Upgrading of Vang Danh Coal Fines Using Reflux Flotation Cell

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Abstract. In the world, the coal fines usually are upgraded in flotation columns (Jameson, Pneufloat, Microcell cells, etc.). Reflux flotation cell is a novel type of flotation column that uses a system of inclined channels to enhance bubble - liquid segregation in flotation. Additionally, in this type of device, a unique froth washing mechanism with pressurized water is used to ameliorate the quality of clean coal. This type of device has a simple structure, high capacity, and allows the receiving of high-quality clean coal. This paper presents the test results of coal fines samples −0.3 mm from Vang Danh underground coal mine (in Quang Ninh, Vietnam) by flotation in a laboratory Reflux flotation cell. The test results show that combined clean coal can be received with the ash content less than 15% and the combustible recovery of more than 80%. This cleaned coal meets the quality standard of 3B fine coals (ash content of 14–16%). The flotation tailing with the ash content of more than 70% can be rejected.

Keywords: Flotation column · Froth washing · Clean coal · Tailing · Vang Danh coal mine

1 Introduction

Nowadays, at the coal mines in the Quang Ninh area, there is a great number of fine coals accumulating in the mud ponds. These fine coals are of size fraction -0.3 mm, and because of having the ash contents of over 30%, it is used as low valued products. In general, the bulk of coal fines in Vietnam is hardly processed but mainly collected using the methods of sedimentation and filtering. In recent years, there are several research works in Vietnam covering the recovery of fine coals by flotation [1–3] but the received clean coals were not of high quality.

In the world, the coal fines usually are upgraded in flotation columns [5–7, 9, 14, 16]. Reflux flotation cell is a novel type of flotation column that uses a system of inclined channels to enhance bubble - liquid segregation in flotation [13]. Additionally, in this type of device, a special froth washing mechanism is employed with pressurized water to ameliorate the quality of cleaned coals. This type of device has a simple structure, high capacity, and allows the receiving of cleaned coals of high quality. The Reflux Flotation Cell has been developed in the University of Newcastle (Australia) in recent [10–12, 15,

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17–19]. In Vietnam, there are several promising investigations which employ this type of column for the ultrafine apatite ore [4].

This paper presents the test results of coal fines samples −0.3 mm from Vang Danh underground coal mine by flotation in a laboratory Reflux flotation cell. In the experiment, many process parameters are investigated and optimized: flotation time, pulp density, feed rate, froth height, wash water, and flotation reagents regime. In order to receive the clean coals and the rejects of satisfactory quality, some flotation flowsheet test works are conducted with additional scavenger stages.

2 Experiment Method

2.1 Material

The test sample is the 0.3 mm coal separated from the 5 A fine coal of Vang Danh coal mine. The test coal sample is subjected to size analysis using standard sieves and the size composition of which is presented in Table 1.

Table 1. Particle size analysis of the flotation feed sample

Size fractions, mm	Yield, %	Ash content, %
0.2–0.3	13.55	29.37
0.1–0.2	50.48	33.02
0.074–0.1	15.67	37.66
−0.074	20.3	43.05
Total	100	35.29

2.2 Reagents

The collector is a mixture of diesel oil and an emulator (tallow amine). The collector is prepared by emulsification in a magnetic stirrer. The frother is methylisobutylcarbinol (MIBC).

2.3 Method

The schematic diagram of the test equipment is shown in Fig. 1.

The test equipment is a two-part flotation column: the upper part is a cylinder of 10 cm in diameter and 1 m in length [4]; the lower part is a 1 m long inclined parallelogram with the cross-session of 10 × 10 cm and the tilt angle of 70°. In the parallelogram, the columns are installed on the inclined plates. At the top of the column, there is a froth washing mechanism in the form of a perforated cone. The flotation pulp is fed into the

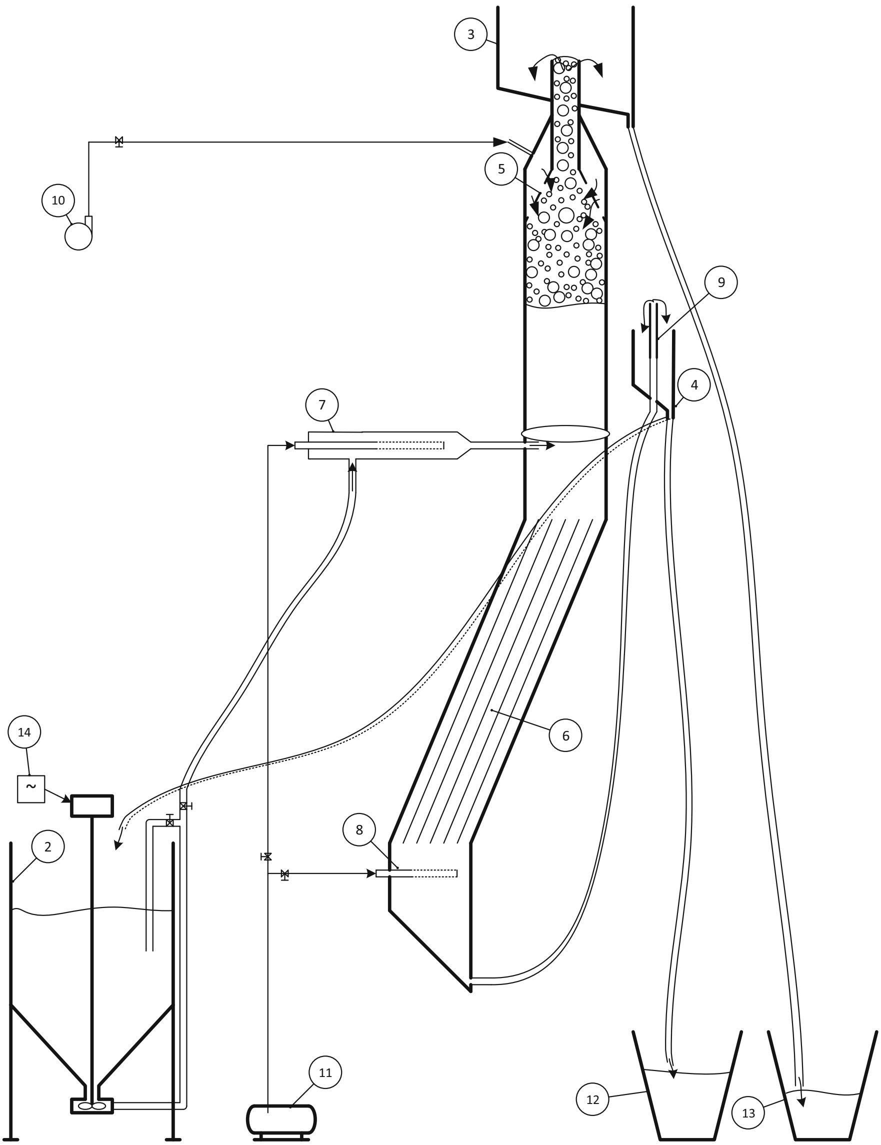

Fig. 1. The schematic diagram of the test flotation column in the type of Reflux Flotation Cell. 1. Flotation column; 2. Feed mixing tank and pump; 3. Froth trough; 4. Tailing discharge mechanism; 5. Wash water distribution plate; 6. Inclined plates; 7. Primary aerator; 8. Secondary aerator; 9. Adjusting pulp level mechanism; 10. Wash water pump; 11. Compressor; 12. Tailing container; 13. Froth container; 14. Inverter

column tangentially at the bottom of the cylinder after mixing with the fine bubble from a perforated rubber tube in an aerator. The fine bubbles are also sabotaged at the bottom of the parallelogram box. The flotation froth, after passing through the washing zone, is discharged in the froth trough. The tailings pass the inclined channels and are removed by a discharge device in the form of a gooseneck tube. The level of the pulp (and the froth height, respectively) can be controlled by choosing the suitable length of this tube. The concentrate and the tailing are discharged in separate containers. The pulp feed rate is adjusted by an inverter, the washing water flowrate - by a valve in the recirculated circuit.

The clean coal and tailing are filtered, dried, and subjected to ash analysis. The combustible recovery is calculated by the formula.

$$E = \gamma P.(100 - AP)/(100 - AF),\ \%$$

where γP is the yield of flotation product; AP and AF are respectively the ash contents of the product and the feed flotation.

3 Results and Discussion

3.1 Factorial Flotation Test

There are several parameters which influence on the coal flotation performance in the columns [6, 9, 14, 18]. In this paper the following parameters are investigated: flotation time, pulp solid content, feed rate, froth thickness, wash water, collector dosage, frother dosage. The test diagram is shown in Fig. 2. The condition of flotation tests are shown in Table 2.

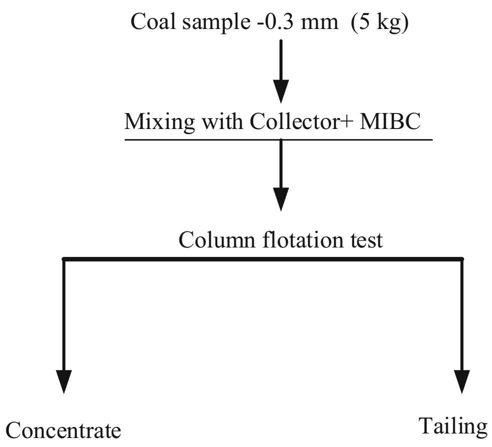

Fig. 2. The factorial test diagram

Table 2. The condition of flotation tests

No test	Flotation time, min	Solid content, %	Feed rate, L/min	Froth thickness, mm	Wash water, L/min	Collector dosage, kg/t	Frother dosage, g/t
1	6	160	8	450	0	1.5	125
2	8	160	8	450	0	1.5	125
3	10	160	8	450	0	1.5	125
4	12	160	8	450	0	1.5	125
5	10	140	8	450	0	1.5	125
6	10	180	8	450	0	1.5	125
7	10	200	8	450	0	1.5	125
8	10	160	7	450	0	1.5	125
9	10	160	9	450	0	1.5	125
10	10	160	10	450	0	1.5	125
11	10	160	9	400	0	1.5	125
12	10	160	9	500	0	1.5	125
13	10	160	9	550	0	1.5	125
14	10	160	9	500	1	1.5	125
15	10	160	9	500	2	1.5	125
16	10	160	9	500	3	1.5	125
17	10	160	9	500	4	1.5	125
18	10	160	9	500	2	1.0	125
19	10	160	9	500	2	2.0	125
20	10	160	9	500	2	2.5	125
21	10	160	9	500	2	2.0	100
22	10	160	9	500	2	2.0	150
23	10	160	9	500	2	2.0	175

3.2 Effect of Flotation Time

The flotation test in this cell is conducted like in the traditional mechanical laboratory cell with the pulp circulated through the column many times in a certain flotation time. Because of that, this time will influence on the clean coal quality and recovery. The test results are shown in Table 3 and Fig. 3.

When changing the flotation time from 6 min to 12 min, all the yield, the combustible recovery, and the ash of clean coal increased. The yield increased from 22.37% to 37.55%, the ash content increased from 8.15% to 12.62%, with the combustible recovery increased respectively from 31.75% to 50.69%. Besides, the tailing ash content also went up from 43.11% to 48.89%.

Table 3. The flotation test results with variable flotation time

N0 Test	Flotation time, min	Clean coal			Tailing ash content, %
		Yield, %	Ash content, %	Combustible recovery,%	
1	6	22.37	8.15	31.75	43.11
2	8	26.42	9.56	36.92	44.52
3	10	36.12	11.55	49.36	48.70
4	12	37.55	12.62	50.69	48.89

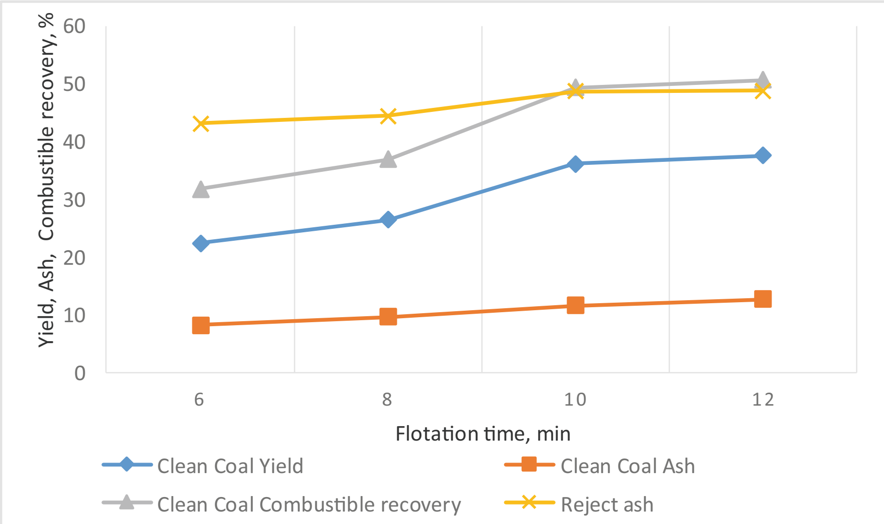

Fig. 3. Effect of flotation time on coal flotation performance

Increasing flotation time to 10 min, we saw the clean coal ash content was 11.55% with a combustible recovery of 49.36% and the tailing ash content of 48.70%. When the flotation time was increased to 12 min, the combustible recovery rose only to 50.69%, but the clean coal ash content increased to 12.62%, the tailing ash content also had an insignificant increase, from 48.7% to 48.89%. Therefore, we will choose the optimal floating time of 10 min for the next series of experiments.

3.3 Effect of Solid Content

The solid content of the flotation feed with the constant feed rate will determine the froth volume and recovery from the cell. Thus this parameter will influence the quality and recovery of flotation products. The test results are shown in Table 4 and Fig. 4.

When increasing the solid content from 140 g/L to 200 g/L, all the yield, the combustible recovery, and the ash of clean coal were increased. The yield increased from

Table 4. The flotation test results with variable solid content

No test	Solid content, g/L	Clean coal			Tailing ash content, %
		Yield, %	Ash content, %	Combustible recovery,%	
5	140	35.12	10.35	48.66	48.79
3	160	36.12	11.55	49.36	48.70
6	180	38.20	13.10	51.31	49.02
7	200	40.32	15.62	52.56	48.55

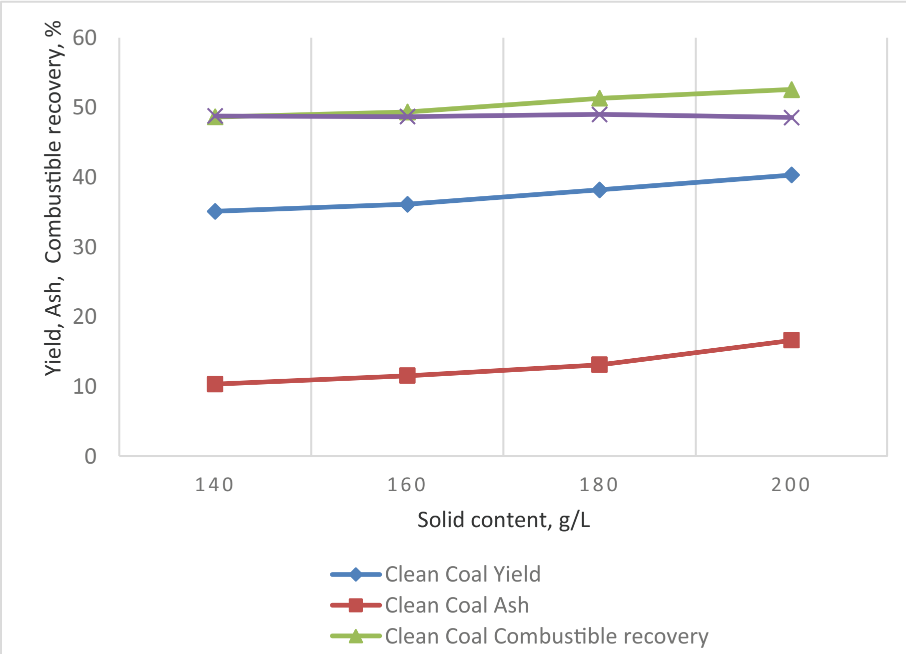

Fig. 4. Effect of solid content on coal flotation performance

35.12% to 40.32%, the ash content increased from 10.35% to 15.62%, with the combustible recovery increased respectively from 48.66% to 52.56%. When this parameter has risen from 140 g/L to 180 g/L, the tailing ash content increased from 48.79% to 49.02%. However, at solid content 200 g/L, the combustible recovery decreases to 48.55%. Besides, the tailing ash content also decreased from 51.34% to 47.44%.

At a solid content of 160 g/L, we saw that the combustible recovery in clean coal was 49.36%, with the ash content of 11.55%. When increasing the solid content to 180 g/t, the combustible recovery increased only to 51.36%, but the clean coal ash content rose to 13.10%. Therefore, we will select the optimal solid content of 160 g/L for the next series of experiments.

3.4 Effect of Feed Rate

The feed rate with the constant other parameters will determine the froth volume, speed, and recovery from the cell. The feed rate also determines the pulp velocity through the column. Therefore, with the feed rate variation, the quality and recovery of the flotation products will be affected. The test results are shown in Table 5 and Fig. 5.

Table 5. The flotation test results with the variable feed rate

No test	Feed rate, L/min	Clean coal			Tailing ash content, %
		Yield, %	Ash content, %	Combustible recovery, %	
8	7	33.18	11.25	45.49	47.20
3	8	36.12	11.55	49.36	48.70
9	9	40.55	12.67	54.72	50.70
10	10	41.15	14.85	54.15	49.58

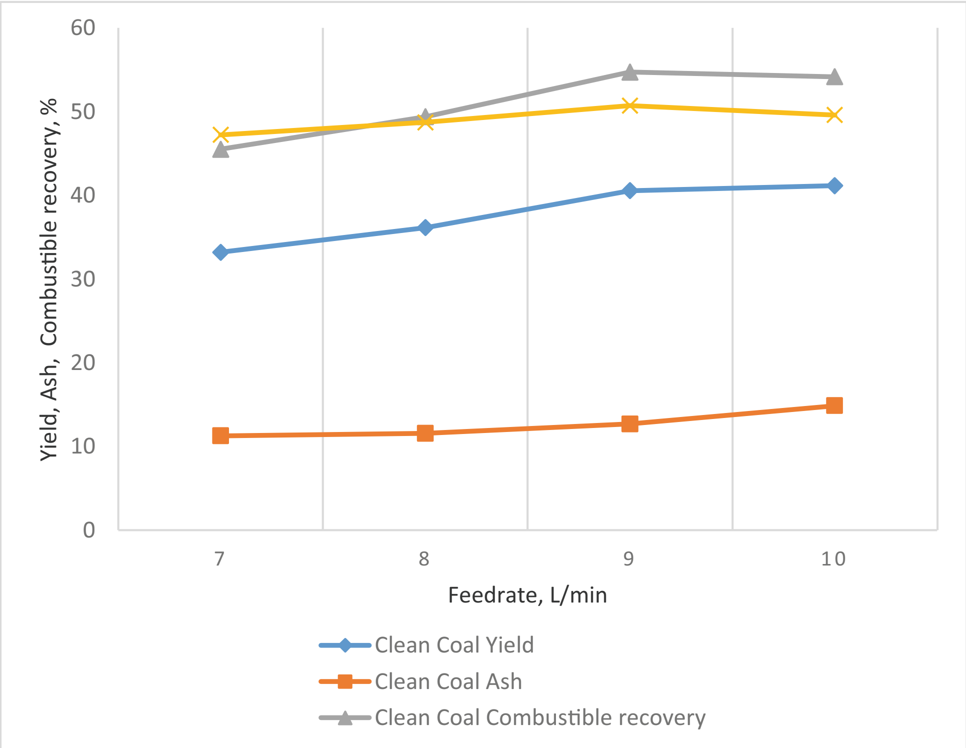

Fig. 5. Effect of feed rate on coal flotation performance

When the feed rate increased from 7 L/min to 10 L/min all the yield, the combustible recovery, and the ash of clean coal rose. The yield increased from 33.18% to 41.15%, the ash content increased from 11.25% to 14.85%, with the combustible recovery increased respectively from 45.49% to 54.15%. Moreover, the tailing ash content increased from 47.2% to 49.58%.

At a feed rate of 9 L/min, we see that the combustible recovery in clean coal was 54.72%, with the ash content of 12.67%. When increasing the feed rate to 10 L/min, the clean coal ash increased sharply to 14.85%, but the combustible recovery was reduced to 54.15%. Therefore, we choose the optimum feed rate of 9 L/min, which is the optimum feed rate for the following series of experiments.

3.5 Effect of Froth Thickness

The froth thickness will influence on the processes in the froth phase [8]. With the increasing of this parameter, the entrainment of ultrafine mineral particles into the froth will be reduced. The test results are shown in Table 6 and Fig. 6.

Table 6. The flotation test results with variable froth thickness

No test	Froth thickness, mm	Clean coal			Reject ash, %
		Yield, %	Ash, %	Combustible recovery, %	
11	400	43.15	13.85	54.89	51.56
9	450	40.55	12.67	54.72	50.70
12	500	34.42	10.12	47.82	48.52
13	550	30.18	8.85	42.51	46.72

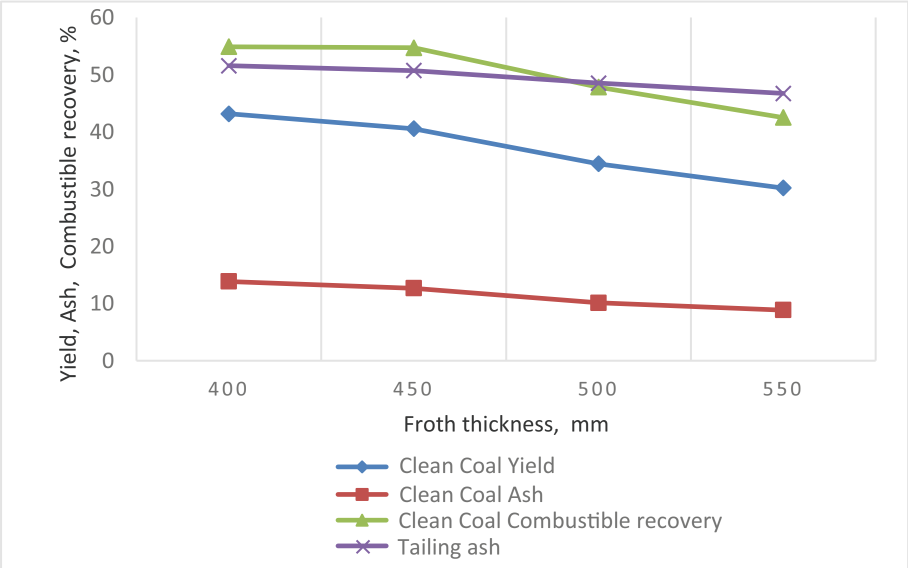

Fig. 6. Effect of froth thickness on coal flotation performance

When increasing the froth layer thickness from 400 mm to 550 mm, all the yield, the combustible recovery, and the ash of clean coal were reduced. The yield decreased from 43.15% to 30.18%, the ash content decreased from 13.85% to 8.85%, with the combustible recovery dropped respectively from 54.89% to 42.51%. Along with that, the tailing ash content also decreased from 51.56% to 46.72%.

At the froth thickness of 500 mm, we received clean coal with a fairly high combustible recovery of 47.82% and an ash content of 10.12%. But when the froth thickness was increased to 550 mm, however, the recovery of coal fell sharply, so we choose the froth thickness of 500 mm as the optimal thickness to be used in the next series of experiments.

3.6 Effect of Wash Water Flowrate

The distinguishing feature of this type of cell is the froth washing process which can be controlled by changing the wash flowrate. With the increase of the wash flowrate, the froth washing will be intensified, the entrainment phenomena will be diminished and therefore the coal product will be cleaner. The test results are shown in Table 7 and Fig. 7.

Table 7. The flotation test results with variable washwater flowrate

No test	Washwater flowrate, L/min	Clean coal			Tailing ash content, %
		Yield, %	Ash content, %	Combustible recovery, %	
12	0	34.42	10.12	47.82	48.52
14	1	32.18	9.20	45.15	47.67
15	2	30.85	8.65	43.54	47.16
16	3	28.76	8.12	40.84	46.26
17	4	25.78	7.62	36.80	44.90

When increasing the wash water flow rate from 0 to 4 L/min, all the yield, the combustible recovery and the ash of clean coal significantly reduced. The weight decreased from 34.42% to 25.78%, and the ash content decreased from 10.12% to 7.62%, with the combustible recovery dropped respectively from 47.82% to 36.8%. Along with that, the tailing ash content also sharply reduced from 48.52% to 44.9%.

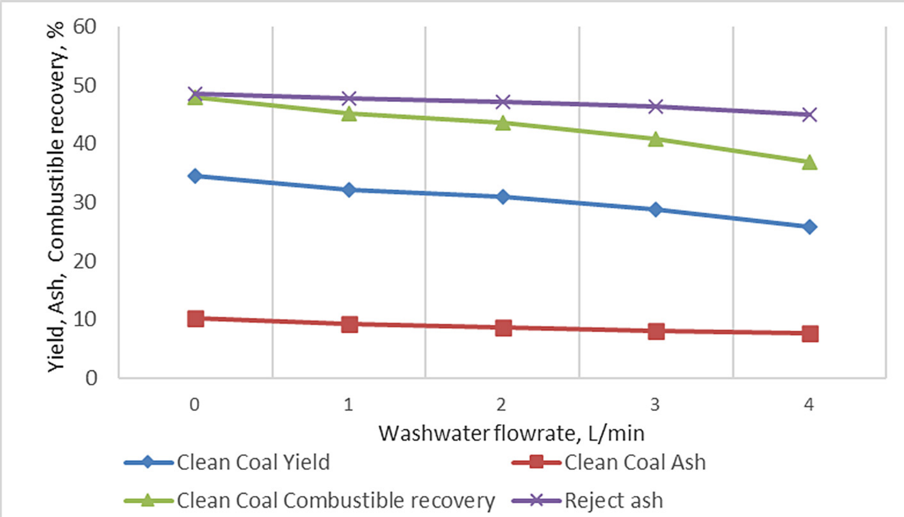

Fig. 7. Effect of wash water flowrate on coal flotation performance

At the wash water flow rate of 2 L/min, we received clean coal with the ash content of 8.65% and the combustible recovery of 43.54%; the tailing ash content was 47.67%. However, when we increase the wash water to 3 L/min, the ash of the clean coal decreased insignificantly to 8.12%, but the recovery fell dramatically. Thus, the wash water flow rate of 2 L/min as the optimal parameter to be used in the next series of experiments.

3.7 Effect of Collector Dosage

Like in a conventional flotation cell, the collector dosage will determine the coal hydrophobicity, and therefore, it will influence the coal flotation process. The test results are shown in Table 8 and Fig. 8.

Table 8. The flotation test results with variable collector dosage

No test	Collector dosage, kg/t	Clean Coal			Tailing ash content, %
		Yield, %	Ash content, %	Combustible recovery, %	
18	1.0	26.72	8.25	37.89	45.15
15	1.5	30.85	8.65	43.54	47.16
19	2.0	31.85	8.82	44.88	47.66
20	2.5	33.28	10.55	46.01	47.65

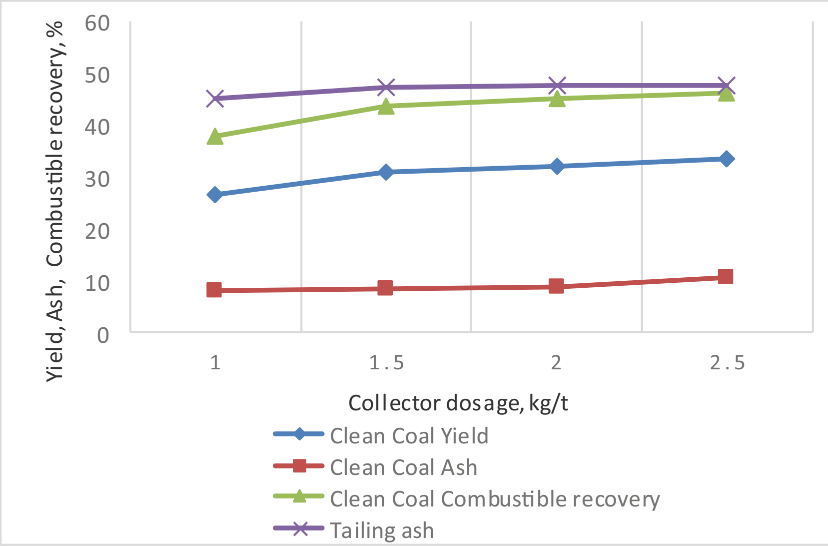

Fig. 8. Effect of collector dosage on coal flotation performance

When increasing the collector dosage from 1 kg/t to 2.5 kg/t, all the yield, the combustible recovery, and the ash of clean coal increased. The yield increased from 26.72% to 33.28%, and the ash content increased from 8.25% to 10.55% and the combustible recovery - respectively, from 37.89% to 46.01%. The tailing ash content also increased from 45.15% to 47.65%.

At the collector dosage of 2 kg/t, we received clean coal with very low ash of 8.82% and the combustible recovery of 47.82%. But when increasing the collector dosage to 2.5 kg/t, however, the ash of clean coal sharply increased to 10.55%, so we select the collector dosage of 2.5 kg/t as the optimal parameter to be used in the next series of experiments.

3.8 Effect of Frother Dosage

The frother type and dosage will determine the froth properties, and therefore, it will influence the entrainment and froth washing phenomena and in the end on the coal flotation performance. The test results are shown in Table 9 and Fig. 9.

When raising the frother dosage from 100 g/t to 175 g/t, all the yield, the combustible recovery, and the ash of clean coal increased. The yield increased from 28.95% to 33.07%; the ash increased from 8.2% to 9.35% and the combustible recovery - respectively, from 41.06 to 46.31%. The tailing ash content also increased from 46.31% to 48.08%.

Table 9. The flotation test results with variable frother dosage

No test	Frother dosage, g/t	Clean Coal			Tailing ash content, %
		Yield, %	Ash content, %	Combustible recovery, %	
21	100	28.95	8.20	41.06	46.31
19	125	31.85	8.82	44.88	47.66
22	150	32.78	9.15	46.03	48.05
23	175	33.07	9.35	46.31	48.08

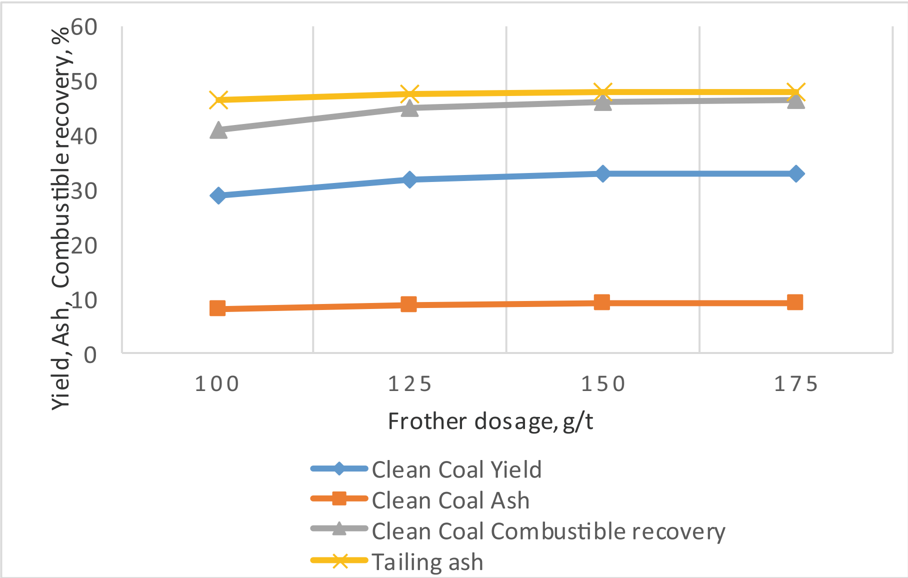

Fig. 9. Effect of frother dosage on coal flotation performance

At the frother dosage of 150 g/t, we received clean coal with low ash of 9.15% and the combustible recovery of 46.03%. Nevertheless, when increasing the frother dosage to 175 g/t, however, the ash of clean coal increased to 9.35%, and the recovery increased insignificantly. So, we choose the frother dosage of 150 g/t as the optimal parameter (Table 10).

Some flow sheet tests with additional one or two scavengers are conducted because the values of clean coal combustible recovery and the tailing ash content were still low and unsatisfactory.

Table 10. The optimal flotation parameters

Flotation process parameters	Values
Sample mass	5 kg
Solid content	160 g/L
Feed rate	9 L/min
Froth thickness	500 mm
Collector dosage	2 kg/t
Frother dosage MIBC	150 g/t
Washing water	2 L/min
Flotation time	10 min

The test flow sheets and the reagent regimes are shown in Figs. 10 and 11.

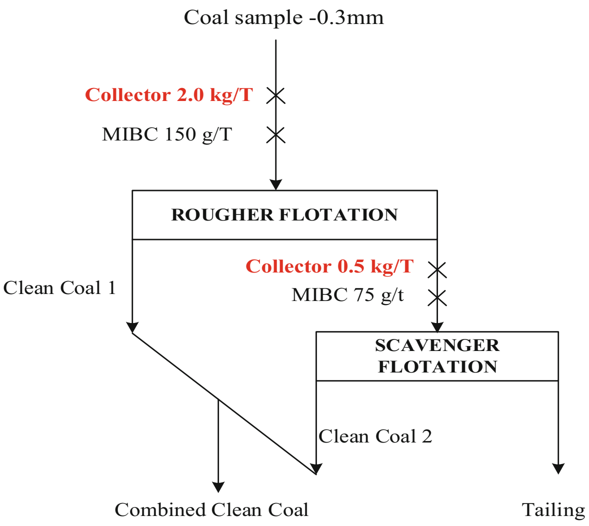

Fig. 10. The test flowsheet with one scavenger

The test results are presented in Table 11. The results showed that flow sheets with one or two scavenger flotation gave better flotation performance. In the test with one scavenger (Fig. 10) the combustible recovery of the clean coal was 72.93%, the combined clean coal ash 12.93%, and the tailing ash content was 61.72%. The test flow sheet with 02 scavengers (Fig. 11) gave the best performance. The combustible recovery of the clean coal was 82.67%, and the combined clean coal ash was 13.94%. The tailing ash content was 70.35%, and the tailing can be rejected.

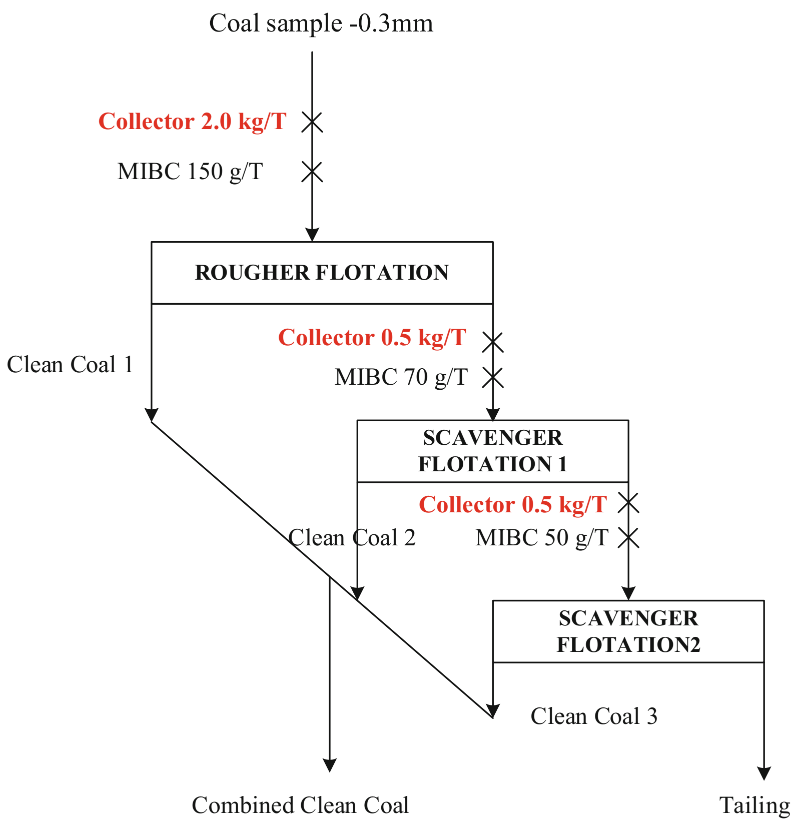

Fig. 11. The test flowsheet with two scavengers

Table 11. The flotation test results with different flow sheets

N^{o}	Flotation flow sheets	Flotation products	Yield, %	Ash content, %	Combustible recovery, %
1	As in Fig. 10	Clean coal 1 (Froth)	32.85	9.18	46.09
		Clean coal 2 (Froth)	21.37	18.70	26.84
		Combined clean coal	54.22	12.93	72.93
		Tailing	45.78	61.72	27.07
		Feed Coal	100.00	35.27	100.00
	Flotation flow sheets	Flotation products	Yield, %	Ash content, %	Combustible recovery, %
2	As in Fig. 11	Clean coal 1 (Froth)	32.80	9.15	46.04
		Clean coal 2 (Froth)	21.28	18.80	26.69
		Combined clean coal	62.18	13.94	82.67
		Tailing	37.82	70.35	17.32
		Feed coal	100.00	35.27	100.00

4 Conclusions

In this study, the test coal sample was in the size fraction below 0.3 mm, prepared from Vang Danh fine coal with the ash content of 35.29%. Several process parameters are evaluated and optimized, such as flotation time, pulp density, feed rate, froth height, wash water, and flotation reagents regime. Several crucial observations can be summarized as follows:

1) The factorial flotation tests were conducted in order to determine the optimal regime for the flotation process in the laboratory column of Reflux Flotation Cell. At the optimal values of the processing parameters, the clean coal was obtained in good quality (with the ash <10%), but the combustible recovery in clean coal and the tailing ash was still low (<50%).
2) The most suitable parameter values were determined: solid content 160 g/L; flotation time 10 min; flotation feed rate 9 L/min; froth thickness 500 mm; wash water 2 L/min; collector dosage 2.0 kg/t; frother dosage 150 g/t.
3) The flotation flow sheet tests with one and two scavengers were conducted. The test flow sheet with two scavengers gave better results. The combined clean coal had the ash content of 13.94%, with a combustible recovery of 82.67%. The tailing ash content was of 70.35%.
4) The recommended flotation flowsheet is shown in Fig. 11.
5) The test results in Table 11 showed that the tests with one or two scavenger flotation gave good flotation performance. In the test with one scavenger (Fig. 10) the combustible recovery of the clean coal was 72.93%, the combined clean coal ash 12.93%, and the tailing ash content was 61.72%. The test flow sheet with two scavengers (Fig. 11) gave the better performance. The combustible recovery of the clean coal was 82.67%, and the combined clean coal ash was 13.94%. The tailing ash content was 70.35%, and the tailing can be rejected.

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