ESTIMATION OF FROTH ZONE RECOVERY IN FLOTATION CELLS

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ABSTRACT

This paper proposes a methodology to estimate froth zone recovery (R_f) from froth upgrading process data. The methodology is based on a semi-empirical approach that relates the recovery-enrichment ratio curve (recovery-grade curve) to the upgrading process taking place across the froth phase. By taking into account the interaction between the pulp and froth zones, R_f may be calculated. The technique relies on determining the maximum practically attainable enrichment ratio, γ', (or grade) that may be produced for a particular ore under specific operating conditions, and relating this value to the froth height. Froth height is also related to the overall recovery to obtain an estimate of the collection zone recovery (R_C). Linear relationships are applied in both cases. A case study is presented to illustrate the above methodology.

Keywords: froth flotation, froth zone recovery, froth depth, froth height, concentrate grade, enrichment ratio.

THE RECOVERY-GRADE (ENRICHMENT RATIO) CURVE

Recovery and concentrate grade, used simultaneously, are the most accepted measures of flotation performance (Schulz, 1970). Investigation of the mineral flotation process applied to a given feed material can often be designed to yield successive paired values of recovery and concentrate grade over the practical range of the course of the flotation separation. These results may be plotted as some combination of cumulative values (Lynch et al., 1981). The recovery-grade curve can be established in the plant or laboratory by varying the separator settings as widely as possible.

To normalise fluctuations, the concept of *enrichment ratio* (γ) may be used, defined as the ratio of the grade of the concentrate to the grade of the feed. Figure 1 depicts the recovery-enrichment ratio curves for a practical separation, for the flotation release curve as defined by Dell (1953) and others (Hanson et al., 1993; Kelly and Spottiswood, 1995), and for the limiting curve of the ore which may be determined from liberation data. Figure 1 also shows the *maximum practically attainable enrichment ratio* (γ') of the flotation system at specific separator settings, and the *maximum theoretically attainable enrichment ratio* (γ_{max}) that can be defined based on the mineralogical nature of the ore (i. e. independently of the separator settings and associated with the degree of liberation of the ore).

Recognising the hyperbolic nature of the recovery-enrichment ratio curve, the present authors have proposed the following empirical equation (model) (Vera et al., 1998) for curve fitting purposes:

$$R = R^* - a \cdot \sinh(b \cdot [\gamma - 1])$$

Equation 1

The equation expresses the flotation recovery as a hyperbolic sine function of the enrichment ratio. The model is defined by three parameters: $\mathbf{R}^*$ is the overall recovery when γ tends to one; **b** is a kind of degree of contamination, causing γ to decrease as recovery increases; and ***a*** is the flexibility of the curve, i. e. whether it is a smooth curve or has a sharp bend or "knee", which is frequently seen in coal or iron ore samples (Vera et al., 1999a).

Figure 1 Practical and release recovery-enrichment ratio curves.

To illustrate the use of Equation 1, a set of results obtained by Johnson (1972) is reproduced in Figure 2. This shows the recovery-enrichment ratio profiles of chalcopyrite for laboratory flotation tests after different grinding times. The experimental data points and the fitted curves obtained using Equation 1 are shown.

It is evident that the recovery-enrichment ratio model (Equation 1) is capable of describing this experimental data well. The equation has been applied to over 100 data sets obtained from the literature with equally good results (Vera et al., 2000). This allows the recovery-enrichment ratio model to be used with confidence.

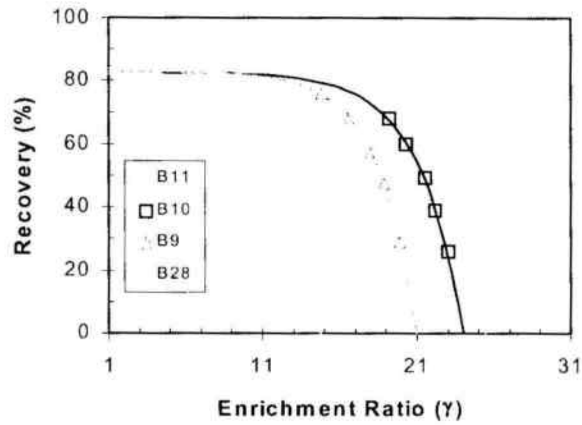


Figure 2 Effect of grinding time on the enrichment ratio profiles of chalcopyrite in batch flotation tests (B11=13 min of grinding time, B10=17 min, B9=21 min and B28=30 min)(after Johnson, 1972).

MAXIMUM PRACTICALLY ATTAINABLE ENRICHMENT RATIO (γ') AND ITS RELATION TO THE FROTH UPGRADING PROCESS

It is well known (Cutting, 1989; Moys, 1989; Malysa, 1998; Ross, 1998) that the main function of the froth zone is the upgrading of the valuable material present in the ore. In order for this upgrading to occur, the amount of interstitial slurry must be minimised, which means that in a conventional froth, the bubble films must be as thin as possible.

The minimisation of the interstitial slurry depends very much on the operating conditions of the flotation separation. The maximum practically attainable upgrading (represented by the value of γ') will be determined by the ore characteristics (size and composition) and the operating conditions.

It may be deduced from fundamental research carried out on froth structures (Neethling and Cilliers, 1998; Neethling et al., 2000) that the maximum practically attainable upgrading corresponds to the enrichment ratio (grade) at the bubble lamella. This value of the enrichment ratio (grade) is measurable at the top layer of the froth phase, when the froth is under or close to equilibrium conditions (Cutting, 1989), i. e. where the lateral flow (horizontal movement) is small or negligible.

Figure 3 relates the recovery-enrichment ratio curve to the upgrading process across the froth zone. It is unusual to note in Figure 3 that the enrichment ratio of the flotation concentrate (γ_{cell}) is less than the maximum practically attainable enrichment ratio (γ'). However, this observation is supported by the findings of Cutting (1989), which clearly showed values of enrichment ratio in the concentrate less than those measured in the froth phase close to the equilibrium conditions.

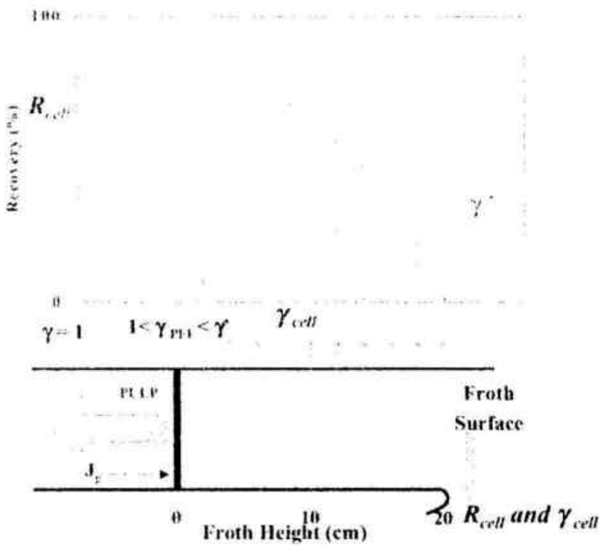


Figure 3 Relating the upgrading process throughout the froth zone with the recovery-enrichment ratio curve.

In order to confirm this, replicate experiments were conducted in a laboratory batch flotation cell with a sample of galena ore from North Queensland, Australia. Before collecting the first concentrate from the cell, the top layer of the froth zone (at the back of the cell) was sampled to obtained a measured value of γ'. After this, timed concentrates were collected so as to determine the recovery-time and the recovery-enrichment ratio profiles.

Figure 4 shows the result of the experiments. It is clear that the measured value of the enrichment ratio (grade) at the top layer of the froth zone ($\gamma'_{meas.}$) is the same as the value of the extrapolated intercept on the enrichment ratio axis (γ'_{calc}) of the recovery-enrichment ratio curve (Equation 1). The experiments have been repeated with a chalcopyrite ore with the same result.

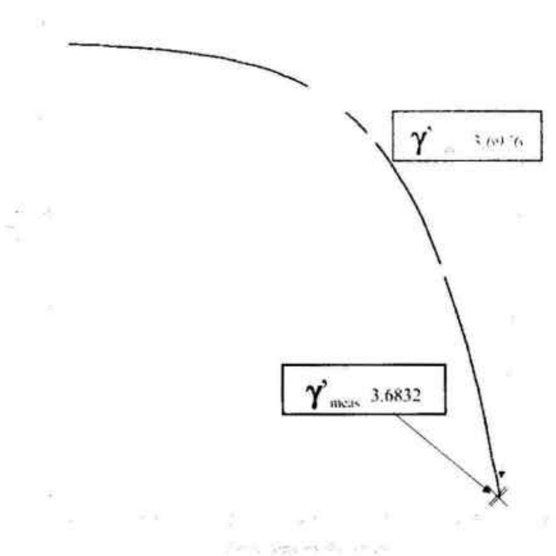


Figure 4 Recovery-enrichment ratio curve for a galena ore obtained in a laboratory batch flotation cell[1]. The values of γ' calculated using the mathematical model (Equation 1) and measured experimentally are shown.

ESTIMATION OF FROTH ZONE RECOVERY USING γ' CONCEPT

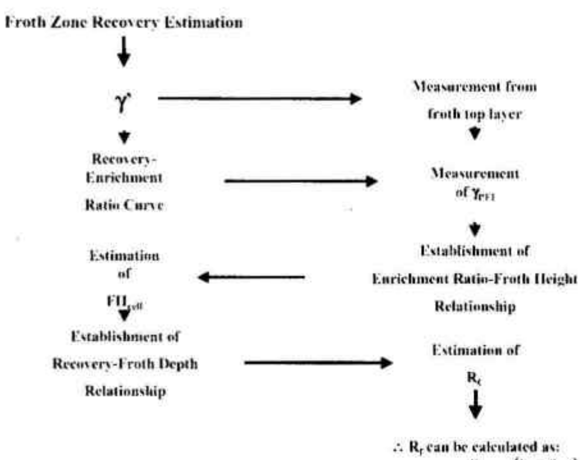
The observation that the grade (enrichment ratio) measured at the very top layer of the froth phase at the back of the cell is the maximum practically attainable enrichment ratio γ' leads to a new methodology for estimating froth zone recovery, R_f, in the cell. R_f is defined as the recovery to the concentrate of particles entering the froth zone from the collection zone. Figure 5 lists the steps involved in determining R_f.

Firstly, γ' must either be estimated from the recovery-enrichment ratio curve or measured by taking a sample of the top layer of the froth zone. Secondly, the enrichment ratio at the pulp-froth interface (γ_{FPI}) must be measured (this implies taking a sample of the pulp at or immediately below the pulp-froth interface)[2]. Thirdly, the equivalent froth height $(FH_{cell})_{eq}$ corresponding to the enrichment ratio of the flotation concentrate (γ_{cell}) is determined from the linear (Vera et al., 1999a)

[1] Operating conditions for batch flotation test: 3-L Agitair cell; P_{80} = 133 μm; impeller speed = 1100 rpm; air flow rate = 5 L/min (J_g = 0.40 cm/s); % Solids = 30, [Collector] = 20 g/t (cond. t.=5 min); [Frother] = 10 ppm (cond. t.=2 min); pH = 8; Pb feed grade = 19.01%.

[2] This parameter may also be estimated if an enrichment ratio-froth height relationship is available, by extrapolation to froth height equal to zero.

enrichment ratio-froth height relationship (γ_{PFI} and γ' establish the range within which γ_{cell} must be found). Fourthly, $(FH_{cell})_{eq}$ allows the linear (Vera et al., 1999b) recovery-froth depth relationship to be established, from which the collection zone recovery (R_C) can be estimated. Finally, froth zone recovery is calculated using the expression of Finch and Dobby (1990) that describes the pulp-froth interaction. An example of this procedure is given below.



$$R_f = \frac{R}{(1-R)} \cdot \frac{(1-R_C)}{R_C}$$

Figure 5 **Summary of the methodology for froth zone recovery estimation.**

MODEL APPLICATION

The new methodology was applied to experimental results reported previously by these authors (Vera et al., 1999b). In this work, the effect of several operating variables (e. g. aeration rate, impeller speed, % solids, etc.) on R_f was investigated in a laboratory scale flotation cell by carrying out flotation tests at a number of different froth heights. In Figure 6a, the recovery-enrichment ratio curve (Equation 1) is applied to one set of experiments in which % solids was varied (%Sol1 = 11%). For this, γ' is determined to be 7.4. Next, in Figure 6b, the equivalent froth height, $(FH_{cell})_{eq}$, for the measured concentrate enrichment ratio (5.1) is determined from the enrichment ratio-froth height relationship[3], and is found to be 0.35 cm. In Figure 6c, this value is used to find R_C (collection zone recovery) by linear extrapolation (R_C = 88%). Finally, the value of R_f is calculated using the expression in Figure 5. R_f is found to be equal to 62%. Table 1 summarises the results for R_f estimation.

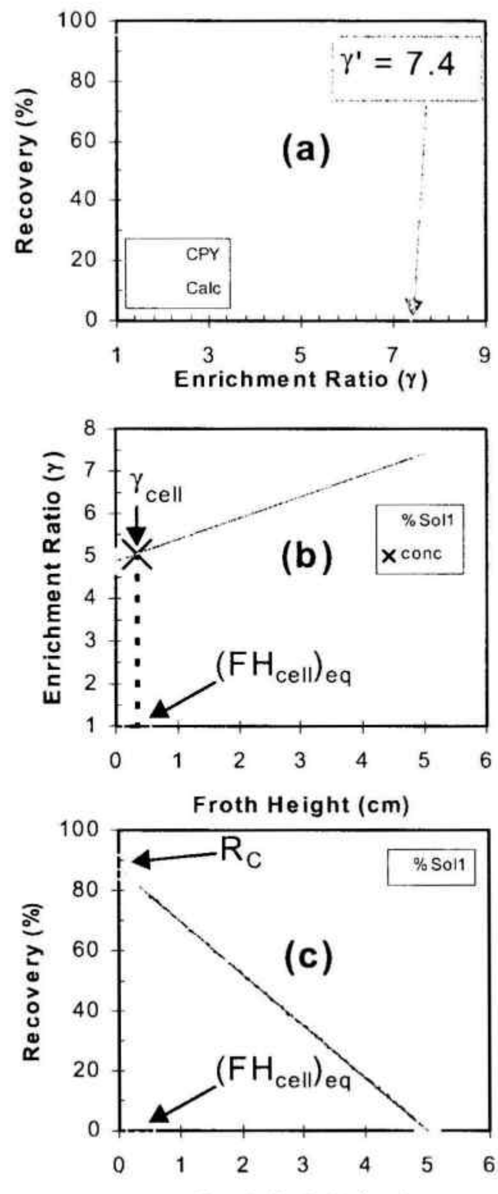


Figure 6 Estimation of R_f using the practically maximum attainable enrichment ratio (γ') concept.

[3] Because work was done at various froth heights, plotting γ_{cell} versus froth height allows γ_{PFI} to be inferred by extrapolation to froth height equal to zero.

Table 1 Summary of results for R_f estimation.

Variable	γ	γ_{PFI}	γ_{cell}	$(FH_{cell})_{eq}$ (cm)	R_{cell} (%)	R_C (%)	R_f (%)
%SolI	7.4	4.9	5.1	0.35	81	88	62

CONCLUSION

This paper has outlined a methodology to estimate froth zone recovery. The approach was developed by relating the upgrading process across the froth phase to the recovery-enrichment ratio curve (or recovery-grade curve). By so doing, the maximum practically attainable enrichment ratio (γ') has emerged as an important parameter in the analysis of flotation performance. It is worth mentioning that the estimation of R_f only requires γ' which can be measured experimentally. In other words, the recovery-enrichment ratio curve is not essential for the exercise.

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