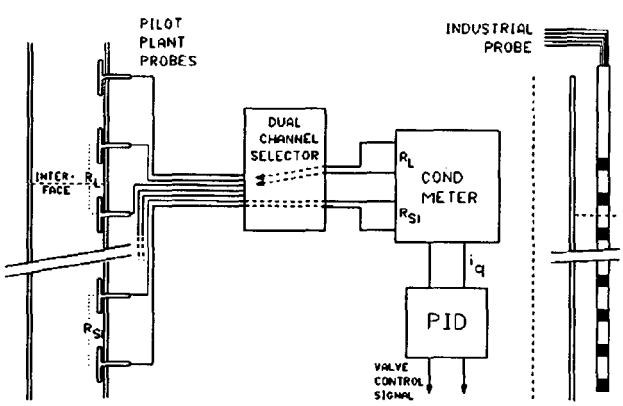

Fig. 10—Schematic representation of the level-control system developed for industrial implementation

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*Ore-dressing abstracts database released**

Mintek, one of the world's leading mineral-research organizations, has made available a new speciality database. The **MINORE** database (Ore-dressing Abstracts) comprises a unique collection of abstracts covering the entire field of ore-dressing techniques.

The abstracts, which have been compiled over a period of 15 years, were produced by Mintek's Jack Levin, a well-known authority in the field of ore-dressing. Jack Levin has applied the expertise accumulated during a lifetime of research in ore-dressing to selecting and writing the abstracts, and the database contains many valuable comments that are not available in the original references.

The database consists of descriptor, title, author, document type, reference, date published, language of the document, and an abstract.

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