



# Effects of flotation operational parameters on froth stability and froth recovery

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## Synopsis

The effect of flotation operational parameters on froth stability and froth recovery was studied. Froth stability was measured using a special column. To determine the froth recovery, the froth height change model and froth height exponential model were used. It was found that since the interactions between the pulp and froth zones affect the time of froth formation, the exponential model is more suitable than the froth height change method for determining the froth recovery. The results showed that superficial air velocity and collector dosage have, respectively, the highest and lowest effect on the froth recovery, while froth recovery decreases sharply with increasing froth height.

## Keywords

froth stability, froth recovery, superficial air velocity, collector dosage, frother dosage.

## Introduction

Froth stability plays an important role in determining selectivity and recovery in flotation (Farrokhpay, 2011). It should be noted that froth with very high stability is not desirable because in addition to recovering the particles attached to the bubbles, it creates favourable conditions for entrainment (Zheng, Franzidis, and Johnson, 2006). Froth stability can be defined as froth retention time, which depends on the structure of the froth and size distribution of the bubbles (Aktas, Cilliers, and Banford, 2008), or decay time of the froth (Tsatouhas, Grano, and Vera, 2006).

Froth stability can be determined by dynamic or static tests. The froth dynamic is determined by measuring the maximum froth height, and the froth static is determined by the time taken the froth to decay after the air is shut off (Farrokhpay, 2011).

The concept of dynamic froth stability was first introduced by Bickerman in 1973 and was later modified by Barbican, Ventura-Medina, and Cilliers (2003). Dynamic froth stability is the ratio of froth volume to the aeration value; if the cross-sectional area of the whole cell is assumed to be the same, the dynamic froth stability is equal to the froth retention time and is calculated using Equation [1]:

$$\sum = \frac{V_f}{Q} = \frac{H_{max}}{J_g} \quad [1]$$

where

$V_f$  is froth volume

$Q$  is air volume flow rate

$H_{max}$  is maximum froth height

$J_g$  is superficial gas velocity.

The effect of particle size has been investigated by several researchers (Achaye, 2018; Norori-McCormac *et al.*, 2017; Cilek and Uysal, 2018; Aveyard *et al.*, 1994; Long Liang *et al.*, 2015; Ata, Ahmed, and Jameson, 2004; Vera *et al.*, 2002). In general, fine particles affect froth stability and the role of hydrophobic particles is significant.

The type and amount of frother also affect the froth stability (Ata, 2009; Gupta *et al.*, 2007; Castro *et al.*, 2013; McFadzean, Marozva, and Wiese, 2015). Ata (2009) examined the separation of particles during bubble coalescence, and found that increasing the frother dosage increases the contact surface and decreases the particle separation, and thus reduces the bubble coalescence and increases the froth stability.

Another factor that affects the froth stability is pH. It can change the behaviour of the minerals in the pulp by affecting the charge level of the particles. Farrokhpay and Zanin (2012) examined the effect

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of water quality on the froth stability for a zinc concentrate from Australia. They found that decreasing the pH increases the froth half-life due to the decrease in the zeta potential of the particle surfaces, and increases the pulp viscosity.

Other factors affecting the froth stability include dissolved oxygen (Do), reduction potential (Eh), and ionic strength (Is) (Farrokhpay and Zanin, 2012; Sheni, Corin, and Wiese, 2018; Manono, Corin, and Wiese, 2012). Increasing the Eh or Is and decreasing the Do results in increased froth stability (Sheni, Corin, and Wiese, 2018). Increasing the Eh increases the number of particles entering the froth phase, which can lead to a higher froth stability. However, due to the increase in the water recovery, the probability of entrainment of particles with poor hydrophobicity is also higher.

Froth recovery, which is the ratio of the mass of particles released into the concentrate through true flotation to the mass of the particles attached at the pulp-froth interface, is often used to measure the performance of the froth phase (Yianatos *et al.*, 2008). This approach focuses on the overall behaviour of the froth, which is used for modelling in flotation plants. The concept of froth recovery was first proposed by Finch and Dobby (1990). In general, froth recovery can be measured by direct or indirect methods. In the direct methods, by measuring the bubble loading, froth recovery can be calculated (Bhondayi and Moys, 2011). The direct methods have been introduced by various researchers, including Falutsu and Dobby (1992), Seaman, Franzidis, and Manlapig, (2004), Dyer (1995), and Rahman, Ata, and Jameson (2013).

One indirect method to measure the froth recovery is using froth height changes and the overall flotation recovery. In this method, the kinetic constant of flotation ( $k$ ) is obtained according to the froth height ( $H$ ) and then an H-k diagram is drawn (Figure 1). Due to the linearity of the constant kinetic-froth height graph, their relationship will be as follows:

$$k = a - b \times H \quad [2]$$

where

$a$  is the width from the origin and is equal to the kinetic constant at a froth height equal to zero (kinetic constant of the collection zone ( $k_c$ ))

$B$  is the length of the origin (the point where the kinetic constant is zero)s.

Equation [2] can be written as:

$$k = k_c \left( 1 - \frac{H}{H_{(k=0)}} \right) \quad [3]$$

According to the froth recovery equation provided by Dobby and Finch (1991), froth recovery is defined as follows (Seaman, Manlapig, and Franzidis, 2006):

$$R_f = \left( 1 - \frac{H}{H_{(k=0)}} \right) \quad [4]$$

This method has been used by various researchers, including Feteris, Frew, and Jowett (1987), Vera, Franzidis, and Manlapig (1999), and Seaman, Franzidis, and Manlapig (2004). Other methods of indirect froth recovery measurement have been discussed by Savassi *et al.* (1997), Alexander, Franzidis, and Manlapig (2003), Yianatos, Bergh, and Cortj (1998), Gorain *et al.*

(1998), Wilson (1952), Neethling (2008), and Amelunxen *et al.* (2018).

### Materials and methods

#### Froth stability measurement

Froth stability was measured using a column similar to that used by Zanin *et al.* (2009) and McFadzean, Marozva, and Wiese (2015) (Figure 2).

#### Froth recovery

Froth recovery was calculated using froth height changes (Equation [5]). Recall that at the maximum froth height, the froth recovery is zero.

$$R_f = \frac{k}{k_c} = 1 - \frac{H}{H_{max}} \quad [5]$$

Froth height can be related to the froth formation time according to Equation [6] (Technological Resources Pty Limited, 2004):

$$\frac{dH}{H_{max}} = \frac{1}{\tau} e^{-t/\tau} dt \quad [6]$$

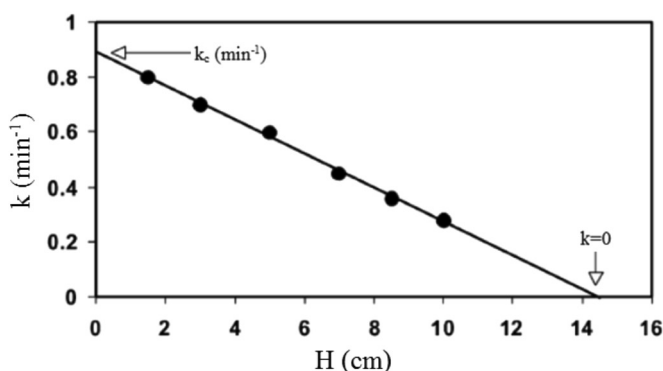


Figure 1 – Relationship between the kinetic constant and froth height (Seaman, Manlapig, and Franzidis, 2006)

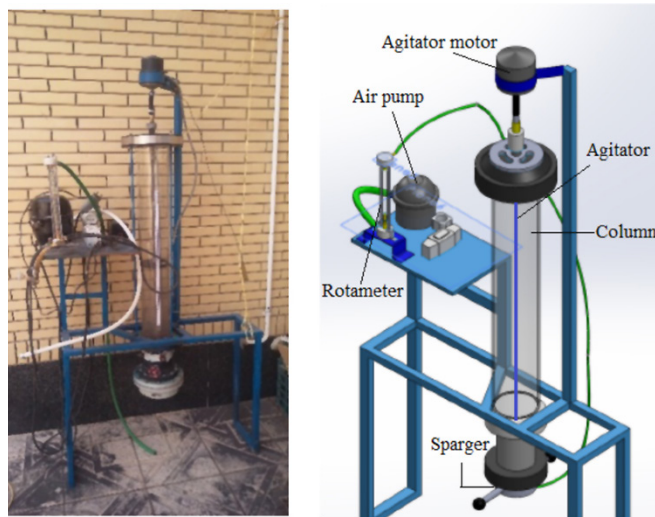


Figure 2 – The froth stability column

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Given that the maximum height occurs at infinite time, the integral of Equation [6] is shown as Equation [7]:

$$\int_H^{H_{max}} \frac{dH}{H_{max}} = \int_t^{\infty} \frac{1}{\tau} e^{-t/\tau} dt \quad [7]$$

$$1 - \frac{H}{H_{max}} = e^{-t/\tau}$$

According to Equations [5] and [7], froth recovery can be calculated using Equation [8]:

$$R_f = e^{-t/\tau} \quad [8]$$

## Test method

One of the most suitable methods for designing experiments is central composite rotatable design (CCRD). This method is useful for examining independent variables that affect the dependent variables and provides a statistical and mathematical procedure for studying the relationship between responses and a number of influential factors (Napier-Munn, 2014).

The experiments were performed using Design Expert software version 10 (DX10). Independent variables or input parameters for this study were: collector and frother dosage, superficial air velocity, and particle size ( $d_{50}$ ). The dependent variables or responses were froth half-life, maximum froth height, and froth recovery.

## Sample specifications

A sample of iron ore concentrate containing sulphide minerals from Gole-Gohar Sirjan Company (Iran) was used. The prepared samples were stored in a dryer at 95°C for 24 hours to dry.

## Sample characterization

Mineralogy studies (XRD and SEM) showed magnetite as the main mineral. The sample also contained haematite, pyrite, and talc. Pyrite was the most important sulphur-bearing mineral in the sample (Figures 3 and 4).

According to the Cyclosizer results, 50% and 80% of the sample were less than 36 and 100  $\mu\text{m}$ , respectively (Figure 5).

## Materials

Potassium amyl xanthate (PAX) and methyl isobutyl carbinol (MIBC) were used as collector and frother, respectively.

## Results and discussion

Since one of the flotation parameters was the particle size, a screen analysis was performed and after homogenization (according to  $d_{50}$ ) the sample was divided into 1 kg portions. Sample analysis is shown in Table I. It seems that sizing does not have a significant effect on the grade of the sample.

For each of the 30 experiments, samples were taken from the froth section and the concentration of solid particles (Pc) was obtained. Sampling was performed about 5 cm above the pulp-froth interface.

The results showed that the concentration of the solid particles had a significance level of 95%. Accordingly, decreasing the particle size, as well as increasing the superficial air velocity ( $V_g$ ), collector dosage ( $Cc$ ), and frother dosage ( $Fc$ ), all result in an increased concentration of the solid particles in the froth phase (Figure 6).

## Froth stability

## Froth formation

According to the results of the variance analysis, the effect of the tested parameters on the froth stability and froth recovery are

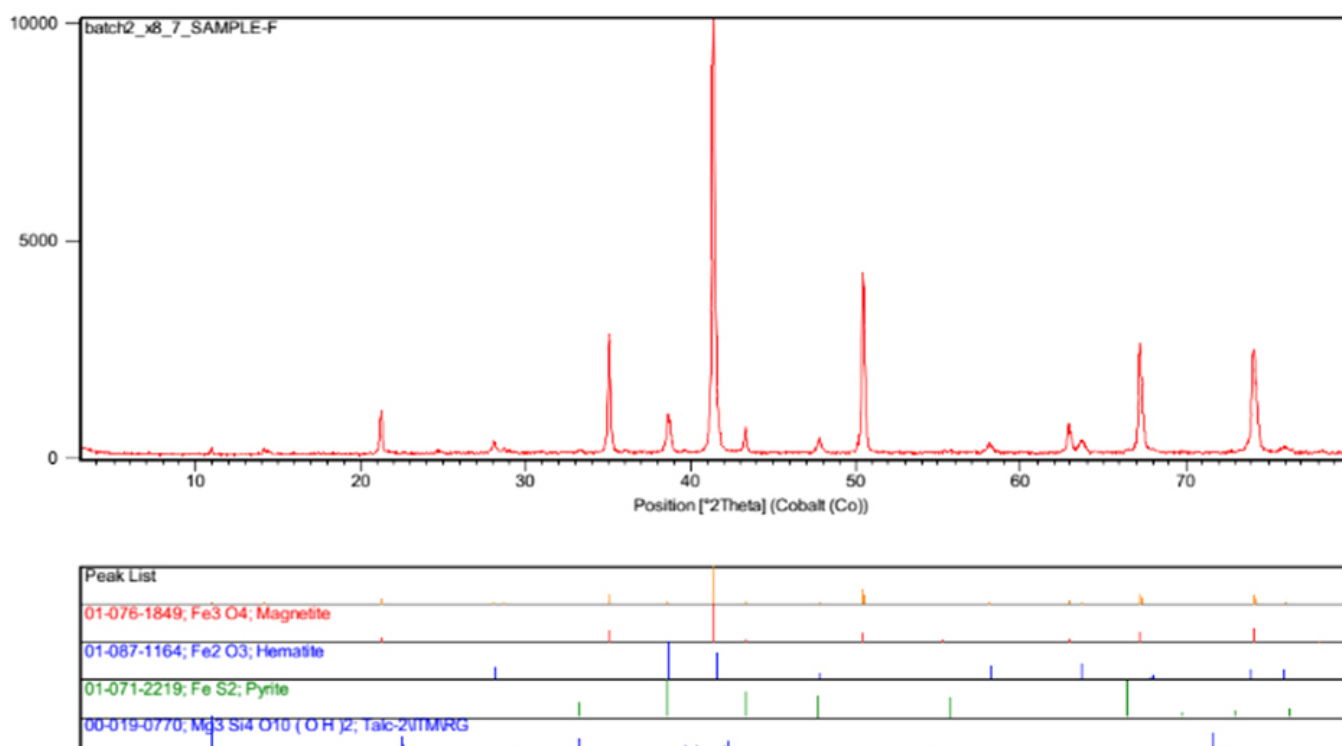


Figure 3—X-ray diffraction (XRD) results on the sample



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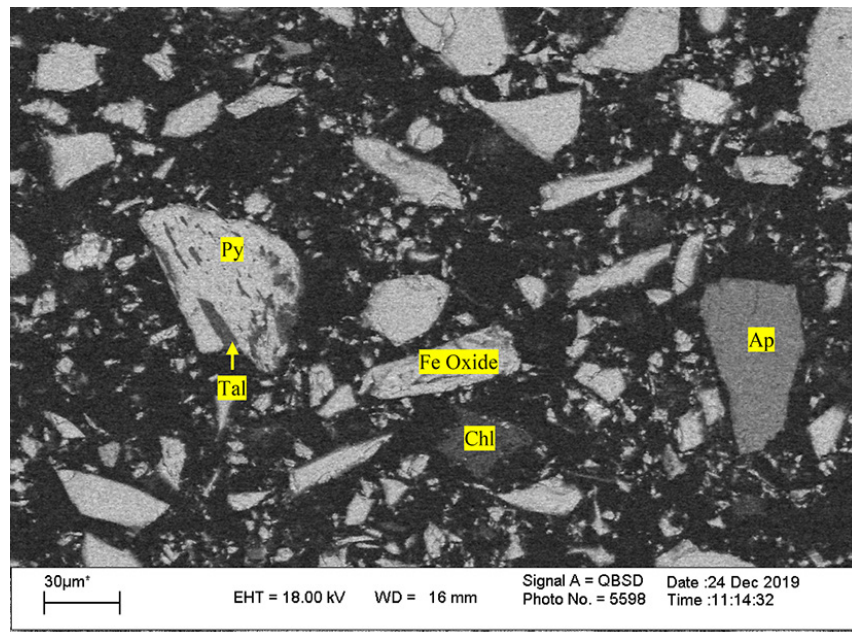


Figure 4—SEM micrograph of the sample, showing iron minerals, pyrite, talc, apatite, and chlorite

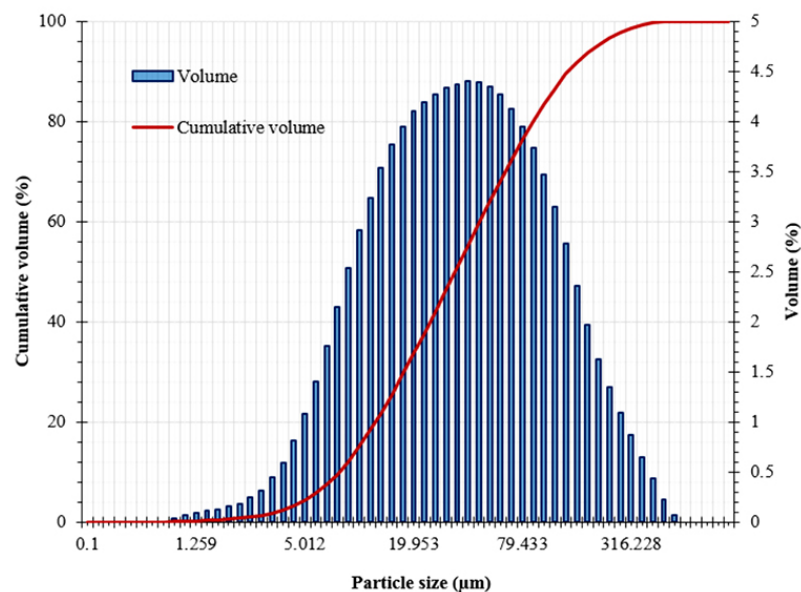


Figure 5—Size distribution of the sample

*Table 1*  
**Chemical analysis of the samples at different  $d_{50}$  sizes**

NO.	$d_{50}$ (μm)	Fe (%)	FeO (%)	S (%)
1	15	67.25	23.34	1.26
2	20	67.63	23.46	1.23
3	36	68.04	23.59	1.22
4	60	68.67	23.84	1.18
5	84	68.78	23.53	1.15

statistically significant at a 95% confidence level. The interaction between the superficial air velocity and frother dosage, and frother dosage and particle size, is also significant, at a 95% confidence level.

Figure 7 shows the effect of various factors on the froth retention time (FRT). It can be observed that increasing the superficial air velocity, collector dosage, or frother dosage increases the FRT, while increasing the particle size reduces the FRT.

The superficial air velocity significantly changes the composition and structure of the froth phase; however, its exact effect is not clear (Li *et al.*, 2016). Increasing the superficial air velocity increases the gas holdup (Pérez-Garibay *et al.*, 2014), as well as the probability of particle-bubble collisions and attachment. This in turn increases the volume of solid particles in the froth phase (James Noel, Prokop, and Tanner, 2002; Al-Fariss, El-Aleem, and El-Nagdy, 2013). Therefore, the higher concentration of particles in the froth phase leads to an increase in the froth height (Figure 6). However, an excessive superficial

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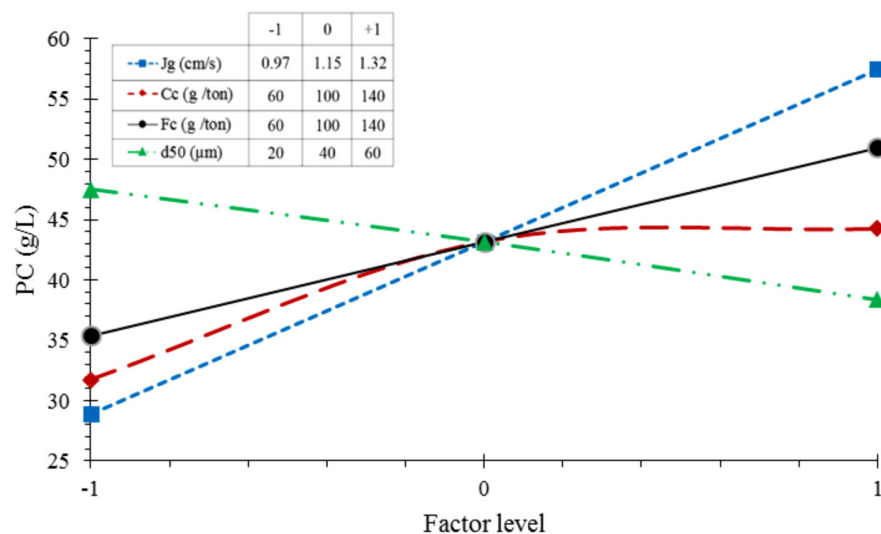


Figure 6—The effect of different variables on the concentration of solid particles in the froth phase

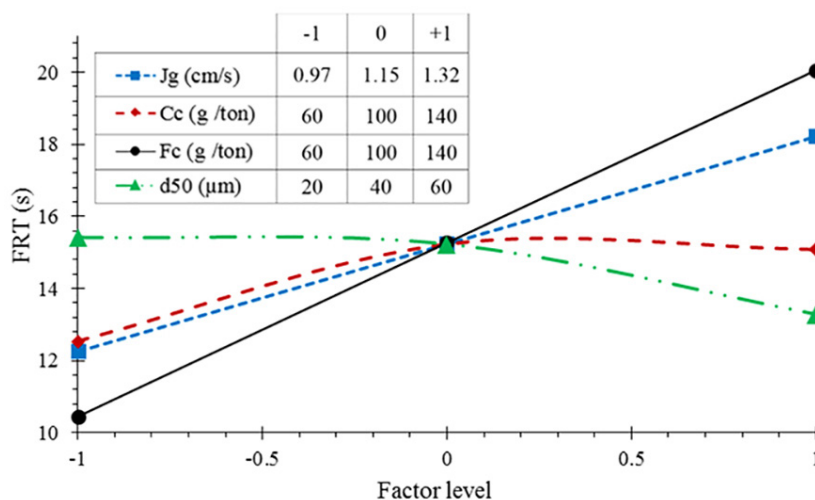


Figure 7—The effect of various factors on froth formation

air velocity can reduce the volume of the particles in the froth phase (Al-Fariss, El-Aleem, and El-Nagdy, 2013).

The enhancement in the bubble load depends on the collector dosage (Eskanolou *et al.*, 2018): at higher collector dosage, the concentration of particles in the froth phase increases due to increased bubble-particle attachment. However, an excessive amount of collector will cause bubble clustering and has a negative effect on the bubble loading (Eskanolou *et al.*, 2018; Ata and Jameson, 2005).

An increase in the frother dosage will reduce the bubbles size (Wei, and Finch, 2014; Zhu *et al.*, 2019) and increase bubble stability. The probability of collision of a particle with a bubble also increases (Reis *et al.*, 2019). Therefore the bubble loading, or in other words the amount of particles that enter the froth phase by attachment to the bubbles, increases, which will stabilize the froth (Ata, 2009). Although small bubbles are beneficial, as noted above, the absence of large bubbles may reduce the flotation recovery (Hassanzadeh *et al.*, 2017).

It seems that the superficial air velocity interacts with the frother dosage (Figure 8). For example, when the frother dosage was increased from 60 to 140 g/t, the maximum froth height at an air velocity of 0.97 and 1.32 cm/s increased by about 7.3 and

15.2 cm, respectively. The same trend was observed for froth retention time.

An increase in the superficial air velocity is accompanied by an increase in the volume of air inside the cell (Pérez-Garibay *et al.*, 2014), and an increase in the frother dosage reduces the bubble size (Wei, and Finch, 2014; Zhu *et al.*, 2019), so the interaction of these two factors results in increasing the number of bubbles, which has a positive effect on the froth formation. It will also increase the likelihood of particles-bubble collisions, which increases the presence of particles in the froth phase.

Increasing the particle size results in fewer particles, which may reduce the slurry viscosity (Cilek and Uysal, 2018; Long Liang *et al.*, 2015; Wei and Finch, 2014). Decreasing the particle size, on the other hand, can reduce the rate of bubble coalescence and consequently decreases the bubble size (Li *et al.*, 2016). This hinders the fluid drainage (Achaye, 2018) which leads to increased froth stability. When the particles are very small, there is a possibility of an increase in entrainment (Cilek and Umuka, 2001; Wang *et al.*, 2015), so it can affect the froth instability.

It is worth mentioning that a significant difference between the maximum initial and the fixed froth height was observed at the maximum value of  $d_{50}$  and frother dosage (Figure 9).

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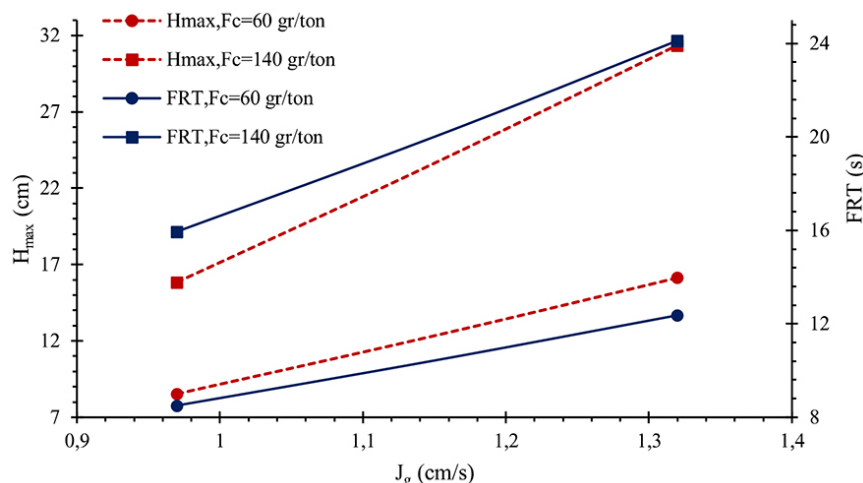


Figure 8—The interaction between superficial air velocity and frother dosage

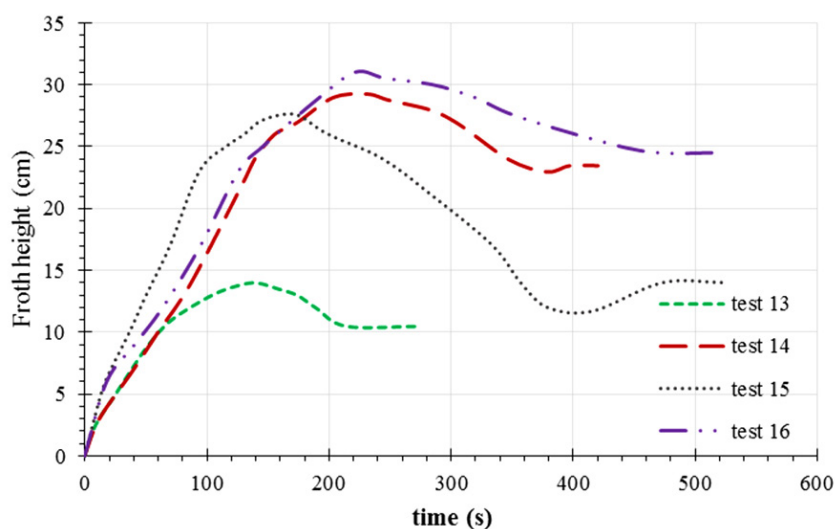


Figure 9—Froth height changes in experiments 13 to 16

### Froth decay

The analysis of variance shows that the effect of independent variables is significant, with a 95% confidence level, while the confidence level for the frother dosage- $d_{50}$  is 90%. It should be noted that the effect of the superficial air velocity ( $J_g$ ), collector dosage ( $C_c$ ) and frother dosage ( $F_c$ ) is similar to that discussed for the froth formation.

Figure 10 shows that the froth half-life increases with increasing the superficial air velocity, collector dosage, frother dosage, and particle size ( $d_{50}$ ).

An increase in fine particles accelerates the process of froth decay, perhaps due to the presence of more water along with the fine particles, which causes the froth to become more fluid (Eskanolou *et al.*, 2018). If the concentration of very small particles increases, the presence of these particles in the froth phase and increased viscosity will retard froth decay.

### Froth recovery

Table II shows the froth recovery results at different froth heights.

### Comparison of the two models

A comparison between the results obtained from two methods

(using Equations [5] and [8]) shows that with increasing froth height, the difference between the two methods decreases. At average heights of 4, 8, 10, and 15 cm, the differences are 6.6, 4.8, 5.4, and 2.0%, respectively.

Figure 11 shows a comparison of the average recoveries for the two models at different froth heights. It can be seen that with increasing froth height, froth recovery obtained in the exponential model is less than that from the froth height change model.

### The effect of various parameters

Experimental design results show that the froth recoveries obtained at froth heights of 4, 8 and 10 cm are at 95% confidence level, but for 15 cm froth height the collector dosage did not have the required level of confidence.

#### (i) Superficial air velocity ( $J_g$ )

Froth recovery increases with increasing  $J_g$ . Increasing the superficial air velocity enhances the froth height and thus results in increased froth stability and consequently froth recovery. Also, according to the froth recovery model, in the same experimental conditions, increasing

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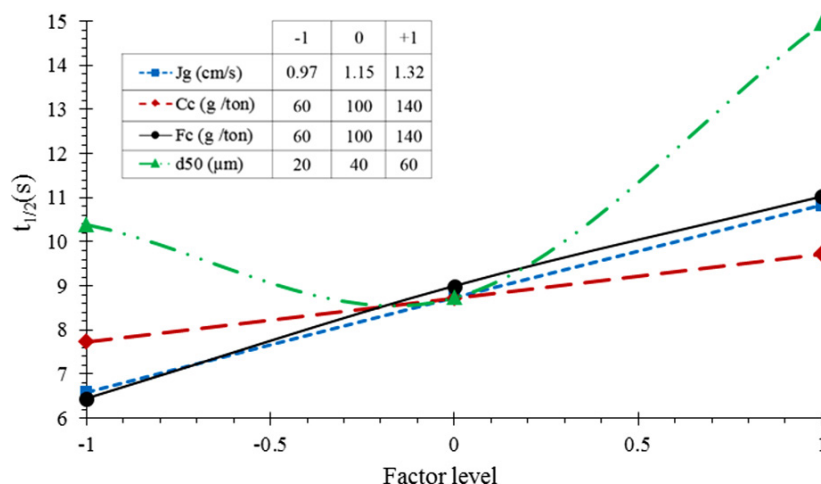


Figure 10—The effect of various factors on froth decay

Table II

Froth recovery % at different froth heights (cm)

No.	Froth height change model (Equation [5])				Exponential model (Equation [8])			
	H=4	H=8	H=10	H=15	H=4	H=8	H=10	H=15
1	31.03	0.00*	0.00	0.00	34.63	0.00	0.00	0.00
2	70.80	41.61	27.01	0.00	79.66	44.31	19.87	0.00
3	50.00	0.00	0.00	0.00	63.62	2.12	0.00	0.00
4	71.43	42.86	28.57	0.00	90.58	52.42	10.34	0.00
5	69.23	38.46	23.08	0.00	69.78	34.13	21.67	0.00
6	86.67	73.33	66.67	50.00	91.95	83.97	74.74	46.43
7	70.37	40.74	25.93	0.00	81.08	37.52	31.69	0.00
8	88.41	76.81	71.01	56.52	86.00	71.67	65.03	50.12
9	0.00	0.00	0.00	0.00	4.54	0.00	0.00	0.00
10	66.67	33.33	16.67	0.00	68.43	25.78	15.59	0.00
11	46.67	0.00	0.00	0.00	50.64	0.00	0.00	0.00
12	73.33	46.67	33.33	0.00	84.41	42.54	28.79	0.00
13	61.90	23.81	4.76	0.00	51.29	18.84	10.13	0.00
14	82.98	65.96	57.45	36.17	70.51	46.48	37.43	24.40
15	71.43	42.86	28.57	0.00	53.21	29.12	18.00	0.00
16	83.67	67.35	59.18	38.78	81.56	57.18	47.49	29.72
17	40.30	0.00	0.00	0.00	41.44	0.00	0.00	0.00
18	86.89	73.77	67.21	50.82	84.76	72.11	50.64	45.01
19	42.86	0.00	0.00	0.00	40.85	0.00	0.00	0.00
20	73.33	46.67	33.33	0.00	82.90	41.69	26.91	1.83
21	20.00	0.00	0.00	0.00	10.00	0.00	0.00	0.00
22	86.89	73.77	67.21	50.82	91.05	79.45	67.57	49.72
23	87.69	75.38	69.23	53.85	91.65	80.94	75.14	57.63
24	60.00	20.00	0.00	0.00	50.82	14.97	7.96	0.00
25	78.14	56.28	45.36	18.03	83.62	48.35	39.54	19.22
26	76.47	52.94	41.18	11.76	81.07	52.56	42.23	14.65
27	77.78	55.56	44.44	16.67	76.83	53.57	42.91	18.93
28	80.00	60.00	50.00	25.00	82.05	64.28	55.23	19.22
29	74.19	48.39	35.48	3.23	66.29	43.94	38.01	1.64
30	77.01	54.02	42.53	13.79	71.88	49.11	32.72	11.85

$J_g$  causes the maximum froth height and the froth formation rate ( $\tau$ ) to be increased, which consequently increases the froth recovery.

Figure 12A shows that the froth recovery at all froth heights increases with increasing  $J_g$ . For example, when the superficial air velocity increases from 0.97 to 1.32 cm/s, froth recovery at heights of 4, 8, 10, and 15 cm increased by 47%, 146%, 117%, and 260% respectively.

### (ii) Collector dosage ( $C_c$ )

Figure 12B shows that increasing the collector dosage leads to an increase in the froth recovery, although the

effect is less pronounced compared to the other studied factors. The maximum increase in froth recovery is about 29%, which is related to a froth height of 8 cm ( $C_c$  increases from 60 to 140 g/t).

The increase in froth recovery is possibly due to an increase in the amount of concentrate due to the increased number of particles entering the froth phase, as well as the positive effect on the froth stability. It was also observed that the effect of the collector dosage decreases with increasing froth height. Since increasing the  $C_c$  leads to the presence of low-hydrophobicity



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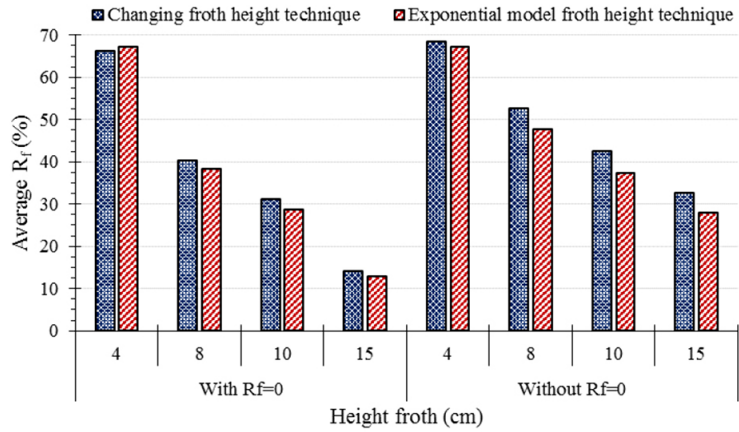


Figure 11—Comparison of two froth recovery models ( $R_f$ ) at different heights according to the maximum froth height ( $H_{max}$ )

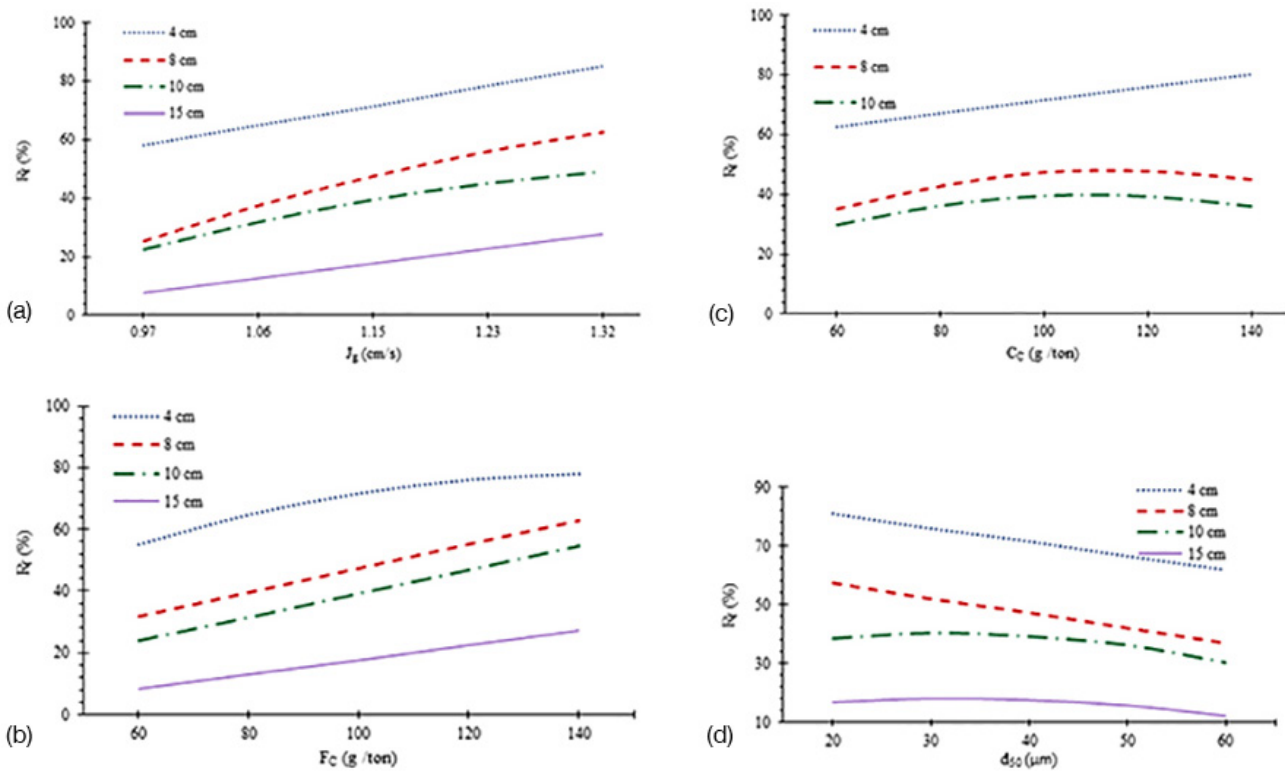


Figure 12—The effect of various factors on the froth recovery ( $R_f$ )

particles in the froth, as the froth height increases, these particles usually leave the froth zone and drop back into the pulp (Pita, 2017), so considering that these particles are not recovered, raising the collector dosage at a high froth height does not have a significant effect on the froth recovery.

### (iii) Frother dosage ( $F_c$ )

Increasing the frother dosage increases the froth recovery, and the effect is similar at different froth heights. For example, in Figure 12C, when froth height is 10 cm, the froth recoveries at dosage of 60 and 140 g/t are 24 and 55%, respectively.

Based on the results, there is an interaction between  $J_g$  and  $F_c$ . However, the interaction varies with the froth height. As the froth height increases, the intensity of the effect of superficial air velocity for frother dosage decreases. Figure 13A shows that when the frother

dosage increases from 60 to 140 g/t with  $J_g = 1.32$  cm/s, froth recovery at a height of 4 cm increases by only 14%, while for heights of 10 and 15 cm, froth recoveries of 134% and 400% were observed, respectively. This can be related to the detachment of particles from the bubbles and increased aeration of the bubbles (Vinnett Contreras, and Yianatos, 2014), which also increases the froth height, leading to an increase in the bubble size (Bhondayi and Moys, 2014). This increases the likelihood of bubbles coalescence, resulting in reduced output concentrations. An increased frother dosage will prevent this phenomena and hence increase the effect on the froth recovery at greater froth heights compared with lower froth heights. Also, at low froth heights, particles have less opportunity to detach from the bubbles, and it seems that at these heights, the effect of the superficial air velocity is much greater than that of frother dosage.



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## (iv) Particle size ( $d_{50}$ )

Figure 12D shows that as the particle size increases, the froth recovery decreases. For example, for froth heights of 4, 8, 10, and 15 cm at  $d_{50} = 20 \mu\text{m}$ , recoveries are about 81%, 58%, 39%, and 17% respectively. The corresponding values for  $d_{50} = 60 \mu\text{m}$  are 62%, 37%, 30%, and 12%. According to previous results, increasing the particle size leads to fewer particles in the froth phase, and hence to a reduction in the bubble loading, transfer of particles to the concentrate zone, froth instability, and particle drainage. Also, with increasing froth height the probability of small particles entering the froth zone through entrainment decreases (Figure 12D). The interaction between  $d_{50}$  and  $F_c$  at froth heights of 10 and 15 cm was found to be significant. The effect of increasing frother dosage on the froth recovery is far greater in the case of fine particles than for coarse particles (Figure 13B). This is due to the fact that fine particles are more susceptible to entrainment. The number of bubbles increases with increasing frother dosage, which consequently increases the amount of fine particles in the concentrate zone.

## Conclusions

Increasing the superficial air velocity, or dosage of collector or frother, increases the rate of froth formation and froth decay. However, the behaviour of the particles at different sizes was found to be different. This indicates that an increase in fine particles has a positive effect on the froth formation due to the increased viscosity of the pulp. However, when the froth decays, the greater loading of fine particles accelerates the process of froth destruction, probably due to the presence of more water along with the fine particles.

The froth recovery results obtained from the exponential model seems to be more accurate than those from the froth height change models. In addition to the effect of froth height, the time to reach the maximum froth height was also considered. It was

found that the superficial air velocity has the greatest effect on the froth recovery, while the collector dosage has the least effect. Increasing the superficial air velocity, collector dosage, and frother dosage had a positive effect on froth recovery, but increasing the particle size led to a lower froth recovery.

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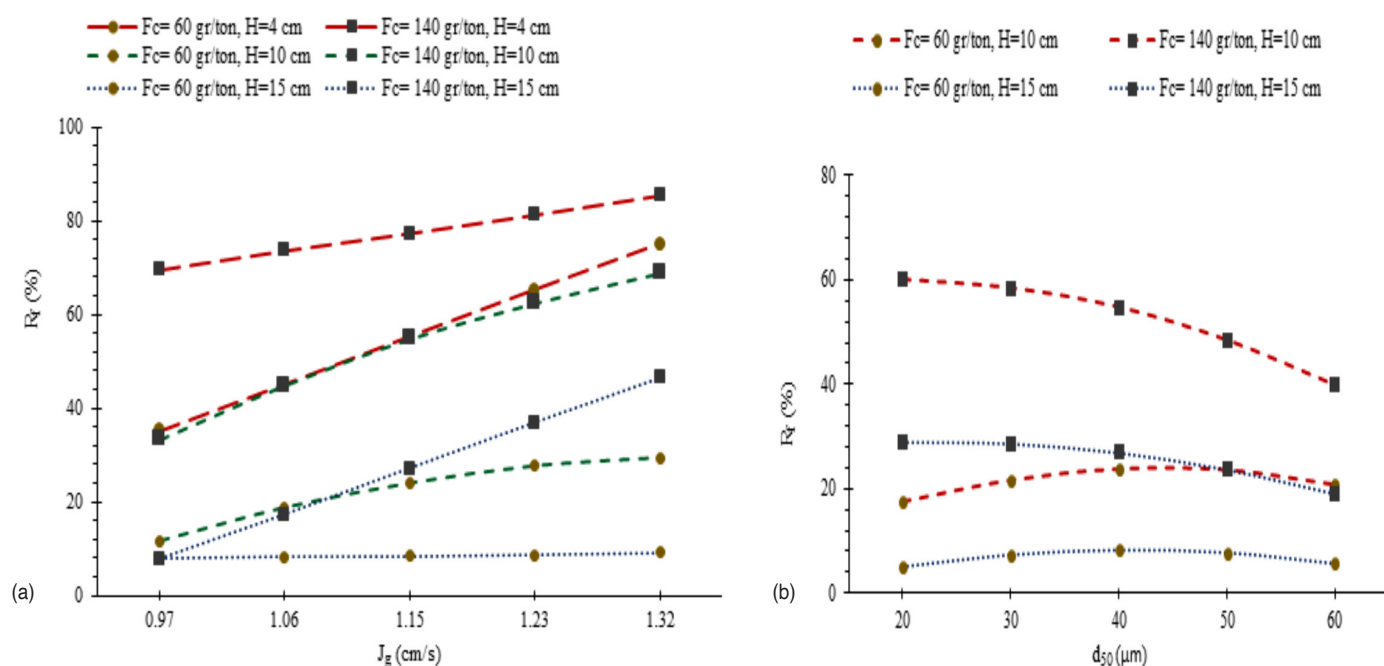


Figure 13—The interaction between various factors and their effect on froth recovery ( $R_f$ )

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