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EXPERT CONTROL OF COLUMN FLOTATION WITH FROTH OVERLOADING PREVENTION

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Abstract: This paper aims at describing an expert control design for grade and recovery optimization in a column flotation plant, also avoiding the froth overloading phenomenon by monitoring concentrate froth solid-to-liquids ratio. Such expert system can be defined by means of simple fuzzy inference systems which basically modify froth depth and gas holdup. *Copyright © 2002 IFAC*

Keywords: column flotation, expert systems, fuzzy logic.

1. INTRODUCTION

In the last few years different solutions for the mineralurgical indexes optimization in flotation columns have been proposed.

Kosick and Dobby (1990) have presented an advanced control based on the compilation of the operators' experience in a knowledge data base.

Bergh and Acuña (1994) have shown the use of hierarchical supervisory control, and Karr (1996) has used genetic algorithms to minimize a cost function which optimizes the concentrate grade.

Hirajima *et al.* (1991) and Berg *et al.* (1998) have used fuzzy systems.

Expert control of column flotation points at optimizing mineralurgical indexes, concentrate grade and recovery. This paper also considers froth overloading phenomenon prevention, which has been traditionally characterized by the maximum possible solids content in the froth product. Practical considerations indicate that when froth solid-to-liquid ratio by volume is higher than 0.4, froth gets so thick that it tends to collapse (Lutrell and Yoon, 1991).

Generally, optimization is carried out by modifying control loops set points implemented on the column, such as, froth depth, gas holdup and bias rate. It will be shown that an efficient expert control system with easy recalibration can be achieved just setting up the first two above mentioned parameters applying occasional changes in the wash water rate and defining adequate supervising policies. Reagents flows are held constant.

The expert system has been designed based on a multivariable predictive control (Chuk *et al*., 2001) applied to a laboratory flotation column (Fig. 1) having the froth depth and gas holdup as outputs, and the tails and air valves positions as manipulated variables.

The mineralurgical indexes behavior analysis has been carried out using a column model developed in two sections: the dynamic and mineralurgical ones. Both are briefly described below.

2. DYNAMIC MODEL

Froth depth has been modeled as $H_f = H_{fh} + H_{fg}$, where H_{fh} is the component due to the hydrostatic height obtained from the volume balance:

$$H_{fh} = H_{fi} - K \int (Q_a + Q_w - Q_c - Q_p)dt \qquad (1)$$

where H_{fi} is the initial froth depth, K a constant, Q_a the feed rate, Q_w the wash water rate, Q_c the tails rate and Q_p the product rate.

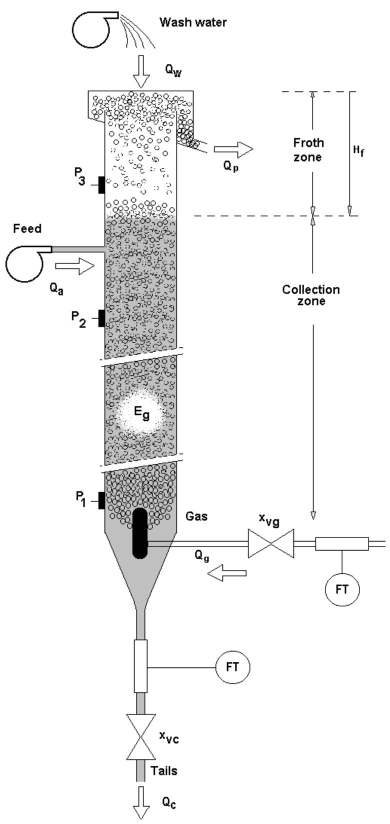

Fig. 1. Flotation column diagram and its instrumentation.

H_{fg} is the Q_g gas rate influence, empirically obtained by identification from input-output relationships as

$$\frac{H_{fg}(z)}{Q_g(z)} = = \frac{z^{-5}(-0.0315 - 0.0161z^{-1} - 0.0165z^{-2} + 0.0640z^{-3})}{1 - 0.573z^{-1} - 0.2441z^{-2} + 0.1823z^{-3}} \quad (2)$$

Tails rate has also been described as the addition of its hydrostatic and gas influences:

$$Q_c = Q_{ch} + Q_{cg} \quad (3)$$

The former depends on the square root of the froth depth and on the x_{vc} pinch valve position lineally:

$$Q_{ch} = (ax_{vc} + b)\sqrt{H - H_{fh}}\,, \quad (4)$$

while the latter, which is empirically obtained, is shown in eq. (5).

$$\frac{Q_{cg}(z)}{Q_g(z)} = \frac{z^{-10}(-0.0609 + 0.1429z^{-1} - 0.1044z^{-2})}{1 - 0.4285z^{-1} - 0.2261z^{-2}} \quad (5)$$

With a similar approach, the E_g gas holdup is expressed as the sum of the gas rate, tails rate and wash water rate influences described in transfer functions (6), (7) and (8), as follows:

$$\frac{E_g(z)}{Q_g(z)} = \frac{z^{-5}(0.0202 + 0.0054z^{-1} + 0.0210z^{-2} - 0.0457z^{-3})}{1 - 0.4830z^{-1} - 0.3049z^{-2} - 0.2079z^{-3}} \quad (6)$$

$$\frac{E_g(z)}{Q_c(z)} = \frac{-0.0029 + 0.0141z^{-1} - 0.0175z^{-2} + 0.0067z^{-3}}{1 - 0.3961z^{-1} - 0.2478z^{-2} - 0.3087z^{-3}} \quad (7)$$

$$\frac{E_g(z)}{Q_w(z)} = \frac{z^{-10}(0.0014 - 0.0011z^{-1} - 0.0007z^{-2})}{1 - 0.4831z^{-1} - 0.4960z^{-2}} \quad (8)$$

3. MINERALURGICAL MODEL

Calculations start obtaining the particle-bubble collision probability. Lootrell and Yoon (1991) have shown that it can be estimated by

$$P_c = (1.5 + 4\,\mathrm{Re}^{0.72}/15)(D_p / D_b)^2 \quad (9)$$

where D_b is the bubble diameter, D_p is the particle diameter and Re is the Reynolds number of the bubble.

The overall probability of collision is

$$P = P_c\,P_a \quad (10)$$

where P_a is the probability of adhesion after the collision. The relative values of P_a for different mineral components determine flotation selectivity. Therefore for the valued mineral i.e. fluorite the overall probability is $P_f = P_c\,P_{af}$.

Once P_f is known, the first-order rate constant for particle capture can be found as

$$k_f = 1.5\,P_f\,V_g / D_b \quad (11)$$

where V_g is the superficial gas velocity.

For recovery calculation, the U_{sp} particle slip velocity and the Re_p particle Reynolds number are necessary. These values can be obtained (Finch and Dobby, 1990) using equations (12) and (13) in a recursive way:

$$\mathrm{Re}_p = \frac{D_p[m].100U_{sp}(1-\Phi_s)}{\mu_l} \quad (12)$$

$$U_{sp} = \frac{981(D_p[m].100)^2(\rho_s - 1)(1-\Phi_s)^{2.7}}{18\mu_l(1 + 0.15\mathrm{Re}_p^{\;0.687})} \quad (13)$$

where ϕ_s is the solids fraction in the slurry, ρ_s is the mean solids density and μ_l is the liquid viscosity.

The mean residence time of the slurry within the column can be obtained from

$$\tau = (L - H_f)(1-E_g)/V_c \quad (14)$$

where L is de column length and V_c is the superficial tails velocity. The particle residence time is

$$\tau_p = \left(\frac{V_c}{V_c + U_{sp}}\right)\tau \quad (15)$$

The Peclet number Pe is a measure of the degree of axial mixing in a column, and it can be determined from the empirical relationship

$$Pe = B[(L/D)V_t/V_g/(1-E_g)]^m \quad (16)$$

Here, L/D is the column length-to-diameter ratio and B=0.7 and m=0.62 are suitable values for a wide range of columns.

With these previous calculations, the collection zone fluorite recovery can be obtained as

$$R_{cf} = 1 - \frac{4Ae^{(Pe/2)}}{(1+A)^2 e^{(\frac{APe}{2})} - (1-A)^2 e^{(-\frac{APe}{2})}} \quad (17)$$

with $A=\sqrt{1+4k_f \tau_p / Pe}$.

The following expression gives the froth recovery:

$$R_f = \left[100 - \frac{180 H_f e^{(-0.2+3.5V_w^2)}}{3V_g + 1}\right]\frac{1}{100} \quad (18)$$

and the fluorite overall recovery is then determined as

$$R_{fcf} = \frac{R_{cf} R_f}{R_{cf} R_f + 1 - R_{cf}} . \quad (19)$$

Considering all the i present mineral species, the total solids recovery is

$$R_{tot} = \sum_{i=1}^{n} R_{fc}(i).f(i) \quad (20)$$

where $f(i)$ is the feed grade of the i mineral component. The concentrate grade is then expressed by

$$c_f = \frac{R_{fcf}}{R_{tot}} f_f . \quad (21)$$

For a given F solids feed rate, the solids concentrate flow can now be written as

$$C = \frac{R_{fcf} f_f F}{c_f} . \quad (22)$$

The froth solid-to-liquid ratio by volume estimation used in the expert system for overloading prevention is

$$Fi = \frac{C}{1000 Q_p R_{os} - C} , \quad (23)$$

in which Q_p is the volumetric concentrate rate.

4. SENSITIVITY ANALYSIS

The sensitivity analysis allows to observe the influence of the different plant variables affecting the three mineralurgical indicators already mentioned: c_f concentrate grade, R_{fcf} recovery, and Fi froth solid-to-liquid ratio by volume. The logical rules to be applied by the expert system result from these analysis conclusions.

Input variables are divided into two groups, i.e., operative variables, used to control the plant performance, and system disturbances.

Operative Variables: H_f Froth depth
E_g Gas holdup
Q_w Wash water rate

Disturbances: Q_a Feed rate
f Feed grade
D_p Particle diameter
R_{sl} Feed solid-to-liquid ratio

Although there are some other disturbances, the ones under consideration affect outputs to a great extent.

Figures 2 to 4 show the mineralurgical indexes variation, expressed as a 0 to 1 fraction together with the operative variables. Similarly, Figures 5 to 8 indicate the disturbances effect. Since the expert system has been designed for a laboratory column, the observed operating ranges of the variables fail to correspond to industrial applications, but the extension for a real plant is immediate.

It can be seen that grade and recovery are mutually excluding objectives. Generally, if a parameter increases, the other diminishes.

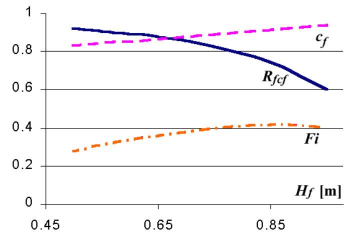

Fig. 2. Mineralurgical indexes variation with froth depth.

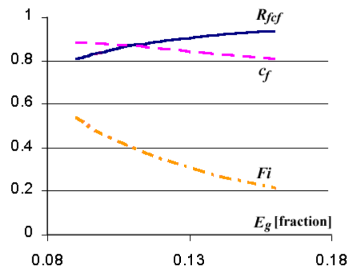

Fig. 3. Variation with gas holdup.

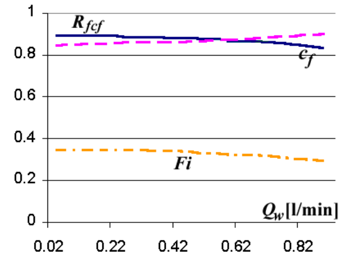

Fig. 4. Wash water rate variation effect.

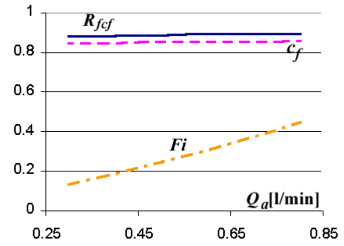

Fig. 5. Feed rate variation effect.

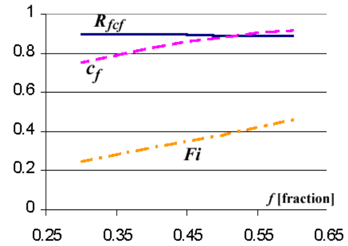

Fig. 6. Feed grade variation effect.

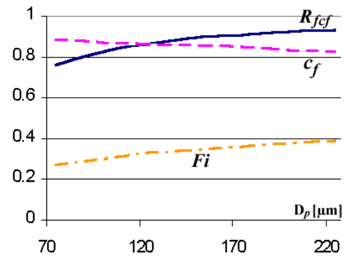

Fig. 7. Particle size effect.

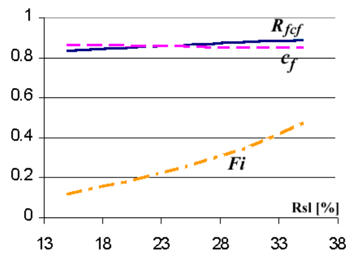

Fig. 8. Feed solid-to-liquid ratio variation effect.

It is worthy to notice that every disturbance under consideration may cause a froth solid-to-liquid ratio increase and a subsequent danger of overloading. Both a gas holdup increment and a wash water increase diminish this value which will be used profitably by the expert system.

3. EXPERT SYSTEM DESIGN

Some authors, like Benaskeur and Desbiens (1999), have proposed cell flotation control using mineralurgical indexes feedback. However, as the system behavior is strongly non-linear, a fuzzy logic based expert system as the one presented below provides a simple and effective solution.

In order to define a strategy for the expert system decisions, three errors related to the mineralurgical indicators under study are defined as inputs, since they show the distance as regards a critical value which should not be broken. For c_f concentrate grade and R_{fcf} recovery such critical value is the lowest one, and for *Fi* froth solid-to-liquid ratio it is the highest one, as follows:

$$Errorcf = c_f - c_{fmin}$$
$$ErrorRfcf = R_{fcf} - R_{fcfmin}$$
$$ErrorFi = Fi - Fi_{max}$$

The expert system outputs are positive increases for the froth depth and gas holdup set points: *DeltaHf* and *DeltaEg*, and for the wash water rate *DeltaQw*.

An *Errorcf* vs. *ErrorRfcf* plane is defined, and two different zones can be seen in Fig. 9, as well. These zones are associated with two distinctive working methods i.e. the optimization mode and the protection mode. The former is determined by means of low grade and recovery, but as the latter presents adequate values it is necessary to pay attention to the system protection due to the froth overloading.

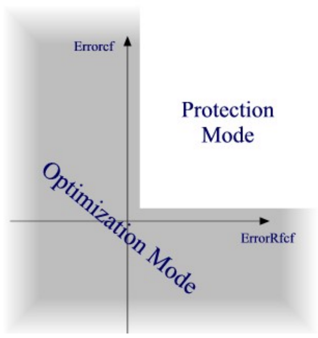

Fig. 9. Expert system operation modes.

3.1 Optimization mode.

When working with the optimization mode it is necessary to bear in mind that the objective is to keep quality and production. The focus is to preserve the concentrate grade and recovery over the minimum values c_{fmin} and R_{fcfmin}, respectively, moving the system to the protection zone.

Taking benefit of the well-known grade-froth depth relation and of the recovery-gas holdup one, the operators' reasoning is moved, linguistically speaking, to fuzzy inference system logical rules, as follows:

If grade is rather low and there is a good recovery, then an increase is exerted on froth depth.

On the contrary,

If the recovery is rather low and there is a good grade, then the gas holdup is slightly increased.

Both indicators may be low in some cases, so the following way of thinking should be applied:

If grade and recovery are low, then froth depth and gas holdup are slightly increased.

This kind of reasoning gives way to two distinctive Mamdani type fuzzy inference systems acting at the same time . One of them modifies the froth depth set point and the other, the gas holdup. Both systems inputs, the *Errorcf* grade and the *ErrorRfcf* recovery errors, are alike. See Fig. 10.

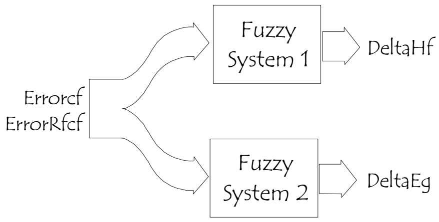

Fig. 10. Two different fuzzy systems acting at the same time in the optimization mode.

Triangular membership functions and minimum inference have been used.

3.2 Protection mode

When the protection mode works, grade and recovery values are acceptable and it is required not to exceed the *Fimax* value.

As it has already been noticed in section 4, a gas holdup increase will reduce the froth solid-to-liquid ratio. At the same time, as the gas holdup has a strong influence in recovery, this variable should be included in the system. In this way, a main fuzzy system -Fuzzy System 1- is defined.

Under certain conditions, a high froth solid-to- liquid ratio and low grade may occur. A froth depth increase in optimization mode would still cause a higher increase in *Fi*. It may be compensated for a light increase of the gas holdup, but mainly with an increment in the wash water rate carried out by a second fuzzy system -Fuzzy System 2-, as it can be seen in Fig. 11.

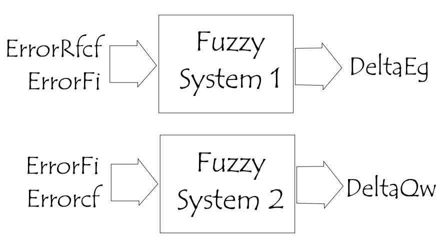

Fig. 11. Protection mode fuzzy inference systems.

4. RESULTS

Some simulated tests in which the objective is to keep grade and recovery above a minimum of 0.8 and the froth solid-to-liquid ratio below 0.4 are shown here.

Fig. 12 depicts the expert system behavior when feed grade decreases causing a concentrate grade fall at the same time. Such a problem is solved in the optimization mode by a froth depth increase. Besides, in Fig. 13 it is possible to see how the expert system solves a recovery decrease caused by a *Dp* mean diameter of particles fall in the optimization mode, by means of an increase of the gas holdup. It is worthy to notice how the recovery, marked in a dotted line, is redetermined when it is next to the admissible lower boundary.

An increase in R_{sl} feed density may cause a noticeable increase in *Fi*, froth solid-to-liquid ratio. Such a problem is cleared up by the protection mode. In Fig. 14 it can be seen that once the variable is reaching its highest upper boundary, an increase in gas holdup makes it return to the security zone.

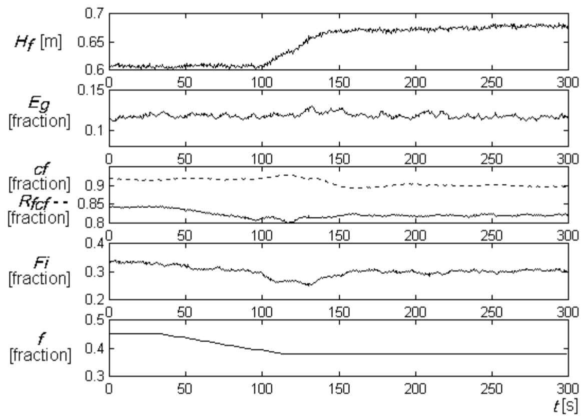

Fig. 12: Expert system responds to a concentrate grade decrease.

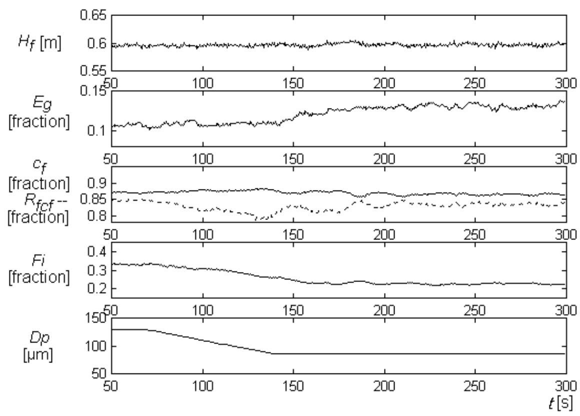

Fig. 13: Expert system responds to a recovery decrease caused by a particle diameter fall.

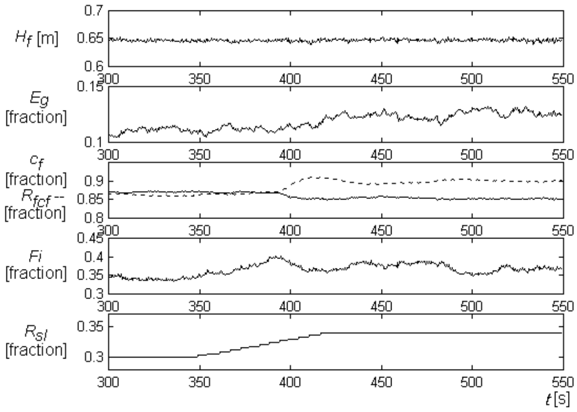

Fig. 14: Solution for froth solid-to-liquid ratio increase by incrementing gas holdup.

Finally, a combination of the optimization mode that restores the grade and the protection mode, reducing the froth solid-to-liquid ratio is depicted in Fig. 15.

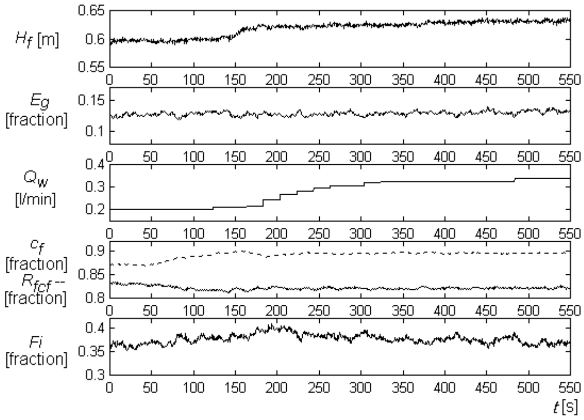

Fig. 15: Optimization and protection modes operating simultaneously.

5. CONCLUSIONS

A simple and effective expert system has been developed. It is able to solve mineralurgical indexes falls and different froth density risk situations caused by common parameters variations in a column flotation plant.

The expert system based on the use of the grade vs. recovery plane has a reduced quantity of rules. The various membership functions concerning fuzzy inference systems are expressed in mineralurgical indexes units. As they are widely known by metalurgical engineers, the system may easily be recalibrated when necessary.

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