Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

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Online publication date: 27 February 2003

To cite this Article Li, B. , Tao, D. , Ou, Z. and Liu, J.(2003) 'Cyclo-microbubble Column Flotation of Fine Coal', Separation Science and Technology, 38: 5, 1125 — 1140
To link to this Article: DOI: 10.1081/SS-120018127
URL: http://dx.doi.org/10.1081/SS-120018127

SEPARATION SCIENCE AND TECHNOLOGY
Vol. 38, No. 5, pp. 1125–1140, 2003

Cyclo-microbubble Column Flotation of Fine Coal

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ABSTRACT

Cyclo-microbubble flotation column (CMFC) is an advanced column flotation technology for fine coal cleaning developed by China University of Mining and Technology (CUMT). It combines cyclone separation with column flotation to enhance pyritic sulfur rejection and separation efficiency. A specially designed external bubble generator is employed to efficiently precipitate fine bubbles on particle surface. A set of screen plates inside the column produces nearly plug-flow condition, which is preferred for flotation process. The CMFC technology has been successfully employed to recover fine coal from discarded waste ponds and replace conventional mechanical cells. Typical commercial testing results are described and analyzed. The column is very effective in cleaning particles down to 45 μm. Laboratory- and pilot-scale testing of

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DOI: 10.1081/SS-120018127 0149-6395 (Print); 1520-5754 (Online)

CMFC has also demonstrated that the CMFC process can produce a superclean coal product of 1.5 ~ 1.6% ash content from a 9.8% ash feed.

Key Words: Coal cleaning flotation column; Cycle-microbubble; Superclean coal.

INTRODUCTION

Froth flotation is the most widely used separation technique for fine coal cleaning. Column flotation, first developed by Boutin and Tremblay,[1] is an advanced froth flotation process. It is well known that column flotation has many advantages over conventional mechanical flotation process,[2–4] including simplicity of construction, no moving parts, low energy consumption, low operating and maintenance costs, higher recovery and product grade, etc. The fundamentals responsible for these advantages of flotation column are the countercurrent flow pattern, absence of mechanical agitation, long collection zone (long residence time) and froth height, and secondary froth upgrading by wash water. Column flotation has been extensively studied in Canada, U.S.A., Australia, and other countries during the last two decades. A variety of columns have been developed, including the Leeds column, the Microcel column, the packed column, the Flotaire column, the hydrochem column, and the Jameson column.[5–10]

Cycle-microbubble flotation column technology was developed and patented by China University of Mining and Technology.[11–13] A series of CMFCs with different capacities,[14] as shown in Table 1 are available for various applications. The first commercial unit of 1.5 m in diameter was manufactured for Zhongliangshan coal preparation plant in 1993. Since then, more than 40 units have been installed in about 30 coal preparation plants. It has been demonstrated that this technology requires lower capital and operating costs and produces better flotation results than mechanical flotation

Table 1. Series of CMFCs.

Type	Capacity (m^3/h)	Pump power (kw)
CMFC-1500	50–60	15
CMFC-2000	100–120	30
CMFC-3000	200–250	55
CMFC-6000 × 6000	400–500	110
CMFC-6000×6000	800–1000	110 × 2

cells. It has been successfully applied to cleaning high-ash (~50%) ultrafine coal that is otherwise considered uneconomical to treat and discarded from coal preparation plants. Moreover, laboratory- and pilot-scale experiments have shown that the CMFC has great potential for producing superclean coal. For example, it can produce a superclean coal product of 1.5 ~ 1.6% ash content from a 9.8% ash feed with a yield of 40 ~ 50%.

CMFC

The patented CMFC is a unique countercurrent flotation column, as shown schematically in Fig. 1. It is characterized by a specially designed external bubble generator and the integration of a cyclone. The patented external bubble generator, as shown in Fig. 2, takes advantage of the Venturi

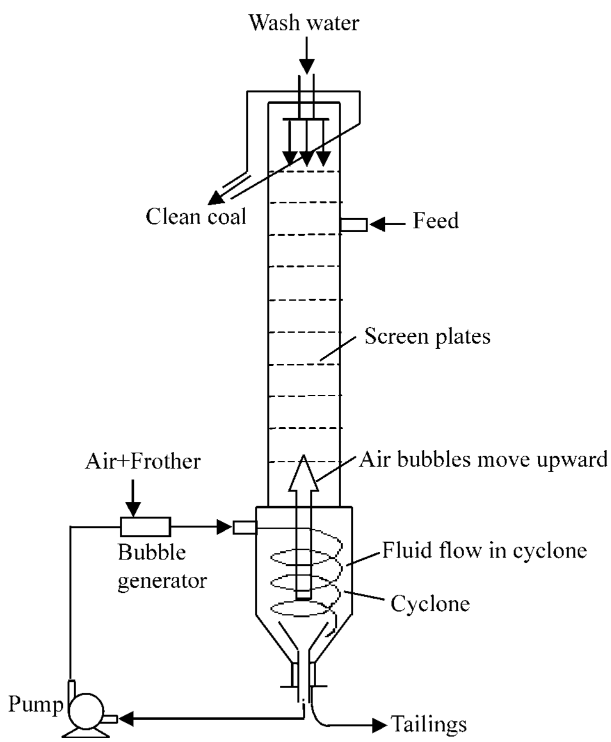

Figure 1. Schematic illustration of CMFC.

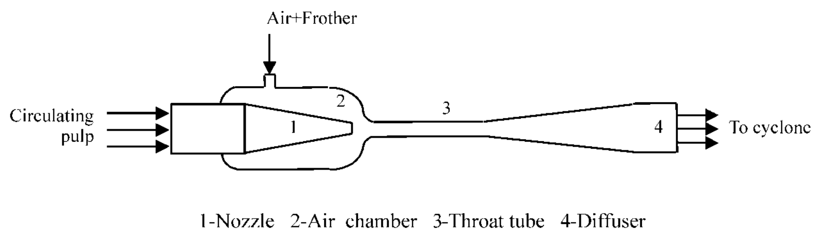

Figure 2. Schematic illustration of bubble generator.

principle. The bubble generator consists of a nozzle, an air chamber, a throat tube, and a diffuser. Circulating middling pulp is pumped into the nozzle and shoots out as a jet flow at high speed. Air and frother are sucked into the air chamber as a result of the negative air pressure created. They then enter the throat tube where air, solid, and liquid are mixed vigorously. Air is either broken into fine bubbles or dissolved in the pulp under high pressure. At the same time, hydrophobic particles in the circulating pulp collide with and attach onto fine bubbles. The dissolved air is released in the diffuser from liquid in the form of fine bubbles as a result of decreased speed and pressure. The active fine bubbles preferentially precipitated on the surfaces of hydrophobic particles greatly enhance the collection probability of fine coal particles. The slurry exiting the bubble generator is fed into the cyclone at the bottom of the column. Hydrophobic particles in the slurry have lower apparent density due to preferential precipitation of bubbles. Hence, the density difference between hydrophobic and hydrophilic particles is magnified, enhancing centrifugal gravity separation performance of fine particles. The scavenging effect of the hydraulic cyclone improves overall flotation recovery and selectivity, which is particularly helpful for the rejection of high-density material such as pyrite from coal.[15] Since cyclone separation performance deteriorates with increasing the diameter, a large-diameter commercial CMFC may have up to 12 cyclones of 60 cm diameter evenly distributed along the circumference.

In order to obtain a quiescent flotation environment in column, a set of screen plates are horizontally placed inside the column. This creates the plug-flow condition and results in a better flotation performance. The distance between the plates and hole sizes are optimized under industrial conditions.

The bubbles created in CMFC are very small, with about 71% smaller than 0.4 mm and 87% smaller than 0.5 mm (average diameter 0.2 mm).[16] Fine bubbles have a lower rising speed, creating more plug-flow condition and increasing residence time inside the column. As a result, they have more chances to collide with solid particles. The effect of bubble size (R_b) on flotation rate (k) under plug-flow can be expressed by Eq. (1),[17] which indicates that use of smaller air bubbles is very effective for increasing flotation rate constant.

$$\mathrm{k} \propto \left(\frac{1}{R_b}\right)^3 \tag{1}$$

EXPERIMENTAL

Lab Column Flotation

The coal sample used in this study for producing superclean coal was jig-cleaned <13-mm anthracite acquired from Taixi coal preparation plant in Ningxia province. Once received, it was crushed to <3 mm by a laboratory jaw crusher. Prior to column flotation, the sample was ground to two different

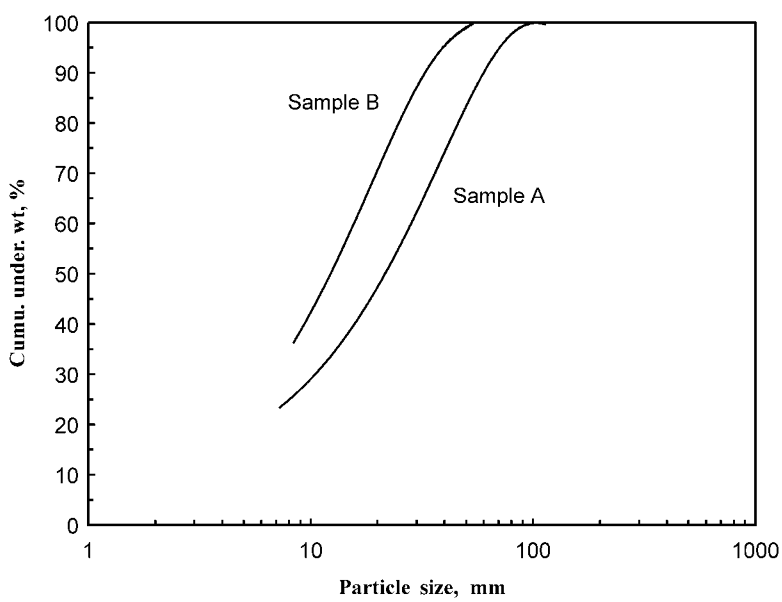

Figure 3. Size analysis graphs of samples A and B.

size distributions, A and B, as shown in Fig. 3. Sample A was 95% below 66.5 μm while sample B was 95% smaller than 37.5 μm. The coal sample contained 9.80% ash, 84.56% fixed carbon, 0.09% sulfur, and 12.86% volatile matter. Petrological analyses of <0.5-mm fraction showed vitrinite as the major maceral component (81.37%) with a small quantity of fusinite. Minerals were mainly in the form of carbonates and quartz.

A laboratory-scale CMFC of 4.5 cm diameter and 200 cm height was used in column flotation tests performed under different operating conditions for producing superclean coal. For the purpose of comparison, mechanical flotation tests were also conducted using a laboratory flotation cell (XFD-1.5L). Since coal samples were ultrafine (<0.1 mm), pulp solids concentration was fixed at 50 g/L for all flotation tests. A commercial-grade hydrin was used as frother. No collector was added since earlier studies on flotation reagents showed no need of collector. Mechanical flotation tests were conducted under the optimum frother dosage of 361 g/t and superficial aeration of 1.5 cm/s.

Release analysis was conducted to provide a baseline for comparison. Release analysis result is considered as the best possible flotation separation for a given coal under a given set of reagent conditions.[18] The release analysis procedure was based on Chinese coal industry standard, as shown in Fig. 4. The goal of the first stage is to separate all hydrophobic particles from hydrophilic ones. Slightly excessive collector was added in the first stage. The following stages were employed to further clean the concentrate from prior stage by successively removing entrained hydrophilic particles. No additional reagent chemicals were added in these stages.

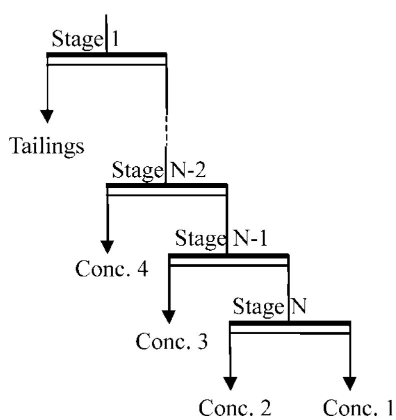

Figure 4. Release analysis flotation procedure.

Commercial Column Flotation

The commercial column flotation tests were performed using an industrial CMFC-2000 column installed in a coal preparation plant located in Shizuishan, Ningxia province, to recover <0.5-mm coal fines.[19] The column was 2.0 m in diameter and 6.5 m in height with an effective volume of 20 m^3. It has 12 bubble generators evenly distributed peripherally at the bottom. Simultaneous feed and product samples of the flotation column were taken daily under the normal operating conditions, i.e., feed rate of about 100 m^3/h, feed solids concentration of 100 g/L, and superficial air rate of 1.5–2.0 cm/s. No wash water was added to froth since froth product quality met specifications in its absence.

Another CMFC-2000 column was employed at a coal preparation plant in Jincheng, Shangxi province, to recover coal from high-ash fine coal slurry.[20] The plant uses a dense-medium circuit to clean coal. No flotation process was adopted in the original process flowsheet. Fine coal slurry was discharged to waste ponds outside the plant due to fine particle size (90% <0.045 mm) and high ash content (~50%). It was considered uneconomical to recover coal from such a slurry using conventional flotation process.

Commercial testing was also conducted with a CMFC-3000 column in Datun coal preparation plant, Jiangsu province, to demonstrate potential benefits of replacing mechanical cells. The flotation feed was <0.5-mm size fraction, while >0.5-mm size fraction was treated by jigs.

RESULTS AND DISCUSSION

Production of Superclean Coal

Coal is the major energy source in China. It accounts for more than 75% total energy consumed in China.[21] Considerable efforts have been made to find new applications of coal other than for combustion, including production of carbon fiber, fuel, chemicals, etc. One of the main obstacles to new applications of coal is the presence of ash-forming minerals.[22] Deeper cleaning of coal is necessary for developing new markets for coal.

The production of superclean coal is often accomplished by chemical methods such as acid leaching, alkali leaching under high pressure at elevated temperature, leaching by molten caustic baths, etc.[23,24] However, chemical methods are too expensive to be commercialized. Sophisticated coal flotation circuits have been proposed to produce ultraclean coal containing less than 0.7% ash and to reduce the sulfur content of the clean coal.[25,26]

Figure 5 shows the experimental results of conventional mechanical flotation and column flotation. Mechanical flotation failed to produce clean coal with ash content lower than 2%. The mechanical flotation result of sample B is inferior to that of sample A, which is consistent with the known fact that the performance of mechanical flotation deteriorates with decreasing particle size. Since the feed size for superclean coal production is usually reduced to less than 100 μm, mechanical flotation is not suitable for this application. CMFC flotation of both coal samples produced clean coal products of ash content less than 2%, i.e., 1.8% at a yield of 57% and 1.5% ash at 50% yield with samples A and B, respectively. Better results of release analysis and column flotation were obtained with sample B. Comparison of column and mechanical flotation results of both samples clearly indicated that CMFC was considerably more efficient than mechanical flotation for fine coal separation.

Commercial Testing

Table 2 shows the size distribution and ash analysis results of the feed and products for CMFC-2000 flotation column in Shizuishan.[19] The column flotation produced a 9.75% ash clean coal product from the 25.94% ash feed with a 66.91% product yield. The flotation separation is effective for all size fractions. It is particularly important to note that both coarse fraction (>0.5 mm) and fine fraction (<0.076 mm) showed effective separation. However, the ash content of <0.076-mm fraction was significantly higher than other size fractions in clean coal. It is believed that the absence of wash water in this particular application allowed nonselective hydraulic entrainment of fine clay particles into the froth product. Figure 6 shows the flotation recovery and separation efficiency as a function of particle size. Both combustible recovery and separation efficiency reached a maximum at particle size about 0.15 mm. The clay entrainment is the main reason for poor separation performance of fine particles, while insufficient liberation and high bubble-particle detachment probability may be responsible for that of coarse particles.

Table 3 shows the density distribution analysis of the feed, clean coal, and tailings of another test.[19] There was 2.75% high-density (>1.8 g/cm^3) fraction in the clean coal, which can be readily removed by wash water if necessary. Figure 7 shows the partition curve for the CMFC-2000 column flotation. The steep slope of the partition curve indicates good flotation performance. The probable error of separation from Eq. (2) is fairly low.

$$E_P = \frac{|\delta_{75} - \delta_{25}|}{2} = \frac{|1.58 - 1.86|}{2} = 0.14 \tag{2}$$

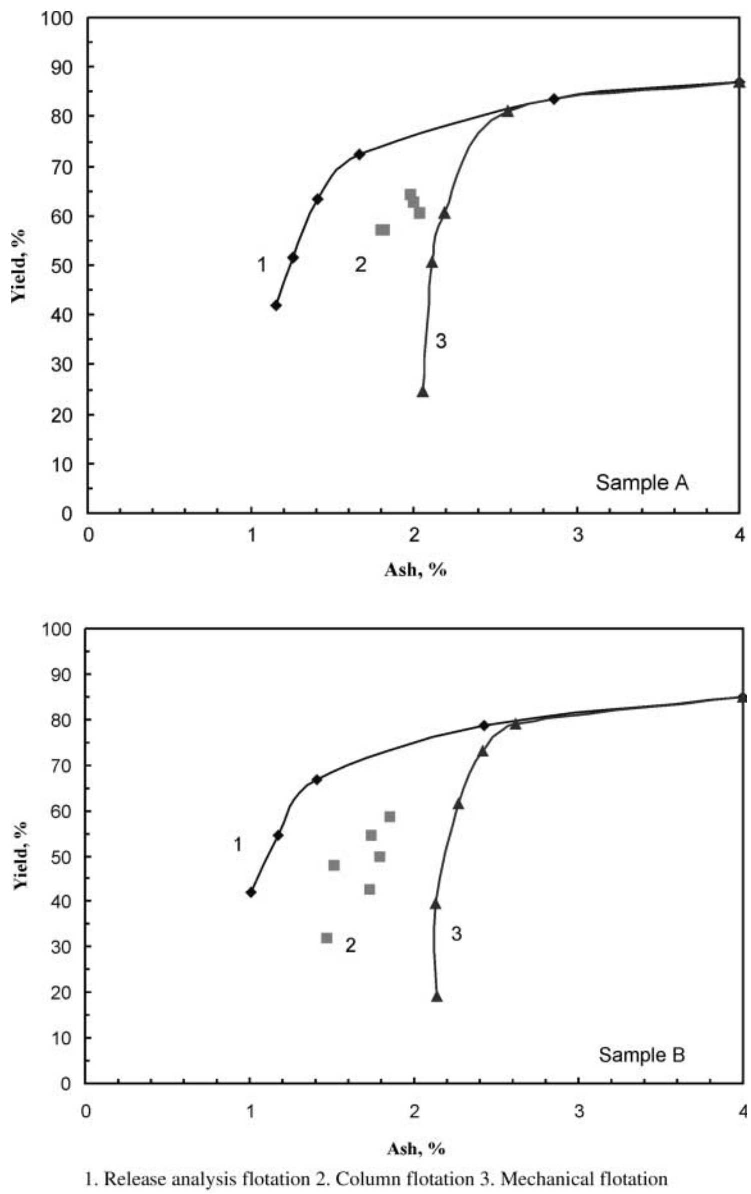

Figure 5. Comparison of results of different flotation methods.

Table 2. Size distribution analysis of CMFC-2000 flotation in Shizuishan.

Size range (mm)	Feed		Clean coal (66.91%)		Tailings (33.09%)		Comb. rec. %	Sep. eff. %
	Wt%	Ash%	Wt%	Ash%	Wt%	Ash%		
>0.5	0.58	20.20	0.50	6.17	0.74	39.37	67.82	50.20
0.5–0.25	13.96	20.08	14.37	7.21	13.14	48.54	79.97	55.24
0.25–0.125	20.11	20.88	22.72	8.61	14.84	58.87	87.32	56.15
0.125–0.076	17.55	25.57	18.61	9.38	15.40	65.14	86.38	60.36
<0.076	47.80	29.99	43.80	11.37	55.88	59.49	77.62	54.37
Total	100.0	25.94	100.0	9.75	100.0	58.68	81.54	56.39

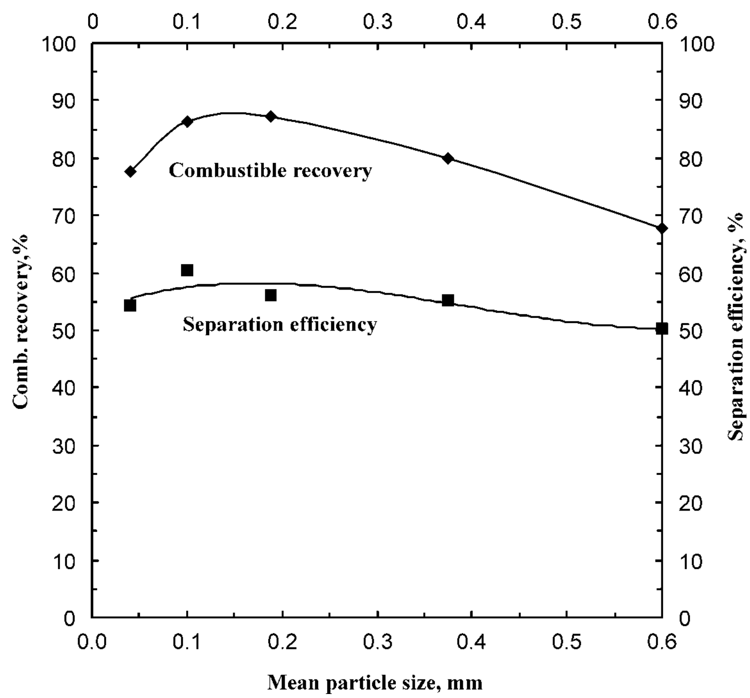

Figure 6. Flotation recovery and separation efficiency for CMFC-2000 in Shizuishan.

Table 3. Density distribution analysis of CMFC-2000 flotation in Shizuishan.

Spec. gravity (g/cm^3)	Feed		Clean coal (72.12%)		Tailings (27.88%)	
	Wt%	Ash%	Wt%	Ash%	Wt%	Ash%
<1.3	18.18	4.03	25.21	4.03	—	—
1.3–1.4	15.99	4.89	22.04	4.87	0.34	7.67
1.4–1.5	27.32	8.40	37.40	8.35	1.24	12.01
1.5–1.6	8.39	16.09	8.59	15.21	7.87	18.57
1.6–1.8	7.31	31.15	4.01	28.25	15.86	33.05
>1.8	22.83	72.38	2.75	66.53	74.69	72.94
Total	100.0	23.97	100.0	9.48	100.0	61.37

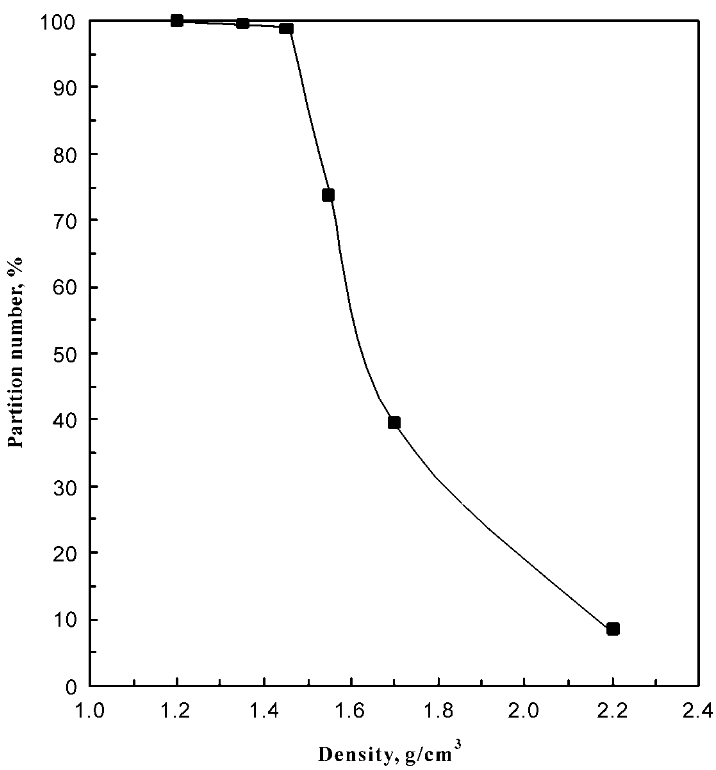

Figure 7. Partition curve for CMFC-2000 column flotation in Shizuishan.

Table 4. Flotation results for CMFC-2000 with Jincheng high-ash coal waste.

No.	Feed ash%	Clean coal Ash%	Clean coal Y%	Tailings Ash%	Tailings Y%	Comb. r %	Sep. eff. %
1	47.11	9.66	45.72	78.65	54.28	78.09	68.72
2		10.77	47.41	79.87	52.59	79.98	69.15
3		10.93	47.31	79.59	52.69	79.67	68.70
4		10.82	47.02	79.32	52.98	79.28	68.48
Aver.	47.11	10.55	46.87	79.36	53.14	79.26	68.76

Table 4 shows the CMFC-2000 flotation results obtained with Jincheng high-ash coal waste.[20] The feed was 100% <0.076 mm and 90% <0.045 mm with an overall ash content of 47.11%. Four flotation tests produced a clean coal of 9.66–10.93% ash content and 45.72–47.41% yield. The average tailings ash was 79.36%, the average combustible recovery was 79.26%, and the average separation efficiency was 68.76%. Obviously, the column flotation was very effective in cleaning the fine coal waste.

Table 5 shows the industrial testing results of CMFC-3000 column with Datun coal in the absence of wash water. The feed was characterized by a large amount of ultrafine fraction, i.e., 65.28% <0.045 mm fraction. Separation efficiency was very low for coarse fractions above 0.074 mm. Since much attention was paid to the flotation of the ultrafine fraction,

Table 5. CMFC-3000 flotation results with Datun coal.

Size range (mm)	Feed		Clean coal (71.82%)		Tailings (28.18%)		Comb. rec. %	Sep. eff. %
	Wt%	Ash%	Wt%	Ash%	Wt%	Ash%		
>0.5	0.45	5.15	0.12	3.81	1.30	5.67	19.31	5.23
0.5–0.25	2.81	4.53	3.03	3.81	2.24	7.29	78.10	12.97
0.25–0.125	9.51	4.77	11.94	4.28	3.32	9.63	90.63	9.77
0.125–0.074	10.95	7.07	13.60	5.81	4.19	18.11	90.42	17.08
0.074–0.045	11.77	13.40	13.02	7.60	8.59	37.11	84.75	39.69
<0.045	64.51	31.29	58.29	12.28	80.36	68.87	82.85	57.38
Total	100.0	23.14	100.0	9.57	100.0	59.85	84.50	54.80

the operating condition might be unfavorable for coarse particles. Low collector and frother dosages were the possible reason for the low recovery of coarse particles. Since the percentages of coarse fractions were low, the overall separation efficiency remained quite high. The dependence of flotation combustible recovery and separation efficiency on particle size, shown in Fig. 8, indicates that the highest combustible recovery (~90%) and separation efficiency (~57%) occurred with the 0.25–0.074-mm and <0.045-mm fraction, respectively. This demonstrated the capability of CMFC for ultrafine coal flotation.

Table 6 compares the flotation performance of CMFC-3000 column and XJM-8 mechanical cell. The data were the average over a period of one month. The CMFC-3000 column produced a much cleaner product at essentially the same tailings ash content as the XJM-8 mechanical cell. In addition, the column feed rate was considerably higher than that of the mechanical flotation machine. The column flotation also has the advantage of lower

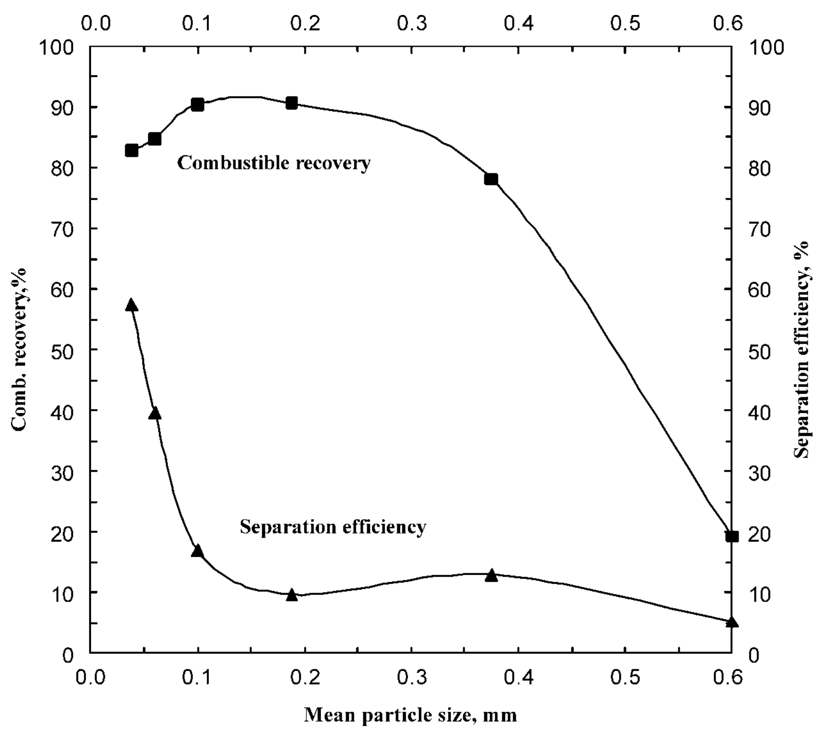

Figure 8. Flotation recovery and separation efficiency for CMFC-3000 in Datun.

Table 6. CMFC-3000 and XJM-comparison of flotation results with Datun coal.

Separator	Feed rate (m^3/h)	Feed ash%	Clean coal ash%	Tailings ash%	Yield%	Power kW
CMFC-3000	200–300	21.24	7.98	50.29	68.66	75
XJM-8	~200	21.24	9.66	49.78	71.14	123

energy consumption compared with the mechanical cell, i.e., 75 kW versus 123 kW.

CONCLUSION

The following conclusions can be made from the experimental results:

1. CMFC is an effective flotation column. Laboratory tests showed that it was able to produce superclean coal from suitable coal feed. For Taixi coal, it produced a clean coal of 1.5–1.8% ash while the mechanical flotation seldom obtained lower than 2% ash.
2. The industrial testing with a CMFC-2000 column showed that the column flotation technology was excellent in cleaning nominally <0.5-mm fine coal. A 25.94% ash flotation feed was efficiently cleaned to 9.75% ash with a 66.91% flotation yield and a 0.14 probable error, even in the absence of wash water. Size distribution analyses of feed and products indicated that all sizes were cleaned effectively, with the highest separation efficiency observed at a particle size of 0.15 mm.
3. Industrial testing demonstrated that the commercial CMFC-3000 column was able to produce high combustible recovery (90%) and separation efficiency (57%) with the 0.25–0.074-mm and <0.045-mm fraction, even without the use of wash water. It is considerably more effective for treating ultrafine coal with high ash contents than conventional mechanical flotation cell. With a coal of 21.24% ash content, testing over a period of one month indicated that the column produced a clean coal product with an average of 7.98% ash at a 68.66% flotation yield.
4. The CMFC was also effective in cleaning fine coal waste. It produced a clean coal product of 9.66–10.93% ash from a 47.11% ash feed at a yield ranging from 45.72–47.41%.

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Received May 2002
Revised August 2002