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A model for predicting dynamic frothability index value for dual-frother blends

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Abstract

Dynamic frothability index (DFI) is a characteristic of any frother, which presents useful information about the frothing properties. The objective of this study is to introduce a prediction model for estimating the DFI values for the dual-frother blends. The proposed model uses the DFI values for the frothers and the mole ratio for the weaker frother to calculate the DFI values for the blends. Frothing properties of a number of solutions were measured using a pneumatic column froth-meter, and were described in terms of the froth retention time and DFI values. The model reliability was confirmed by comparing the experimental and predicted DFI values for different frother blends including *n*-butanol/methyl isobutyl carbinol (MIBC), ethanol/MIBC, iso-amyl alcohol/MIBC, and poly propylene glycol (PPG)-250/MIBC, with high determination coefficients (> 95%). A reference chart was also proposed for a rapid estimation of the DFI value for a frother mixture.

Keywords: *Frothers, Frothability, Frother Blends, Prediction Model.*

1. Introduction

The significance of frothers in controlling the flotation efficiency has been well-known [1]. In addition to the formation of froths, frothers have considerable effects on increasing the air dispersion in a flotation machine, reducing the coalescence of individual bubbles in the pulp, and decreasing the rate at which the bubbles rise to the surface [2].

It has been observed that the frother blends can be more effective than the single frothers in achieving the best technical and economic advantages [3]. Based upon the direct experimental observations in both the batch laboratory and continuous large-scale flotation cells, the use of a frother significantly increases, first, the possibility of a particle-bubble contact, and, secondly, the efficiency of sticking after such a contact. Thus a major role of a frother is to increase the rate of flotation significantly [4]. In terms of this role, the two terms “selective” and “powerful” are used to characterize frothers. The former refers to the attachment of a hydrophobic particle to an air bubble, which can be used in the flotation of very fine particles, whereas the latter, which indicates the frothing capacity of the frother, provides higher recoveries and better performance in the flotation of coarser particles [5-7]. Therefore, blending of flotation frothers is becoming a common practice, and apparently, enhances the flotation performance of the broad particle size distribution typical of a flotation feed. Two frother classes commonly used in the flotation practice today are alcohols and polyglycols. Alcohol frothers are mixtures of the alcohols containing 5–8 carbon atoms, either straight- or branched-chained, whereas polyglycol frothers are a large class with varying structures and molecular weights that are the strongest utilized surface active frothers [1, 3]. As a general guideline, the alcohol frothers tend to be more effective for the selective fine-particle recovery, while the polyglycol frothers are more effective for the selective coarse-particle flotation. For recovery across the particle size spectrum, a mixture of alcohol and polyglycol frothers may offer an advantage. Another argument for the mixed frothers is that there are two functions: a single-frother system probably means a compromise on the hydrodynamic (air dispersion) or froth stability, while a dual-frother system offers the possibility of independently controlling both [8].

A limited number of works have been undertaken to understand the action of frother blends in the froth-flotation process. Malysa et al. [9] have investigated the effect of *n*-alkanol frothing systems including *n*-butanol, *n*-pentanol, and *n*-hexanol on the flotation performance of different coal samples. By comparing the flotation results as a function of DF1, they showed that the flotation yields were not dependent on the kind of *n*-alkanol used. For example, *n*-butanol, *n*-pentanol, and *n*-hexanol showed the same collecting properties. Laskowski et al. [10] have measured the bubble size and DFI for methyl isobutyl carbinol (MIBC) blended with various polypropylene alkyl ethers, and suggested that the blend critical coalescence concentration (CCC) was between the two individual frother CCCs, and that, the froth properties were dominated by polyglycol. Tan et al. [11] have found that mixtures of low and high molecular weight polypropylene glycols show better foaming properties than single frothers. They proposed a froth-stabilizing mechanism based upon the blends increasing the surface elasticity. Gupta et al. [12] have conducted a research program to determine the effects of frother mixtures on the froth flotation performance for a broad-sized distributed coal flotation feed. They prepared three mixed frother systems as follow: frother “x”, composed of alcohol and ketone group chemicals; frother “y”, consisting of alcohol and aldehyde group chemicalsand frother “z”, as a blended product of alcohol and polyglycol ether group chemicals. They found that the mixed frother “z” was clearly superior compared to the mixed frother “x” and the mixed frother “y”, in terms of the selectivity and kinetics. Elmahdy and Finch [13] have studied the effects of blending polyglycols with alcohols on the bubble size, gas hold-up, and froth height on a two-phase system. They suggested that the advantage of blends was to provide some independent control over the two frother functions; one frother may control the bubble size, and another may manipulate the froth stability. Ngoroma et al. [2] have demonstrated how blending low molecular weight alcohols with commercially available frothers impacted the solids and water recovery as well as the valuable mineral recovery and concentrate grade in different platinum group minerals (PGM) ores using the batch flotation tests. Higher water and solid recoveries together with higher valuable mineral recoveries (>90% copper and >70% nickel) were obtained from the tests using the frother blends. Recently, Dey et al. [3] have used weak and powerful frothers for studying the surface activity and frothability of frother blends at various concentrations. They showed that the foam stability for single MIBC was much less; however, it could be improved significantly using a small amount of the strong frother (PPG). It was also found that the coal concentrate contained high ash with single PEG due to high froth stability that resulted in the entrainment of the gangues, while single MIBC produced a high-grade concentrate with a low recovery.

The point emerging from these studies is that frothability, either as frothing capacity and stability or as water recovery of any frother system, is a significant property that influences many aspects of a flotation practice. The objective of this study is to develop a model to predict the DFI values for the dual-frother mixtures.

2. Experimental

2.1. Materials

The frothing surfactants used in this work were *n*-butanol, iso-amyl alcohol, ethanol, MIBC (alcohols), and PPG-250 (polyglycol). The frothers were used either individually or as blends, at different dosages. All the surfactants were of analytical-grade, and were used without further purification. The pH value for the pure surfactant samples was measured, and found to be 7±2.

2.2. Dynamic frothability measurement

The frothability tests were carried out using a froth column-meter (Model FS-200*i*, KFK$^{®}$, Iran) of 50-mm interior diameter and a glass cylindrical tube of 600-mm height. The froth was generated by aerating the surfactant solution using a fritted glass sparger at the bottom of the froth column-meter. The fritted glass had a diameter of 40 mm and a pore size of 85 mesh (160 microns). To start with the test, the froth column was filled with 200 mL of distilled water. The initial height of the liquid within the column was recorded. A small amount of compressed air was then introduced in order to flush out the water trapped in the fritted glass disc. A pre-determined amount of frother, either single or blend, was added to the distilled water from the top of the column. The flow-meter was set to a pre-determined air flow rate range (0–3 l/min). When the froth height reached the equilibrium, the total froth height (maximum froth height) was recorded. The froth height is the difference between the total froth height and initial liquid height. All the tests were conducted at the ambient temperature (25±1 °C) in a well air-conditioned room. Each test was replicated three times, and an average value was reported.

3. Results and discussion

3.1. Frothing characterization of single frother systems

In order to determine the DFI value for the studied individual frothers, first, the volume of the produced froth was plotted against the gas flow rate, and the retention time of the froth was calculated:

$$rt = \frac{\Delta V}{\Delta Q} \quad (1)$$

where *rt* is the froth retention time (s), *V* is the gas volume (in liquid and foam) (cm^3), and *Q* is the gas flow rate ($\mathrm{cm}^3\ \mathrm{s}^{-1}$).

The DFI value was then calculated using the following relationship [14]:

$$\mathrm{DFI} = \left(\frac{\partial rt}{\partial c}\right)_{c=0} \quad (2)$$

where *c* is the froth concentration. The DFI values for the studied frothers were calculated and tabulated in Table 1.

Table 1. Dynamic frothability index for individual frothers.

Frother	Molecular weight	DFI (s $\mathrm{dm}^3\ \mathrm{mol}^{-1}$)
Ethanol	46.07	1349.7
n-Butanol	74.12	1977.3
Iso-amyl alcohol	88.17	10517
MIBC	102.17	38172
PPG-250	260	423694

3.2. Frothing characterization of dual-frother systems

The frother blends investigated in this study were *n*-butanol/MIBC, ethanol/MIBC, iso-amyl alcohol/MIBC, and PPG-250/MIBC. For each frother blend, different mole ratios for each frother were added to distilled water and mixed well. Then the DFI values were calculated and plotted *vs.* the complete mole ratio spectrum of the weaker frother. The DFI-mole ratio plot for *n*-butanol and the MIBC mixture is shown in Figure 1a. As it can be observed in this figure, the DFI variation follows a decreasing exponential trend as the *n*-butanol mole ratio decreases. The equation fitted to this plot can be stated as follows:

$$\mathrm{DFI} = b e^{-a m_r} \quad (3)$$

$$m_r = \frac{m_{\text{weak frother}} Mw_{\text{weak frother}}}{m_{\text{weak frother}} Mw_{\text{weak frother}} + m_{\text{powerful frother}} Mw_{\text{powerful frother}}}$$

$$m_{\text{weak frother}} + m_{\text{powerful frother}} = 1$$

where m_r is the mole ratio of the weak frother, *m* is the mole fraction, *Mw* is the molecular weight of the frother, and *a* and *b* are constants. Eq. (3) can also be rearranged in the logarithmic form as follows:

$$\mathrm{LnDFI} = -a m_r + b \quad (4)$$

Figure 1b shows the logarithmic form of Figure 1a. It is necessary to note that *f*(DFI) is meaningful if it is only confined to lower limit (0, $\mathrm{LnDFI}_{\text{powerful frother}}$) and upper limit (1, $\mathrm{LnDFI}_{\text{weak frother}}$). Thus slope *a* is defined as follows:

$$a = \frac{y_2 - y_1}{x_2 - x_1} = \frac{\mathrm{LnDFI}_{\text{powerful frother}} - \mathrm{LnDFI}_{\text{weak frother}}}{1-0} = \Delta\mathrm{DFI}_{\log} \quad (5)$$

and the intercept point *b* is $\mathrm{DFI}_{\text{powerful frother}}$. Therefore, Eq. (4) would find the general form of:

$$\mathrm{LnDFI}_{\text{frother blend}} = -\Delta\mathrm{DFI}_{\log} m_{r,\text{weak frother}} + \mathrm{LnDFI}_{\text{powerful frother}} \quad (6)$$

Figure 1a shows the experimental DFI values plotted against the values predicted using Eq. (6). The fitting accuracy was examined using the determination coefficient (*R*-squared, R^2), calculated as follows [15]:

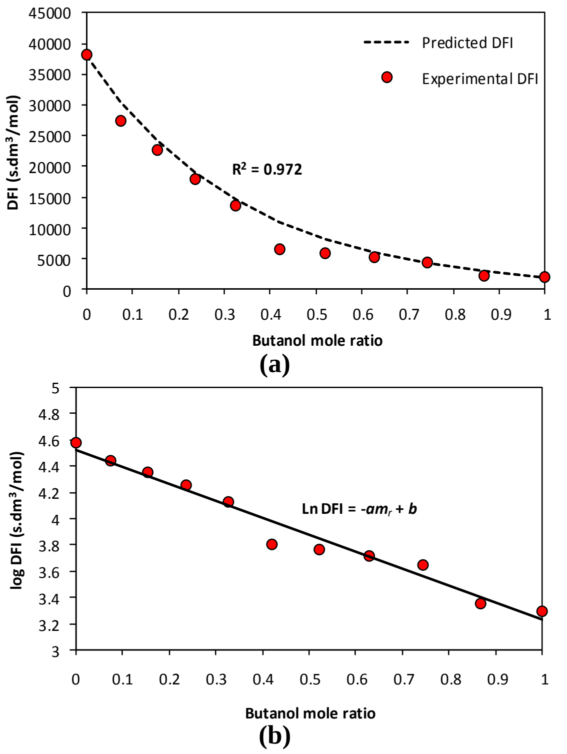
$$R^2 = 1 - \frac{SS_{\text{res}}}{SS_{\text{tot}}} \quad (7)$$

where SS_{res} and SS_{tot} are the residual and total sum of squares, respectively.

$$SS_{\text{res}} = \sum_{\mathrm{i}} (\mathrm{DFI}_{\text{blend, exp, i}} - \mathrm{DFI}_{\text{model, exp, i}})^2 \quad (8)$$

$$SS_{\text{tot}} = \sum_{\mathrm{i}} (\mathrm{DFI}_{\text{blend, exp, i}} - \overline{\mathrm{DFI}}_{\text{exp}})^2 \quad (9)$$

As it can be seen, the model is capable of predicting the DFI value for the *n*-butanol/MIBC blends with an acceptable accuracy (R^2 = 97.23%).

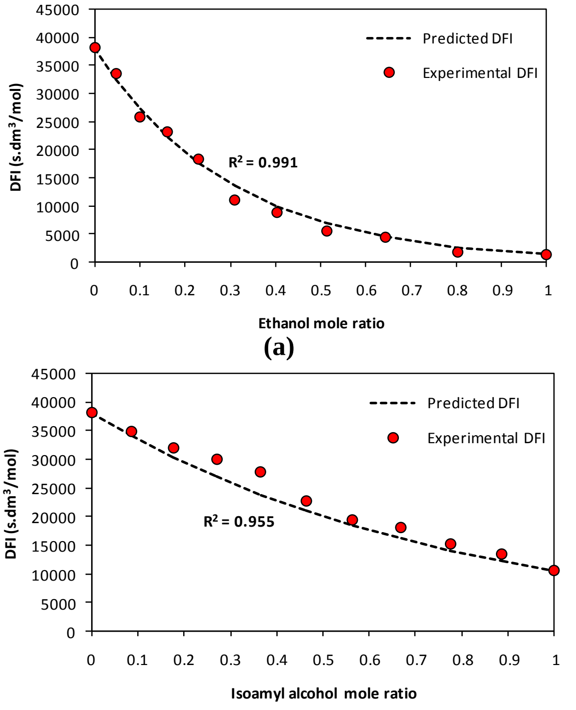


(a)

(b)

Figure 1. Variation in DFI *vs.* mole ratio for n-butanol/MIBC blend, (a) experimental *vs.* predicted values, (b) logarithmic form.

The DFI values for other frother mixtures were also measured and compared with those calculated using Eq. (6). The comparison results are shown in Figure 2. Referring to the coefficients of determination, the model can be applied as a reliable means for the prediction of frothing characteristics of any dual-frother blend.



(a)

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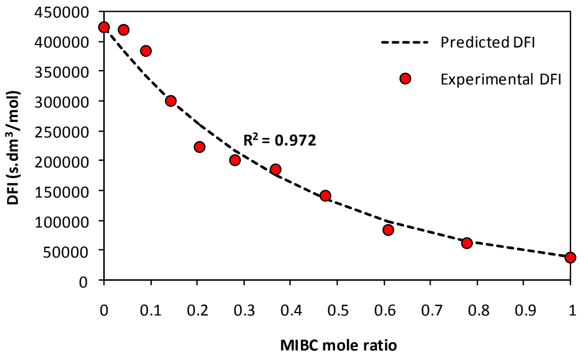

(c)

Figure 2. Variations in DFI *vs.* mole ratio for (a) ethanol/MIBC blend, (b) iso-amyl alcohol/MIBC blend, (c) MIBC/PPG-250 blend.

The DFI values for numerous industrial frothing agents have been studied by different investigators. Table 2 lists the DFI values reported in the literature. Therefore, Eq. (6) may be applied to develop a reference chart for estimating the DFI values for any combination of frothers. Figure 3 shows the proposed reference chart in the logarithmic form for the dual-frother systems including polyglycol and alcohol frothers, which was plotted using Eq. (6), and the data was given in Table 2. In order to find the DFI value for a new blend, the DFI values for the powerful and weaker frothers should be found on the left-side y-axis and right-side y-axis, respectively, and a cross line should be drawn. The vertical line connecting the mole ratio for the weaker frother on the x-axis to the DFI cross line shows the DFI value for the frother blend.

4. Conclusions

Frother blends are usually used in industrial flotation practices due to their technical and economic advantages. This work introduced a prediction model for the estimation of the dynamic frothability index (DFI) values for the dual-frother systems. Comparisons between the DFI values predicted by the proposed model and those measured experimentally for different frother blends show that the model has an acceptable accuracy. Moreover, a reference chart was proposed for fast prediction purposes.

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Table 2. Molecular weight and DFI values for flotation frothers.

	Mw, g mol^{-1}	DFI, s dm^3 mol^{-1}
Aliphatic alcohols:		
n-butanol	74.12	1,339 [16]
n-butanol[*]	74.12	1,271 [16]
2-butanol	74.12	826 [16]
t-butanol	74.12	1,588 [16]
n-pentanol	88.15	5,517 [16]
n-hexanol	102.17	33,779 [16]
n-heptanol	116.2	40,867 [16]
n-octanol	130.23	79,338 [16]
Iso-amyl alcohol	88.17	10,517
MIBC	102.17	34,000 [17]; 35,020 [18]; 36,991 [16]; 37,000 [14]
2-ethyl hexanol	116.23	141,147 [16]
Diacetone alcohol	116.16	12,000 [16]
Cyclic alcohols:		
α-terpineol	154.25	137,988 [18]; 138,000 [14]; 138,901 [16]
Alkoxy paraffins:		
TEB	176.29	252,589 [16]
Polyglycol ether:		
$CH_3(C_3H_6O)OH$	90.12	5,700 [17]
$CH_3(C_3H_6O)_2OH$	148.12	35,000 [17]
DF-200	206.29	196,000 [17]
DF-250	264.37	208,000 [17]
DF-1012	397.95	267,000 [17]

[*]Test conducted in distilled water.

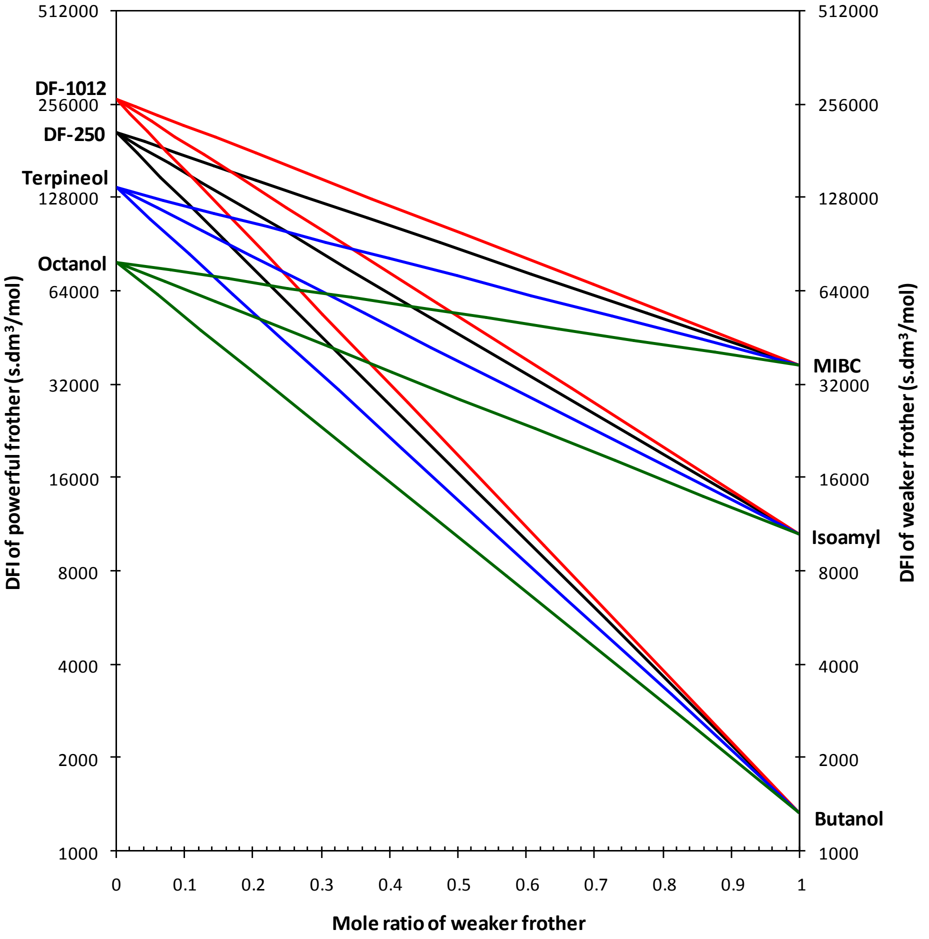

Figure 3. Reference chart proposed for fast estimation of DFI values for dual-frother blends.

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ارائه مدلی به‌منظور پیش‌بینی شاخص کفسازی دینامیکی مخلوط‌های دوتایی کفسازها

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چکیده:

شاخص کفسازی دینامیکی (DFI) مشخصه ذاتی هر کفساز است که اطلاعات مفیدی در خصوص خواص کفسازی آن ارائه می‌دهد. هدف از این پژوهش ارائه مدلی جدید به‌منظور پیش‌بینی و تخمین شاخص کفسازی دینامیکی مخلوط‌های مضاعف کفسازها است. در این مدل، مقادیر شاخص کفسازی دینامیکی کفسازها و نسبت مولی کفساز ضعیف‌تر به‌عنوان پارامترهای مدل برای محاسبه شاخص کفسازی دینامیکی مخلوط مورد استفاده قرار می‌گیرند. مقایسه مقادیر شاخص کفسازی اندازه‌گیری شده و پیش‌بینی شده برای مخلوط‌های مختلف شامل n-butanol/MIBC، ethanol/MIBC، isoamyl/MIBC و PPG-250/MIBC نشان داد که مدل با ضریب تعیین بیش از ۹۵٪ از دقت بسیار مطلوبی برخوردار است. همچنین، به‌منظور پیش‌بینی مقادیر شاخص کفسازی سایر مخلوط‌های دوتایی از کفسازها، با استفاده از مدل پیشنهادی یک نمودار مرجع نیز پیشنهاد شد.

کلمات کلیدی: کفساز، قابلیت کفسازی، مخلوط کفسازها، مدل پیش‌بینی.