

## A Simple Model for the Calculation of Entrainment in Flotation

Ozcan Y. Gulsoy<sup>†</sup>

Mining Engineering Department, Hacettepe University, Beytepe, Ankara, Turkey

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**Abstract**—Theoretical and experimental studies have been performed to analyze the entrainment of both hydrophilic and hydrophobic particles in flotation. A new model is proposed for the entrainment based on the water recovery trend. Two sets of timed flotation experiments were carried out to validate the model. These experiments were realized with quartz and pyrite as the only mineral in the pulp and with various frother concentrations and pulp densities. The chemical conditions of the pulp were adjusted to float pyrite as hydrophobic and to depress quartz as hydrophilic mineral. The solids recovery for each size fraction and water recovery was measured in these experiments. The proposed empirical model equation was checked against experimental observations. It was observed that the model equation well represented the entrainment-water relationship. Since hydrophilic mineral recovery mainly depends on the entrainment, the data obtained from quartz only tests were first fitted to the entrainment equation. The fit for quartz data was found to be satisfactory. This shows that the proposed model could be used to define the behavior of hydrophilic particles in a batch flotation test. The same model was applied for pyrite only tests and contribution of entrainment to hydrophobic mineral recovery was calculated. The results provided accurate interpretation of hydrophobic mineral entrainment, which is difficult to directly measure.

Key words: Flotation, Entrainment, Modeling, Separation, Water Recovery

### INTRODUCTION

In flotation, hydrophobic particles are attached to air bubbles and travel upward by the rising bubbles to the froth zone, whereas the hydrophilic particles go down in the liquid phase with the tailings. However, the water among the air bubbles also carries the hydrophilic particles to the froth phase. This mechanism is defined as entrainment in flotation. Entrainment is a significant recovery mechanism and the dominant means of recovery for hydrophilic particles. Moreover, concentrate grade is also deteriorated by entrainment. It is also known that some of the hydrophobic particles could be carried into the concentrate by this mechanism. The entrained particles are mainly carried into the froth with entrained liquid. This also depends on the size of air bubbles [Bando et al., 2000; Ata and Jameson, 2005]. The bubble size is affected by many factors such as air flow rate, frother dosage, and feed particle size distribution [Lee, 2003; Gorain et al., 1995]. The entrainment of the liberated hydrophilic particles could be easily determined by measuring the amount recovered in the concentrate, since it is assumed that all of them are recovered by entrainment. Therefore, the modeling of hydrophilic mineral entrainment is simpler than that for hydrophobic mineral entrainment, which is difficult to measure. Models were first developed for hydrophilic particles due to the measurement simplicity and then could be applied to hydrophobic ones.

The hydrophilic entrainment is the main cause of increased recovery of fine particles in the concentrate. Jowett [1966] was the first to study this subject. Later, many researchers related entrainment with water recovery and used degree of entrainment or classification function to define the hydrophilic mineral entrainment

[Bishop and White, 1976; Engelbrecht and Woodburn, 1975; Johnson et al., 1974; Kirjavainen, 1989; Kirjavainen and Laapas, 1988; Laplante et al., 1989; Lynch et al., 1974; Rahal et al., 2001; Savassi et al., 1998; Subrahmanyam and Forssberg, 1988; Thorne et al., 1976; Warren, 1985; Zheng et al., 2004]. Only Ross [1990] defined a transfer factor for both floated and entrained particles and claimed that it was suitable for hydrophobic entrainment.

The aim of the present study is to develop an empirical model based on flotation time to describe both hydrophilic and hydrophobic mineral entrainment. The variations in the recoveries of both water and entrained hydrophilic particles were examined as a function of flotation time. In this method, a two-parameter-model equation was proposed. One parameter mainly describes the trend of both water recovery-time and entrainment-time relations, and the other defines the amount of solids recovered by entrainment. This time based model also provides a possibility to calculate the hydrophobic entrainment.

### EXPERIMENTAL

Two sets of flotation experiments with different feed materials were performed. Pyrite and quartz were separately used in these sets as flotation feed materials. The test samples, glass grade quartz ( $\text{SiO}_2 > 99.5\%$ ) and pyrite concentrate, were obtained from Toprak Enerji A.Ş. and Etibank Küre Copper Flotation Plant (Turkey), respectively. The particle size of the pyrite concentrate and quartz were  $< 90 \mu\text{m}$  and  $< 200 \mu\text{m}$ , respectively. In pyrite flotation, Potassium Amyl Xanthate (KAX) was used as collector at pH 5.5. The frother used in the experiments was Poly Propylene Glycol (PPG). The same reagents (collector and frother) were also used in the flotation tests in which quartz was used as the only feed material. Collector dosage and pulp pH were kept constant in both sets of flotation ex-

<sup>†</sup>To whom correspondence should be addressed.

E-mail: ogulsoy@hacettepe.edu.tr

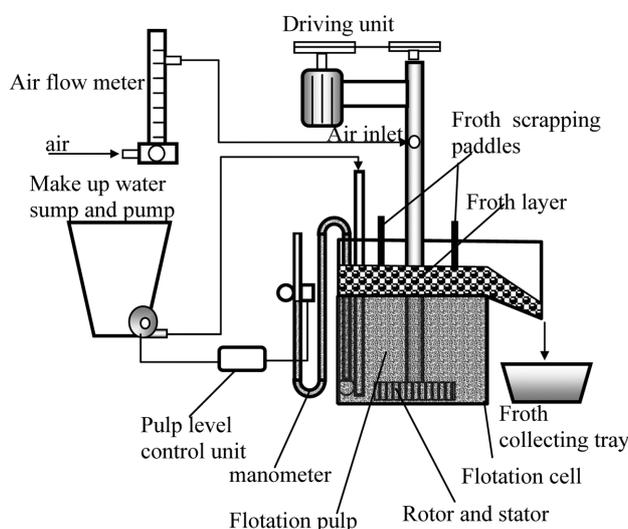
periments. However, higher frother dosages were used to provide sufficient froth layer in the flotation tests with quartz. In these experiments, the effects of frother dosage and pulp solids content on the entrainment of both hydrophilic and hydrophobic minerals were investigated.

Humboldt Wedag type laboratory flotation machine with cell volume of 2 L was used in the experimental study. The cell was modified to include a pulp level control system based on the measurement of pulp level with a manometer. The changes in the height of the water in the manometer were sensed by an optical system which controls a pump transforming make up water to the cell. The pH level and frother concentration of the make up water were the same as the flotation pulp. The airflow was supplied from an air compressor and controlled with an air flowmeter. Prescribed amounts of solids and water were put into the flotation cell. Chemicals given in Table 1 were added to the pulp. After conditioning with the chemicals, the flotation experiment was started by turning on the air. This created a froth layer laden with minerals on the flotation cell. Two pedals were used to scrap the froth containing floated and entrained particles by keeping the depth of froth scraping constant. The scrapped froth was taken from the cell into concentrate trays (Fig. 1).

**Table 1. Experimental conditions**

| Conditions                     | Pyrite only tests  | Quartz only tests                                     |
|--------------------------------|--------------------|---|
| Pulp solids content by wt.     | 35%                | 15%, 25%, 35%   |
| Pulp volume                    | 2 L                | 2 L   |
| Collector dosage (KAX)*        | 35 mg/L            | 35 mg/L   |
| Frother dosage (PPG)**         | 10, 24 and 49 mg/L | 17, 30, 45 mg/L<br>25, 44, 67 mg/L<br>33, 59, 90 mg/L |
| pH                             | 5.5                | 5.5   |
| Impeller speed in conditioning | 1,700 rpm          | 1,700 rpm   |
| Impeller speed in flotation    | 1,500 rpm          | 1,500 rpm   |
| Conditioning time              | 10 min.            | 10 min  |
| Air flow rate                  | 6.5 L/min          | 6.5 L/min   |

\*KAX: Potassium Amyl Xanthate, \*\*PPG: Poly Propylene Glycol



**Fig. 1. Experimental setup.**

The time scale was initialized at the moment when the air was turned on, and concentrates were collected by regular scrapping between the incremental time intervals of 0, 0.25, 0.50, 1, 1.75, 2.75, 4.75 and 8.75 minutes. Each concentrate was collected in a separate tray and weighed in wet condition. Seven concentrates were collected in each test, filtered, and dried. Therefore, the water and solid recoveries were determined for each time interval. The size distribution of the products was determined by using a Coulter Counter (CC) Type D particle size analyzer, and fractional recoveries were also calculated. The flotation conditions are summarized in Table 1.

## MODEL DESCRIPTION

The simple kinetic model (flotation rate equation) used in flotation is analogous to a first order chemical reaction. The fit of this model to the experimental flotation data is very good in most cases. However, there is no logical justification for the chemical analogy, and therefore, this approach is quite empirical [Bushell, 1962]. The overall rate of flotation in a practical particle separation process depends on many factors so that it is not yet possible to attempt a fundamental calculation of the time dependency [Lee et al., 2002]. However, it is often preferred to evaluate the flotation performance due to its simplicity and prediction power. Since the theoretical basis of the flotation systems is very complex, generally empirical models depending on the analogy between chemical reaction and flotation have been derived and used. Empirical models have been developed also for entrainment in flotation. These models were developed generally for hydrophilic particles since the measurement of hydrophobic mineral entrainment is almost impossible. Hence, an empirical model, which has the basis from the flotation rate equation, was proposed in this study to define the relationship between water recovery and entrainment also for hydrophobic minerals.

It is known that the relationship between cumulative water recovery and time is similar to that of cumulative entrainment and time. In order to develop a model, first, water recovery was defined as a function of flotation time, and then, this relation was implemented into simple water recovery and entrainment relation. The simplest relationship between water recovery and entrained fine solids is a linear relationship for a defined flotation time as explained by Warren [1985].

$$R_w = e \cdot R_e \quad (1)$$

The empirical parameter  $e$ , depending on the particle size and density is defined as the entrainment factor by Warren [1985].  $R_e$  (recovery of entrained solids, %) is the ratio of the amount of entrained solids to the total solids in the flotation cell.  $R_w$  is the amount of water recovered. Eq. (1) was defined for a constant flotation time, and the amount of water recovered is a dependent variable in this equation.

The amount of water recovered depends on so many factors and the recovery mechanism is very complex. It is almost impossible to define a theoretical relationship between water recovery and flotation time. Several mathematical models were studied during modeling, but the following was preferred due to its simplicity and better performance against the experimental data. Therefore, the relationship between water recovered and flotation time was defined by the following empirical equation in this study.

$$R_w = k(1 - \exp(-t\beta)) \quad (2)$$

$k$  and  $\beta$  are empirical model parameters. These parameters depend on the test conditions and flotation equipment. The effect of operational conditions on the model parameters was discussed in an earlier study [Gülsoy et al., 1998].

Substitution of  $R_w$  in Eq. (1) gives,

$$R_{(t)} = (ek)(1 - \exp(-t\beta)) \quad \text{or} \quad R_{(t)} = \alpha(1 - \exp(-t\beta)) \quad (3)$$

The resulting equation is an entrainment model for a kinetic flotation test, where  $\alpha$  is a constant depending on particle size as in Eq. (1).  $\beta$  is an identical parameter in both Eqs. (2) and (3). Hence, it provides a link between water recovery and entrained solids on the basis of flotation time. In this study, it was defined as the coefficient of the water flow trend for a given flotation system.

In flotation, hydrophilic entrainment can be measured directly; however, there is no practical way to measure the entrainment of hydrophobic particles. The model parameters for hydrophilic particles can be determined easily from the fit of Eq. (3) to measured data. This model can also be used to predict the amount of entrained hydrophilic solids in different flotation time for studied conditions. However, the problem is to distinguish the contribution of entrainment and true flotation to the recovery of hydrophobic minerals, particularly at fine particle size range. It is apparent that the contributions made by entrainment to the recovery of hydrophobic particles could not be determined by using only Eq. (3) due to the measurement difficulties. However, since Eq. (3) is time-based, it can be used to calculate the contribution of entrainment to flotation in conjunction with cumulative recovery time relationship, which is used to define flotation rate of hydrophobic mineral.

In order to calculate the recovery of hydrophobic minerals by entrainment, the value of  $\beta$  was calculated from Eq. (2), and then the value of  $\alpha$  for hydrophobic mineral was determined from the cumulative recovery data by a constrained non-linear optimization algorithm. The two constraints used in the calculations are:

-The total amount of entrained minerals towards the end of a flotation test could reach, at most, to the total amount recovered, and even the total amount is accepted as entrainment at the last stage. This will not affect the general trend of the entrainment. Hence, the entrainment could be maximized at the last time interval,

-The amount of entrained mineral must not exceed the recovery at any time.

## RESULTS

### 1. Quartz Only Data

The correlation between the amount of cumulative water ( $R_w$ ) and flotation time ( $t$ ) is shown in Fig. 2 for the test carried out for 35% solids and 90 mg/L frother. Eq. (2) was fitted to the all water recovery data and very good correlation was obtained for each test. The calculated values are also shown in Fig. 2. For the same test, Eq. (3) was fitted to cumulative quartz recovery data. The experimental vs. calculated results for different size fractions are presented in Fig. 3.

As it is observed from Fig. 2, the prediction of proposed model is in accord with experimental observations.

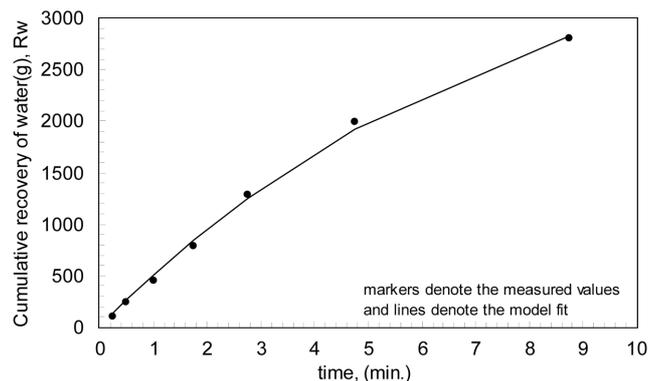


Fig. 2. Variation of cumulative recovery of water with flotation time (quartz only test, 35% solids content, 90 mg/L frother).

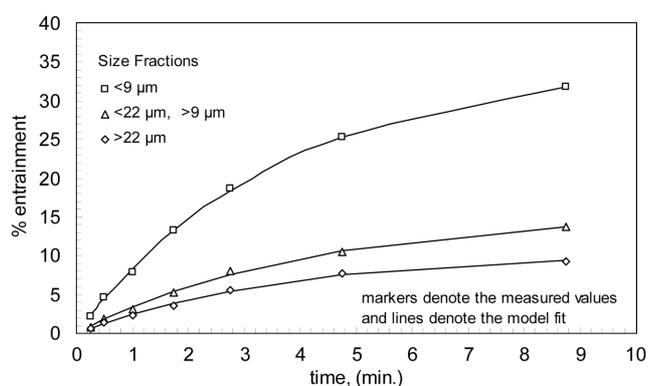


Fig. 3. Variation of cumulative recovery of quartz in each size fraction with flotation time (quartz only test, 35% solids content, 90 mg/L frother).

Fig. 3 shows that cumulative quartz recoveries for different size fractions could successfully be predicted. This also proves that the model proposed could be used to define the entrainment based on flotation time. The model parameters obtained from the fit of Eq. (3) to the quartz only test data are given in Table 2.

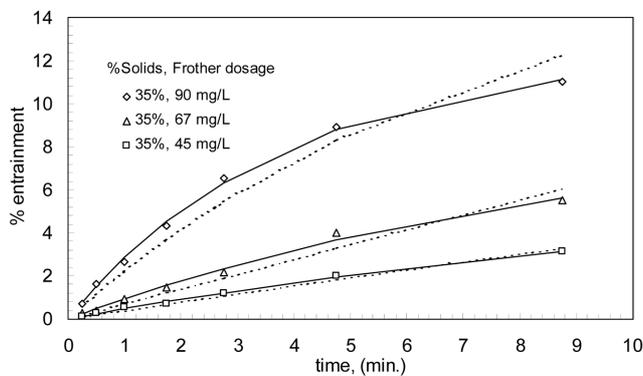
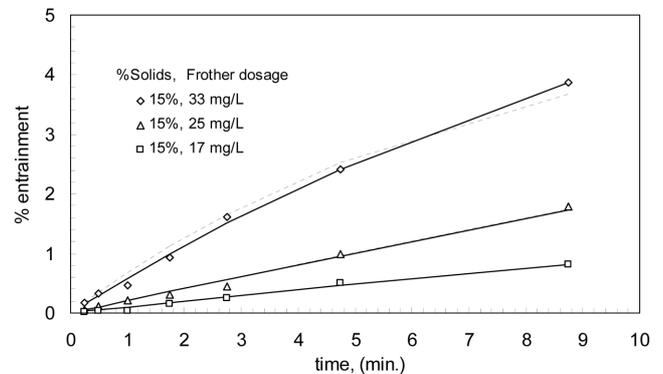
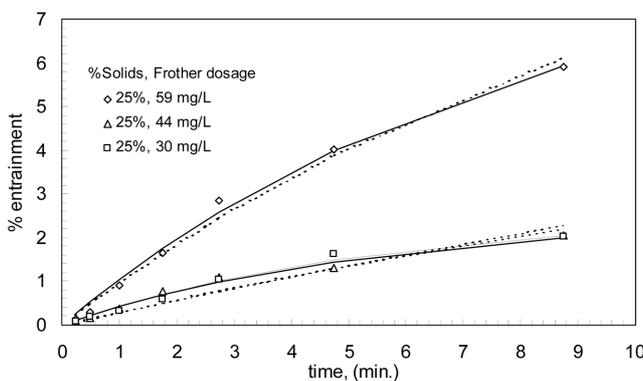
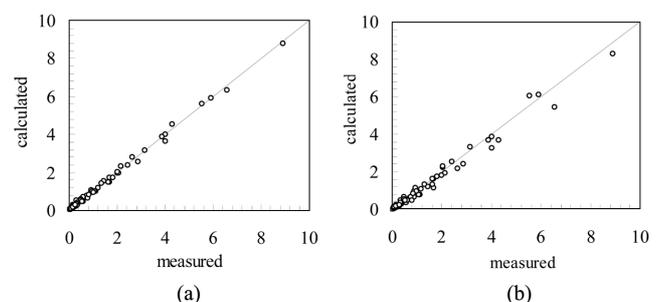
$\alpha$  and  $\beta$  are just fitting parameters. However, the tabulated data show that  $\alpha$  increases with increasing particle size in the same system conditions, whereas  $\beta$  changes only with system conditions. In addition to this, similar  $\beta$  values were obtained from the fit of Eq. (2) to water recovery data for the same test conditions. In the table, the high  $r^2$  ( $r^2 = 1 - \text{Residual SS} / \text{Corrected SS}$ ) values indicate that the data were fitted reasonably well by the model.

Cumulative quartz recovery plots at varying frother dosage and solids contents are presented with markers in Figs. 4-6. In these figures, the solid lines represent the fit of Eq. (3) to the experimental data. Eq. (2) was also fitted to the water recovery data for each test and corresponding  $\beta$  values were calculated. Then, using the  $\beta$  values calculated from Eq. (2), Eq. (3) was re-fitted to the experimental data. These fits are also presented as dashed line in Figs. 4-6.

As can be seen from the figures, the fit was not deteriorated significantly when  $\beta$  values, calculated from water recovery, were used in the model. This proves that  $\beta$  is an identical parameter for both Eq. (2) and Eq. (3) and establishes the link proposed between water recovery and entrained solids on the basis of flotation time.

**Table 2. Model parameters for quartz only tests**

|          | <50 $\mu\text{m}$ , >22 $\mu\text{m}$ | <22 $\mu\text{m}$ , >9 $\mu\text{m}$ | <9 $\mu\text{m}$ | <50 $\mu\text{m}$ , >22 $\mu\text{m}$ | <22 $\mu\text{m}$ , >9 $\mu\text{m}$ | <9 $\mu\text{m}$ | <50 $\mu\text{m}$ , >22 $\mu\text{m}$ | <22 $\mu\text{m}$ , >9 $\mu\text{m}$ | <9 $\mu\text{m}$ |
|----------|---------------------------------------|--------------------------------------|------------------|---------------------------------------|--------------------------------------|------------------|---------------------------------------|--------------------------------------|------------------|
|          | %35 solids, 90 mg/L                   |                                      |                  | %35 solids, 67 mg/L                   |                                      |                  | %35 solids, 45 mg/L                   |                                      |                  |
| $r^2$    | 0.97                                  | 0.98                                 | 0.97             | 0.98                                  | 0.97                                 | 0.96             | 0.99                                  | 0.99                                 | 0.99             |
| $\alpha$ | 2.68                                  | 3.72                                 | 9.14             | 0.68                                  | 1.35                                 | 4.19             | 0.20                                  | 0.43                                 | 1.65             |
| $\beta$  | 0.60                                  | 0.62                                 | 0.60             | 0.68                                  | 0.72                                 | 0.68             | 0.96                                  | 1.00                                 | 0.91             |
|          | %25 solids, 59 mg/L                   |                                      |                  | %25 solids, 44 mg/L                   |                                      |                  | %25 solids, 30 mg/L                   |                                      |                  |
| $r^2$    | 0.99                                  | 0.98                                 | 0.98             | 0.97                                  | 0.97                                 | 0.99             | 0.98                                  | 0.98                                 | 0.98             |
| $\alpha$ | 0.76                                  | 1.68                                 | 4.96             | 0.31                                  | 0.68                                 | 2.32             | 0.19                                  | 0.47                                 | 1.93             |
| $\beta$  | 0.78                                  | 0.78                                 | 0.83             | 0.67                                  | 0.71                                 | 0.73             | 0.93                                  | 0.92                                 | 0.83             |
|          | %15 solids, 33 mg/L                   |                                      |                  | %15 solids, 25 mg/L                   |                                      |                  | %15 solids, 17 mg/L                   |                                      |                  |
| $r^2$    | 0.99                                  | 0.99                                 | 0.99             | 0.97                                  | 0.97                                 | 0.96             | 0.99                                  | 0.98                                 | 0.97             |
| $\alpha$ | 0.42                                  | 0.99                                 | 2.84             | 0.24                                  | 0.61                                 | 1.94             | 0.07                                  | 0.12                                 | 0.53             |
| $\beta$  | 0.82                                  | 0.89                                 | 0.86             | 0.70                                  | 0.73                                 | 0.71             | 0.93                                  | 1.09                                 | 1.04             |

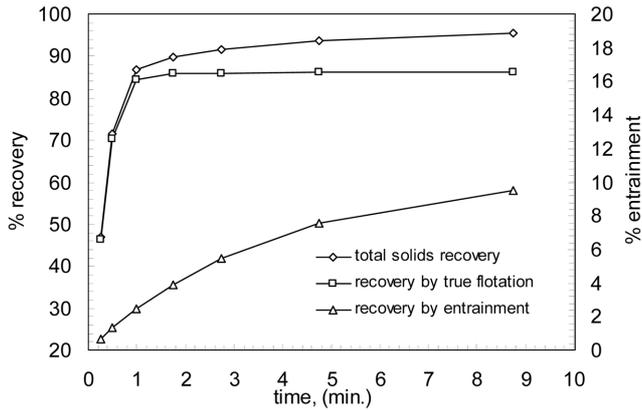
**Fig. 4. Measured and calculated recovery data (quartz only test).****Fig. 6. Measured and calculated recovery data (quartz only test).****Fig. 5. Measured and calculated recovery data (quartz only test).****Fig. 7. Correlation between measured and calculated recovery values from the two model fitting approaches. (a) model fit using only Eq. (3), (b) model fit using  $\beta$  calculated from Eq. (2) as constant in Eq. (3).**

An overall comparison of the measured versus predicted quartz recoveries obtained by using Eq. (3) and using  $\beta$  obtained from water recovery relationship (Eq. (2)) is given in Fig. 7. As can be seen from Fig. 7, the fit obtained in both cases was similar.

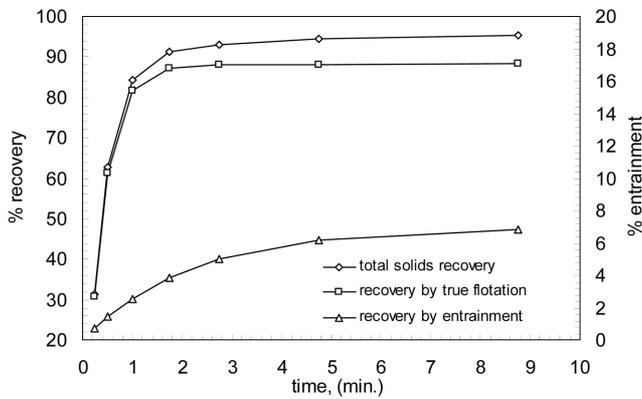
Finally, it was concluded that the model proposed (Eq. (3)) was a useful tool to evaluate the hydrophilic mineral entrainment on the basis of flotation time and could be used for hydrophobic mineral entrainment.

## 2. Pyrite Tests

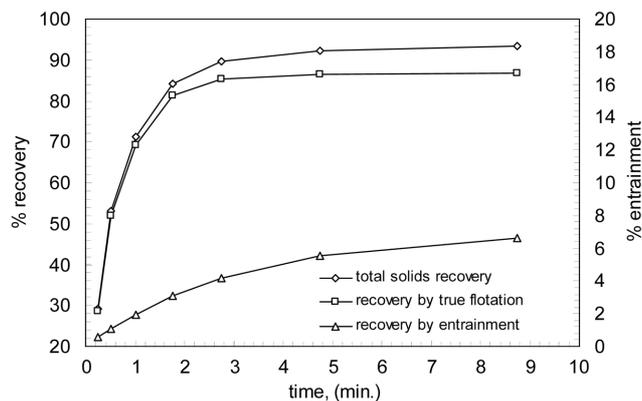
The second set of the flotation tests were performed using pyrite at the flotation conditions given in Table 1.  $\beta$  values were calculated from Eq. (2) using cumulative water recovery data and used as a constant in Eq. (3). Then, the corresponding  $\alpha$  value was calculated for each test by constrained nonlinear regression. During the regression, constraints, given in model description section, were considered. Hence, it was possible to calculate the amount of entrained hydrophobic minerals at any time. But these are just predicted values and it is not possible to compare these predictions with



**Fig. 8. Variation of recovery by true flotation and entrainment with time (Frother dosage: 49 mg/L, pyrite only test).**



**Fig. 9. Variation of recovery by true flotation and entrainment with time (Frother dosage: 24 mg/L, pyrite only test).**



**Fig. 10. Variation of recovery by true flotation and entrainment with time (Frother dosage: 10 mg/L, pyrite only test).**

measured data since the entrainment of hydrophobic minerals cannot be measured. The contributions of entrainment for three different frother dosages are given in Figs. 8, 9 and 10.

As seen from the Fig. 8-10, increasing frother dosage caused an increase in water recovery and this also increased the amount of entrained solids as expected. Reasonable values were obtained for entrainment of hydrophobic minerals by using this approach. Since

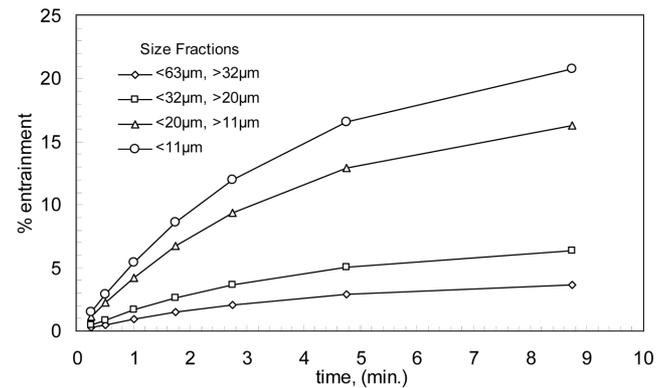
there is not any practical way to measure the entrainment of hydrophobic mineral, logical results are important to evaluate the prediction capacity of a model. Experimental results also revealed the good prediction capacity of the proposed model.

The amount of entrained solids increases with decreasing in particle size (Trahair [1981], Bishop and White [1976], Engelbrecht and Woodburn [1975], Johnson et al. [1974]). Hence, entrainment has very important role especially on the recovery of fine particles. The relationship between the amount of entrained hydrophilic particles and particle size is also given in Fig. 11 for the test condition with 35% solids content and 49 mg/L frother dosage.

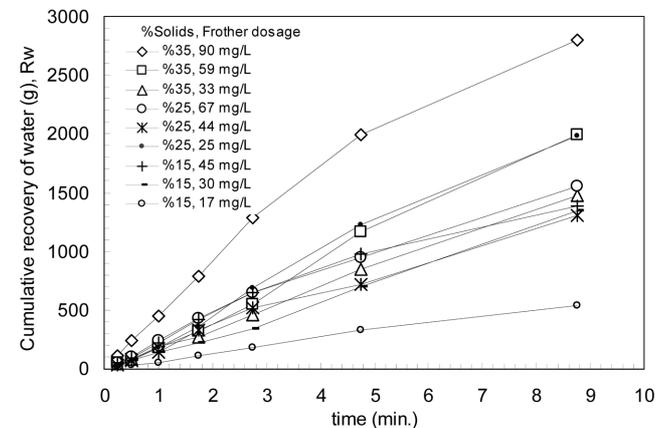
The effect of particle size on the entrained solids occurred as expected. The critical role of the entrainment on the recovery of fine sizes is seen in Fig. 11. This agrees with literature and also proves that the proposed model yields accurate predictions.

### DISCUSSION

In the experimental studies, flotation conditions were selected to obtain a wide range of water recovery observations, which is a key parameter for entrainment. The water recovered in all quartz only tests as a function of flotation time is given in Fig. 12. As seen from the figure, a wide range of entrainment was expected due the wide



**Fig. 11. The effect of particle size on the entrainment of hydrophobic minerals (pyrite only test).**



**Fig. 12. Water recovery as a function of time for different test conditions.**

range of water recovery. The proposed model was found to be satisfactory for this range.

It is possible to calculate hydrophilic entrainment by other methods proposed in the literature. However, it is very difficult to extend these studies for hydrophobic minerals. Only, Ross [1990] defined a transfer factor for both floated and entrained particles. He assumed that hydrophobic particles at the end of a batch test could only be recovered by entrainment. However, in his approach, there is no control for each time interval. The model proposed in this study has ability to calculate entrainment for each time interval.

In a flotation system, water reported to the concentrate would carry both hydrophilic and hydrophobic minerals to the concentrate. In this study, it was shown that the water recovery trend could be used to calculate hydrophilic entrainment. Therefore, since mechanically no difference is expected between the entrainment of hydrophobic and hydrophilic minerals, the same approach could also be used for hydrophobic mineral entrainment. Since the frother dosage is a factor determining the water recovery and entrainment, the hydrophobic mineral entrainment calculated for different frother dosages is given in Fig. 13.

As expected, entrainment is decreasing with decreasing frother dosages since the decrease in frother dosage reduces water recovery. Therefore, it may be concluded that the amount of entrained solids can be controlled by adjusting the parameter affecting the

water recovery.

The relation between  $\alpha$  and particle size is given in Fig. 14. As can be seen from the figure,  $\alpha$  which is related to entrainment is decreasing with increasing particle size for different frother dosages, as expected. It is also related to the water recovered.

The results demonstrated that accurate interpretation of hydrophobic entrainment can be obtained by the application of this proposed model. It may be especially helpful if the difficulties in the measurement of hydrophobic mineral entrainment are taken into account.

In this study, the tests were carried out with single minerals. Therefore, a difference in entrainment could be expected with mineral mixtures or real ores. However, Trahar [1981] explained that the presence of hydrophobic particles does not have an essential effect on the entrainment of hydrophilic gangue at moderate pulp densities. For all cases, the entrainment would be similar to the water recovery and it is easy to calculate the entrainment since water recovery is the only determining factor.

The proposed approach can be applied to industrial flotation banks. Once water recovery trend is established by measuring the water recovery in each cell, entrainment of mineral species can be calculated. Hence, the entrainment can be controlled by the variables affecting the water recovery.

## CONCLUSION

In general, entrainment models are based on the water recovery. However, there is no time dependency in such models. Furthermore, most of the models developed for entrainment of hydrophilic particles could not be practically applied to hydrophobic mineral entrainment.

In this study, an empirical equation was proposed to predict the water recovery as a function of flotation time. The results showed that the same model could be also used to define the entrainment of hydrophilic minerals in a wide range of water recovery. The model structure is different from the water dependent entrainment equations proposed in the literature. First, the proposed model was found to be very suitable for hydrophilic particles. The extension of this model for hydrophobic particles was also very successful. Therefore, it may be concluded that the time-based model proposed in this study could be easily used in the entrainment of both particle types. It characterizes the changes in flotation conditions with time during the operation, and moreover, provides a trend for water recovery and entrainment throughout the flotation. Hence, it could be used for control of the grade and recovery in industrial applications.

## NOMENCLATURE

- $R_e$  : recovery of entrained particles
- $R_{e(t)}$  : recovery of entrained particles at time  $t$  [%]
- $R_w$  : water recovered [g]
- $e$  : entrainment factor (empirical) in the literature
- $k$  : water recovery factor (empirical)
- $\alpha$  : entrainment factor (empirical) in this study [ek]
- $\beta$  : water recovery trend (empirical)
- $t$  : flotation time (s)

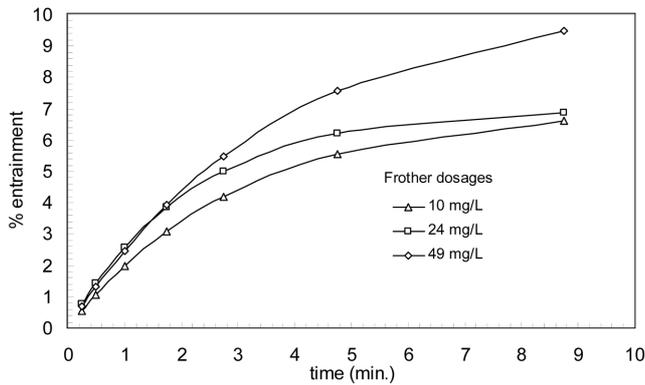


Fig. 13. The effect of frother dosage on the entrainment of hydrophobic minerals.

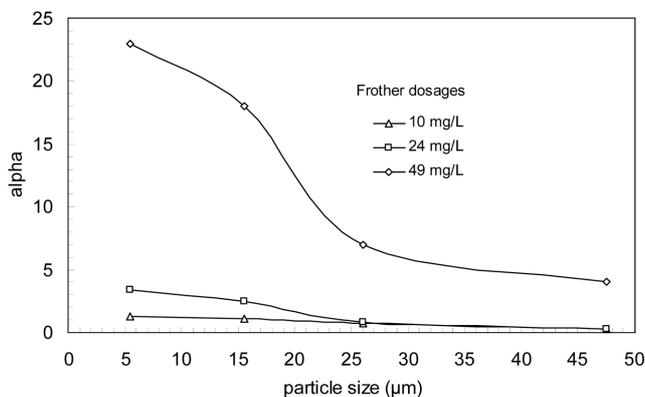


Fig. 14. The effect of particle size on  $\alpha$  for different frother dosages.

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