Bubbling properties of frothers and collectors mix system

Khandjamts Batjargal [1], Onur Guven [2], Orhan Ozdemir [1], Stoyan I. Karakashev [3], Nikolay A. Grozev [3], Feridun Boylu [4], Mehmet Sabri Çelik [4,5]

[1] Istanbul University-Cerrahpaşa, Mining Engineering Department, 34500, Istanbul, Turkey

[2] Adana Alparslan Türkeş Science and Technology University, Mining Engineering Department, 01700, Adana, Turkey

[3] Sofia University, Physical Chemistry Department, "St. Kliment Ohridski", Sofia 1164, Bulgaria

[4] Istanbul Technical University, Mineral Processing Engineering Department, 34469, Istanbul, Turkey

[5] Harran University, Rectorate, Şanlıurfa, Turkey

Corresponding authors: orhanozdemir@iuc.edu.tr (Orhan Ozdemir), mcelik@itu.edu.tr (Mehmet Sabri Çelik)

Abstract: This paper studies the effect of the type and concentration of selected frothers and collectors mix system on the bubble sizes (Sauter mean diameter, *SMD*) of bubbling flow produced in a micro flotation cell and the determination of bubble size distribution (*BSD*). The usage of dodecyl amine hydrochloride (*DAH*) collector on the critical coalescence concentration of commercial frothers *PPG200*, *PPG400*, and *PPG600* was investigated in detail. The results of these studies showed that the usage of *DAH* decreased the *CCC* of these frothers. Each frother + collector mixing system exhibited its unique ability in preventing coalescence of the bubbles in the order of *PPG200 < PPG400 < PPG600*. The factorial experiments established that the type of the frother, collector, and their concentration had a major effect on the size of the bubbles. The *BSD* in the presence of *PPG600 + DAH* mix system resulted in a little bit wider *BSD* which indicated the effect of frother type in mixed systems.

Keywords: critical coalescence concentration (CCC), Sauter diameter (d_{32}), bubble size distribution (BSD)

1. Introduction

Flotation is a separation process providing the selective enrichment of particles based on their hydrophobicity degree and their affinity to attach to bubbles (Guven et al., 2015). In this manner, the flotation kinetics rate and the particle-bubble collision frequency strongly depend on bubble size and bubble size distribution (*BSD*). Therefore, the properties of frothers such as frother type and concentration have the strongest influence on the gas dispersion properties besides the effects of other parameters on bubble size (Batjargal et al., 2021). The effect of some commercial frothers on bubble size has been investigated recently (Grau et al., 2005; Szyszka, 2008). In these studies, it was reported that this effect can be ascribed to their ability on inhibiting bubble coalescence. In other words, when two bubbles come in and encounter each other, the liquid film between these bubbles becomes thinner and breaks which will cause the bubbles to coalesce (Leja, 1982). If the coalescence of bubbles does not occur within seconds, they rise to the surface and form a foam or froth. As it is well-known from the literature, the bubble size decreases rapidly until a transition value, referred to as the critical coalescence concentration (*CCC*) (Cho et al., 2002; Nesset et al., 2007). Although at concentrations above the *CCC*, bubble size does not materially decrease, it does lead to increased water recovery to the froth with the attendant increase in unselective particle entrainment (Zhang et al., 2010; Welsby, 2014; Zangooi et al., 2017). These effects of some frothers have already been well reported in the literature (Cho et al., 2002; Grau and Laskowski, 2006; Nesset et al., 2007; Maldonado et al., 2008; Zhang et al., 2010; Gomez et al., 2011; Kracht et al., 2013; Welsby 2014; Vazirizadeh et al., 2016; Zangooi et al., 2017; Mohagheghian and Elbing, 2018; Guven et al., 2020; Karakashev et al., 2020). The coalescence of the bubbles is important in controlling the interfacial area in equipment that comes into contact with the gaseous liquid and in the formation of bubbles in micro-flotation devices. Bubble size distribution (*BSD*) by measuring foam properties (gas retention, bubble numbers, and bubble size) is important in flotation practice. To assess

this effect on an industrial scale, the bubble surface area flux is typically estimated from the gas rate and *BSD* measurements, where complete *BSD* is compressed to an overall value, namely the Sauter mean diameter (d_{32}) (Guven et al., 2005; Vazirizadeh et al., 2016; Karakashev et al., 2020). As it is well known from the literature, the Sauter mean bubble diameter (d_{32}) and the mean number diameter of the sample are calculated along with other associated parameters (Grau and Laskowski, 2006; Kracht et al., 2013; Kowalczuk, 2016; Mohagheghian ve Elbing, 2018).

On the other hand, other factors such as air velocity, collector (and other reagents) type and concentration, pulp ionic strength, and used machine also control the *CCC*, bubble size, and *BSD* (Wills and Finch, 2016). The results of bubble–bubble coalescence can depend on the presence of frothers and surfactants in the solution as well as on the bubble size. The tendency for bubbles to coalesce influences the size distribution in bubble suspensions. For example, Narsimhan and Ruckenstein (1986) observed a decrease in the mean bubble size in a bubble column as the concentration of surfactants was increased.

To our knowledge, significant progress has not been made over the past few years on characterizing and understanding the hydrodynamic properties of frothers and collectors and their effect on bubble size and *CCC* performance. This new understanding of the relationship between chemistry and hydrodynamics has dramatic implications for how flotation circuits should be controlled and optimized. Therefore, this study aimed to determine the differences between single frothers and frother + *DAH* by adding the concentration of collectors in the presence of different commercial frothers (*PPG200*, *PPG400*, and *PPG600*) in terms of critical coalescence concentration (*CCC*). Additionally, to better understand the surface activity of the frothers, bubbling properties and bubble size distribution were evaluated for each frother and collector in the air-water phase. Therefore, the effects of only frothers, only collectors, and their mixtures on *CCC* values in the absence of particles can be shown in the light of these findings.

In this context, the critical coalescence concentration and bubble size distribution for the different commercial frothers of *PPG200*, *PPG400*, and *PPG600* in the absence of the presence of *DAH* collector without particles were determined by measuring the variation of solution turbidity as a function of light intensity.

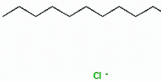## 2.   Materials and methods

2.1. Materials

In this study, all the frothers (polypropylene glycols (*PPG200*, *PPG400*, and *PPG600*) were provided by BASF Company (Germany). Dodecyl amine hydrochloride (*DAH*) with 97% purity obtained from Sigma Aldrich was used as a collector. The chemical properties of the frothers and collector are shown in Tables 1 and 2, respectively.

All measurements were carried out at a constant room temperature of 23±1°C. Before each test, the glassware was rinsed in ethanol (99% purity, MERCK) and washed with distilled water, followed by steam cleaning, and drying in a clean oven. Each frother solution was mixed at 500 rpm for 5 min to allow the frother to solve in the aqueous phase.

Table 1. Chemical properties of the frothers

Chemical	Hydroxyl Value (mgKOH/g)	Molecular Weight (g/mol)	Formula	HLB	pH (Solution of 1%)	Molecular Structure
PPG200 (n~3.5)	510~623	180~220	$OH(C_3H_6O)_nH$	10.55	5.0~7.0	
PPG400 (n~6.5)	255~312	360~440	$OH(C_3H_6O)_nH$	8.69	5.0~7.0	
PPG600 (n~10)	170~208	540~660	$OH(C_3H_6O)_nH$	8.25	5.0~7.0	

Table 2. Chemical properties of the collector

Chemical	Form	Purity (%)	Molecular Weight (g/mol)	Formula	CMC (mol/dm³)	Density (g/cm³)	Molecular Structure
DAH	Solid	≥ 99%	221.81	$C_{12}H_{28}ClN$	1.5×10^{-2} (25°C)	1.0 (20°C)	

2.2.   Methods

2.2.1. Bubble coalescence measurements of frothers and collectors mix system

The captured images during bubble size measurements and the schematic representation of the unit are shown in Figs. 1a and 1b, respectively. Two different parts of the test device, mechanical and optoelectronic, can be distinguished. A mechanical part is used to produce bubbles at a known volume and speed. The optoelectronic part consists of a light source and electronic equipment for signal conversion, data acquisition, and data processing. In this setup, a 30×220 mm micro flotation cell with a volume of 155 cm³ was used. By using a light source in the measurements, the light is sent to the bubbling solutions prepared at various concentrations. Some of the light passing through the cell is absorbed by the solution, while the light intensity of the part leaving the cell (not adsorbed) is measured with an adapter (Thorlabs, USA). The procedure for the definition of *CCC* was extensively explained in a previous paper by Guven et al. (2020). Briefly, the critical coalescence concentration for the frothers was determined at 50% values of the bubble coalescence (Nguyen et al., 2012). All the experiments were repeated 3 times, and the average error for the measurements was about ±2 mW.
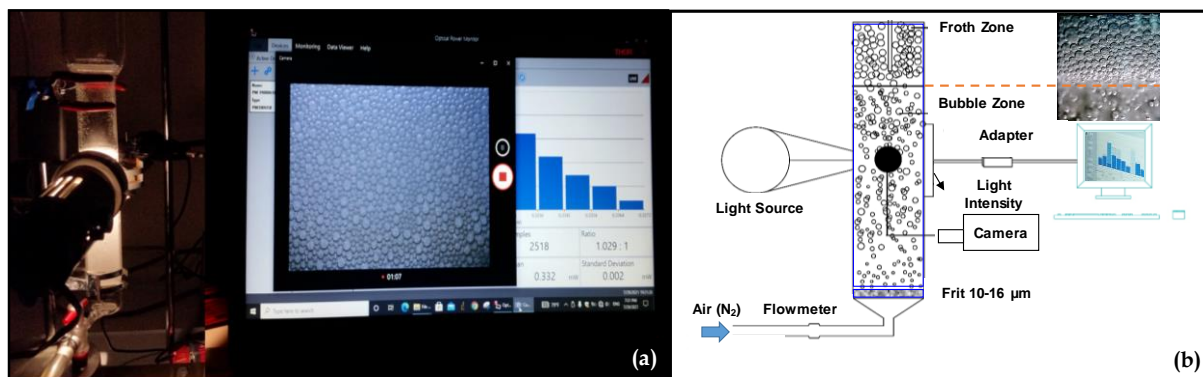

Fig. 1. (a) Experimental setup for bubble coalescence measurements (b) Schematic representation of bubble coalescence measurements

In these experiments, the effect of the collectors on the bubble coalescence of the frother was investigated. As given in Fig. 3 that the *CCC* values of *PPG600*, *PPG400*, and *PPG200* were determined as 3, 4, and 11 ppm, respectively. The idea was to obtain the effect of collectors on the bubble coalescence for the selected frothers, therefore it was decided to choose the 50% of the *CCC* concentrations of the frothers; 1, 2, and 6 ppm for *PPG600*, *PPG400*, and *PPG200*, respectively as presented in Table 3. And, all experiments were carried out at these concentrations. The solutions in all experiments were mixed for 10 min at constant room temperature (23±1°C), 500 rpm mixing speed, and prepared as 100 cm³.

Bubble incorporation measurements using the collector and frothers were performed with the pre-prepared solutions using the frit pore size of the micro-flotation cell with 10-16 μm and the setup shown in Fig. 1a. This was achieved by measuring the light intensity values every 60 sec following the addition of N₂ gas to the system with a 50 cm³/min air rate.

2.2.2. Sauter mean diameter (*SMD*) measurements

These measurements were also made with the system shown in Fig. 1. The procedure for these measurements can be defined as follows; after filling the column cell with aqueous solutions of tested frothers and a mixture of frothers and collectors, N₂ gas was sparged through the system at a 50 cm³/

Table 3. The concentration of *DAH* collectors and frothers

PPG200		*DAH*		*PPG400*		*DAH*		*PPG600*		*DAH*	
ppm	(mol/dm³)	ppm	(mol/dm³)	ppm	(mol/dm³)	ppm	(mol/dm³)	ppm	(mol/dm³)	ppm	(mol/dm³)
6		1	4.51×10^{-6}	2		1	4.51×10^{-6}	1		1	4.51×10^{-6}
6		3	1.35×10^{-5}	2		3	1.35×10^{-5}	1		3	1.35×10^{-5}
6		5	2.25×10^{-5}	2		5	2.25×10^{-5}	1		5	2.25×10^{-5}
6	3×10^{-5}	7	3.16×10^{-5}	2	5×10^{-6}	7	3.16×10^{-5}	1	1.66×10^{-6}	7	3.16×10^{-5}
6		10	4.51×10^{-5}	2		10	4.51×10^{-5}	1		10	4.51×10^{-5}
6		100	4.51×10^{-4}	2		100	4.51×10^{-4}	1		100	4.51×10^{-4}

min rate. After 60 sec of conditioning, the representative images and video recordings of bubbles were captured by a digital camera (Bushman MOS 8 Led Microscope, Bushman Equipment Inc., Menomonee Falls, WI, USA) with a 50X magnification rate while the light was sent through this column from a constant location of the cell (around 10 cm above the plane of the frit). This location was selected based on the volume of the solution and the sizes of the cell as well. Based on previous measurements of *CCC* values of frothers, at least 20 images were captured for each concentration of frothers as 1, 2, and 6 ppm for *PPG600*, *PPG400*, and *PPG200* respectively in different collector concentrations (1, 3, 5, 7, 10, and 100 ppm). Thus, the bubble diameters in terms of Sauter Mean Diameter (d_{32}) (*SMD*) were calculated using free *ImageJ* software (Version 1.8.0) by using Eqs. 1 and 2 with an accuracy of 0.05 mm.

$$\frac{V_b}{A_b} = \frac{\frac{4}{3}\cdot\pi\cdot(d_v/2)^3}{4\pi\cdot(d_s/2)^2} = \frac{(d_v/2)^3}{3(d_2/2)^2} = \frac{d_{32}}{6} \tag{1}$$

$$d_{32} = 6\frac{V_p}{A_p} \tag{2}$$

where d_s and d_v are the surface diameter and the surface volume of the bubbles, respectively, and V_b and A_b are the volume and area of the bubbles, respectively.

3.   Results and discussion

3.1. Effects of frothers and collector on critical coalescence concentration

First, the effect of three different frothers on bubble size under varying concentration conditions was investigated. During these measurements, 50 cm³/min N₂ gas was sparged through the pure water, and then the light intensity values were measured as a function of time, to determine the optimum time value for the light intensity. As seen in Fig. 2, while it was not stable up to 60 sec, it became almost stable after this time. For this reason, the optimum time was determined as 60 sec.

Under these conditions, the coalescence rates of the bubbles as a function of concentration were found under a constant gas flow rate, and the results are shown in Fig. 3. As can be seen from the results, the bubble incorporation rate was at lower concentrations in the presence of *PPG600*, while in the presence of *PPG200*, this occurred at higher concentrations.
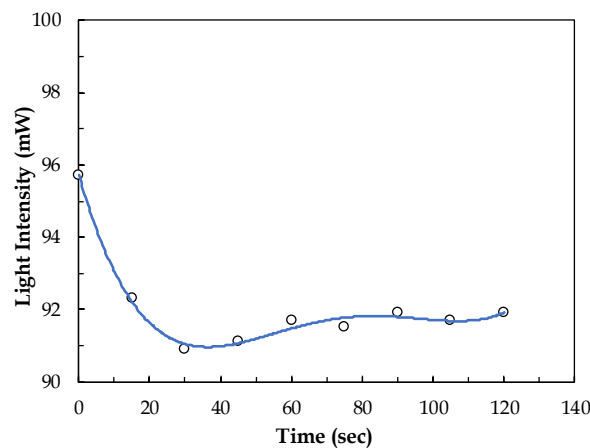

Fig. 2. Light intensity values of distilled water at 50 cm³/min air flow rate according to time

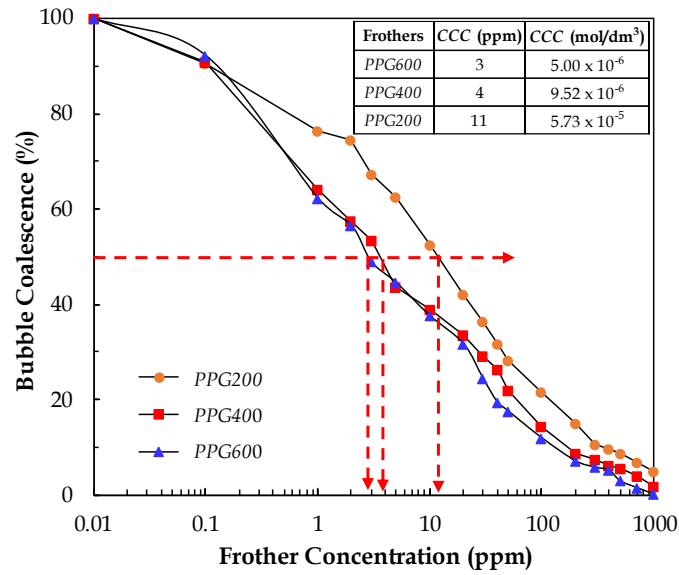| Frothers	CCC (ppm)	CCC (mol/dm³)
PPG600	3	5.00×10^{-6}
PPG400	4	9.52×10^{-6}
PPG200	11	5.73×10^{-5}

Fig. 3. Variation of % bubble coalescence against the concentration of different frothers

It could be concluded from the results as shown in Fig. 3 that generally *PPG600* and *PPG400* achieve *CCC* values at low concentrations when comparing frothers of the poly-glycol family with each other. It was stated that it could be related both to the increase in the number of poly-glycol and to the molecular weight. The results of the bubble association measurement in the presence of frothers depending on the *DAH* concentration are shown in Fig. 4. As seen in Fig. 4a, the *CCC* of *PPG200* is 11 ppm without *DAH*, while the *CCC* of *PPG200* is 6 ppm in the presence of *DAH* (6 ppm *PPG200* + 5.3 ppm *DAH*). The *CCC* of other frothers was decreased in the presence of *DAH*. The results are presented in Table 5.
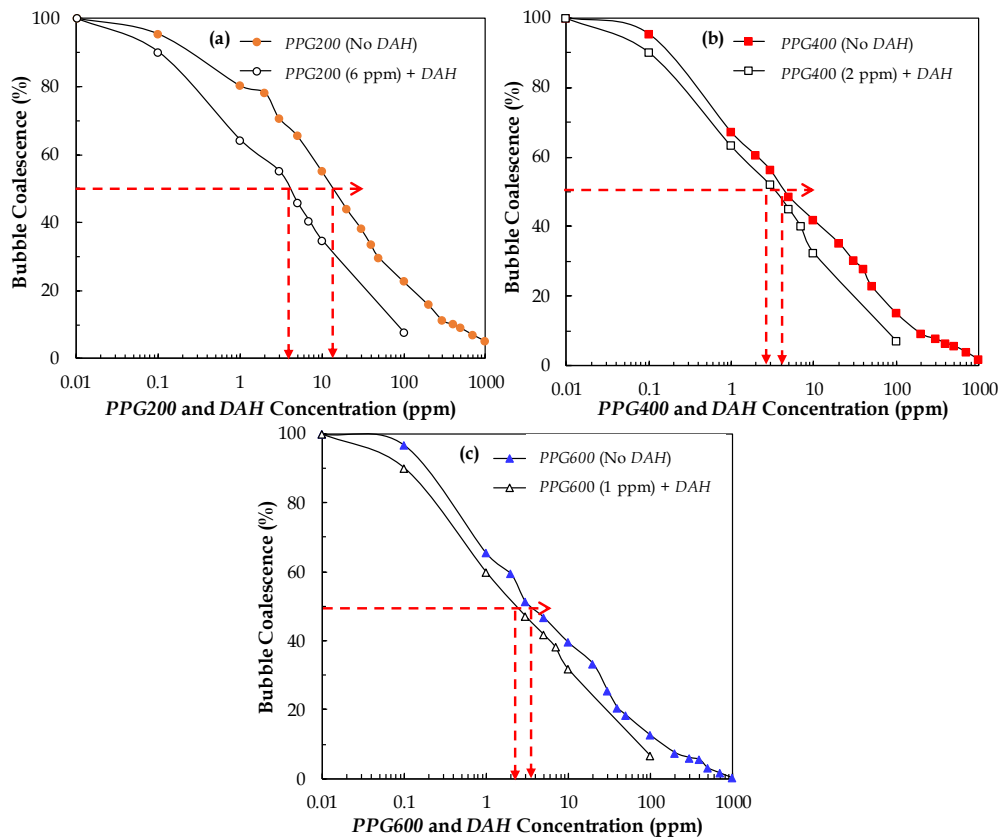

Fig. 4. Bubble coalescence results for frothers as a function of *DAH* concentration (a) *PPG200*, (b) *PPG400*, (c) *PPG600*

Appropriate interaction of collector and frother was observed between *DAH* and Polypropylene glycols. This can be ascribed to the chemical structures of these reagents. In other words, both *DAH* and *PPG* have an oxygen atom in their structure; therefore, they can form a hydrogen bond, which ensures a good steady-state. Thus, the *DAH* collector also presents frother characteristics that in a mixed system of *DAH* and other types of frothers, it will be possible to reach the *CCC* point in a lower concentration. In addition, as mentioned in a previous study, the usage of a commercial anionic collector (BD-15, Da-Cemex Company) consisting of mainly oleic acid and frother in the same system would not only change the surface tension values but also vary the zeta potential of bubbles which in turn affects the critical coalescence concentration of bubbles (Karaguzel et al., 2010). Accordingly, as shown in Fig. 4, *CCC* values of *DAH* collector (*PPG200*, *PPG400*, and *PPG600*) mixed with frothers were determined as 5.3 ppm for *PPG200*, 3.2 ppm for *PPG400*, and 2.7 ppm for *PPG600* in air bubble coalescence measurements.

Among the *CCC* values of *PPG* (200, 400, 600) belonging to the polypropylglycol family, the *PPG200 + DAH* system showed more activity. According to these results, when the frothers (*PPG200*, *PPG*400, and *PPG600*) are mixed with the *DAH* collector, the *CCC* values were determined as 11.3 ppm for *PPG200*, 4.29 ppm for *PPG400*, and 2.70 ppm for *PPG600*.

Table 5. *CCC* values of the frother in the presence of *DAH*

	CCC (ppm)		
	PPG200	*PPG400*	*PPG600*
No DAH	11	4	3
With DAH	5.3* + 6 ppm *PPG200*	3.2** + 2 ppm *PPG400*	2.7*** + 1 ppm *PPG600*
Total	11.3	4.29	2.90
	*2.4×10^{-5} mol/dm³	**1.44×10^{-5} mol/dm³	*** 1.23×10^{-5} mol/dm³

3.2. Effect of frothers and collector (mix system) on *SMD*

In the mix test series, the effect of *PPG* (*200*, *400*, and *600*) different frothers and collectors on bubble size under varying concentration conditions was investigated. First, 50 cm³/min N_2 gas was sparged through pure water, and then the light intensity values are measured every 60 sec. Under the same flow rate, the effect of frother + *DAH* was also investigated on *SMD* (d_{32}) by processing bubble images captured on the micro flotation cell from a single viewing point with *ImageJ* software, and the results are shown in Fig. 5 and Table 6. Additionally, Figs. 7 and 8 present the images of these bubbles of these frothers obtained according to the frother concentration and *DAH* + frothers mix system.

As seen in Fig. 5, the *SMD* values of bubbles of the mixing system of *PPG* (*200*, *400*, and *600*) with
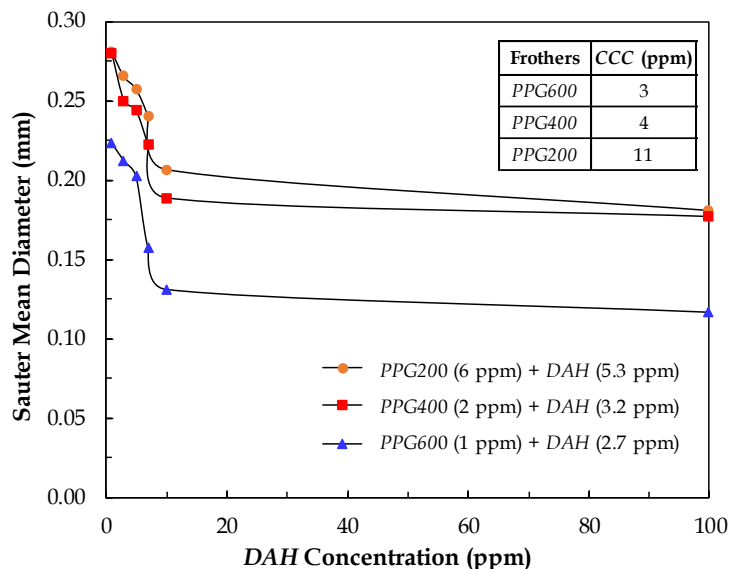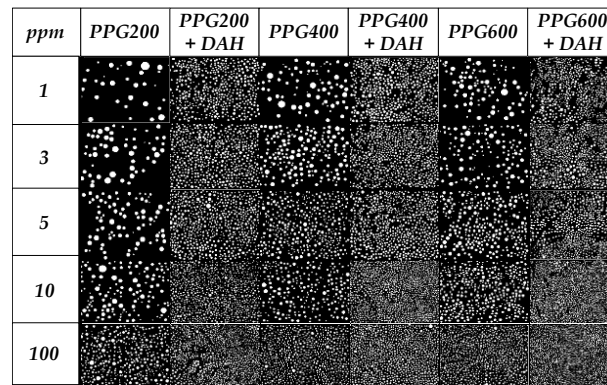

Fig. 5. Effect of frothers + *DAH* on the *SMD* of bubbles (frit diameter: 10-16 μm)

Table 6. Effect of frothers and frothers + collector's concentration on *SMD* of bubbles

Frother Type	SMD (mm)
PPG200 10 ppm	0.408
PPG200 6 ppm + *DAH*	0.207
PPG400 10 ppm	0.365
PPG400 2 ppm + *DAH*	0.188
PPG600 10 ppm	0.309
PPG600 1 ppm + *DAH*	0.131

the *DAH* collector at 1, 2, and 6 ppm concentrations were observed to decrease more, then reached a minimum at 10 ppm *DAH* and no changed up to 100 ppm. At higher concentrations from 1 ppm to 100 ppm, a gradual and significant reduction was found in these frother types, in line with previously reported critical coupling concentration results (Guven et al., 2020). According to the data at 10 ppm here and considering the SMD of each collector + frother mixture, the concentration of 10 ppm can be accepted as a critical point for most mixed systems. These results can be seen in the *ImageJ* pictures in Figs. 6 and 7 which present the images of the bubbles of these frothers using the *ImageJ* program, obtained according to the collector concentration, in addition to *SMD* as a function of frother + *DAH* concentration.

Fig. 6. Effect of frother and frother + *DAH* concentration on *SMD* of bubbles (Frit Diameter: 10-16 µm)
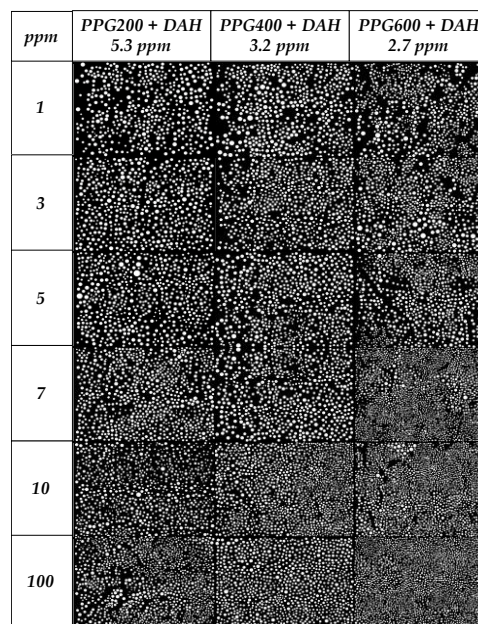
Fig. 7. *ImageJ* picture of the size of the frothers obtained by different frothers + *DAH*

8

Physicochem. Probl. Miner. Process., 58(5), 2022, 152890

3.3. Bubble size distribution (*BSD*)

As mentioned before, bubble size distribution (*BSD*) is one of the most important factors in flotation and depends on frother type and concentration, air flow rate, and frit pore size (Batjargal et al., 2021). Figure 8 shows the bubble size distribution with respect to frother type at constant concentration of frothers + concentration of collectors (1, 3, 5, 7, 10, and 100 ppm), air flowrate (50 cm^3/min), and frit pore size (10–16 μm). As it can be seen from Fig. 8 that it was observed that the bubble sizes of the frothers were reduced more when *PPG* (*200*, *400*, and *600*) at concentrations of 1, 2, and 6 ppm was mixed with the *DAH* collector.
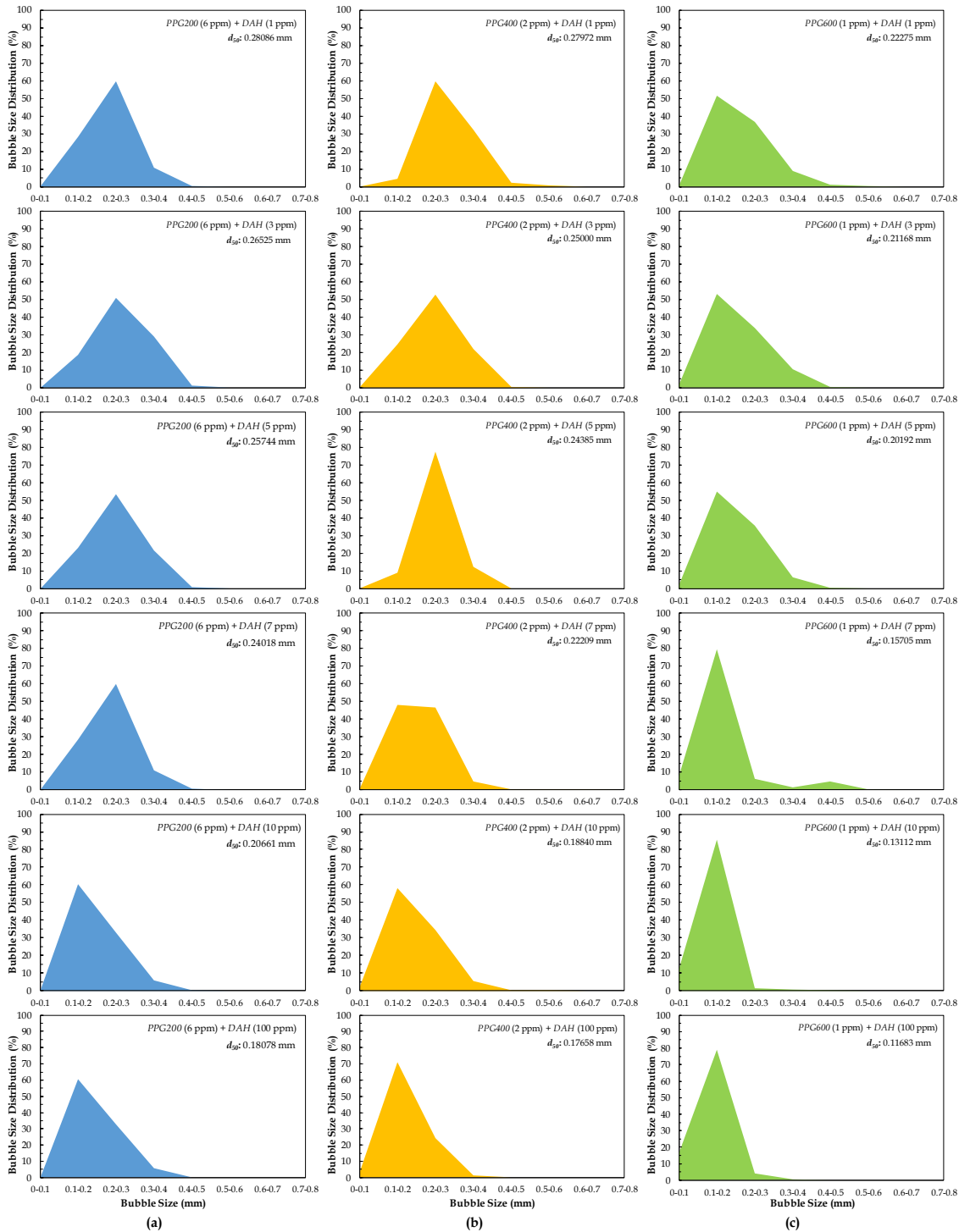

Fig. 8. Effect of frother type + collector type mixing system on *BSD* at different concentrations of the collector (50 cm^3/min air flow rate and frit pore size of 10–16 μm: *PPG200 + DAH*, *PPG400 + DAH*, and *PPG600 + DAH*)

It is worth noting that these results are not unexpected considering the frother feature of *DAH* in addition to its collector role in flotation. Similar results were also reported in Corona-Arroyo et al. (2015) for the dodecylamine (*DA*)-*MIBC* blend. It was reported that a significant decrease was obtained in terms of the *CCC* for *MIBC* in the presence of 4 mg/dm^3 *DA* while the lower concentrations of amine were not found effective on bubble size distributions, especially for *MIBC*. Thus, in this series of tests, polyglycol type frothers reported to be more powerful compared to *MIBC* were used (Elmahdy and Finch, 2013). Considering that knowledge in mind, six concentrations of the *DAH* as 1, 3, 5, 7, 10, and 100 ppm were examined to clearly show the contribution of the amine-frother blend in flotation systems. In Fig. 8, depending on the type of frother and collector, the bubbles produced in the presence of frothers + collector mixing systems were revealed at lower dimensions with the frother. For example, frothers + *DAH* (1 ppm) mixing system while the *BSD* in the presence of *PPG600* (1 ppm) accumulated between 0–0.4 mm and the d_{50} of *BSD* was determined at 0.22 mm, *PPG200* (6 ppm) gave the highest *BSD* variation between 0–0.6 mm, and the d_{50} of *BSD* was 0.2808 mm.

Additionally, the maximum *BDS* values for each frother were plotted as a function of *DAH* concentration. As shown in Fig. 9, while *PPG600* gave the highest *BSD* values with the increasing *DAH* concentration, *PPG200* and *PPG400* almost gave the same result as a function of *DAH* concentration.
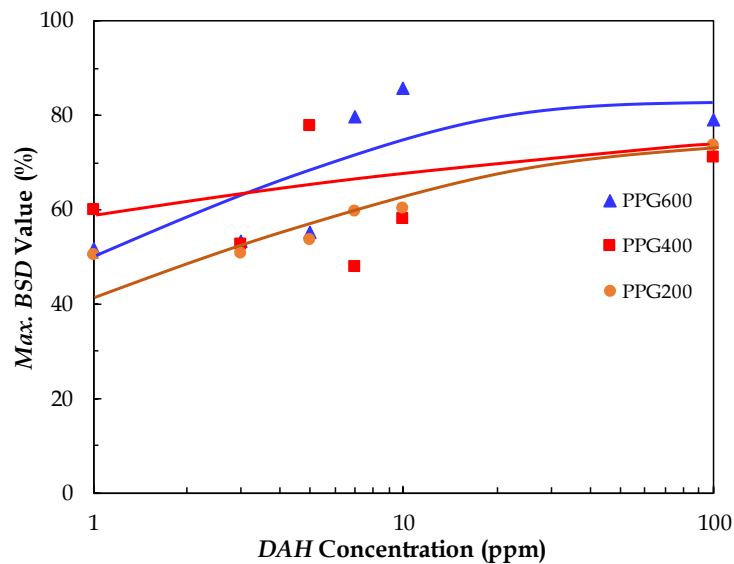

Fig. 9. *Max. BSD* values for each frother as a function of *DAH* concentration

4. Conclusions

The results of this study showed that upon the addition of *DAH* to the solutions of different frothers such as *PPG200*, *PPG400*, and *PPG600*, the *CCC* values of these frothers decreased to 11.3 ppm, 4.29 ppm, and 2.90 ppm in the same order which is quite important for flotation systems. And, accordingly, the highest *SMD* value for *PPG200* 6 ppm + 1 ppm *DAH* was 0.28 mm, while the lowest *SMD* value for *PPG600* was 1 ppm + 100 ppm *DAH* 0.1311. Even in all frothers + *DAH*, 3 ppm was immediately found at a very sufficient critical break concentration point. This can be explained by the fact that *DAH* is a significantly stronger surfactant than these frothers.

Additionally, when 10 ppm concentration was compared in all frothers and frothers + collector mix systems, the *SMD* value for *PPG200* was 0.408 mm, while it decreased to 0.207 mm for *PPG200* 6 ppm + *DAH* mix system. Therefore, it was found that the *SMD* of all frother + collector mix systems decreased by about 2 times. Moreover, when 10 ppm concentrations were compared in all frothers + collector mix systems were more concentrations.

The *BSD* of frothers + collectors mix systems also followed the same order obtained for *SMD* values; the finest distribution gradually exhibited a little larger distribution for *PPG200* + *DAH* mix system. It was shown that *SMD* and *BSD* of all mixing systems were found to be suitable even at the lowest concentration.

In sum, these results showed that tuning the flotation conditions such as the type of frother and collector mix systems, their molecular weight, their molecule's functional groups, and their concentrations would be very effective in adjusting bubble size which in turn affects the flotation recovery.

Acknowledgments

References

BATJARGAL, K., GUVEN, O., OZDEMIR, O., KARAKASHEV, S.I., GROZEV, N.A., BOYLU, F., ÇELIK, M.S., 2021. *Adsorption kinetics of various frothers on rising bubbles of different sizes under flotation conditions*. Minerals, 11(3), 304.

CORONA-ARROYO, M.A., LOPEZ-VALDIVIESO, A., LASKOWSKI, J.S., ENCINAS-OROPESA, A., 2015. *Effects of frothers and dodecylamine on bubble size and gas holdup in a downflow column*. Miner. Eng., 81,109-115.

CHO, Y.S., LASKOWSKI, J.S., 2002. *Effect of flotation frothers on bubble size and foam stability*. Int. J. Miner. Process. 64, 69–80.

ELMAHDY, A.M., FINCH, J.A., 2013. *Effect of frother blends on hydrodynamic properties*. Int. J. Miner. Process. 123, 60-63.

GOMEZ, C.O., FINCH, J.A., MUÑOZ-CARTES, D., 2011. *An approach to characterise frother roles in flotation*. In Proceedings of the 8th International Mineral Processing Seminar Procemin, Santiago, Chile, 30 November–2 December, 223–231.

GRAU, R.A., LASKOWSKI, J.S., HEISKANEN, K., 2005. *Effect of frothers on bubble size*. Int. J. Min. Process 76, 225–233.

GRAU, R.A., LASKOWSKI, J.S., 2006. *Role of frothers in bubble generation and coalescence in a mechanical flotation cell*. Can. J. Chem. Eng. 84, 170–182.

GUVEN, O., CELIK, M.S., DRELICH, J.W., 2015. *Flotation of methylated roughened glass particles and analysis of particle-bubble energy barrier*. Miner. Eng. 79, 125–132.

GUVEN, O., BATJARGAL, K., OZDEMIR, O., KARAKASHEV, S.I., GROZEV, N.A., BOYLU, F., ÇELIK, M.S., 2020. *Experimental procedure for the determination of the critical coalescence concentration (CCC) of simple frothers*. Minerals 10, 617.

KARAGUZEL, C., 2010. *Selective separation of fine albite from feldspathic slime containing colored minerals (Fe-Min) by batch scale dissolved air flotation (DAF)*. Miner. Eng. 23, 17-24.

KARAKASHEV, S.I., GROZEV, N.A., BATJARGAL, K., GUVEN, O., OZDEMIR, O., BOYLU, F., ÇELIK, M.S., 2020. *Correlations for easy calculation of the critical coalescence concentration (CCC) of simple frothers*. Coatings 10, 612.

KOWALCZUK, P.B., DRZYMALA, J., 2016. *Physical meaning of the Sauter mean diameter of spherical particulate matter*. Particul. Sci. Technol. 34, 645–647.

KRACHT, W., REBOLLEDO, H., 2013. *Study of the local critical coalescence concentration (l-CCC) of alcohols and salts at bubble formation in two-phase systems*. Miner. Eng. 50, 77–82.

LEJA, J., 1981. *Surface Chemistry of Froth Flotation*. Plenum Press: New York.

MALDONADO, M., DESBIENS, A., DEL VILLAR, R., GIRGIN, E., GOMEZ, C., 2008. *On-line estimation of bubble size distributions using Gaussian mixture models*. In Proceedings of the V International Mineral Processing Seminar, Santiago, Chile, 22–24 October, 389–398.

MOHAGHEGHIAN, S., ELBING, B.R., 2018. *Characterization of bubble size distributions within a bubble column*. Fluids 3, 13.

NARSIMHAN, G., RUCKENSTEIN, E., 1986. *Hydrodynamics, enrichment, and collapse in foams*. Langmuir 2, 494.

NESSET, J.E., FINCH, J.A., GOMEZ, C.O., 2007. *Operating variables affecting the bubble size in forced-air mechanical flotation machines*. In Proceedings of the 9th Mill Operators' Conference 2007, Fremantle, WA, Australia, 19–21 March, 55–65.

NGUYEN, P.T., HAMPTON, M.A., NGUYEN, A.V., and BIRKETT, G.R., 2012. *The influence of gas velocity, salt type and concentration on transition concentration for bubble coalescence inhibition and gas holdup*. Chem. Eng. Res. Des. 2012, 90(1), 33–39.

SZYSZKA, D., 2008. *Critical coalescence concentration (CCC) for surfactants in aqueous solutions*. Minerals 8, 2-10.

VAZIRIZADEH, A., BOUCHARD, J., CHEN, Y., 2016. *Effect of particles on bubble size distribution and gas hold-up in column flotation*. Int. J. Miner. Process. 157, 163–173.

WELSBY, S.D.D., 2014. *Pilot-scale froth testing at Highland Valley Copper*. In Proceedings of the 46th Annual Meeting of the Canadian Mineral Processors Conference, Ottawa, ON, Canada, 21–23 January, 301–314.

WILLS, B.A., FINCH, J., 2016. *Wills' Mineral Processing Technology*. An Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery, eighth ed.

ZANGOOI, A., GOMEZ, C.O., FINCH, J.A., 2017. *Mapping frother distribution in industrial flotation circuits*. Miner. Eng. 113, 36–40.

ZHANG, W., NESSET, J.E., FINCH, J.A., 2010. *Water recovery and bubble surface area flux in flotation*. Can. Metall. Q. 49, 353–362.