Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

Improvement of the Flotation Selectivity in a Mechanical Flotation Cell by Ultrasound

Emin Cafer Cilek[a]; Selcuk Ozgen[b]
[a] Department of Mining Engineering, Faculty of Engineering and Architecture, S. Demirel University, Isparta, Turkey [b] Department of Mining Engineering, Faculty of Engineering, A. Kocatepe University, Afyonkarahisar, Turkey

Online publication date: 22 February 2010

To cite this Article Cilek, Emin Cafer and Ozgen, Selcuk(2010) 'Improvement of the Flotation Selectivity in a Mechanical Flotation Cell by Ultrasound', Separation Science and Technology, 45: 4, 572 — 579
To link to this Article: DOI: 10.1080/01496390903484966
URL: http://dx.doi.org/10.1080/01496390903484966

Separation Science and Technology, 45: 572–579, 2010

ISSN: 0149-6395 print/1520-5754 online
DOI: 10.1080/01496390903484966

Taylor & Francis
Taylor & Francis Group

Improvement of the Flotation Selectivity in a Mechanical Flotation Cell by Ultrasound

Emin Cafer Cilek[1] and Selcuk Ozgen[2]
[1]*Department of Mining Engineering, Faculty of Engineering and Architecture, S. Demirel University, Isparta, Turkey*
[2]*Department of Mining Engineering, Faculty of Engineering, A. Kocatepe University, Afyonkarahisar, Turkey*

In this study, the effect of ultrasound on froth and pulp phases has been investigated in the flotation of two different ore samples, namely barite and chalcopyrite. In order to determine the overall flotation rate constants at various froth depths, incremental recoveries obtained from the flotation tests with and without ultrasound were fitted to a first-order rate equation. Thus, the recoveries of froth and pulp phases were calculated.

The use of ultrasound speeded up the bubble coalescence and therefore reduced the froth phase recovery in the ultrasonic flotation of both barite and chalcopyrite. In addition, the results indicate that there is a considerable effect of ultrasound on the pulp phase recovery in the chalcopyrite flotation whereas no significant differences in the separation performance were obtained from the ultrasonic flotation of barite with and without ultrasound. The results also indicate that a pronounced selectivity effect was obtained from the ultrasonic flotation of both barite and chalcopyrite. The use of ultrasound in the froth remarkably improves the quality of the chalcopyrite concentrate, especially at the shallow froths. Therefore, either effective pulp volume can be increased without sacrificing the separation selectivity or the pulp density can be decreased to obtain better product quality at shallow froths in the ultrasonic flotation of chalcopyrite.

Keywords barite; chalcopyrite; flotation; froth phase; ultrasound

INTRODUCTION

The overall recovery of flotation is the result of the interaction between the pulp phase and the froth phase. In addition, several sub-processes occur in the froth phase such as drainage, bubble coalescence, detachment, re-attachment, particle entrapment in liquid films, etc., and it is not only individual contributions but also their interactions that determine the performance of the froth phase. Therefore, the flotation performance strongly depends on the properties of the froth phase, and determining of the froth phase performance is very important from the both design and simulation of the flotation circuit perspective (1–9). The overall flotation recovery R_o can be described by the following equation (2–5,9,10):

$$R_o = \frac{R_p R_f}{1 - R_p + R_p R_f} \tag{1}$$

where R_f is the froth zone recovery and R_p is the collection zone recovery. Figure 1 illustrates the interaction effect of the pulp phase and the froth phase on the overall flotation recovery. It is evident that the froth phase cannot be negligible in obtaining sufficient flotation performance in flotation of an ore.

On the other hand, evidence from the literature that the use of ultrasound is one of the important treatment methods used to improve the flotation performance. Ultrasound not only improves the effectiveness and activity of the flotation reagents but also can modify the surfaces of the minerals in the pulp (11–20). Most of the previous works have been conducted to understand the reagent–valuable mineral interaction mechanisms in the ultrasonic flotation from the overall flotation performance point of view. The objective of this study is therefore to investigate the effect of the use of ultrasound in the froth on performances of the froth phase in flotation of two different ores (sulphide and oxide) and to evaluate the effect of ultrasound on the interaction of these phases existing in a flotation cell. In addition, by the use of ultrasound in the froth, it is expected that the selectivity of the froth phase will be improved and thus, higher quality concentrates will be produced. In other words, the present study was developed to determine and interpret potential improvement in the separation selectivity as well as the overall flotation efficiency regarding the use of ultrasound in the froth.

Received 19 June 2009; accepted 10 October 2009.
Address correspondence to Emin Cafer Cilek, Department of Mining Engineering, Faculty of Engineering and Architecture, S. Demirel University, Isparta, TR, 32260, Turkey. Tel.: +90 2462370428; Fax: +90 2462370859. E-mail: emin@mmf.sdu.edu.tr

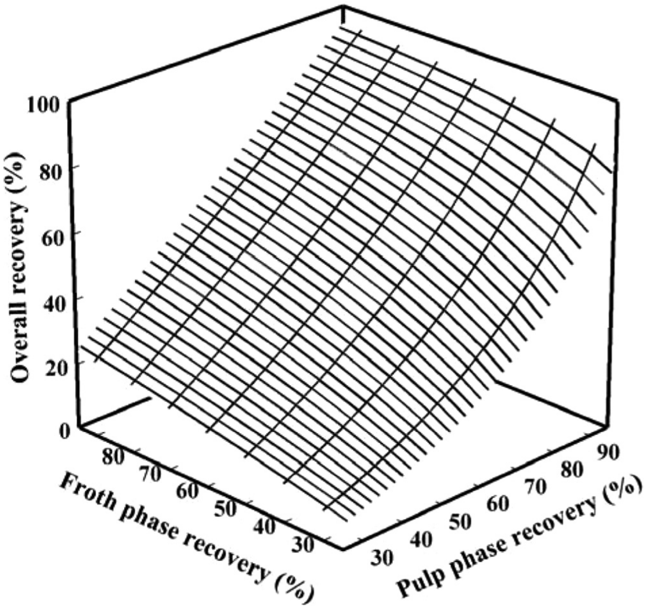

FIG. 1. Effect of the phases prevailing in a mechanical flotation cell on overall flotation recovery.

EXPERIMENTAL

Material

Two different ore samples were used as material because the different chemical conditions are used in their flotation. In addition, since the feed characteristics such as particle size distribution (Fig. 2) and feed grade of each ore are quite different from each other, the froth characteristics and the froth removal rate will be considerably different. By studying with two different materials, it is expected that the effect of the ultrasound on the pulp phase and the froth phase will comprehensively be evaluated and will be compared. The first material is a barite ore containing 74.4% $BaSO_4$, 13.5–18% $CaCO_3$ and 12% SiO_2, which are liberated at 0.15 mm. A copper-iron sulphide ore sample containing 1.2–1.8% Cu and 19.5–23.8% Fe was used in the experiments as other type ore. Minerals of this ore are chalcopyrite associated with pyrite in a non-sulphide gangue (mainly quartz). The liberation size of the minerals is minus 0.038 mm. The samples were crushed to minus 2.8 mm and then representatively divided by standard sampling procedure to use in the grinding stage.

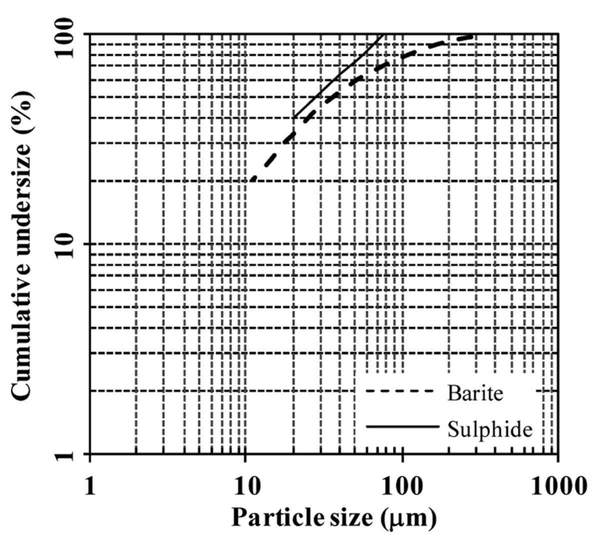

FIG. 2. Particle size distributions of the samples used in the tests.

Method

As mentioned previously, ultrasound may be applied during the different stages of flotation, such as during conditioning or during flotation (13–16,18). In the light of previous works on this subject and the results of the preliminary tests conducted, an experimental programme was planned to elucidate the effects of froth depth and impeller speed on the phases in the cell with and without ultrasound. The range of the operating parameters and the optimum chemical conditions used in the flotation tests are given in Table 1.

Flotation tests were performed in a Denver laboratory flotation machine with a two-liter cell, in which an ultrasonic probe (Bandelin Sonoplus HD 2200, 20 kHz, 0.2 kW) is located in the froth phase (Fig. 3). The flotation reagents used in this study were supplied by Cytec Industries, USA. Froth products were collected to determine the overall rate constant at preset time intervals for the tests conducted with and without ultrasound. Predetermined froth depth (±2 mm) was kept constant by the addition of make-up water into the cell by using a variable speed peristaltic pump. The froth was scrapped every five seconds. Each froth product was filtered, dried, weighed, and assayed for barium or copper.

The metallurgical performance of the froth phase can be expressed in terms of froth recovery (R_f), which is calculated as the total rate of transfer from the pulp to

TABLE 1
Flotation conditions used in the tests

	Copper sulphide ore	Barite ore
pH of pulp	11, (CaO)	9, (NaOH)
Depressant (g/t)	–	20, (Dextrin)
Collector (g/t)	80, (Aerophine 3418 A)	200, (Aero 730)
Flotation time (min)	0.5, 1, 2, 3	0.25, 0.5, 1, 2.5
Frother (g/t)	50, (Oreprep F-507)	50, (Oreprep F-507)
Pulp density (% solids)	18	18
Airflow rate (L/min)	6	6
Froth depth (mm)	5, 15, 25 ± 2	5, 15, 25 ± 2
Impeller speed (rpm)	1000, 1250, 1500	1000, 1250, 1500

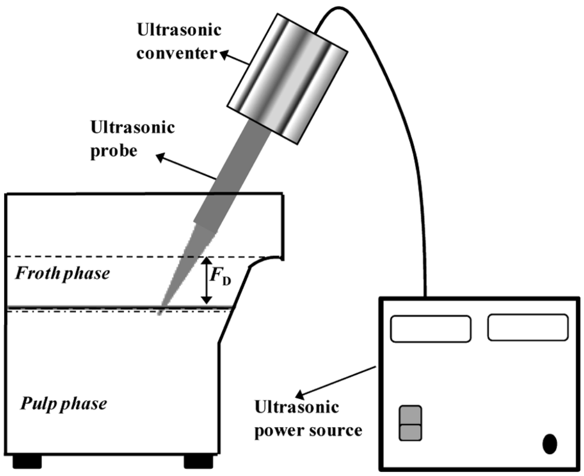

FIG. 3. A schematic illustration of experimental setup.

the concentrate divided by the rate of transfer from the pulp to the froth phase (1,3–5,7,10):

$$R_f = \frac{k_o}{k_p} \tag{2}$$

By floating with almost no froth layer, it is generally assumed that the flotation rate constant obtained represents flotation of minerals in the pulp phase. The methodology for determining R_f consists in operating the cell at various froth depths, keeping the pulp volume constant. The overall recovery is measured at each froth depth (F_D), from which the flotation rate constant at each froth depth is obtained. Values of k_o are plotted against the froth depth and k_p, and $(F_D)_{k_o=0}$ are obtained by extrapolation (1,3–5,9). This allows the calculation of R_f at any froth depth using Eq. (3).

$$R_f = \left[1 - \frac{F_D}{(F_D)_{k_o=0}}\right] \tag{3}$$

where, $(F_D)_{k_o=0}$ is the maximum froth depth, which is a function of the flotation conditions and the froth characteristics. Above this froth depth, no froth product is available.

Numerous empirical and phenomenological models based on various assumptions for flotation can be found in the literature (8,20–22). In this study, the rate data obtained from the tests was fitted to the modified first-order rate equation.

$$R_o = RI\{1 - \exp[-k_o(t + b)]\} \tag{4}$$

where, R_o is the overall flotation recovery (%) at time t (min), b is the time correction factor, and RI and k_o are the ultimate recovery (%) and the overall rate constant (min^{-1}), respectively.

RESULTS AND DISCUSSION

In order to estimate unknown model parameters (RI, k_o, and b), the experimental data (incremental recoveries and time) were treated by a nonlinear estimation method called Levenberg-Marquard using statistical software, Statistica. The coefficient of determination was more than 0.993 in all the cases, and this verifies the consistency of the model (Eq. (4)) used. The overall flotation rate constant obtained were plotted against froth depth as shown in Figs. 4 and 5, and the pulp phase rate constant, k_p, was obtained for each ore. By using these data generated, the pulp phase recovery and the froth phase recovery were calculated by using Eqs. (1) and (2 or 3), respectively.

Effect of Ultrasound on Flotation of Barite

Figure 6 shows that the effect of the froth depth and the impeller speed on froth phase recovery and the pulp phase recovery. As mentioned previously, the literature suggests

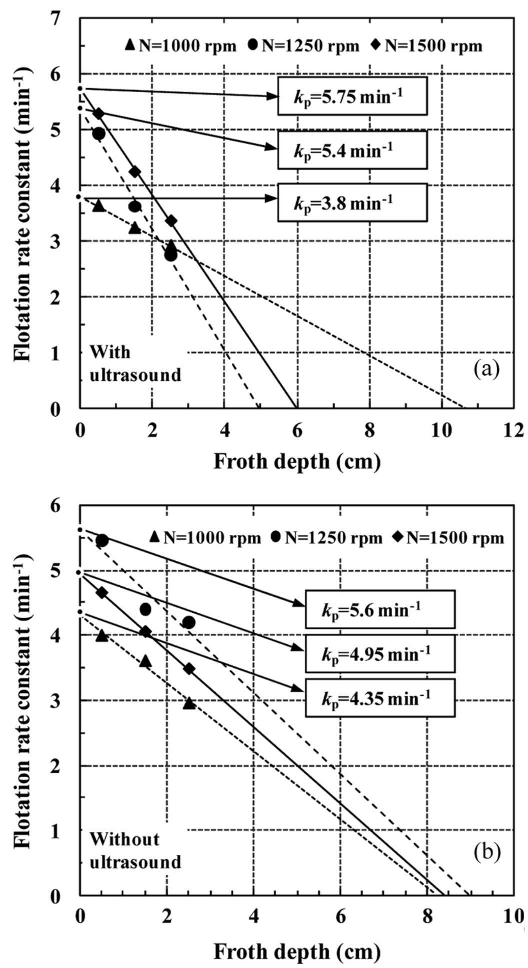

FIG. 4. Overall flotation rate constant for barite as a function of froth depth with (a) and without (b) ultrasound and determination of pulp phase rate constant.

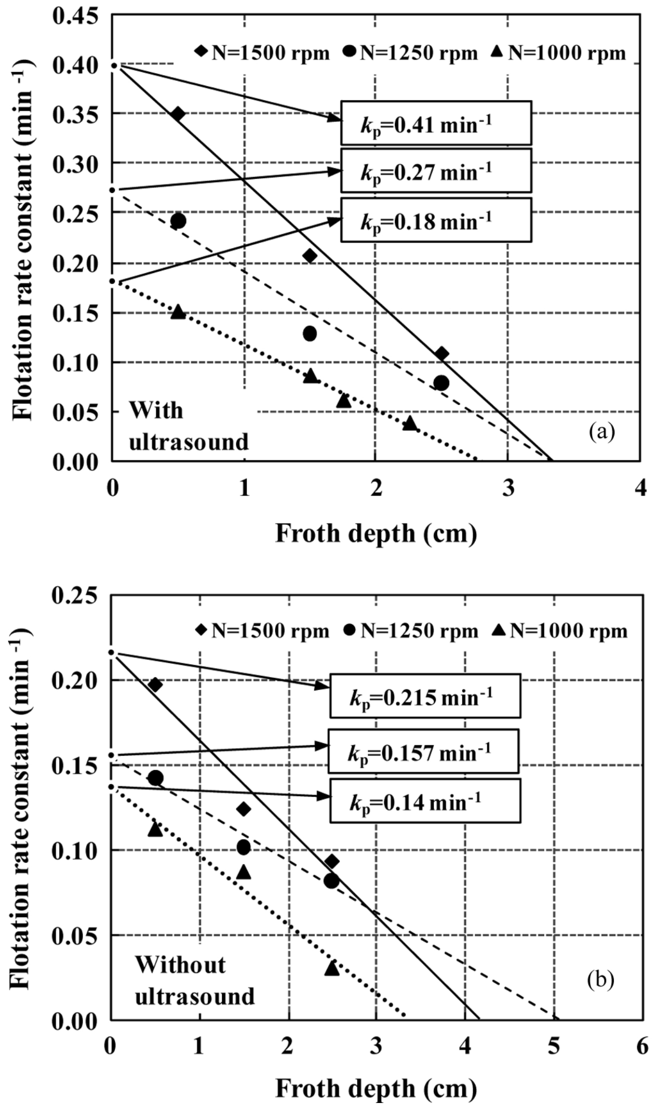

FIG. 5. Overall flotation rate constant for chalcopyrite as a function of froth depth with (a) and without (b) ultrasound and determination of pulp phase rate constant.

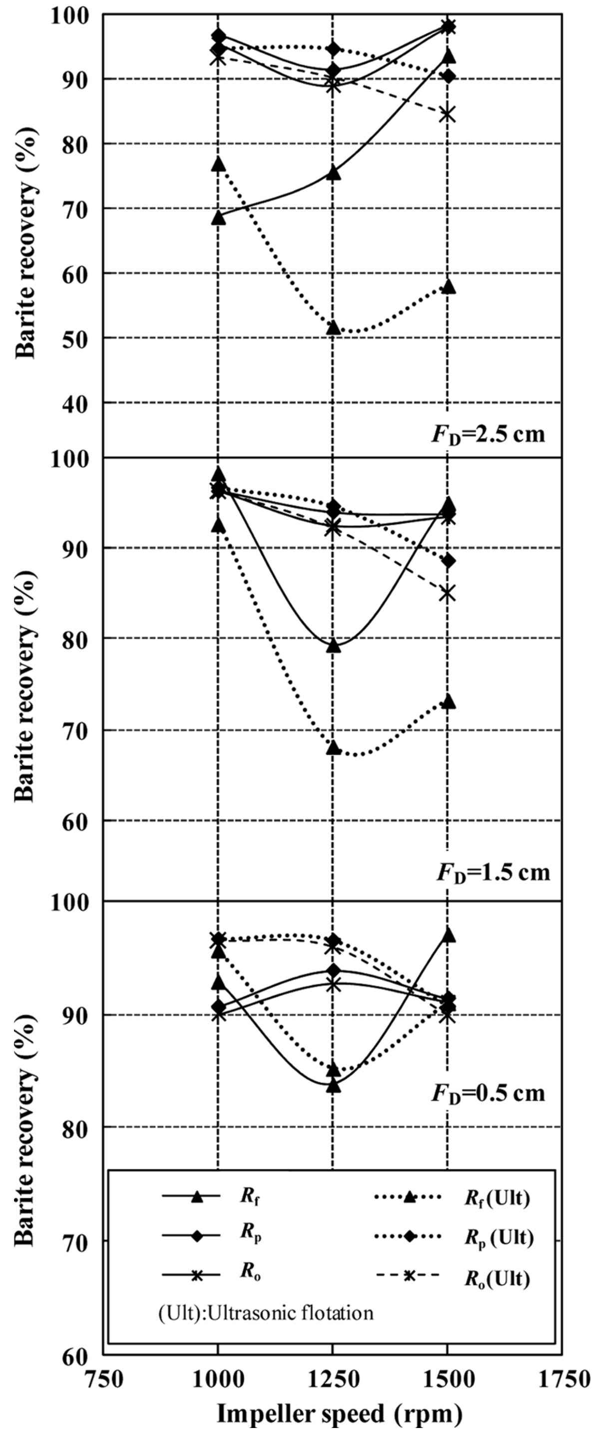

FIG. 6. Overall barite recovery and barite recoveries of the phases as a function of impeller speed.

that ultrasonic preconditioning of the pulp and/or ultrasonic flotation improves the flotation performance (13,14,16,18). It is clear that the use of ultrasound in the froth has a pronounced negative effect on the barite recovery of each phase. Thus, there are no significant differences in the overall barite recoveries obtained from the tests with and without ultrasonic are apparent from the results shown in Fig. 6. It is believed that the mode of ultrasonication in the tests is the main reason for this decrease in separation efficiency. Although the ultrasonic probe was located in the froth phase to enhance the separation selectivity, it increases the bubble coalescence in the froth phase, which possibly explains the observed decrease in the froth phase recovery and the overall flotation recovery.

By visual observation, it was possible to see that the ultrasonic probe located in the froth was surrounded by the coarse bubbles, indicating that the bubble coalescence was one of the significant events that occurring in the froth phase. Figure 7 shows that the effect of the froth depth and impeller speed on the grade of the barite concentrates produced from the flotation tests with and without ultrasound. It is evident that the separation selectivity of barite flotation is slightly improved by the use of ultrasound in the froth phase at the high level impeller speed. These results agree with the results presented in Fig. 5, showing the maximum froth height at different impeller speeds. It is obvious from Figs. 5 and 7 that all the froth depths used in the experiments can be defined as the shallow froth for the barite flotation, which contains high feed grade. Therefore, it can be concluded that the barite grade of the concentrate obtained from the tests with and without ultrasound is independent of the froth depth used in these tests, as can be seen from Fig. 7.

To sum up the findings of Figs. 6 and 7, the use of ultrasound in the froth has a two-fold effect on the froth phase. First of all, it acts to reject the entrained particles in the inter-bubble water (both barite and gangue particles), selectively, and not attached particles, which results in an increase of the barite grade of concentrate. Secondly, the use of ultrasound in the froth phase causes an increase in the bubble coalescence, thereby reducing the froth phase recovery. In addition, since there are no significant differences in the pulp phase recoveries obtained from the barite flotation with and without ultrasound, a negligible effect of the use of ultrasound in the froth phase on the overall barite flotation recovery is observed.

Effect of Ultrasound on Flotation of Chalcopyrite

Figure 8 shows the effect of froth depth and impeller speed on chalcopyrite recoveries of the phases. It is evident that the use of ultrasound in the froth phase has a pronounced negative effect on the chalcopyrite recovery of the froth phase. It must be noted that it was possible to see that the ultrasonic probe located in the froth was surrounded by the coarse bubbles, indicating that the bubbles were coalesced in the chalcopyrite flotation like as in the ultrasonic flotation of barite. It is well known that the bubble coalescence is not only a parameter critical to the transport of particles and water through the froth but also it reduces the available bubble surface area, resulting

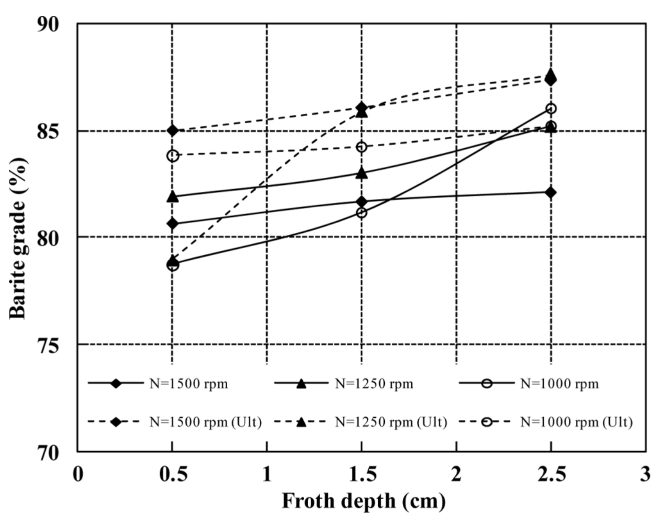

FIG. 7. Effect of ultrasound on quality of barite concentrate.

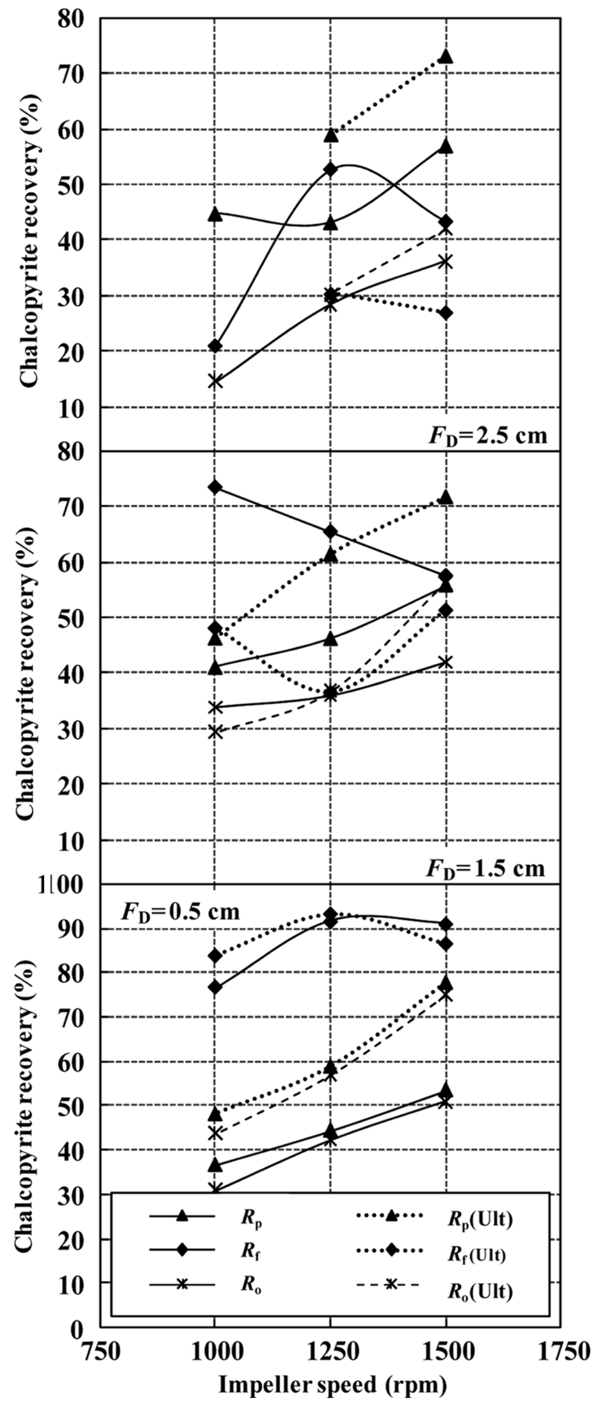

FIG. 8. Overall chalcopyrite recovery and chalcopyrite recoveries of the phases as a function of impeller speed.

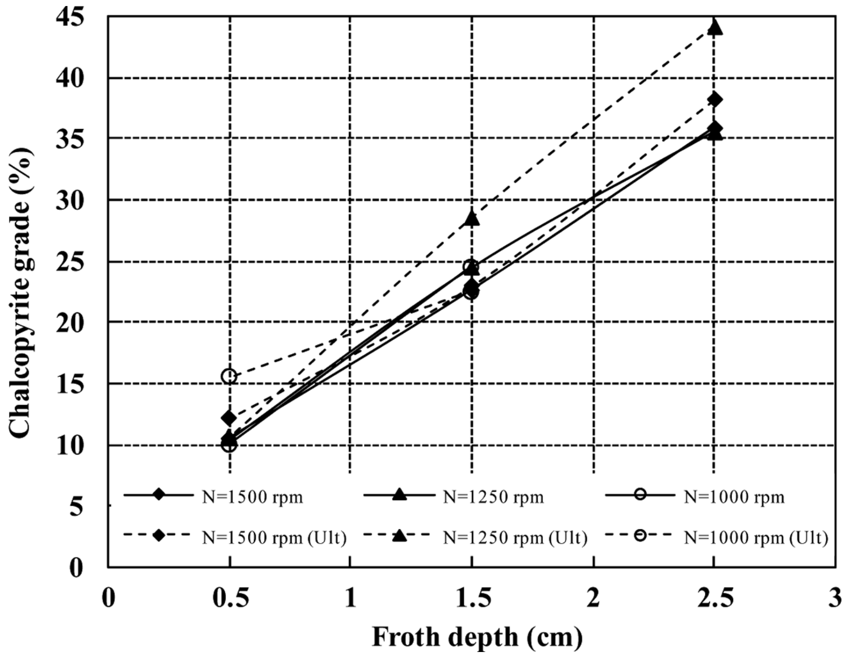

FIG. 9. Effect of ultrasound on quality of chalcopyrite concentrate.

in particle detachment from bubbles in the froth phase. The observed bubble coalescence is attributed to the cavitation that has taken place on the phase boundaries. In other words, the use of ultrasound in the froth primarily influences the solid/liquid interface generating cavitation and thereby enhances the drainage of the fine particles from the froth to pulp. It therefore decreases density and viscosity of the water (pulp) between the bubbles. Both phenomena can cause an increase in the bubble coalescence. Opposite to the ultrasonic barite flotation, the overall recovery increases in the ultrasonic flotation of the sulphide ore, whereas the froth phase recovery decreases in this case. As shown, the impeller speed has a significant effect on the pulp phase recovery obtained from the ultrasonic flotation of chalcopyrite. The effect on the pulp phase recovery is believed to be caused by the increased probability of attachment at more intensive agitation conditions which occurred by cooperation of high impeller speed and ultrasound. These results indicate that the performance of each phase can selectively be improved by the use of ultrasound in the flotation of low grade ores. In addition, the effect of the froth depth on the chalcopyrite recovery is more pronounced in the ultrasonic flotation, as can be seen from Fig. 8. It is evident that the ultrasonic flotation is more effective at low level froth depths, i.e., the shallow froths. At this point, it must be noted that no material is transferred from the froth to concentrate in the ultrasonic flotation tests conducted at high level froth depth (25 mm) and low level impeller speed (1000 rpm). Similarly, the effect of ultrasound on the chalcopyrite flotation performance at a low level of the impeller speed (1000 rpm) is negligible, especially at the deepest froths.

The effect of ultrasound on the quality of chalcopyrite concentrate is illustrated in Fig. 9. The use of ultrasound in the froth remarkably improves the quality of the chalcopyrite concentrate, unexpectedly at the shallow froths, as can be seen from Fig. 9. On the other hand, the overall chalcopyrite recovery has a maximum at this froth depth. It is evident that the use of ultrasound in flotation of the sulphide ore at the shallow froth improves not only the grade concentrate but also the overall flotation recovery.

The differences in the volumetric flow rate of concentrates obtained from the flotation tests with and without ultrasound are given in Table 2. In addition to the differences between the maximum froth depths obtained for barite and chalcopyrite (Figs. 4 and 5), the differences in the concentrate flow rates in Table 2 clearly indicate that the froth characteristics of the ultrasonic barite flotation are considerably different from those of the ultrasonic chalcopyrite flotation. It must be noted that 50–70% of barite in the ore was floated in the first 30 seconds during the ultrasonic barite flotation. The froth volume and concentrate overflow rate obtained from the ultrasonic barite flotation at all the froth depths were so high that the prospective effect from the use of ultrasound could not be obtained. For example, the use of ultrasound can enhance the pulp phase recovery due to an increase in the activity of the reagents used, which enhance the efficiency of the barite flotation in the pulp phase like as the ultrasonic sulphide flotation. As a result of these differences, a negligible

TABLE 2
Comparison of concentrate volumetric flow rate obtained from the flotation tests with and without ultrasound

	Froth overflow rate (mL/min)			
Froth depth (mm)	Sulphide flotation	Sulphide flotation (Ultrasonic)	Barite flotation	Barite flotation (Ultrasonic)
25	31.88	63.56	402.2	381.2
15	102.1	162.4	489.2	514.8
5	376.4	475.2	614.8	578.4

improvement in the efficiency of the ultrasonic barite flotation was observed.

CONCLUSIONS

The results show that the use of ultrasound speeded up the bubble coalescence, which probably reduced the froth phase recovery in the ultrasonic flotation of both barite and chalcopyrite. A possible explanation is that the use of ultrasound in the froth influences primarily the solid/liquid interface generating cavitation and thereby speeds up the drainage of the particles in the water between the bubbles. It therefore decreases the density and the viscosity of the pulp between the bubbles. Both phenomena cause an increase in the bubble coalescence, which results in decrease in the froth phase recovery.

The use of ultrasound in the froth phase has resulted in significant improvement in the efficiency and selectivity of the chalcopyrite flotation at intermediate and low level froth depths. These results suggest that the shallow froth provides a significantly higher throughput capacity without sacrificing the separation selectivity in the ultrasonic flotation of the sulphide ore.

There is no significant difference in the separation performance obtained from the barite flotation with and without ultrasound. On the other hand, the experimental results obtained from the ultrasonic barite flotation clearly suggest that the separation selectivity can be improved by ultrasound.

The results obtained in this study highlight that the separation selectivity and efficiency can significantly be improved by the use of ultrasound in the froth phase in flotation of many ore types. In addition, Djendova and Mehandj (1992) reported that the use of ultrasound in an industrial copper flotation plant could be economically feasible, provided that the capital cost can be kept low. Therefore, the use of ultrasound in a flotation plant is easily applicable using one or more ultrasonic probes, which are commercially available in a range of configurations and sizes.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support of the Scientific and Technological Research Council of Turkey (TÜBİTAK) and The Scientific Research Funding Unit of the Suleyman Demirel University under Project No.: 106M128 which made this study possible.

REFERENCES

1. Feteris, S.M.; Frew, J.A.; Jowett, A. (1987) Modelling the effect of froth depth in flotation. *Inter. J. Miner. Process*, 20: 121–135.
2. Finch, J.A.; Dobby, G.S. (1990) *Column Flotation*; Pergamon Press: Oxford, 103–110.
3. Vera, M.A.; Franzidis, J.P.; Manlapig, E.V. (1999a) The JKMRC high bubble surface area flux flotation cell. *Miner. Eng.*, 12 (5): 477–484.
4. Vera, M.A.; Franzidis, J.-P.; Manlapig, E.V. (1999b) Simultaneous determination of collection zone rate constant and froth zone recovery in a mechanical flotation environment. *Miner. Eng.*, 12 (10): 1163–1176.
5. Mathe, T.Z.; Harris, M.C.; O'Connor, C.T. (2000) A review of methods to model the froth phase in non-steady state flotation systems. *Miner. Eng.*, 13 (2): 127–140.
6. Vera, M.A.; Mathe, Z.T.; Franzidis, J.P.; Harris, J.-P.; Manlapig, E.V.; O'Connor, C.T. (2002) The modelling of froth zone recovery in batch and continuously operated laboratory flotation cells. *Int. J. Miner. Process.*, 64: 135–151.
7. Alexander, D.J.; Franzidis, J.P.; Manlapig, E.V. (2003) Froth recovery measurement in plant scale flotation cells. *Miner. Eng.*, 16: 1197–2003.
8. Nguyen, A.V.; Schulze, H.J. (2004) *Colloidal Science of Flotation*; Marcel Dekker Inc.: New York, 745–777.
9. Schwarz, S.; Grano, S. (2005) Effect of particle hydrophobicity on particle and water transport across a flotation froth. *Colloids and Surfaces A: Physicochem. Eng. Aspects*, 256: 157–164.
10. Zanin, M.; Wightman, E.; Grano, S.R.; Franzidis, J.-P. (2009) Quantifying contributions to froth stability in porphyry copper plants. *Int. J. Miner. Process.*, 91 (1–2): 19–27.
11. Nicol, S.K.; Engel, M.D.; Teh, K.C. (1986) Fine particle flotation in an acoustic field. *Inter. J. Miner. Process.*, 17: 143–150.
12. Slaczka, A. (1987) Effect of an ultrasonic field on the flotation selectivity of barite from a barite-fluarite-quartz ore. *Inter. J. Miner. Process.*, 20 (2), 193–210.
13. Celik, M.S. (1989) Effect of ultrasonic treatment on the floatability of coal and galena. *Separation Science and Technology*, 24 (14): 1159–1166.
14. Djendova, S.; Mehandj, V. (1992) Study of the effects of acoustic vibration conditioning of collector and frother on flotation of sulphide ores. *Int. J. Miner. Process.*, 34: 205–217.
15. Zhou, Z.A.; Xu, Z.; Finch, J.A.; Hu, H.; Rao, S.R. (1997) Role of hydrodynamic cavitation in fine particle flotation. *Int. J. Miner. Process.*, 51: 139–149.
16. Aldrich, C.; Feng, D. (1999) Effect of ultrasonic preconditioning of pulp on the flotation of sulphide ores. *Miner. Eng.*, 12: 701–707.

17. Farmer, A.D.; Collings, A.F.; Jameson, G.J. (2002) Effect of ultrasound on surface cleaning of silica Particles. *Int. J. Miner. Process.*, 60: 101–113.
18. Ozkan, S.G. (2002) Beneficiation of magnesite slimes with ultrasonic treatment. *Miner. Eng.*, 15: 99–101.
19. Gurpinar, G.; Sonmez, E.; Bozkurt, V. (2004) Effect of ultrasonic treatment on flotation of calcite, barite and quartz. *Miner. Process. and Extr. Metall.*, 113: 91–95.
20. Ozkan, S.G.; Kuyumcu, H.Z. (2007) Design of a flotation cell equipped with ultrasound transducers to enhance coal flotation. *Ultrason. Sonochem.*, 14: 639–645.
21. Agar, G.E.; Chia, J.; Requis-c, L. (1998) Flotation rate measurements to optimize an operating circuits. *Miner. Eng.*, 11 (4): 347–360.
22. Wills, B.A. (1997) *Mineral Processing Technology*, 6th Ed.; Butterworth-Heinemann: Oxford, 284–316.