

Article

Sustainable Recovery of Fine Coal Slime Through Particle Size Classification and Reflux Flotation Cell Technology

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Abstract

Guided by the objectives of sustainable coal utilization and resource efficiency improvement, this study investigated the recovery of fine, high-ash coal slime using a Reflux Flotation Cell (RFC). Particle size analysis showed that the -0.074 mm fraction accounted for approximately 33.3% of the feed and exhibited poor flotation performance in conventional classification flotation, resulting in substantial combustible matter losses. To improve the recovery of this fine fraction, flotation experiments were conducted using the RFC. Under the optimum operating conditions, combustible matter recovery of the -0.074 mm fraction reached 89.92%, approximately 10 percentage points higher than that achieved by conventional flotation. The improved performance enhances the utilization of low-grade coal resources while reducing combustible matter losses to tailings. The superior separation performance of the RFC is attributed to its unique hydrodynamic characteristics. High-shear flow in the downcomer generates abundant microbubbles and promotes particle–bubble collisions, whereas the inclined channels accelerate gangue settling through the Boycott effect, improving the separation efficiency of fine particles. These results demonstrate that the RFC provides an effective approach for the sustainable recovery of fine coal slime and offers theoretical support for improving resource utilization and reducing solid waste generation in coal preparation.

Keywords: fine coal slime; reflux flotation cell; flotation; sustainable resource utilization; classified particle sizes



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1. Introduction

Flotation is widely used as an effective beneficiation technique for separating fine and ultrafine particles [1–3]. It is extensively applied in the mineral industry, processing an estimated over 2 billion tons of minerals and coal annually. With accelerating industrialization worldwide, the large-scale exploitation of mineral resources has led to the depletion of easily processable ores [4,5], while the proportion of low-grade, finely disseminated, and complex refractory resources has rapidly increased, placing significant pressure on coal preparation plants.

The flotation efficiency of coal slime is influenced by multiple factors, including coal quality characteristics, pulp concentration, reagent regime, and particle size distribution [6]. Coal floatability varies with metamorphic degree, showing a polarized trend: lignite and anthracite exhibit poor hydrophobicity due to high porosity or overly dense structures,

while bituminous coal (e.g., coking coal) achieves optimal hydrophobicity [7,8], with contact angles increasing with carbon content up to a peak before declining. Pulp concentration impacts separation by regulating reagent distribution and particle collision efficiency; higher concentrations reduce reagent consumption but hinder coarse particle flotation (due to fine slime interference), while lower concentrations increase throughput but lower dry coal capacity, necessitating dynamic adjustments based on feed slime content. Reagent selection must align with coal slime properties: low-activity collectors suit easily floatable slimes, whereas high-activity reagents target refractory fine slimes. Coarse particles require frothers generating small, long-lasting bubbles to enhance attachment, while fine particles benefit from larger, fragile bubbles to strengthen secondary enrichment [9]. Particle size significantly affects flotation kinetics, with 0.074–0.25 mm particles showing the fastest rates. Coarse and fine particles compete for reagents due to surface area disparities; fine particles dominate adsorption, leaving coarse particles insufficiently hydrophobic and prone to tailings loss. Precise control of reagent dosage is essential to maintain flotation selectivity and minimize entrainment, while size-by-size or classified processing enhances separation efficiency by accommodating the distinct flotation kinetics of different particle size fractions [10].

Mixed coal slime flotation has several drawbacks, including excessive feed size ratios, contamination of clean coal with high-ash fines, and significant fluctuations in the combined clean coal quality. To address these issues, researchers have proposed a classified flotation process for coal slime. This method leverages the distinct flotation behaviors of particle size fractions in coal slime. Using classification equipment, the feed is separated into coarse and fine fractions, which are then processed with tailored reagents and equipment to achieve optimal clean coal ash content and yield [11–13]. Huang et al. [14] optimized classified flotation conditions for refractory coal slime dominated by high-ash fine particles, using 0.074 mm as the classification cutoff. The results showed that the optimal flotation conditions for the 0.5–0.074 mm and <0.074 mm particle fractions included a collector dosage of 1000 g/t, a frother dosage of 100 g/t, and a pulp concentration of 80 g/L. The <0.5 mm fraction could not produce clean coal with ash content below 10%. The cumulative yield from classified flotation exceeded full-size flotation by 2.55%. Chao Ni [15] conducted orthogonal tests on the classified flotation of coal slime from a plant in Shandong province. Six flotation kinetic models were used to fit the experimental flotation data. For coal particles in the size range of 0.5–0.25 mm, the second-order rectangular distribution model showed the best fitting performance. For the samples between 0.25 and 0.125 mm and those between 0.125 and 0.074 mm, the first-order matrix distribution model is the most suitable. Since mixed flotation compromises clean coal quality, researchers employed orthogonal tests, size analysis, and stepwise release flotation to identify particle size distribution as the primary factor affecting flotation efficiency, leading to the adoption of classified flotation [16]. By narrowing feed size ranges (e.g., 0.125 mm cutoff), hydrocyclones separate feed into +0.125 mm (processed via flotation machine and filter) and –0.125 mm (processed via flotation column and filter press). This strategy leverages the strengths of flotation machines (coarse-particle recovery through sufficient bubble–particle contact) and columns (intensive cleaning of high-ash fines), thereby minimizing fine slime contamination [17,18]. In summary, classified flotation effectively reduces clean coal ash content, enhances yield, and enriches organic-rich coal particles, outperforming full-size flotation. Despite these encouraging results, classified flotation alone cannot fundamentally overcome the poor floatability of ultrafine coal slime. The flotation recovery of particles smaller than 0.074 mm remains limited because of low collision efficiency, severe slime entrainment, and insufficient selectivity. Therefore, a more efficient flotation device is still required for the recovery of classified ultrafine coal slime.

In the early 21st century, a novel system called the Reflux Flotation Cell (RFC) emerged. Pioneered by Dickinson and Galvin [19–21], this system was designed to enhance bubble–liquid separation and improve the segregation of hydrophobic and hydrophilic particles. Their research incorporated inclined channels below a vertical separation chamber, strengthening bubble–liquid separation. The Boycott effect, observed in inclined channels, accelerates particle settling compared to vertical configurations—demonstrated in phenomena such as oxalate-prevented agglomeration or rapid blood cell sedimentation [22]. Davis and Gecol further revealed that inclined settlers enable particle separation based on size and density: larger, denser particles settle into the underflow, while smaller, lighter particles migrate to overflow. As particle concentration increases, hindered settling slows sedimentation rates, driving more particles toward overflow [23]. The RFC also features multichannel designs, fritted spargers, and sleeve-type downcomers. Its advantages lie in two key aspects: generating ultrafine bubbles and delivering high liquid shear rates to enhance bubble–particle collision efficiency and mineralization [24]. Although classified flotation has been demonstrated to improve the flotation performance of coal slime, the flotation efficiency of fine (<0.074 mm) coal particles remains unsatisfactory because of their low collision probability with bubbles, high entrainment of gangue minerals, and poor selectivity. Existing studies have mainly optimized reagent regimes or classification conditions, while the potential of combining classified flotation with advanced flotation equipment has received limited attention. In particular, the application of the Reflux Flotation Cell (RFC) to the recovery of ultrafine classified coal slime has rarely been systematically investigated.

This study constructs such a system and applies it to the flotation of classified -0.074 mm coal slime particles. Using coal samples from a Mongolian coal preparation plant, this study employs classified flotation with equipment such as flotation machines and RFC. Images of bubbles in the RFC device were captured using a high-speed camera and processed with ImageJ 1.54j to obtain the bubble diameter distribution and analyze and calculate the bubble surface area flux.

2. Method and Methodology

2.1. Materials

The raw coal samples mentioned in this paper were obtained from a coal preparation plant in Inner Mongolia. CCl_4 , CHBr_3 , and C_6H_6 were purchased from Maclean Biochemical Co., Ltd. (Shanghai, China) Kerosene and sec-octanol were obtained from Shanghai Aladdin Biochemical Technology Co., Ltd. (Shanghai, China).

2.2. Sample Properties

The raw coal was processed into experimental and analytical samples, which were sealed to prevent oxidation. A fully automated industrial analyzer was used to determine moisture, ash, volatile matter, and other parameters. The elemental analyzer can be used to determine the contents of major elements (e.g., C, H, N, S) in the material, which in turn allows for inference of the degree of coalification and the metamorphic stage of the sample.

Based on industrial analysis (Table 1) and elemental analysis (Table 2), this sample is classified as a medium-ash, low-sulfur coal. The calculated fixed carbon (FC_d) content reaches 58.82%, indicating excellent sorting potential.

Table 1. Proximate Analysis of Raw Coal.

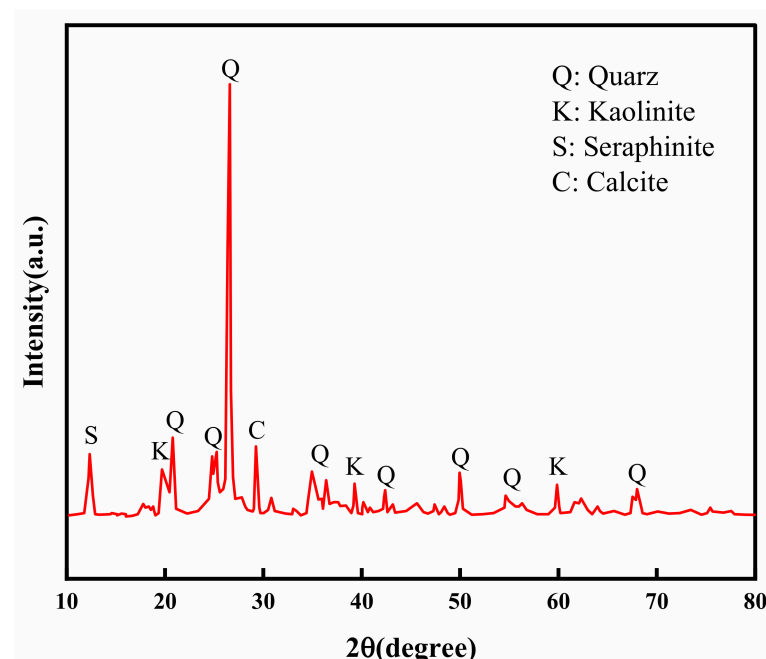
Parameter	Mad/%	Aad/%	Vad/%	FCad/%
Content	0.92	21.23	19.55	58.30

Table 2. Elemental Analysis of Raw Coal.

Element	Cdaf/%	Hdaf/%	Odaf/%	Ndaf/%	St, ad/%
Content	86.64	4.78	6.99	0.76	0.83

The coal samples were analyzed using a D8 DISCOVER X-ray diffractometer (Bruker, MA, USA), with data processed via Jade 6.0 software.

Analysis of Figure 1 reveals that this coal sample consists primarily of quartz, with minor amounts of kaolinite, seraphinite, and calcite. Quartz, benefiting from its pronounced hydrophilicity, contrasts with coal's inherent hydrophobicity, enabling its effective separation from coal concentrate by flotation. However, minerals like kaolinite readily form slime that coats the surface of coal concentrate, diminishing its flotation performance and resulting in poor flotation outcomes. Furthermore, minerals like kaolinite are prone to entrainment during flotation, further impairing separation efficiency. The presence of numerous easily muddable products, such as kaolinite and chlorite, in the fine particles necessitates the implementation of graded flotation measures to ensure adequate yield. This approach enhances the recovery efficiency of the coal concentrate.

**Figure 1.** X-Ray Diffraction Pattern of The Sample.

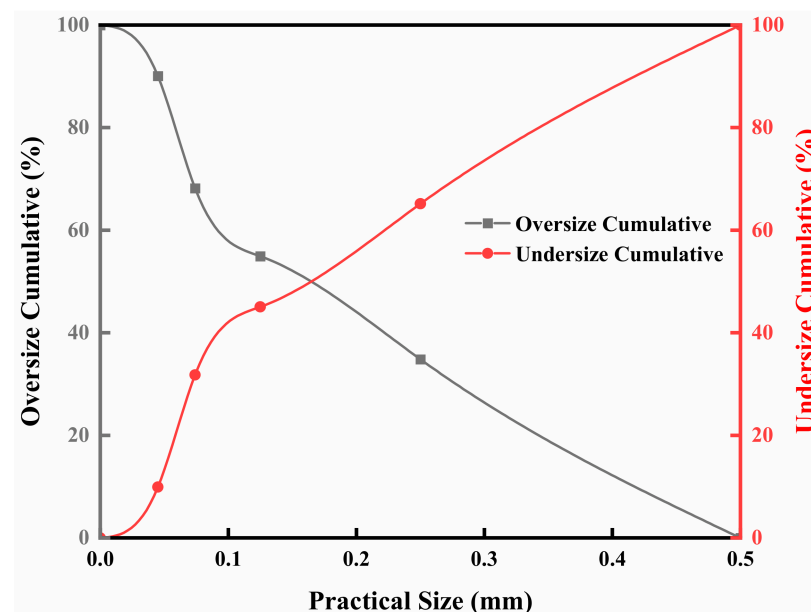
Density analysis was carried out using five organic heavy liquid mixtures composed of CCl_4 , CHBr_3 , and C_6H_6 , with densities of 1.3 g/cm^3 , 1.4 g/cm^3 , 1.5 g/cm^3 , 1.6 g/cm^3 , and 1.8 g/cm^3 .

Table 3 presents the density analysis results of the raw coal. The fraction with a density above 1.8 g/cm^3 accounts for 5.04%, and this fraction shows a high ash content of 77.34%. The proportion of the 1.3 g/cm^3 density fraction is 61.84%, which is the dominant density fraction, and the ash content is 9.89%. The yield of the low-density fraction ($\sim 1.4 \text{ g/cm}^3$) reached 77.74%, and the ash content was 10.95%. The results show that low-density coal samples account for the main proportion, which indicates that the material is favorable for flotation.

Table 3. Density Analysis of Raw Coal.

Density Fraction (g/cm ³)	Yield/%	Ash Content/%	Float Cumulative		Sink Cumulative	
			Yield/%	Ash Content/%	Yield/%	Ash Content/%
<1.3	61.84	9.89	61.84	9.89	100	20.41
1.3–1.4	15.9	15.05	77.74	10.95	38.16	37.47
1.4–1.5	7.16	35.32	84.9	13.00	22.26	53.48
1.5–1.6	6.6	49.68	91.5	15.65	15.1	62.10
1.6–1.8	3.46	63.58	94.95	17.40	8.5	71.74
>1.8	5.04	77.34	100	20.41	5.04	77.34
Total	100	20.41				

Particle size analysis (Figure 2) was conducted by wet sieving with standard sieves of apertures 0.25 mm, 0.125 mm, 0.074 mm, and 0.045 mm. Table 4 presents the proximate analysis results of the raw coal. The 0.5–0.25 mm size fraction is the most prominent, with a yield of 34.82%. The yields for the 0.25–0.125 mm and 0.074–0.045 mm size fractions also reached 20.12% and 21.91%, respectively. The overall particle size distribution of the coal sample showed an uneven, wave-like pattern with a relatively high amonumberunt of fine particles. The yield of the <0.074 mm fraction was 31.82%, making up roughly one-third of the total sample. However, this fine coal slurry tends to become muddy, which negatively impacts flotation efficiency. Therefore, conventional mixed flotation produces suboptimal results. Graded flotation is needed to improve the recovery of combustible material in the concentrate, thereby enhancing flotation efficiency.

**Figure 2.** Particle Size Analysis of Raw Coal.**Table 4.** Structural Parameters of the Equipment.

Parameter	Unit	Value
Vertical section cross-sectional area	mm ²	100 × 100
Inclined section cross-sectional area	mm ²	100 × 100
Inclined channel length	mm	500
Inclination angle	°	70
Inclined plate thickness	mm	4

2.3. XFD Single-Cell Flotation Experiments

The coal slime used in the flotation experiments was separated into five particle size fractions: 0.5–0.25 mm, 0.25–0.125 mm, 0.125–0.074 mm, 0.074–0.045 mm, and <0.045 mm. Each fraction was weighed and then placed into the flotation cell. The flotation tests were conducted under fixed operating conditions. First, after pouring the pulp into the cell, it was stirred for 4 min. Next, kerosene was added as a collector at a dosage of 600 g/t, followed by another 3 min of stirring. Then, sec-octanol was added as a frother at a dosage of 150 g/t, with continued stirring for 2 min. Subsequently, the air valve was opened for 30 s, and froth scraping was performed for 3 min. The product was filtered using a vacuum filter, dried in an oven, weighed on a balance, and finally burned in a muffle furnace to calculate the combustible recovery rate of clean coal for each product.

2.4. Stepwise Release Experiments

Stepwise release tests were performed using an XFD flotation cell. The pulp concentration was 100 g/L, the agitation speed was 2000 r/min, and the air injection rate was 0.05 m³/h. Kerosene (dose: 600 g/t) served as the collector, while sec-amyl alcohol (dose: 150 g/t) acted as the frother. The roughing process was stopped no visible mineralized froth was produced for 10 s. Before each concentrating stage, the air valve was closed, and the entire concentrate foam pulp scraped from the previous stage was reinjected into the flotation cell. Then, the flotation machine was turned on and agitated for 2 min. Next, water was added to ensure the pulp level was approximately 10 mm below the second calibration line in the flotation cell. Stirring continued for 30 s, followed by rapid water addition to raise the pulp level to the second calibration line. The air valve was then opened, and froth was continuously collected until no visible mineralized froth was produced for 10 s. The experiment concluded after one rougher and four cleaner stages. The combined rougher-cleaner process gradually separated the coal particles in accordance with the experimental protocol. Experimental results were obtained through product calculation and analysis.

2.5. RFC Experiments

The RFC (Reflux Flotation Cell) system was assembled using purchased materials. The RFC mainly features a traditional vertical section and an inclined section. The entire device was built from acrylic panels, with specific parameters listed in Table 4.

3. Results and Discussion

3.1. Effect of Coal Particle Size on Flotation Performance

The raw coal slime used in this section's flotation tests was separated into the following particle size ranges: 0.5–0.25 mm, 0.25–0.125 mm, 0.125–0.074 mm, 0.074–0.045 mm, and <0.045 mm. Each fraction was weighed, transferred to the flotation cell, and floated under consistent conditions.

From Figure 3, it can be observed that under fixed conditions, the ash content of clean coal varies across the particle size ranges of coal slime: 0.5–0.25 mm, 0.25–0.125 mm, 0.125–0.074 mm, 0.074–0.045 mm, and less than 0.045 mm. The corresponding ash contents are 16.14%, 16.98%, 17.04%, 17.89%, and 17.97%, respectively. It can also be noted that the ash content of the 0.25–0.125 mm and 0.125–0.074 mm particle size ranges is nearly identical, while the ash content of the 0.074–0.045 mm and less than 0.045 mm ranges shows minimal difference.

Figure 4 shows that the recovery of clean coal through flotation varies among the five particle size fractions of coal slime. The recovery rates for the 0.5–0.25 mm, 0.25–0.125 mm, 0.125–0.074 mm, 0.074–0.045 mm, and <0.045 mm fractions are 92.21%, 87.58%, 86.73%, 82.49%, and 81.02%, respectively. The data suggest that the recovery rates

for the 0.25–0.125 mm and 0.125–0.074 mm fractions are very similar, and the recovery values for the 0.074–0.045 mm and <0.045 mm fractions are also comparable. Based on Figures 3 and 4, since the ash content is higher and the recoverable combustible matter is lower for the 0.074–0.045 mm and <0.045 mm particle size fractions—and the values for these two fractions are not significantly different—and since the <0.074 mm particles are smaller and require higher energy input to increase the probability of flotation adhesion, 0.074 mm was selected as the particle size for classification flotation.

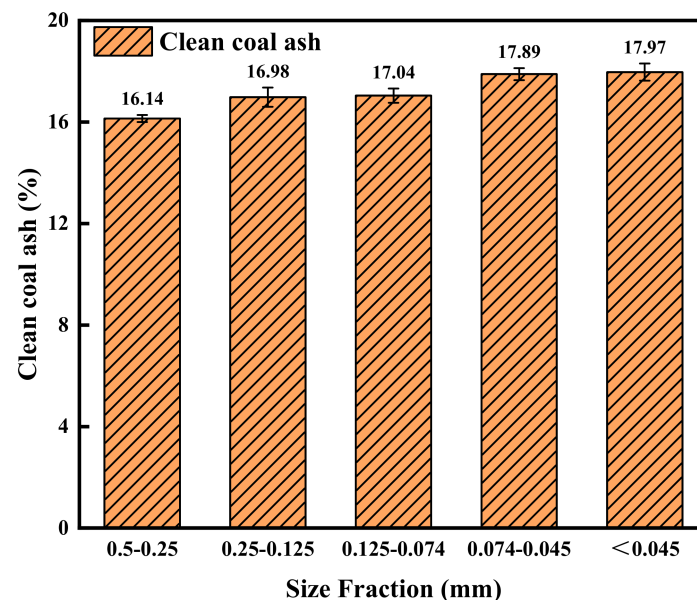


Figure 3. Ash Content of Clean Coal by Size Fraction.

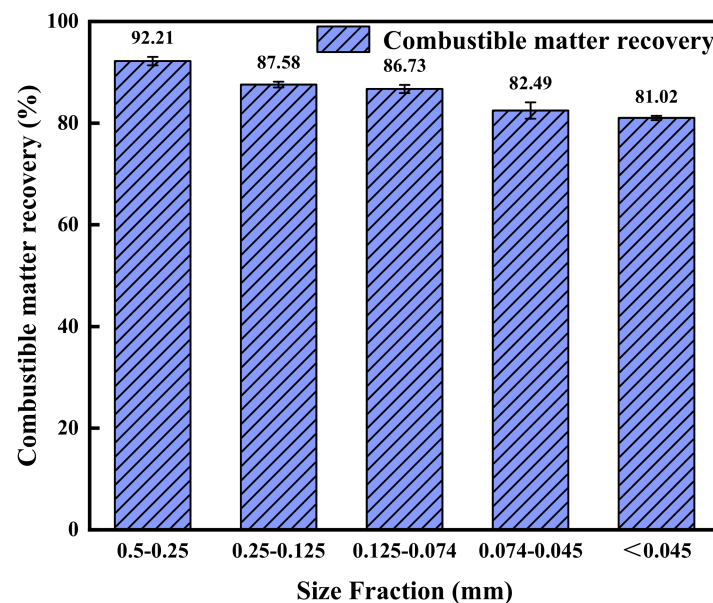


Figure 4. Combustible Matter Recovery of Clean Coal by Size Fraction.

3.2. Classified Size Fraction Distribution Release Flotation Experiment

The cumulative yield–ash curves for clean coal from each particle size fraction were plotted based on the experimental results, as shown in Figure 5. They were obtained under the same flotation conditions used for the stepwise release tests of different particle size fractions. When the ash content of clean coal is below 10%, the cumulative yields of the <0.5 mm, 0.5–0.25 mm, 0.25–0.074 mm, and <0.074 mm fractions reach 70.76%, 73.21%,

77.39%, and 69.82%, respectively. The theoretical combustible recovery values are 80.82%, 83.76%, 87.16%, and 79.37%. The flotation performance of coal slime can be assessed by comparing the combustible recovery across the full particle size range (<0.5 mm) and the classified size fractions. The implied order of floatability is: 0.25–0.074 mm > 0.5–0.25 mm > (<0.5 mm) > (<0.074 mm).

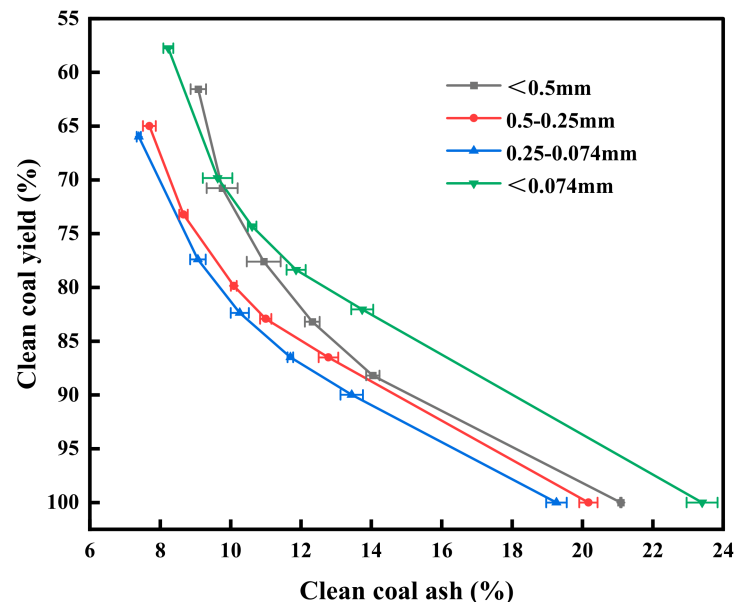


Figure 5. Yield–Ash Curves of Clean Coal for Different Coal Slime Size Fractions.

3.3. Optimization of Feeding Concentration for Each Size Fraction

From Figure 6a, it can be observed that as the pulp concentration increased from 25 g/L to 150 g/L, the ash content of clean coal for the <0.5 mm particle size range initially increased, then gradually stabilized, and finally rose again, maintaining an overall upward trend. The yield and combustible recovery of clean coal first increased to a peak, then declined. The optimal pulp concentration was 100 g/L. At this level, the ash content dropped to the lowest point of 18.03%, while the yield and combustible recovery reached their highest values of 84.64% and 87.14%. Figure 6b illustrates the effect of pulp concentration. As the pulp concentration increased from 25 g/L to 150 g/L, the ash content of the 0.5–0.25 mm fraction gradually rose. Conversely, the yield and combustible recovery initially increased, then stabilized once they reached an optimal level. The best pulp concentration was 75 g/L, resulting in the lowest ash content (14.66%) and the highest yield (82.26%) and combustible recovery (88.17%).

Figure 6c illustrates the effect of pulp concentration on the 0.25–0.074 mm particle size fraction. As the concentration grows from 25 g/L to 150 g/L, the ash content fluctuates but generally increases. The yield and combustible recovery of clean coal first rise, then fall, and finally stabilize. The ideal pulp concentration is 75 g/L. At this point, the ash content reaches its lowest value of 16.45%, while the yield and combustible recovery reach their maximum values of 90.45% and 94.91%.

Figure 6d presents the results for the <0.074 mm particle size fraction. As the pulp concentration increases from 25 g/L to 150 g/L, the ash content initially decreases, then gradually increases. The yield and combustible recovery first peak, then decline, and ultimately level off. The optimal pulp concentration is 50 g/L. At this level, the ash content is at its lowest at 17.35%, and the yield and combustible recovery achieve their highest values of 73.21% and 76.92%.

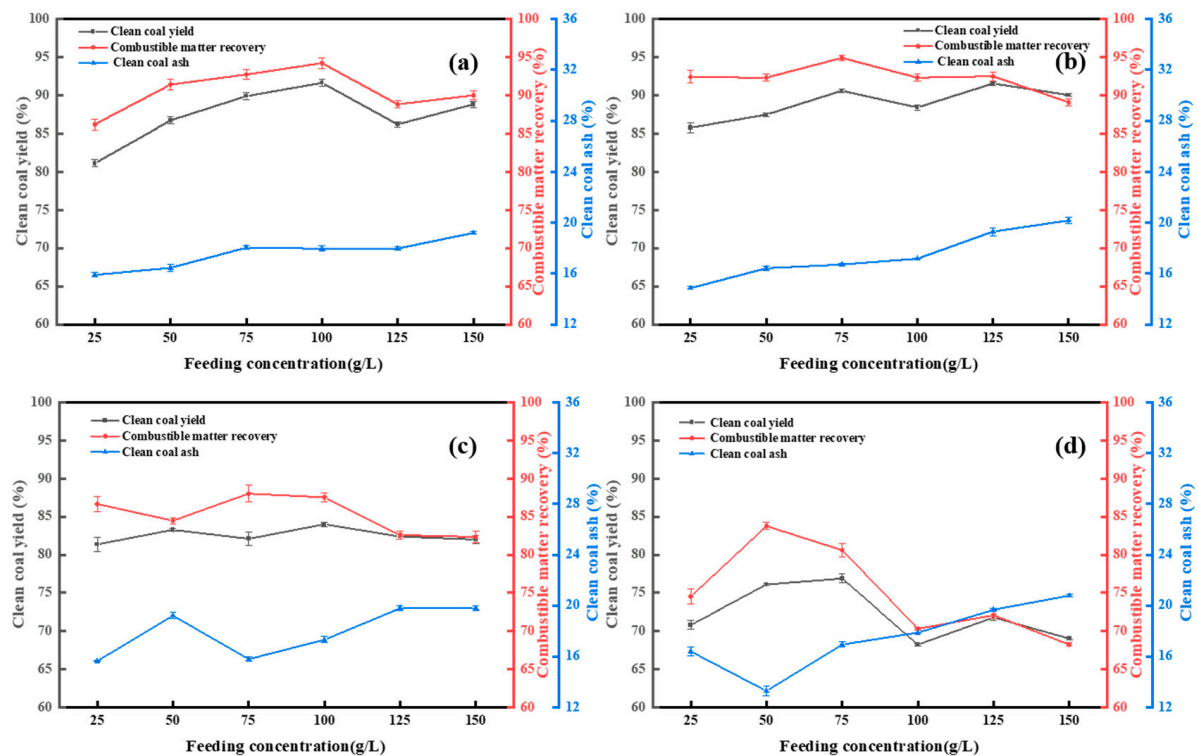


Figure 6. Relationship between feeding concentration and flotation performance indicators. (a) <0.5 mm size fraction; (b) 0.5–0.25 mm size fraction; (c) 0.25–0.074 mm size fraction; (d) <0.074 mm size fraction.

From Figure 6, it can be seen that as the pulp concentration gradually increases, the order of combustible recovery rates for both classified and full particle size ranges of clean coal is 0.25–0.074 mm > 0.50–0.25 mm > (<0.5 mm) > (<0.074 mm). Therefore, increasing the pulp concentration of coal slime raises the number of mineral particles in the slurry, which enhances the likelihood of particle–bubble attachment and boosts clean coal yield. However, excessively high pulp concentrations increase slurry viscosity, impairing bubble dispersion and potentially leading to lower clean coal yields and higher ash content. Based on the optimal pulp concentrations identified for each particle size range in this study, it is clear that finer coal slime particles (<0.074 mm) perform better at lower pulp concentrations during flotation, while coarser particles (0.25–0.5 mm) are more suitable at higher pulp concentrations.

3.4. Research on RFC Enhanced Flotation of Fine Particles

3.4.1. Aeration Rate Optimization Using RFC

From Figure 7, it can be seen that as the aeration rate rises from 0.2 m³/h to 1.6 m³/h, the ash content of clean coal for the <0.074 mm particle size range consistently increases. Meanwhile, the yield and combustible recovery of clean coal initially increase to a peak and then level off. The optimal aeration rate for this particle size range is 1.2 m³/h, with an ash content of 17.13%, a yield of 76.74%, and the highest combustible recovery of 87.12%. Overall, the ash content of flotation products increases linearly due to the increased entrainment of gangue particles into the liquid overflow, which results in higher ash levels. The yield and combustible recovery of flotation products grow with higher aeration rates. Within the aeration range of 0.2–1.6 m³/h, the combustible recovery varies between 81% and 87%. This phenomenon can be explained by two factors: First, higher gas flow rates increase bubble density in the downcomer and launder, enhancing the chances of bubble–particle collisions and attachments, thereby improving combustible recovery.

Second, elevated gas flow rates boost liquid overflow rates, promoting the entrainment of finer particles, which leads to higher yield and combustible recovery. Due to their low gravitational and inertial forces, ultrafine particles tend to follow the entrained liquid flow. In conventional flotation, hydraulic entrainment is often the main mechanism for fine particle recovery.

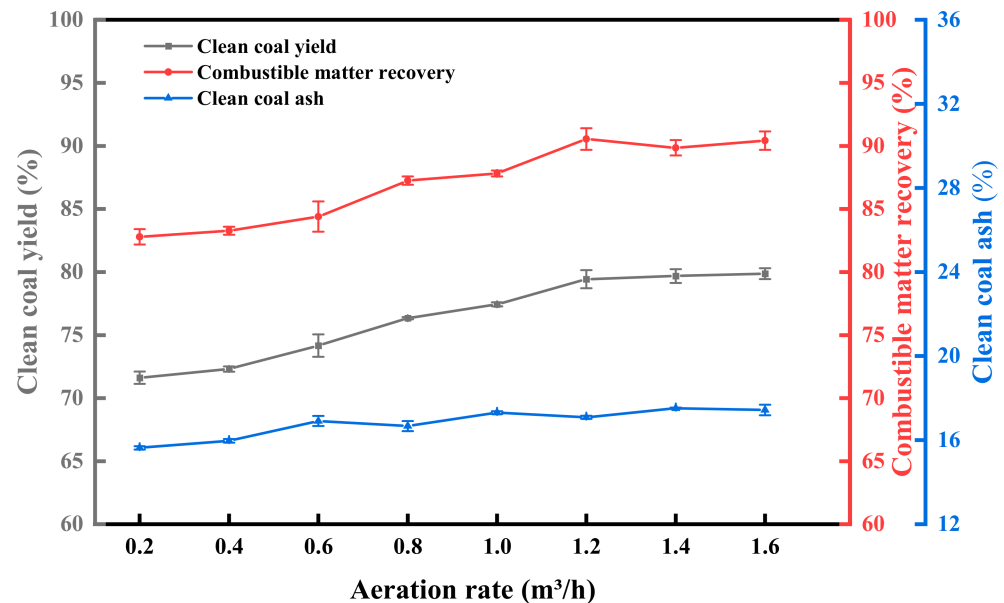


Figure 7. Relationship between aeration rate and flotation performance indicators using RFC.

3.4.2. Feed Rate Optimization Using RFC

From Figure 8, it is clear that as the feed rate increases, the ash content of clean coal gradually rises. When the feed rate increases from 0.5 L/min to 2.5 L/min, both yield and combustible recovery initially increase slowly and then reach an optimal point. As the feed rate further increases from 2.5 L/min to 4.0 L/min, the yield and combustible recovery gradually decline before stabilizing. The optimal feed rate is 2.5 L/min, which results in the lowest ash content (16.41%) and the highest yield (78.53%) and combustible recovery (89.92%). Overall, the ash content of flotation products increases steadily due to gangue particles being entrained into the overflow before separation, driven by higher feed rates. Within the range of 0.5–4.0 L/min, the clean coal yield varies from 72% to 79%, and combustible recovery from 84% to 89%. However, both the yield and combustible recovery curves first increase, then peak, decline, and stabilize. At low feed rates (e.g., 0.5 L/min), insufficient bubble generation and oversized bubbles reduce bubble–particle collision efficiency, leading to lower initial yield and recovery. As the feed rate reaches 2.5 L/min, both peak. Beyond this point, excessive feed rates shorten flotation retention time, which decreases coal particle interaction with the collector and lowers yield and recovery.

3.4.3. Effect of Bubble Surface Area Flux in RFC

Bubble diameter is one of the most critical parameters governing bubble–particle collision, attachment, and aggregate stability during flotation. Yoon et al. [25] demonstrated that the collision probability increases exponentially with the ratio of particle diameter to bubble diameter. Moreover, numerous studies have reported that a moderately intensified turbulent environment promotes bubble–particle collision and attachment efficiencies [26].

The bubble surface area flux (S_b) is defined as the total bubble surface area passing through a unit cross-sectional area per unit time. It is widely recognized as an important parameter characterizing the particle-carrying capacity and flotation kinetics of flotation

systems. S_b can be calculated from gas-phase parameters such as bubble size, superficial gas velocity, and gas holdup, as described in Equation (1).

$$S_b = 6J_g/D_b \quad (1)$$

where J_g is the superficial gas flux and D_b is the bubble diameter.

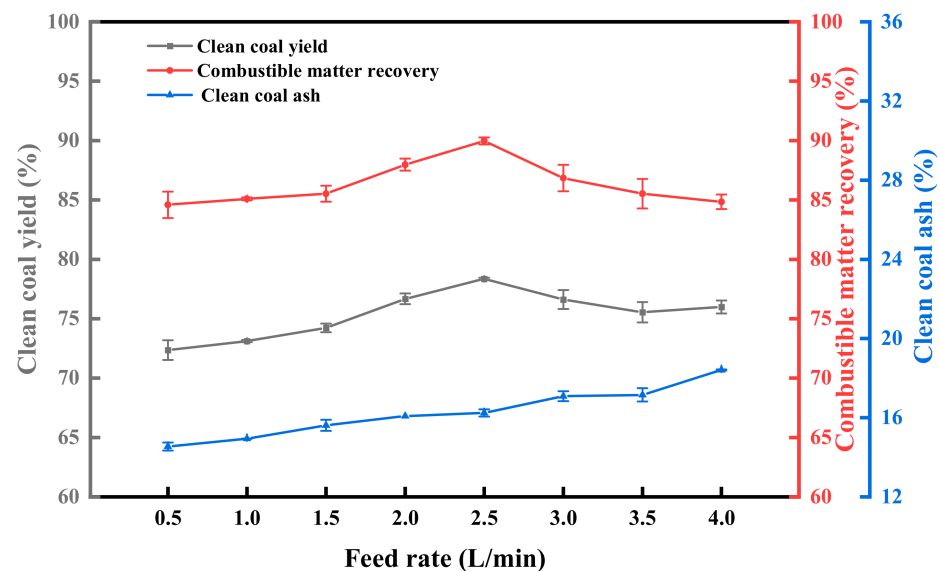


Figure 8. Relationship between feed rate and flotation performance indicators using RFC.

In conventional flotation systems, S_b is typically limited to 12–120 s^{-1} due to constraints imposed by flotation kinetics and froth stability [27]. Excessively high superficial gas and liquid velocities can destabilize the froth layer, hinder concentrate overflow, increase entrainment into the underflow, and consequently reduce flotation recovery. In contrast, the RFC incorporates an inclined channel section that provides secondary separation of mineralized particles reporting to the underflow, enabling stable operation under significantly higher gas and liquid fluxes.

Bubble images were captured using a high-speed camera system and processed with Image J software to determine bubble size distributions, Figure 9 shows the cumulative frequency distribution of bubble diameters at different V_g values. Subsequently, S_b was calculated using Equation (1). Figure 10 presents the variation in S_b under different superficial liquid and gas velocities, with a maximum value of 446.74 s^{-1} .

As shown in Figure 10a, S_b increased approximately linearly with increasing superficial gas velocity. This trend is primarily attributed to the direct proportional relationship between S_b and superficial gas velocity. Although bubble diameter increased slightly with increasing gas velocity, the strong shear environment within the RFC downcomer effectively suppressed bubble coalescence, maintaining relatively stable bubble sizes with maximum diameters below 0.8 mm. Consequently, the increase in gas velocity resulted in a continuous increase in S_b .

Figure 10b illustrates the influence of superficial liquid velocity on S_b . At relatively low superficial gas velocities (0.91–1.83 cm/s), S_b increased nearly linearly with increasing liquid velocity. However, at higher superficial gas velocities (2.20–3.94 cm/s), S_b initially increased and then approached a plateau, reaching a maximum value of 446.74 s^{-1} at a superficial liquid velocity of 7.35 cm/s and a superficial gas velocity of 3.94 cm/s.

The different trends can be attributed primarily to variations in bubble size. Under low gas velocity conditions, increasing liquid velocity enhances bubble breakup through shear forces, resulting in smaller bubbles and consequently higher S_b values. In contrast,

under high gas velocity conditions, the elevated bubble concentration requires substantially greater energy input for further bubble size reduction. As a result, bubble diameter becomes less sensitive to changes in liquid velocity, leading to a reduced growth rate of S_b .

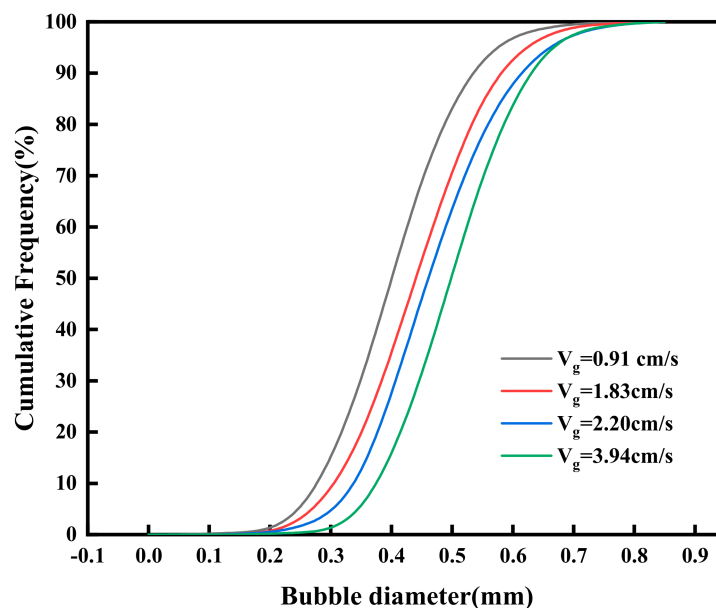


Figure 9. Cumulative Frequency of Bubble Diameters at Different V_g Values.

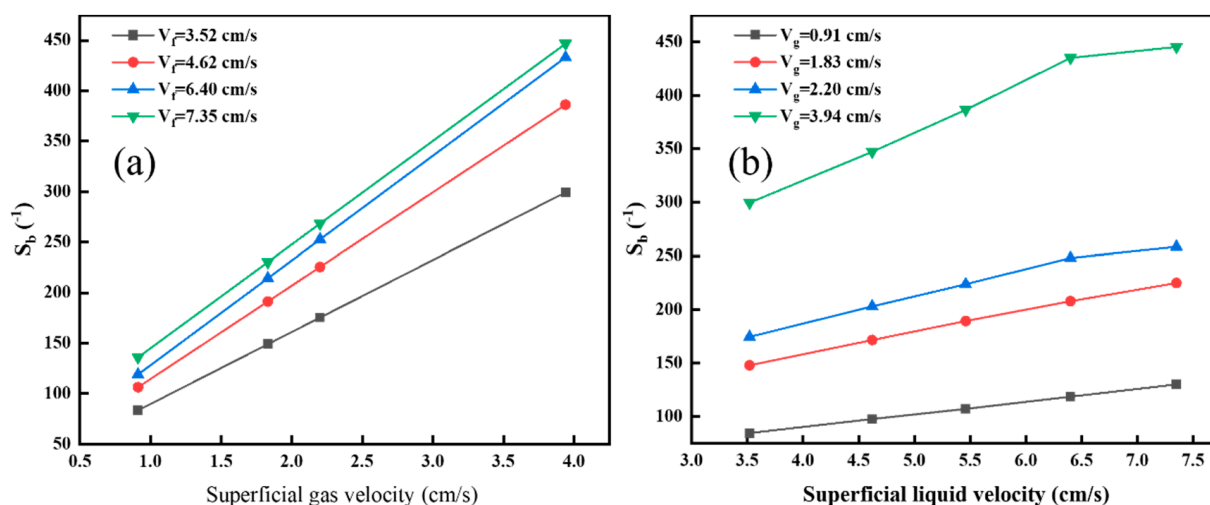


Figure 10. Variation in bubble specific surface area flux: (a) at constant superficial liquid velocity; (b) at constant superficial gas velocity.

The flotation performance shown in Figure 8 is consistent with the variation in bubble surface area flux presented in Figure 10. As the feed rate increased to an appropriate level, the higher superficial liquid velocity promoted bubble breakup and increased the S_b value, thereby providing a larger gas–liquid interfacial area and increasing the probability of bubble–particle collision and attachment. Consequently, combustible matter recovery reached its maximum at a feed rate of 2.5 L/min. When the feed rate was further increased, the residence time of particles in the RFC became insufficient despite the relatively high S_b , resulting in a decline in flotation performance.

Overall, the observed increase in S_b with superficial liquid velocity provides a fundamental basis for flotation intensification in the RFC. Under moderate feed throughput conditions, the increase in S_b enhances the gas–liquid interfacial area and promotes bubble–particle collision and attachment, resulting in improved combustible matter recovery.

However, when the feed rate is further increased, the shortened particle residence time partially offsets the benefit of the elevated S_b , leading to a decline in flotation performance.

3.4.4. Yield Advantage Provided by the RFC Inclined Channel

The hydraulic advantage in the inclined channel can be interpreted using the PNK theory, which originated from the pioneering studies of Ponder [28] and Kinoshita [29]. The analytical model and hydraulic advantage equations adopted in this work follow the formulation developed by Galvin et al. [21]. The schematic diagram is shown in Figure 11. According to Galvin et al. [21], the hydraulic advantage factor F is a dimensionless hydraulic advantage factor representing the ratio of the effective settling area of an inclined channel to its projected vertical cross-sectional area. A larger value of F indicates a greater effective settling area and therefore a stronger Boycott effect, which is presented in Equation (2).

$$F = \frac{wB + BL \cos \theta}{wB} = 1 + \frac{L \cos \theta}{w} \quad (2)$$

Here, w is the horizontal width of the channel, B is the width of the channel perpendicular to the horizontal direction, L is the length of the channel, and θ is the inclination angle of the channel relative to the horizontal direction. Substituting the vertical width of the inclined channel $z = w \sin \theta$ into Equation (3), following Galvin et al. [21], we can obtain Equation (4):

$$F = 1 + \frac{L \cos \theta}{z / \sin \theta} = 1 + \frac{L \sin \theta \cos \theta}{z} \quad (3)$$

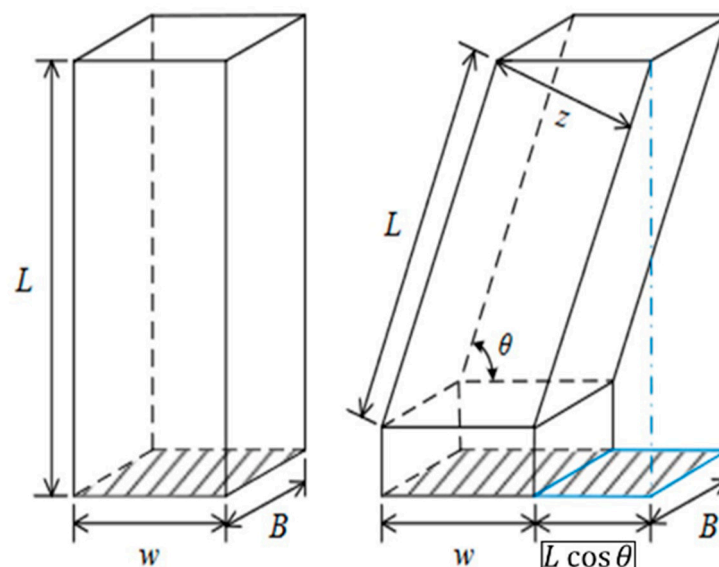


Figure 11. The effective area of channels at a tilt angle θ (shaded represents the effective settlement area of each system).

According to Equation (3), it can be seen that the hydraulic advantage obtained can be increased indefinitely, or even to infinity. However, this is not actually possible. The measurement of the real benefit of the inclined plate area is limited. In terms of the ratio of U/U_t , the separation efficiency of the liquid system is expressed by Equation (4):

$$\eta = \frac{U/U_t}{F} = \frac{U/U_t}{1 + L \sin \theta \cos \theta / z} \quad (4)$$

This expression indicates that the separation efficiency is governed by the balance between the superficial liquid velocity and the particle settling velocity, while the in-

clined geometry modifies the effective transport distance through the geometric factor $L \sin \theta \cos \theta / Z$.

U represents the surface air velocity in the vertical direction, and U_t is the particle's terminal velocity. By adjusting the particle size distribution, particle density, apparent fluidization velocity, the number of evenly spaced inclined channels across the container, the length of the plate, and the inclination angle, and based on the principle of dimensional analysis and experimental results and the empirical relationship proposed by Galvin et al. [21], the hydraulic advantage can be expressed as follows.

$$\eta = \frac{1}{1 + 0.133 \cos \theta Re_t^{1/3} (L/z)} \quad (5)$$

By combining Equation (4) with Equation (5), the actual yield advantage of RFC can be obtained as follows:

$$\frac{U}{U_t} = \frac{1 + L \sin \theta \cos \theta (L/z)}{1 + 0.133 \cos \theta Re_t^{1/3} (L/z)} \quad (6)$$

When the aspect ratio approaches infinity, the apparent velocity U of the vertical section is replaced by the apparent velocity U' of the inclined section, and the expression $\frac{U}{U_t}$ is converted to Equation (7):

$$\frac{U'}{U_t} = 7.5 Re_t^{-1/3} \quad (7)$$

Equation (7) indicates that under sufficiently large aspect ratios, the hydraulic performance becomes independent of the inclination angle while remaining primarily controlled by the particle Reynolds number. This simplified equation indicates that the apparent velocity needed for long-distance particle transport of a specific size is independent of the inclination angle. It is related to the Reynolds number of the particles. Therefore, in inclined channels, increasing the effective settlement area results in faster settlement than in standard vertical channels. This is another benefit of adding a tilt to the RFC channel.

The inclined channel provides two main advantages during coal slurry flotation. First, the larger cross-sectional area increases the terminal rise velocity of bubbles, helping them overcome downward liquid flow and enabling hydraulic upward transport within the inclined channel, which improves bubble separation from the liquid phase. Second, the larger effective settling area in the inclined channel allows for faster sedimentation compared to traditional vertical channels. Together, these effects make the RFC perform better in the flotation of fine coal slurry particles. That is why the RFC achieves higher separation efficiency than conventional flotation machines.

All variables in Equations (2)–(7) were expressed in SI units. The geometric parameters w , B , L and z are expressed in meters (m), while the superficial liquid velocity U and particle terminal settling velocity U_t are expressed in meters per second ($\text{m} \cdot \text{s}^{-1}$). The Reynolds number Re_t , hydraulic advantage factor F , separation efficiency η , and aspect ratio L/z are dimensionless. Therefore, each equation is dimensionally consistent.

4. Conclusions

Under optimal operating conditions, the combustible recovery of -0.074 mm coal slime using the Reflux Flotation Cell (RFC) reaches 89.92%, which is significantly higher than the 78.33% obtained using conventional mechanical flotation. This corresponds to an improvement of approximately 10 percentage points, demonstrating the superior separation efficiency of the RFC for fine coal particles. Based on the experimental results, the RFC increased combustible matter recovery from 78.33% to 89.92%, corresponding to an improvement of 11.59 percentage points. Assuming the treatment of 1000 kg of ultrafine coal slime, approximately 116 kg of additional combustible matter could be

recovered compared with the conventional flotation process, indicating a corresponding reduction in combustible material discharged to tailings. Although this estimation is based on laboratory-scale data, it demonstrates the potential of the proposed process to improve resource utilization efficiency and reduce solid waste generation. For an industrial coal preparation plant treating 1 Mt of ultrafine coal slime annually, the additional combustible matter recovered could theoretically reach approximately 1.16×10^5 t, highlighting the significant sustainability potential of the RFC.

The enhanced performance can be primarily attributed to the intensified bubble–particle interaction within the RFC system. The downcomer section of the RFC generates a highly turbulent microenvironment, which promotes the formation of finer bubbles and increases local shear rates. As a result, the bubble surface area flux is significantly enhanced, leading to a higher probability of collision and attachment between hydrophobic coal particles and air bubbles. This improved contact efficiency is particularly beneficial for fine and ultrafine coal slimes, where flotation efficiency is typically limited by poor collision probability and low attachment stability.

In addition, the unique inclined-channel structure of the RFC plays a critical role in phase segregation. The inclined plates induce a strong “Boycott effect,” which accelerates the hindered settling of hydrophilic gangue particles. This effect shortens the residence time of high-density particles in the flotation zone and facilitates their rapid migration toward the bottom region, where they are efficiently discharged through the tailing outlet. Consequently, the separation between hydrophobic and hydrophilic particles is further sharpened, contributing to both higher recovery and improved concentrate quality.

Despite the promising flotation performance obtained in this study, the applicability of the proposed method to different coal types and industrial operating conditions requires further verification. Future work will focus on CFD-assisted hydrodynamic analysis, pilot-scale validation, and optimization of RFC structural parameters to further improve flotation performance. It should be noted that the present comparison was performed under the standard operating conditions of each flotation device. Since the RFC and the conventional mechanical flotation cell exhibit different hydrodynamic characteristics and particle residence time distributions, future studies will incorporate RTD measurements and residence-time-matched comparisons to further elucidate the contribution of hydrodynamics to flotation performance.

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