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Optimization of external reagent addition on coal slime flotation with compound reagents

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Abstract: The appropriate selection and optimization of flotation reagents are essential for enhancing the quality of flotation coal, reducing reagent consumption, and lowering production costs in coal preparation plants. Currently, most coal preparation plants utilize compound reagents in their production processes. However, these compound reagents often fail to optimize both bubble formation and collection efficiency simultaneously, resulting in excessive reagent consumption during production. This study uses the compound reagent (XZ) employed by Xinzheng Clean Coal Company as a case study to thoroughly investigate the causes of its high reagent consumption and to perform optimization experiments. First, the differences in flotation performance between the XZ compound agent and the kerosene-sec-octanol system were compared. Next, the causes of high XZ agent consumption were identified using infrared spectral analysis, and finally, the response surface methodology (RSM) was applied to optimize the reagent system. Experimental results indicated that the effectiveness of the XZ agent primarily depended on its ester and ether groups, although its foaming performance was inadequate. The addition of sec-octanol significantly enhanced its foaming performance. Response surface optimization revealed that when the XZ agent dosage was 1000 g/t, secoctanol dosage was 275 g/t, and slurry concentration was 90 g/L, the recovery of combustible matter peaked at 98.95%. When the XZ agent dosage was 997.33 g/t, sec-octanol dosage was 191.27 g/t, and slurry concentration was 60 g/L, the flotation perfection index reached its highest value of 58.12%. Further analysis revealed that a moderate froth layer height improves flotation performance, whereas excessively high or low froth layers negatively impact the flotation performance.

Keywords: flotation, height of froth layer, responsive surface optimization

1. Introduction

In contemporary coal processing, coal slurry flotation technology plays a crucial role as a key separation method and has attracted considerable attention for its ability to improve coal resource utilization, enhance fine coal quality, and reduce environmental pollution (Gui and Cao et al., 2017; Shi and Wang et al., 2018; Mao and Bu et al., 2020; Zhen and Li et al., 2020; Hazare and Pradhan et al., 2023). By separating fine-grained coal from mineral impurities, coal slurry flotation technology not only increases the yield of refined coal but also enhances the overall quality of coal products, thus meeting market demand for high-quality coal (Naik and Reddy et al., 2005; Ao and Zhang et al., 2024). Additionally, fine coal treatment reduces the emission of harmful substances, promoting environmentally sustainable production in coal processing plants (Bao and Liu et al., 2023; Dai and Chen et al., 2024; Gao and Li et al., 2024; Vasumathi and Gharai et al., 2024).

The efficiency of coal flotation largely depends on the proper selection and application of flotation chemicals, including collectors and frothers. Collectors are critical to the success of the flotation process, as they modify the surface properties of coal particles (Wang and Wang et al., 2023; Shen and Li et al.,

2024; Wang and Cheng et al., 2024; Xie and Zhang et al., 2024). Frothers improve flotation efficacy by facilitating bubble generation in the pulp, enabling coal particles to adsorb onto the bubbles and form a froth layer (Melo and Laskowski, 2006; Singh and Dey et al., 2017; Khoshdast and Hassanzadeh et al., 2023; Pawliszak and Bradshaw-Hajek et al., 2024). Foam formation and stabilization are essential prerequisites for successful flotation and are key factors affecting the coal slurry flotation recovery rate. Thus, froth characteristics in the flotation process are critical to flotation performance (Harris and Jia, 2000; Cho and Laskowski, 2002; Batjargal and Guven et al., 2023). However, the use of collectors and frothers, and their interactions, significantly impact the flotation efficiency (El-Shall and Abdel-Khalek et al., 2000; Kursun, 2014; Cao and Chen et al., 2020; Pan and Gresham et al., 2022). Patra et al(Patra and Basu et al., 2021) investigated the interaction of two collectors, tetrahydrofurfuryl oleate (C1) and tetrahydrofurfuryl ether (C2), with a new frother. The results showed that the synergistic effect of the collectors and frother led to a higher yield (53%) and lower ash content (10%). Cheng et al. (2022) systematically investigated the interactions among the reagents. A comparative analysis of the interactions between four collectors and two frothers revealed that the collectors enhanced the stability of ether alcohol within the two-phase foam. Additionally, the maximum froth height and half-life of the three-phase froth were influenced by the interactions between the collectors and frothers.

The flotation conditioning process typically begins with the introduction of a collector to enhance the hydrophobicity differential between the target minerals. This is followed by the addition of a frother, which generates a sufficient quantity of bubbles and stabilizes the foam layer, thereby promoting the attachment of hydrophobic minerals to the foam phase. The frother is typically an active compound with low surface tension. Additionally, some studies have explored the combined use of collectors and frothers to optimize flotation efficiency. For example, Batjargal et al. assessed the frothing characteristics of frother-collector mixtures using a dynamic foam analyzer. Their findings demonstrated that the frother-collector mixtures exhibited the smallest bubble sizes (Batjargal and Guven et al., 2023). Zhou et al. investigated the gas dispersion properties of collector/frother blends and found that the majority of these blends resulted in an increase in gas holdup (Zhou and Jordens et al., 2016). Currently, some coal processing plants utilize mixtures of frothers and collectors as flotation reagents, simplifying the chemical addition process. However, fixed ratios of collectors and frothers in these mixtures can lead to conflicts between foam stability and the regulation of mineral hydrophobicity. Moreover, the predetermined ratio of active ingredients often results in excessive frother usage, leading to heightened froth stability in the concentrate and significant entrapment of gangue minerals. This, in turn, complicates the defoaming process during subsequent filtration. In cases where high froth stability is required by flotation equipment, increasing the dosage of compound reagents results in excessive collector consumption, leaving substantial chemical residues in the tailings pond and interfering with the concentration and clarification of circulating water. Additionally, excessive use of collectors may cause undesirable ash to be entrapped in the concentrate, causing ash content to exceed regulatory limits. However, there is no literature addressing the limitations of frother-collector mixtures as flotation reagents or proposing potential improvement measures. Therefore, investigating and optimizing the effects of compound reagents on flotation is crucial for enhancing coal flotation efficiency, optimizing production processes, and fostering the sustainable development of coal preparation plants.

This paper presents an experimental analysis and diagnosis of the high flotation reagent (XZ) consumption at Xinzheng Clean Coal Company. First, the difference in flotation performance between the on-site reagent and the laboratory reagent is compared; further, the response surface optimization method is employed to determine the optimal flotation reagent system. While continuing to use the original reagent system of the coal preparation plant, the flotation concentrate ash content is further stabilized through the addition of supplementary reagents, ensuring the ash content of the clean coal meets quality standards and reducing reagent loss.

2. Experimental materials and methodology

2.1. Materials and Instrumentation

The coal samples for this experiment were sourced from the incoming raw coal at Xinzheng Coal Preparation Plant. The samples were dried, sieved through a 0.5 mm mesh, and the undersized materials were collected for further experiments. The results of the proximate and ultimate analyses of

the coal samples are provided in Table 1. It was observed that the ash content was 21.02%, while the C, H, O, N, and S contents were 88.11%, 3.87%, 5.64%, 1.72%, and 0.53%, respectively. The particle size distribution of the coal sample was analyzed with a laser particle size analyzer (GSL-1000, Liaoning Instrument Research Institute Co., Ltd., China). The results, shown in Fig. 1, indicated that the D₅₀ and D₈₀ values were 130.62 μ m and 194.45 μ m, respectively. The reagents utilized in the experiments are listed in Table 2, while the instruments employed are detailed in Table 3.

Table 1 Proximate and elemental anal	vsis of coal sample, %
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Proximate Analytics					Eler	mental Analy	vsis	
Mad	Ad	V_{daf}	FCd	S _{t,d}	O_{daf}	C_{daf}	H_{daf}	N_{daf}
1.16	21.02	12.99	68.72	0.53	5.64	88.11	3.87	1.72



Fig. 1 Particle size distribution

Fable 2. List	t of expe	erimental	reagents
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Name	Note
Diesel	Analytical purity
Sec-octanol	Analytical purity
Ethanol	Analytical purity
XZ reagents	Compounding agents

Table 3. List of experimental equipment

Name	Remarks/Specifications	Purpose
Unit flotation cell	XFDⅢ-1.5L	Flotation
Electronic scale	600g/0.01g	Weighing
Laser particle analyzer	GSL-1000	Particle-size determination
Ultrasonic cleansing machine	VGT-1613T	Particle dispersion
Unit flotation cell	XFD II -0.5L	Size mixing

2.2. Flotation experiment

The flotation experiment was performed using an XFD III -1.5 L flotation machine with a slurry concentration of 60 g/L, an aeration rate of 0.2 m³/h, and a stirring speed of 1900 r/min. The flotation experiment proceeded as follows: 90 g of coal samples were placed into the flotation cell, water was added to the marked level, and stirring was applied for 3 minutes to adjust the slurry. The collector was

then added, and the slurry was stirred for another 3 minutes, followed by the addition of the frother with stirring for 30 seconds. After aeration for 10 seconds, froth collection commenced and continued for 3 minutes before the experiment was concluded. The frother was subsequently added, followed by stirring for 30 seconds. After 10 seconds of aeration, froth collection resumed for 3 minutes, and the experiment was concluded. The concentrate and tailings were collected separately for drying, weighing, and ash content analysis, and the flotation concentrate yield (γ), combustible matter recovery (*E*), and flotation purification index (η) were calculated. The calculation formulas are presented as follows:

$$\gamma = \frac{\mathbf{m}_1}{\mathbf{m}_1 + \mathbf{m}_2} \tag{1}$$

$$E = \frac{\gamma(100 - A_j)}{100 - A_y}$$
(2)

$$\eta = \left(\frac{\gamma_j}{100 - A_y} \times \frac{A_y - A_j}{A_y}\right) \times 100\%$$
(3)

where: m_1 is the quality of refined coal, m_2 is the quality of tailing coal; γ_j is the yield of refined coal; A_j and A_y are the ash content of flotation clean coal and raw coal, respectively.

2.3. Foaming performance test

A custom-built device was used to measure the two-phase and three-phase froth layer height. The methodology for the two-phase froth layer height test was as follows: XZ reagents were applied at a dosage of 1000 g/t, with sec-octanol ranging from 100 g/t to 500 g/t in 100 g/t increments. After adding 0.5 L of clean water to the 0.5 L flotation machine, the slurry was added according to the flotation procedure, and the adjusted solution was transferred to the custom-built device. The aeration rate was set at 1.0 m³/h, and the difference between the initial liquid level and the highest froth point was recorded as the maximum froth layer height. For the three-phase froth test, 30 g to 45 g of coal samples were placed into a 0.5 L flotation machine, and the remainder of the procedure followed that of the two-phase froth test.

2.4. Fourier transform infrared spectroscopy (FTIR) test

The samples were analyzed using a Nicolet IS50 Fourier Transform Infrared (FTIR) Spectrometer, manufactured by Thermo Fisher Scientific (USA). The procedure began with background subtraction, followed by applying the XZ agent onto the test bench. The wavelength range for the analysis was set between 400 and 4000 cm⁻¹.

3. Experimental results and analysis

3.1. Comparison of the effect of kerosene-sec-octanol and field agents

The results comparing the flotation effects of kerosene, 2-octanol, and the XZ reagent are presented in Fig. 2. When kerosene and 2-octanol are utilized as flotation reagents (Fig. 2 a), an increase in kerosene dosage from 100 g/t to 1000 g/t results in a rise in the flotation combustible recovery rate from 71.64% to 97.19%. The flotation improvement index initially increases and subsequently decreases, reaching 54.89% at 1000 g/t. In the case of the XZ reagent (Fig. 2 b), increasing the dosage from 100 g/t to 4000 g/t results in an increase in the flotation combustible recovery rate from 38.37% to 80.91%, which gradually stabilizes after surpassing 2000 g/t. The flotation improvement index rises from 28.87% to 53.27% and stabilizes after exceeding 2000 g/t. Comparing the flotation results of the XZ reagent with those of kerosene and 2-octanol reveals that at a kerosene dosage of 500 g/t, the combustible recovery rate reaches 96.87%, while the flotation improvement index attains 52.31%. In contrast, with the same dosage of the XZ reagent, the combustible recovery rate is only 36.81%, and the flotation improvement index is 29.25%. Only when the dosage of the XZ reagent exceeds 2000 g/t do the combustible recovery rate and flotation improvement index match the results achieved with a kerosene dosage of 500 g/t. These findings indicate that when the dosage of the XZ reagent is comparable to that of kerosene, its corresponding performance metrics are significantly lower than those of kerosene and 2-octanol. However, when the dosage of the XZ reagent exceeds 2000 g/t, its combustible recovery rate and flotation improvement index become comparable to those of the kerosene and 2-octanol system.



Fig. 2. Coal flotation performance with different reagents (a) kerosene-sec-octanol (b) XZ reagents



Fig. 3. Flotation fome characteristics: (a) and (b) for kerosene dosage of 500 g/t and 1000 g/t, respectively; (c) and (d) for XZ agent dosage of 500 g/t and 1000 g/t

During the experiment, it was observed that significant differences existed in the foam layers under identical reagent dosage conditions (Fig. 3). When kerosene and 2-octanol were used as flotation reagents, the foam layer was notably dense, whereas the foam layer was sparse and thin with the XZ reagent. A comparison of Figs. a and b with Figs. c and d reveals that the foam layers in Figs. a and b are thicker and exhibit stronger foaming ability, while the foam layers in experiments c and d are thinner. This discrepancy may partly explain why the flotation improvement index and combustible recovery rate of the XZ reagent are lower than those obtained with kerosene and 2-octanol.

To further investigate the reasons for the suboptimal foaming performance of the XZ agent, the agent was analyzed by infrared spectroscopy. According to the infrared spectra of the XZ agent in Fig. 4, there are numerous hydrophobic functional groups in the composite agent near 2957 cm⁻¹, 2925 cm⁻¹, and 2855 cm⁻¹, which typically correspond to the stretching vibrations of (C-H) bonds attached to hydrogen atoms on sp³-hybridized carbon atoms. These absorption peaks are characteristic of the stretching vibrations of saturated (C-H) bonds, commonly found in saturated hydrocarbon compounds (Zhou and Albijanic et al., 2018) The absorption peak at 1735 cm⁻¹ primarily corresponds to the stretching vibration of carbonyl (C=O) groups in ester compounds (Zhang and Jiang et al., 2015) The absorption peak at 1368 cm⁻¹ is primarily linked to the symmetrical bending vibration of methyl (-CH₃) groups, typically found in alkanes and other methyl-containing compounds (Nag and Biswas et al., 2011) Absorption peaks at 1255 cm⁻¹ typically correspond to (C-O) bond stretching vibrations, particularly in esters and ethers (Petersen and Rosenberg et al., 2008). The absorption peaks at 1025 cm⁻¹ are usually indicative of (C-O) bond stretching vibrations, commonly found in ethers (Liao and Yang et al., 2022). Fig. 4, indicates that the XZ reagents consists of an alkane-based collector and an ether or ester-based frother. The intermolecular forces between ester or ether molecules and water are weaker than those of hydroxyl groups, resulting in lower water solubility. Due to the low solubility of the frother, most of the agent remains undispersed in the slurry, and except for a small portion dissolved in water, the majority accumulates at the slurry surface. This facilitates easy removal with the froth and water layer, leading to reduced effectiveness (Petukhov and Batyaev, 2020). This fundamental property explains the suboptimal foaming performance of the XZ agent.



Fig. 4. FTIR of XZ reagents

3.2. Influence of sec-octanol dosage on the foaming performance

To improve the quality of flotation froth and enhance flotation performance, the XZ agent was optimized by adding sec-octanol. The maximum froth layer heights for both the two-phase and threephase systems were measured, with the results presented in Fig. 5. At a sec-octanol concentration of 100 g/t, the maximum height of the two-phase froth was 6 cm (Fig. 5a, b). When the sec-octanol dosage was increased to 500 g/t (Fig. 5e), the maximum froth layer height rose from 6 cm to 14 cm (Fig. 5f). In contrast, the three-phase froth experiments, involving coal samples (Fig. 5c), exhibited a more pronounced increase in froth height. At 100 g/t sec-octanol, the froth height increased from 6 cm to 10 cm (Fig. 5d), and further increasing the dosage to 500 g/t (Fig. 5g) resulted in a maximum froth height of 36 cm. Notably, as the sec-octanol concentration increased, the difference in froth height between the two-phase and three-phase systems became more significant. This phenomenon is attributed to the substantial reduction in surface tension caused by sec-octanol, which facilitates the formation of a more stable froth layer, allowing more particles to enter the froth phase (Koca and Aksoy et al., 2017; Bu and Zhang et al., 2020). Furthermore, the presence of solid particles in the three-phase system contributes to enhanced froth stability compared to the two-phase system. This effect can be ascribed to the adsorption of particles onto bubble surfaces, forming an "armor" that inhibits liquid drainage from the lamella, thereby stabilizing the froth structure (Bu and Wang et al., 2020; Zhao and Zhang, 2025). The variation in froth layer height as a function of sec-octanol dosage is illustrated in Fig. 6.



Fig. 5 Maximum froth layer height recorded under various conditions: (a) (b) 100 g/t of sec-octanol for two-phase froth formation; (c) (d) 100 g/t of sec-octanol for three-phase froth formation; (e) (f) 500 g/t of sec-octanol for two-phase froth formation; (g) (h) 500 g/t of sec-octanol for three-phase froth formation.



Fig. 6 Variation of maximum height of froth layer with different dosage of sec-octanol

3.3. Response surface method modeling and optimization

3.3.1. Response surface modeling

Based on the experimental results presented in the previous section, it was observed that the combination of sec-octanol and collector agents significantly enhanced the characteristics of the froth layers in both two-phase and three-phase slurries. To further investigate the interactive effects of sec-octanol and collector agents on the flotation performance of coal samples, a response surface optimization analysis was performed. The experimental design for the response surface analysis is detailed in Table 4. The effects of three variables – specifically, the dosage of the XZ collector agent, the dosage of the frothing agent, and the slurry concentration – on flotation performance were investigated across three levels.

Two replicates were performed at the center point to assess the pure error. The flotation parameters corresponding to the experiment were selected as response variables. Response surface data analysis and modeling were conducted using Design-Expert V.8.0.6.1 software, and the experimental design scheme is detailed in Analysis of **variance for regression equations**

The final equation representing the actual factors affecting the maximum height of the froth layer is:

$$R_{1} = +85.55139 - 0.15678 \times A - 0.016 \times B - 0.6 \times C + 8.05556E^{-5} \times A \times B + 1.20833E^{-3} \times A \times C + 3.71875E^{-5} \times A^{2} - 3.55556E^{-5} \times B^{2}$$
(4)

The final equation for the actual factor of combustible recovery rate is:

$$R_{2} = +112.5746 + 0.029504 \times A + 0.087532 \times B - 1.10231 \times C - 4.44748 E^{-5} \times A \times B - 9.74515 E^{-6} \times A^{2} - 7.86525 E^{-5} \times B^{2} + 7.39897 E^{-3} \times C^{2}$$
(5)

The final equation for the actual factor of the flotation improvement index is:

$$R_{3} = +50.43038 + 4.66628E^{-3} \times A + 0.018959 \times B - 9.61176E^{-3} \times C - 1.63352E^{-5} \times A \times B + 3.54091E^{-6} \times A^{2} - 1.69238E^{-3} \times B^{2}$$
(6)

Table 5

Factor	Name	Unit	Min	Max	Median
А	Collector	g/t	200	1000	600
В	Frother	g/t	50	500	275
С	Slurry	g/L	60	90	75
	concentration				

Table 4. Experimental influence factor level coding

3.3.2. Analysis of variance for regression equations

The final equation representing the actual factors affecting the maximum height of the froth layer is:

$$R_{1} = +85.55139 - 0.15678 \times A - 0.016 \times B - 0.6 \times C + 8.05556E^{-5} \times A \times B + 1.20833E^{-3} \times A \times C + 3.71875E^{-5} \times A^{2} - 3.55556E^{-5} \times B^{2}$$
(4)

The final equation for the actual factor of combustible recovery rate is:

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(6)

std	Run	А	В	С
5	1	200	275	60
10	2	600	500	60
12	3	600	500	90
8	4	1000	275	90
6	5	1000	275	60
7	6	200	275	90
2	7	1000	50	75
14	8	600	275	75
9	9	600	50	60
11	10	600	50	90
1	11	200	50	75
3	12	200	500	75
4	13	1000	500	75
13	14	600	275	75

Table 5. Design proposal

From **Błąd! Nieprawidłowy odsyłacz do zakładki: wskazuje na nią samą.**, The model F-value of 4.39 implies the model is significant There is only a 4.55% chance that a "Model F-Value" this large could occur due to noise.

Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case AB, AC are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy).

From Table 7, The Model F-value of 5.57 implies the model is significant. There is only a 2.64% chance that a "Model F-Value" this large could occur due to noise.

Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case B, AB, and B²are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy).

As can be seen from Table 8, The Model F-value of 4.09 implies the model is significant. There is only a 4.36% chance that a "Model F-Value" this large could occur due to noise.

Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy)

Table 6. The variance analysis results of the response value R_1

	Sum of		Mean	F	p-value	
Source	Squares	$d_{\rm f}$	Square	Value	Prob > F	

Model	659.9786	7	94.28265	4.391197	0.0455	significant
А	0.5	1	0.5	0.023287	0.8837	
В	66.125	1	66.125	3.079759	0.1298	
С	28.125	1	28.125	1.309917	0.2960	
AB	210.25	1	210.25	9.792354	0.0203	
AC	210.25	1	210.25	9.792354	0.0203	
A ²	118.0083	1	118.0083	5.496216	0.0575	
B2	10.8	1	10.8	0.503008	0.5048	
Residual	128.825	6	21.47083			
Lack of Fit	128.7	5	25.74	205.92	0.0529	not significant
Pure Error	0.125	1	0.125			
Cor Total	788.8036	13				

Table 7. The variance analysis results of response value R_2

	Sum of		Mean	F	p-value	
Source	Squares	d_{f}	Square	Value	Prob > F	
Model	304.9684	7	43.56691	5.567057	0.0264	significant
А	39.85062	1	39.85062	5.092183	0.0649	
В	125.285	1	125.285	16.00914	0.0071	
С	0.102163	1	0.102163	0.013055	0.9128	
AB	64.08748	1	64.08748	8.189212	0.0287	
A ²	7.779777	1	7.779777	0.994114	0.3572	
B2	50.73473	1	50.73473	6.482975	0.0437	
C ²	8.868646	1	8.868646	1.133251	0.3280	
Residual	46.95505	6	7.825842			
Lack of Fit	46.67891	5	9.335783	33.80863	0.1298	not significant
Pure Error	0.276136	1	0.276136			
Cor Total	351.9234	13				

Table 8. The variance analysis results of response value R_3

	Sum of		Mean	F	p-value	
Source	Squares	d_{f}	Square	Value	Prob > F	
Model	38.03572	6	6.339286	4.09379	0.0436	significant
А	25.04284	1	25.04284	16.17219	0.0051	
В	0.009101	1	0.009101	0.005878	0.9410	
С	0.166295	1	0.166295	0.10739	0.7527	
AB	8.645524	1	8.645524	5.583114	0.0501	
A ²	1.069912	1	1.069912	0.690929	0.4333	
B2	2.446829	1	2.446829	1.580115	0.2491	
Residual	10.83959	7	1.548513			
Lack of Fit	7.790026	6	1.298338	0.425745	0.8237	not significant
Pure Error	3.049564	1	3.049564			
Cor Total	48.87531	13				

3.3.3. Response surface analysis

The response surface diagram derived from the predictive model equations illustrates the influence of frother dosage, collector dosage, and pulp concentration on the maximum height of the foam layer. Based on the design summary, response surfaces were generated for the maximum foam layer height,

flotation improvement index, and combustible recovery rate of the three-phase foam from the aforementioned experiments.



Fig. 7. Contour plots a, b and c for the maximum height of the froth layer correspond to slurry concentrations of 60 g/L, 75 g/L and 90 g/L, respectively

Fig. 7 illustrates the effect of collector concentration and frother concentration on the height of the foam layer under varying slurry concentration conditions. Fig. 7 a presents a contour map for a slurry concentration of 60 g/L. It can be observed that when the collector dosage is fixed at a lower level, the maximum height of the foam layer decreases with an increase in frother dosage. When the collector dosage exceeds 480 g/t, the height of the foam layer increases with the frother dosage. Fig. 7 b presents a contour map for a slurry concentration of 75 g/L, while Fig. 7 c presents a contour map for a slurry concentration of 90 g/L. The overall trends observed in the three Figs. are consistent.

Fig. 7 illustrates the effect of collector and frother concentrations on the froth layer height under different slurry concentrations. Figs. 7a, 7b, and 7c correspond to contour plots at slurry concentrations of 60 g/L, 75 g/L, and 90 g/L, respectively, with an overall consistent trend. When the collector dosage is relatively low, the maximum froth layer height decreases as the frother dosage increases. However, when the collector dosage exceeds 480 g/t, the froth layer height increases with increasing frother dosage. Additionally, the contour line patterns are directly related to the degree of interaction between the factors, where a more linear trend indicates an insignificant interaction. As shown in Figs. 7 and 8, a significant interaction exists between the collector and frother (AB), which is consistent with the small p-value of AB in the analysis of variance (0.0501, Table 8). Similar interactions between collectors and frothers have also been reported in the literature (Bu and Zhang et al., 2020). This result is primarily influenced by two factors: on the one hand, frother can reduce surface tension and, to some extent, act as emulsifiers to facilitate the dispersion of collectors (non-polar hydrocarbon oils). On the other hand, excessive frother molecules may affect the particle-bubble interaction process, increasing the particle-bubble attachment probability and thereby further influencing the stability of the froth layer(Castellanos and Crespo et al., 2003; Zhu and Zhu et al., 2021).



Fig. 8. Contour plots of combustible recovery rate a, b, and c correspond to slurry concentrations of 60 g/L, 75 g/L, and 90 g/L, respectively.

Fig. 8 a presents a contour map of the combustible recovery rate at a pulp concentration of 60 g/L. Fig. 8 a illustrates that when the frother dosage is fixed at a low level, the combustible recovery rate increases with the increase in collector dosage. When the frother dosage reaches 500 g/t, the combustible recovery rate initially increases and then decreases with an increase in collector dosage. When the collector dosage is fixed at a low level, the combustible recovery rate increases with the increase in frother dosage. When the collector dosage is 1000 g/t, the combustible recovery rate initially increases and then decreases with an increase in frother dosage. The maximum value of 97.13% is achieved at a sec-octanol dosage of 275 g/t. Fig. 8 b,c exhibit similar patterns to that of Fig. 8 a.



Fig. 9. Contour plots of flotation Improvement Index a, b, and c correspond to slurry concentrations of 60 g/L, 75 g/L, and 90 g/L, respectively

Fig. 9 a presents a contour map of the flotation improvement index at a pulp concentration of 60 g/L. It shows that when the collector dosage is less than 540 g/t, the flotation improvement index decreases as the frother dosage decreases. When the collector dosage exceeds 540 g/t, the flotation improvement index initially increases and then decreases with an increase in frother dosage at a fixed collector concentration. Fig. 9 b and Fig. 9 c exhibit a similar trend to Fig. 9 a, with a maximum value of 58.12% observed when the collector dosage is 997.33 g/t, the frother dosage is 191.27 g/t, and the pulp concentration is 60 g/L.

At a pulp concentration of 60 g/L, as the foam layer height increases, the flotation improvement index exhibits a trend of first increasing and then decreasing, reaching its maximum value at a foam layer height of 13 cm. Similarly, the combustible recovery rate also increases initially and then decreases with an increase in maximum foam layer height, reaching its maximum value at a foam layer height of 17 cm. These findings indicate that an excessively high or low foam layer is detrimental to the enhancement of both the combustible recovery rate and the flotation improvement index; thus, maintaining an optimal foam layer height is critical for improving the combustible recovery rate.

4. Conclusion

- (1) The foaming performance of the XZ agent alone is insufficient, requiring a dosage greater than 2000 g/t to achieve a flotation improvement index greater than 55% and a combustible recovery rate exceeding 80%.
- (2) When the XZ agent is combined with sec-octanol, the two-phase and three-phase foam heights could be increased by a maximum of 5 cm and 15 cm, respectively. This combination allows for a reduction in the XZ agent dosage to 1500 g/t, thereby improving cost efficiency without compromising flotation performance.
- (3) Excessively high or low froth layer heights negatively impact flotation performance, and optimal flotation is achieved only when the froth layer height is maintained at an intermediate level, resulting in cost reductions and improved efficiency.

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