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Correlation of the entrainment factor with frother types and their mixtures in the column flotation

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Abstract. In flotation, entrainment is a mechanical mass transfer process and it is based on the changes depending on the establishment of linear relationship between water and solid recovery. The present paper presents results obtained in investigating the effect of frother mixture concentrations on the entrainment of fine particles' during the column flotation. The aim of the present study was to investigate more specifically the relationship between the recovery via entrainment of a range of different hydrophilic calcite particles. For this, to determine entrainment factor of fine particle was used a mixture of artificial ore (celestite/calcite; 1:1). The results showed that the frother mixtures had important effect on the grade and recovery, superficial air rate, gas hold-up and entrainment of fine gangue particles. Entrainment factors for frother mixtures were compared in flotation column. Kirjaveinen (1989) model was used for explaining the specific entrainment factor (Pi) of hydrophilic particles and it has been observed that this model supports the results of this study. This, together with the increased recovery, resulted in higher celestite grades of valuable mineral recovered to the concentrate when using the frother mixtures (Pine Oil+MIBC).

Keywords: Entrainment, Column flotation, Frothers, Celestite, Calcite.

Sürüklenme faktörünün kolon flotasyonunda kullanılan köpürtücü tür ve karışımlarıyla ilişkisi

Özet. Flotasyonda, su ile taşınım mekanik bir kütle transfer işlemidir ve katı-su kazanımı arasında doğrusal bir ilişki kurulmasına bağlı değişim gösterir. Bu çalışmada, kolon flotasyonunda ince tanelerin sürüklenmesi üzerine farklı miktarlarda köpürtücü karışımlarının etkisi incelenmektedir. Çalışmanın amacı, hidrofilik kalsit tanelerinin sürüklenmesi yoluyla geri kazanım arasındaki ilişkiyi daha spesifik olarak incelemektir. İnce tanelerin sürüklenme faktörünü belirlemek için yapay cevher karışımı (selestit / kalsit; 1: 1) kullanılmıştır. Deneysel sonuçlar, köpürtücü karışımlarının tenör-verim, yüzeysel hava hızı, gaz tutunumu ve ince gang tanelerinin sürüklenmesi üzerinde önemli bir etkiye sahip olduğunu göstermiştir. Farklı tür ve miktarlarda köpürtücü karışımları için sürüklenme faktörleri, kolon flotasyonunda karşılaştırılmıştır. Hidrofilik tanelerin spesifik sürüklenme faktörünü (Pi) açıklamak için Kirjaveinen (1989) modeli kullanılmış ve bu modelin bu çalışmanın sonuçlarını desteklediği görülmüştür. Çamyağı + MIBC köpürtücü karışımı kullanıldığında, konsantrede verim artmış ve daha yüksek tenörlü selestit konsantresi elde edilmiştir.

Anahtar Kelimeler: Su ile taşınım, Kolon flotasyonu, Köpürtücüler, Selestit, Kalsit

1. INTRODUCTION

In entrainment, particles suspended in the water between bubbles enter froth zone from the collection zone and are conducted to the concentrate. Both hydrophobic and hydrophilic mineral particles in pulp can experience entrainment. Entrainment is widely accepted to be

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the dominant mechanism of during enrichment of fine-sized ores, particularly in the size range below 45 µm. Entrainment starts in the pulp phase. Since entrainment has a harmful effect on the grade of the concentrate, a number of studies have been performed to understand entrainment mechanisms. Many researchers have developed models with an objective of predicting entrainment in a flotation cell. They have worked on understanding the factors affecting entrainment, the mechanisms, measurement techniques and the modelling [2-23]. There is a direct relationship between entrainment and water recovery, which is generally dependent on froth characteristics. Therefore, water recovery plays an important role in recovering gangue minerals by entrainment [3,10,24]. Wang et al. [25] commented the literature on flotation entrainment and both theoretical and empirical models that have been developed to simulate entrainment and explaining the various mechanisms of interest. Zheng et al. [26] and Kirjavainen [1,27] developed models to define and estimate the recovery of hydrophilic particles by entrainment. Kirjavainen [27] suggested a mathematical model for the degree of entrainment of hydrophilic particles in a continuous laboratory flotation system. Experiments were carried out using quartz and phlogopite minerals at different slurry densities with only frother added. The relationship between the water and the gangue recovery was defined for continuous flotation system at steady state by Kirjavainen [1,6,27] in Eq. (1):

$$P = W^{0.7} \Big/ \left(W^{0.7} + b\Psi\eta^{-0.5\Psi} m^{0.5\Psi - 0.4}\right) \qquad (1)$$

where P is the entrainment factor (the ratio of the recovery of gangue and water), W is the water recovery (kg/m^2 /s), m is the particle mass (pg), g is the slurry viscosity (mPas), Ψ is a dynamic shape factor, while b is a constant. Kirjavainen [6] can be replaced for batch flotation system in Eq. (2):

$$R_i = 1 - \exp(-P_i R_w) \;,\; P_i = \ln(1 - R_i) / -R_w \qquad (2)$$

where R_i is the relationship between recovery of the ith gangue fraction, P_i is the entrainment factor that depends on the particle characteristics and process variables.

The entrainment process is affected by a number of factors in the pulp and froth during flotation. Among them; frother types and concentrations, superficial air rate, superficial feed rate, superficial wash water rate, air-hold-up, bias rate, collection and cleaning zone height, residance time, collector types and concentrations, etc. have been parameters. Many of these parameters have been studied by many researchers [1,5,6,27-38].

Kursun [39] presented a problem of entrainment in conventional and column flotation. The results demonstrated that the frother concentration and particle size had important effect on the grade and recovery, flotation time and fine gangue entrainment. Kursun [40] was defined that the frother types and concentrations and superficial air rates had significant effects on calcite and water recoveries and entrainment behaviour of calcite in column flotation. The results have shown that MIBC improved the recovery and grade of celestite concentrate and entrainment factor was obtained as the lowest for MIBC frother (celestite grade and recovery, 89.95%, 87.11%, entrainment factor (Pi: 0.365)) and 4 minute is determined as optimum residence time since the lowest entrainment factor has provided. Kirjaveinen [1] model was used for the determination of specific entrainment factor of hydrophilic particle in both studies [30,31].
Unlike the course of the study in Kursun 2017 [40], within paper presents results obtained in investigating the effect of frother mixtures (Pine Oil+MIBC, Pine Oil+Aerofroth 88, MIBC+Aerofroth 88) concentrations (ratio 1:1) on the entrainment factor. The effect of frothers on the degree of entrainment is important for selective flotation, but the mechanism causing the effect is still poorly known. The purpose of the present study should be maximum recovery with the minimum gangue contamination in the laboratuary type column flotation. Hence, determination of entrainment factors using only calcite (97.78% $CaCO_3$) and celestite (97.20% $SrSO_4$) ore mixtures in different frother mixtures were aimed.

2. EXPERIMENTAL

2.1. Materials and reagents

In the current study, in order to obtain accurate entrainment factor, entrainment tests were performed, under the identical operating conditions using MIBC (metil izobütil karbinol -$C_6H_{14}O$), Pine Oil (complex mixtures of monoterpene hydrocarbons (alpha, beta-pinene) and oxygenated monoterpenes (terpineol, borneol, bornyl acetate)), Aerofroth 88 (2-Ethylhexanol- $C_8H_{18}O$) and Pine Oil+MIBC, Pine Oil+Aerofroth 88, MIBC+Aerofroth 88 mixtures frothers. The minerals to the experiments, calcite and celestite were supplied from BMT Gypsum Co. (Sivas-Turkey) and Barit Mining Co.

(Sivas-Turkey), respectively (Table 1). A similar particle size distribution of the celestite and calcite as shown in Figure 1 was achieved by a ball mill grinding. Celestite samples were prepared to several particle size ranges (-106+75μm, 75+53μm, -53+38μm) by screening and calcite samples were screened to size fraction of -38μm.

Table 1. Chemical analysis of the samples [39-40]

	Component	%
Celestite	$SrSO_4$	97.20
	$CaSO_4.2H_2O_4$	2.32
	Others (Fe_2O_3+Al_2O_3+MgO)	0.48
Calcite	CaO	54.42
	LOI	43.36
	Others (MgO, Fe_2O_3, Al_2O_3, Na_2O, SO_3, K_2O, SiO_2<0.01)	2.22

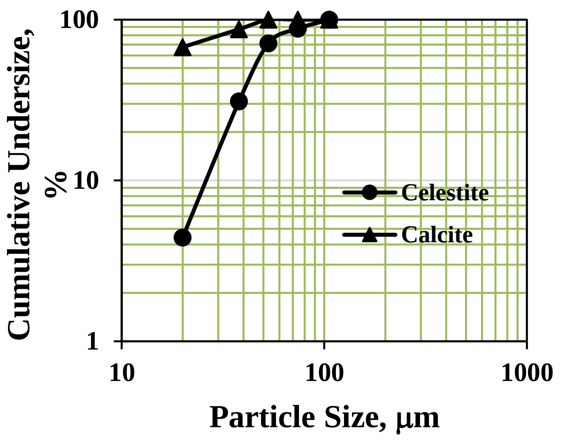

Figure 1. Particle size distributions of the celestite and calcite after grinding

NaOH (sodium hydroxide) was used to adjust the pH (WTW INO LAB 740, Germany) of the slurry to 10.0. The anionic collector used was Na-oleate (600 $g.t^{-1}$) and Pine Oil, MIBC and Aerofroth 88 were added to the pulp as frother. On the other hand, Pine Oil, MIBC and Aerofroth 88 were used as 40 $g.t^{-1}$, 80 $g.t^{-1}$, 120 $g.t^{-1}$, 160 $g.t^{-1}$, respectively. These reagents were prepared daily prior to the tests using distilled water. Table 2 shows the ranges of dosages for these reagents along with major operating parameters used of experiments.

Table 2. Operating conditions used in column flotation test [39-40]

Operating parameters	
pH	10.0
Pulp density (%)	20
Na-oleate ($g.t^{-1}$)	600
Frother dosage ($g.t^{-1}$)	40-80-120-160
Superficial air velocity ($cm.sec^{-1}$)	0.5-1.0-1.5-2.0
Superficial feeding velocity ($ml.min^{-1}$)	400
Superficial wash water velocity ($ml.min^{-1}$)	150

2.2. Entrainment tests

Entrainment tests using the fully liberated celestite and calcite were performed in column cell. The column flotation system consists of a plexiglas circular column 750 mm in height and 50 mm in a diameter, a conditioner 12.75 liter (300x240x200 mm) in volume, a flowmeter, two peristaltic pumps (Watson Marlow 323U/D, UK) for feeding and tailing exit, a compressor supplying air to the column. The column was mounted on a chassis, and a universal shower attached on the top was used as the washing system. A universal shower-type wash water system that is located from 20 mm above the top of the column. Wash water was introduced through a perforated plexiglas container situated just above the froth zone. Bubbles were produced using air spargers and a pump having a maximum pressure greater than 0.012 MPa with 1.8 rpm. The air feed to column was organized by a flow at different air rates. During the experiments, extra care was taken in order not to disturb the froth by the wash water added. The volume of the feed tank was five times the volume of the column. The feed to column was introduced from the upper section of the collection zone by pumping the slurry from a mixing thank that was agitated at 60 rpm (a mechanical stirrer-IKA-WERK RW 20 (Anke&Kunkel, Germany)). In order to obtain concentrates and tailing, certain period of time was allowed for the system to reach

steady state after testing the parameters. Tap water (pH: 7.8) was used in the experiments.
Bubble diameters were moderated by recording the bubbles for 40 sec. from the air-water phases (45 cm above the column base) using a camera (CANON EOS 5D-Mark II, Japan). Images were seized by illuminating the column and putting a black panel behind the wall. Camera was focused on midpoints of (both height and width) the front cross section of the column. Bubble diameters were measured on the milli-metric scale using a capture program running on the computer.

3. RESULTS and DISCUSSION

3.1. The effect of bubble diameters, superficial air rates and air-hold up on entrainment

In Figure 2, the variation of gas holdup with the superficial air rates using different frother types and mixtures (15 g.t^{-1}) is illustrated in a two-phase system (water/air). In the experiments, Pine Oil, MIBC, Aerofroth 88, Pine Oil + MIBC (1:1), Pine Oil + Aerofroth 88(1:1) and MIBC + Aerofroth 88 (1:1) were used as frother and frother fixed. The lowest value of gas holdup (ε_g: 3.70%) was provided by using Pine Oil at the superficial air rate of 0.5 cm.sec^{-1}, while the highest value (ε_g: 33.00 %) was achieved at the superficial air rate of 2.5 cm.sec^{-1} with the Aerofroth 88.
In the case of the use of frother mixtures, the the lowest value of gas holdup (ε_g: 4.6 %) was obtained by using Pine Oil+MIBC at the superficial air rate of 0.5 cm.sec^{-1}. On the other hand, the highest value (ε_g: 30.12 %) was reached at the superficial air rate of 2.5 cm.sec^{-1}. with the MIBC+Aerofroth 88 mixture. The gas hold-up was increased when superficial air rate were increased.

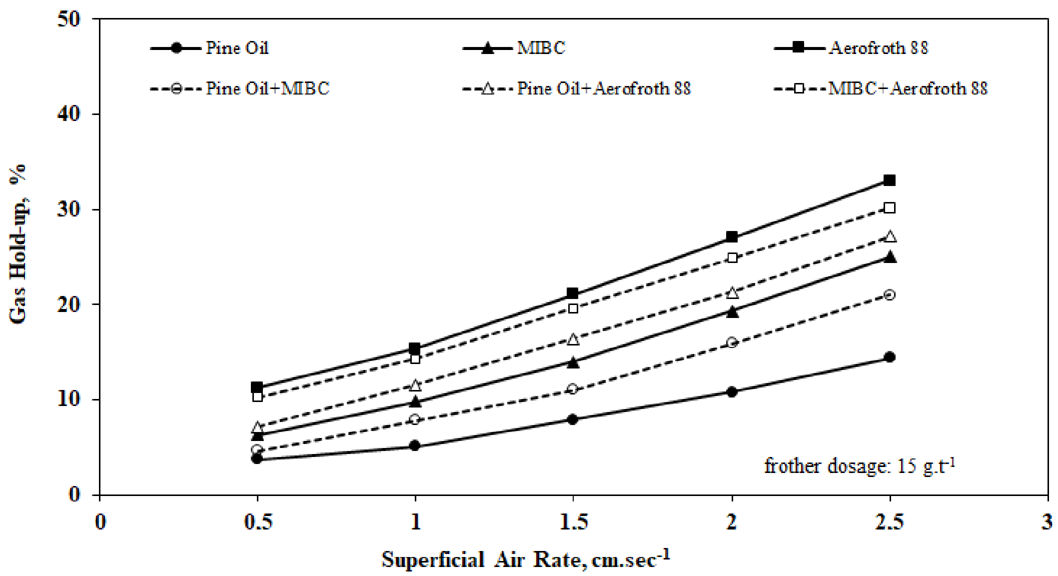

Figure 2. Variation of gas holdup with superficial air rate for different frother types and frother mixtures (1:1)

Three different frothers and mixtures were tested in this research: Pine Oil, MIBC, Aerofroth 88, Pine Oil+MIBC (1:1), Pine Oil+Aerofroth 88 (1:1) and MIBC+Aerofroth 88 (1:1). Variation of average bubble diameter with superficial air rate for the combinations of different frother types and frother mixtures were given in Figure 3.
For instance, at 15 g.t^{-1} frother concentration and 0.5 cm.sec^{-1} of superficial air rate with Pine Oil, MIBC and Aerofroth 88, the average bubble diameter was 1.26, 1.20 and 1.01 mm, respectively. When the air rate was increased to 2 cm.sec^{-1}, the average bubble diameter was decreased to 1.75, 1.68 and 1.40 mm for Pine Oil, MIBC and Aerofroth 88, respectively. On the other hand, the same situation was observed in the frother mixture. When the air rate was increased to 0.5 cm.sec^{-1}, the average bubble diameter was decreased to 1.22, 1.18 and 1.30 mm for Pine Oil+MIBC, Pine Oil+Aerofroth 88, MIBC+Aerofroth 88, respectively. 2.0 cm.sec^{-1} of superficial air rate with Pine Oil+MIBC, Pine Oil+Aerofroth 88, MIBC+Aerofroth 88 the average bubble diameter was 1.26, 1.20 and 1.01 mm, respectively.
In a two-phase system (water/air), bubble pictures photographed at different superficial air rates when using Pine Oil, MIBC, Aerofroth 88, Pine Oil+MIBC (1:1), Pine Oil+Aerofroth 88 (1:1) and

MIBC+Aerofroth 88 (1:1) as frother are illustrated in Figure 4.

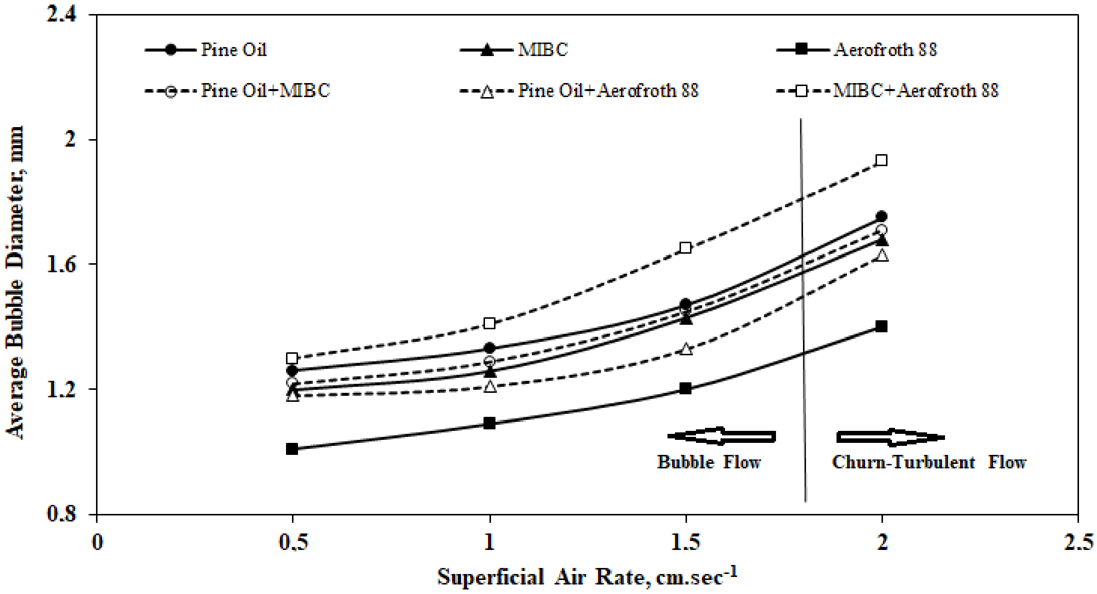

Figure 3. Variation of average bubble diameter with superficial air rate for the combinations of different frother types and frother mixtures (1:1) at frother concentration 15 g.t^{-1}

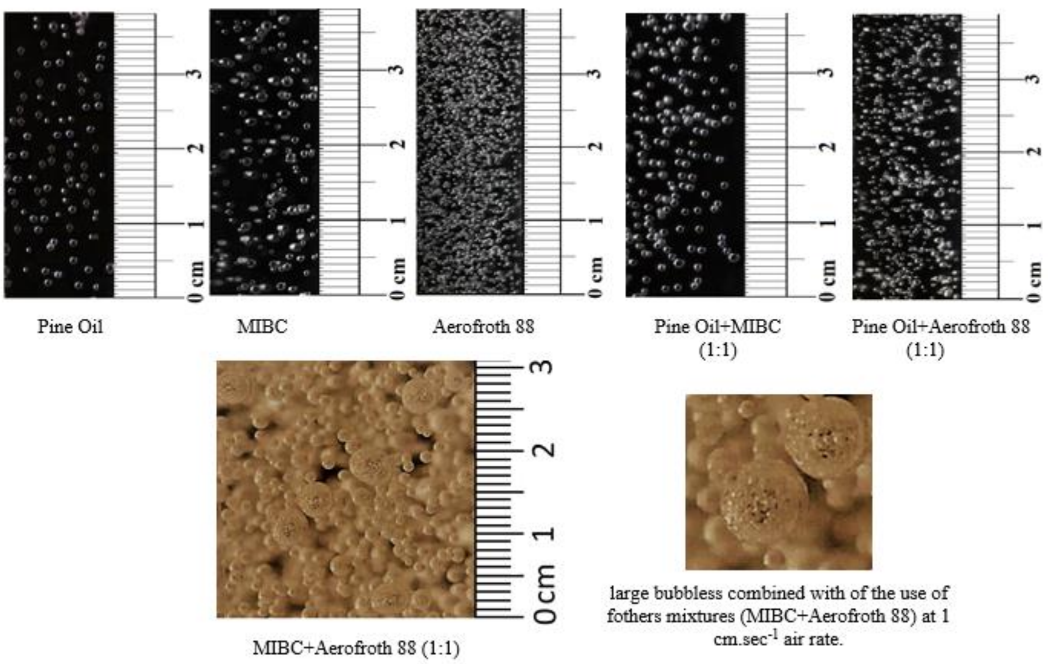

Figure 4. Bubble pictures photographed at different air rates when using Pine Oil, MIBC, Aerofroth 88 [40], Pine Oil+MIBC, Pine Oil+Aerofroth 88, MIBC+Aerofroth 88 as frother (1 cm.sec-1)

3.2. The effect of frother types-dosages and frother mixtures types-dosages on entrainment

The celestite and calcite used in these tests was fully liberated, and will therefore be recovered into the concentrate solely by entrainment. In a three-phase system (water/air/particle), the superficial air rates using different frother types, concentration, frother mixtures and flotation times is illustrated in Table 3 (a-b).

Table 3 (a-b). Entrainment factor and recoveries of celestite, calcite and water as a function of flotation time with various frother types-concentration and mixtures frother in column flotation (celestite (-106+38μm), calcite (-38μm))

Frother Concentration ($g.t^{-1}$)	Time (min)	Pine Oil						MIBC						Aerofroth 88					
		Recovery (%)			Grade (%)			Recovery (%)			Grade (%)			Recovery (%)			Grade (%)		
		Celestite	Calcite	Water	Celestite	Calcite	p_t	Celestite	Calcite	Water	Celestite	Calcite	p_t	Celestite	Calcite	Water	Celestite	Calcite	p_t
40	1	39.74	6.51	12.44	58.63	41.37	0.541	51.41	5.91	14.02	71.52	28.48	0.434	52.21	8.21	13.36	52.44	47.56	0.641
	2	42.11	8.84	14.83	61.24	38.76	0.624	54.80	8.78	20.63	73.24	26.76	0.445	56.68	10.36	15.07	54.92	45.08	0.652
	3	48.96	14.04	26.49	63.52	36.48	0.571	57.63	11.55	24.92	78.55	21.45	0.493	57.92	15.65	26.80	55.21	44.79	0.635
	4	52.21	16.79	35.76	66.11	33.89	***0.524***	67.36	12.07	33.81	76.82	23.18	***0.380***	65.80	19.21	34.24	57.83	42.17	***0.623***
80	1	62.41	11.25	21.13	71.88	28.12	0.492	75.52	9.21	23.41	81.41	18.59	0.413	73.51	14.05	21.57	57.50	52.50	0.702
	2	70.24	13.41	25.67	75.21	24.79	0.561	77.28	11.32	27.48	83.34	16.66	0.437	77.80	16.63	26.59	59.25	40.75	0.684
	3	74.11	17.20	33.96	79.12	20.88	0.519	83.48	13.33	35.51	83.25	16.75	0.403	79.21	20.18	34.94	59.92	40.08	0.645
	4	77.92	19.09	44.13	82.05	17.95	***0.480***	87.11	16.06	47.89	89.95	10.05	***0.365***	82.93	23.72	43.60	61.48	38.52	***0.622***
120	1	62.64	12.61	24.37	74.81	25.19	0.553	71.51	11.92	24.97	84.31	15.69	0.484	75.11	15.54	24.82	53.49	46.51	0.774
	2	64.73	15.26	28.95	75.24	24.76	0.572	72.93	13.78	28.63	81.12	18.88	0.518	77.28	17.99	27.65	54.66	45.34	0.761
	3	66.21	18.49	37.01	77.02	22.98	0.564	74.18	17.23	36.97	80.21	19.79	0.511	79.41	22.34	36.13	56.05	43.95	0.743
	4	70.38	23.23	48.86	78.20	21.80	***0.542***	78.82	21.74	49.21	84.51	15.49	***0.498***	80.24	25.88	45.86	56.98	43.02	***0.733***
160	1	66.44	15.94	26.02	65.74	34.26	0.694	73.04	15.52	30.81	79.61	20.39	0.547	77.64	29.41	42.27	59.41	40.59	0.824
	2	72.24	20.11	32.82	63.12	36.88	0.684	75.67	16.83	32.24	78.55	21.45	0.571	78.11	30.34	41.99	59.12	40.88	0.861
	3	72.09	21.74	39.32	62.83	37.17	0.678	76.41	20.37	38.11	79.14	20.86	0.598	79.86	33.05	46.12	56.95	43.05	0.870
	4	65.13	27.37	51.50	62.16	37.84	***0.622***	73.26	24.08	51.11	75.59	24.41	***0.539***	82.23	36.88	57.95	54.88	45.12	***0.794***

Constant Conditions; pulp density: 20%, collector concentration: 600 $g.t^{-1}$ Na-oleate, superficial feed rate: 400 $ml.min^{-1}$, superficial wash water rate: 150 $ml.min^{-1}$, superficial air rate: 1 $cm.sec^{-1}$

(a) Pine Oil, MIBC and Aerofroth 88 [39,40]

Frother Concentration ($g.t^{-1}$)	Time (min)	Pine Oil+MIBC (1:1) Recovery (%) Celestite	Calcite	Water	Grade (%) Celestite	Calcite	P_t	Pine Oil+Aerofroth 88 (1:1) Recovery (%) Celestite	Calcite	Water	Grade (%) Celestite	Calcite	P_t	MIBC+ Aerofroth 88 (1:1) Recovery (%) Celestite	Calcite	Water	Grade (%) Celestite	Calcite	P_t
40	1	51.20	6.70	15.11	74.88	25.12	0.459	43.12	7.21	11.97	54.72	45.28	0.625	50.66	9.81	15.10	49.69	50.31	0.683
	2	57.48	8.25	17.19	75.29	24.71	0.501	49.72	10.41	17.96	56.88	43.12	0.612	55.21	13.77	21.44	51.88	48.12	0.691
	3	64.24	10.41	23.39	76.81	23.19	0.470	52.41	14.36	24.18	57.58	42.42	0.641	56.48	16.41	26.67	53.01	46.99	0.672
	4	70.13	11.24	35.49	77.30	22.70	***0.336***	58.88	19.51	35.99	59.72	40.28	***0.603***	66.71	21.44	32.40	53.31	46.69	***0,745***
80	1	67.88	7.51	18.46	84.59	15.41	0.423	60.41	9.41	17.20	49.77	50.23	0.574	70.51	12.24	17.56	44.72	55.28	0.743
	2	72.68	8.28	19.87	86.06	13.94	0.435	66.16	12.03	24.00	50.88	49.12	0.534	76.48	16.48	24.82	52.79	49.21	0.723
	3	85.10	11.63	30.18	89.49	10.51	0.410	69.84	16.05	30.20	55.82	44.18	0.579	81.14	23.48	35.96	53.06	46.94	0.744
	4	89.13	12.08	53.68	91.82	8.18	***0.239***	75.15	21.32	46.02	66.59	33.41	***0.522***	85.11	35.21	61.04	60.29	39.71	***0.712***
120	1	69.41	10.23	20.83	85.52	14.48	0.518	59.65	12.05	18.42	57.80	42.20	0.697	68.24	15.48	22.51	56.79	43.21	0.747
	2	72.11	11.02	22.50	83.59	16.41	0.519	63.51	17.72	27.59	56.90	43.10	0.707	70.83	24.48	37.39	55.72	44.28	0.751
	3	79.47	15.75	31.68	85.18	14.82	0.541	69.07	20.98	34.14	54.01	45.99	0.690	74.21	31.67	50.44	54.61	45.39	0.755
	4	83.71	22.31	55.37	87.34	12.66	***0.456***	73.04	28.80	49.75	64.21	35.79	***0.623***	79.07	38.77	65.76	55.49	44.51	***0.746***
160	1	70.99	11.95	22.36	81.38	18.62	0.569	56.21	16.45	25.03	60.22	39.78	0.718	69.47	21.07	29.12	58.19	41.81	0.812
	2	71.17	13.16	24.20	80.17	19.83	0.583	59.48	20.11	30.97	59.76	40.24	0.725	71.07	27.69	39.82	56.16	43.84	0.814
	3	74.08	19.41	35.32	82.06	17.94	0.611	67.77	23.48	35.83	54.93	45.07	0.747	71.98	36.78	56.82	53.79	46.21	0.807
	4	75.98	25.44	56.35	81.59	18.41	***0.521***	69.94	30.05	50.76	60.44	39.56	***0.704***	73.03	45.31	75.15	50.88	49.12	***0.803***

Constant Conditions; pulp density: 20%, collector concentration: 600 $g.t^{-1}$ Na-oleate, superficial feed rate: 400 $ml.min^{-1}$, superficial wash water rate: 150 $ml.min^{-1}$, superficial air rate: 1 $cm.sec^{-1}$

(b) Pine Oil+MIBC, Pine Oil+Aerofroth 88 and MIBC+Aerofroth 88

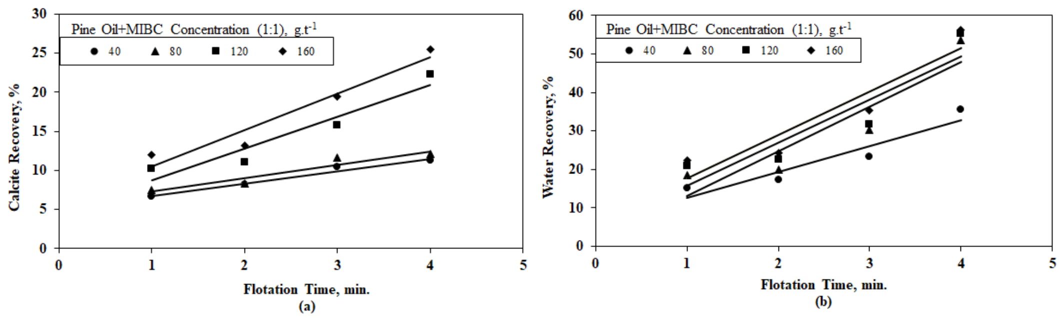

Figure 5(a-b). Calcite and water recoveries as a function of flotation time with various Pine Oil+MIBC concentration

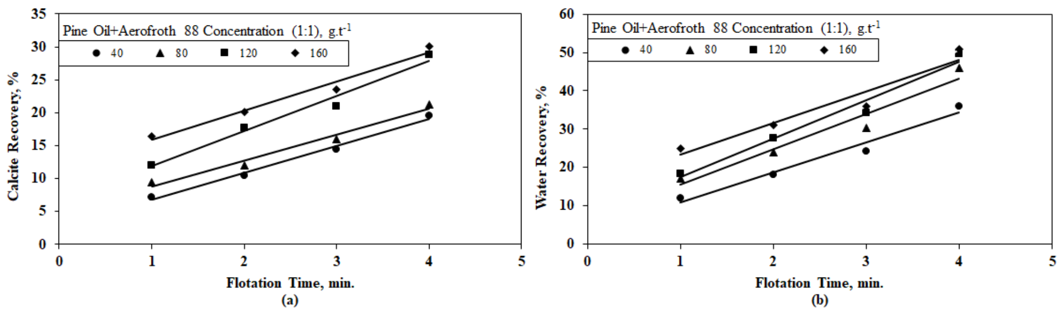

Figure 6(a-b). Calcite and water recoveries as a function of flotation time with various Pine Oil+Aerofroth 88 concentration

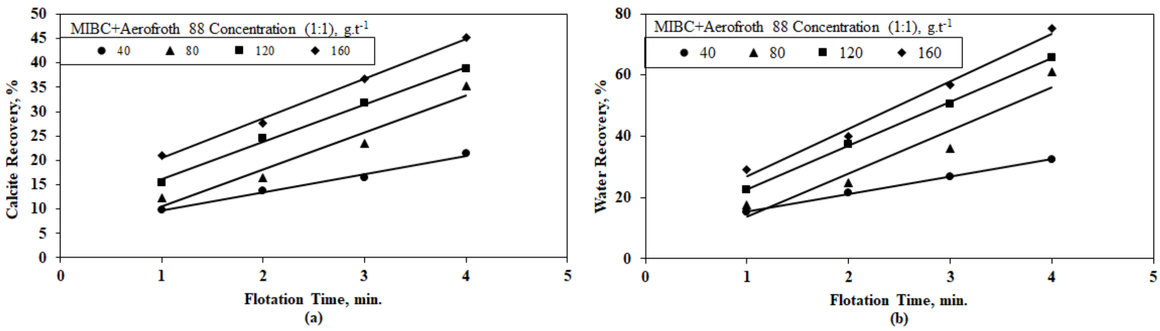

Figure 7(a-b). Calcite and water recoveries as a function of flotation time with various MIBC+Aerofroth 88 concentration

In general, calcite and water recovery were increased with increased frother concentration [39,40]. Since the recovery of fine gangue increases with water recovery, lower product grades were expected for 80 g.t^{-1} Pine Oil, MIBC, Aerofroth 88, concentration. Above 80 g.t^{-1} frother concentration, the celestite grade was decreased with increasing Pine Oil, MIBC, Aerofroth 88, Pine Oil+MIBC, Pine Oil+Aerofroth 88 and MIBC+Aerofroth 88 concentration. In the frother concentration 80 g.t^{-1}, the celestite grade and recovery (4 min) was reached high value using different frother types Pine Oil, MIBC, Aerofroth 88 (Pine Oil: 71.88% grade; 62.41% recovery, MIBC: 81.41% grade; 75.52% recovery, Aerofroth 88: 57.50% grade; 73.51% recovery). The same findings were also obtained in Pine Oil+MIBC,

Pine Oil+ Aerofroth 88 and MIBC+Aerofroth 88 frother mixtures (Pine Oil+MIBC: 91.82% grade; 89.13% recovery, Pine Oil+Aerofroth 88: 66.59% grade; 75.15% recovery, MIBC+Aerofroth 88: 60.29% grade; 85.11% recovery). As shown in Figure 8, the highest grade and recovery values were obtained by using a mixture of Pine Oil+MIBC frother mixture at 80 g.t^{-1}.

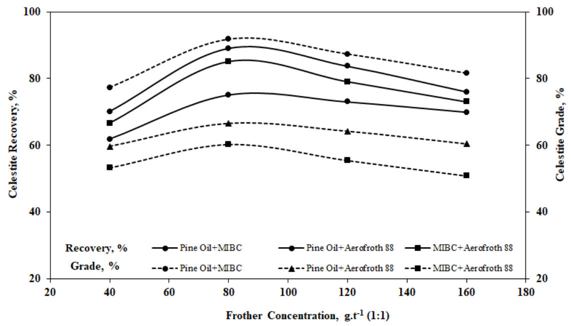

Figure 8. Celestite recoveries and grades as a function of flotation time with various frother type-concentration and frother mixtures (at 4 minutes of flotation time)

As can be seen (Figure 9), the entrainment factor increased with increasing concentration of both single frother (Pine Oil, MIBC, Aerofroth 88) and frother mixtures (Pine Oil+MIBC, Pine Oil+Aerofroth 88, MIBC+Aerofroth 88). When increasing the concentration of Pine Oil, MIBC and Aerofroth 88, from 40 g.t^{-1} to 160 g.t^{-1}, the entrainment factor increased from 0.514 to 0.621, from 0.380 to 0.539 and from 0.623 to 0.794, respectively (Table 3a). For the same change in the concentration of PineOil+MIBC, Pine Oil+Aerofroth 88 and MIBC+Aerofroth 88, entrainment factor increased from 0.336 to 0.521, from 0.603 to 0.704 and from 0.745 to 0.803, respectively (Table 3b).

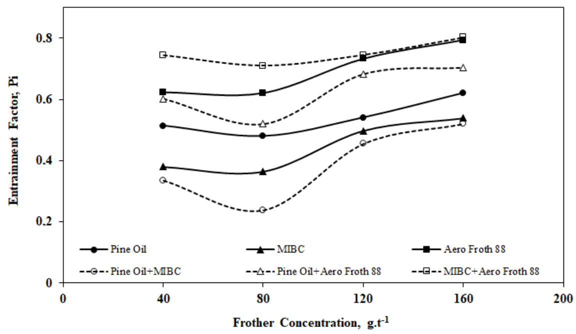

Figure 9. Variation of entrainment factor with various frother types-concentrations and frother mixtures (1:1)

The highest entrainment (ε_g: 0.711) factor value was obtained with MIBC+Aerofroth 88 while the lowest entrainment factor (ε_g: 0.239) was obtained by using Pine Oil+MIBC frother mixture at 80g.t^{-1} (Figure 10). This was supported by the traced linear relationship between the entrainment factor and solid/water recovery acquired from the tests performed using different frother types, frother concentrations and frother mixtures.

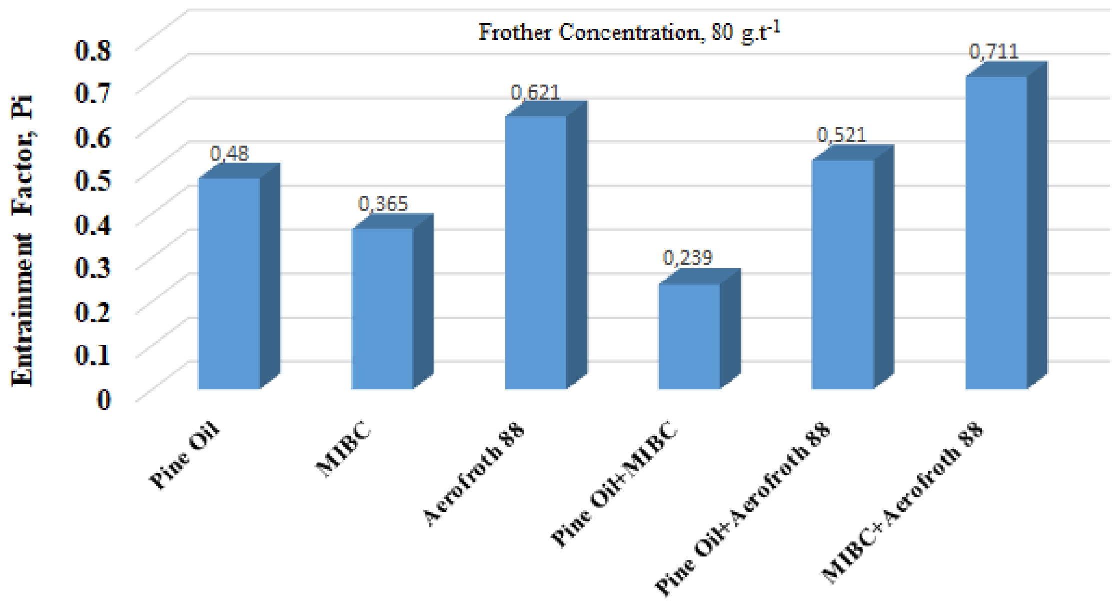

Figure 10. Variation of entrainment factor with various frother types and frother mixtures (1:1)

4. CONCLUSION

The column flotation experiment was performed using a mixture of liberated celestite as the valuable mineral and as the gangue mineral calcite, to indicate the primary factors affecting the entrainment factor. The obtained experimental results performed allow the following conclusions to be drawn:

. Superficial air rates, air hold-up and frother concentrate are three parameters that directly effective each other. When superficial air rate and the frother concentration were increased, the bubble diameter was decreased. Above a certain superficial air rate value, bubbly flow conditions were destroyed and turbulence flow conditions were formed producing large bubbles. When frother concentration was increased, bubble size was demonstrate to decrease importantly at the pulp/froth interface, which resulted in an increase in gas holdup (ε_g).

. In the MIBC Aerofroth 88 frother mixture, small bubbles collided in the pulp/froth interface and occured form large bubbles. In this case, bubbly flow conditions were lost and churn-turbulent flow conditions prevailed accompanied by large bubbles. This case, the amount of particles that can overcome the downward gravitational force to be recovered by the entrainment mechanism to the final concentrate increased, and the entrainment factor increased. As a result, the concentrate was contaminated by fine calcite minerals.

This was explained by the observed linear relationship between the entrainment factor and liquid velocity at the pulp/froth interface obtained from the tests performed using different frother types and concentrations. It has been seen that there is a linear relationship between calcite and water recoveries. Beside, the type, concentration and mixture of frother had exceptional effect on calcite. The recovery was increased, but the selectivity was decreased. The lowest entrainment factor was obtained with 80 $g.t^{-1}$ of frother concentration for Pine Oil+ MIBC frother mixture (εg: 0.239).

. Experimental results show that the entrainment factor varied significantly frother type, frother concentration and frother mixture. The recovery of calcite by entrainment was affected by Pine Oil+MIBC, Pine Oil+Aerofroth 88 and MIBC+Aerofroth 88 frother mixture. These results suggest that the frother types, frother concentration and frother mixtures at the flotation is a key factor which affects the entrainment factor. Kirjaveinen Model's [1] has been seen supported the results of this study.

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