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Statistically modelling of coal flotation in a pilot plant scale column cell

Sajad Mohammadnejad [a], Mohammad Karamoozian [a, *], Masoud Nouri [b]

[a] *Faculty of Mining, Petroleum and Geophysics, Shahrood University of Technology, Shahrood, Iran.*

[b] *Tabas parvadeh coal preparation plant, Tabas, Iran.*

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ABSTRACT

The objective of this study was to investigate the impact of various operational parameters, including aeration rate, feed flow rate, collector and frother dosage, on the efficiency of coal flotation. A pilot-scale column flotation process was utilized. CCD method and ANOVA were used to develop the process model from the input-output data set of the pilot scale column flotation process and to test the weight recovery models and concentrate ash percentage. By optimizing the parameters, such as using a fuel oil collector dosage of 900 g/t, MIBC frother dosage of 340 g/t, and an aeration rate of 10594.6 ml/min, the column flotation operation achieved a recovery of 50.06% and an ash concentrate of 11.6%. The results showed that the aeration rate had the most significant influence on the ash content of concentrate and recovery, compared to the collector and frother dosages.

Keywords: *Modelling, Column flotation, Coal, Response surface method.*

1. Introduction

Coal is defined as a heterogeneous combustible sedimentary rock formed from plant remains by processes involving the compression of materials buried in basins, initially of moderate depth with an ash content of less than 50% [1]. Due to the production of large amounts of fine coal, especially -1 mm size, by the mechanized operations of mines, coal processing has received much attention [2]. To produce coal that is used as coke in the steel industry, it is necessary to use more precise methods of processing minerals, such as flotation with controlled conditions. Coal with a coke number higher than 7 and an ash content of less than 12% is suitable for the steel industry [3]. In coal washing plants, there is always a pressure to produce coal with low ash content, because an increase of 1% of coal ash beyond the critical limit leads to an increase in the consumption of about 4-5% of coke and also a decrease in the efficiency of the blast furnace by about 3-6%. [4].

Froth flotation is the most common method of fine coal processing in coal preparation plants [2]. Froth flotation using differences in the surface properties of minerals, such as coal is known as an efficient method for processing minerals [5]. Coal cleaning, mineral beneficiation, wastewater treatment, soil recovery, oil recovery, and paper deinking are among the industries in which froth flotation is used [6].

One of the common methods in mineral flotation is the column flotation method. Column flotation is a process that is used for the selective separation of minerals by attaching air bubbles to hydrophobic minerals suspended in the pulp and transferring them to the froth layers. [7]. In the early 1960s, the column flotation technique was first proposed by Boutin and Tremblay and has been significantly refined and improved as a major mineral separation technology in the mining industry [8]. Flotation column is widely used for low-grade ore [9]. Compared to mechanical cells, column flotation has the advantages of lower capital and operating costs, higher separation efficiency (higher product grade and recovery), and better flexibility for automatic process control. In the 1960s and 1970s, due to the industry's need for high performance, a significant amount of research was devoted to the design of high-capacity machines [6]. The stability of the froth, the size of the bubble, the amount of reagent and the rate of flotation are the factors affecting the flotation. Aeration is one of the important parameters for effective suspension and distribution of particles in the pulp. Effective aeration is required to disperse the bubbles, and the air flow rate must be high enough to create a stable froth layer in addition to creating enough bubbles to contact the particles. The air flow rate has a great effect on coal flotation [10]. Despite the many studies related to aeration in column flotation cells on a laboratory scale, the effect of aeration rate on other operational parameters, such as the amount of chemical consumption, needs to be further investigated. This research was carried out in a pilot-scale flotation cell and Response Surface Method (RSM) has been used to investigate the process space and variables to improve and model coal flotation.

2. Material and Methods

The coal sample was collected from the hydrocyclone overflow of the Parvadeh Tabas coal washing plant without any chemicals being fed to the column flotation cells. The Parvadeh Tabas coal washing plant is located in the center of Iran and has a capacity of 300 tons per hour. Coal washing at this factory is done by two methods: gravity and flotation which the gravity method is carried out using Triflow devices, while flotation is performed with column cells. The pilot-scale column flotation device in the laboratory (6 m high and 11 cm in diameter) is shown in Figure 1. The experiments were carried out at neutral pH. The

* Corresponding author. *E-mail address:* m.karamoozian@shahroodut.ac.ir (M. Karamoozian).

analysis of the tested coal sample is presented in Table 1. Gas oil was used as a collector to increase the hydrophobicity of coal particles. Methyl Isobutyl Carbinol (MIBC) was used as a frother agent to create stable, portable froth of hydrophobic materials. The ash fraction and weight in each coal particle size section are shown in Figure 2.

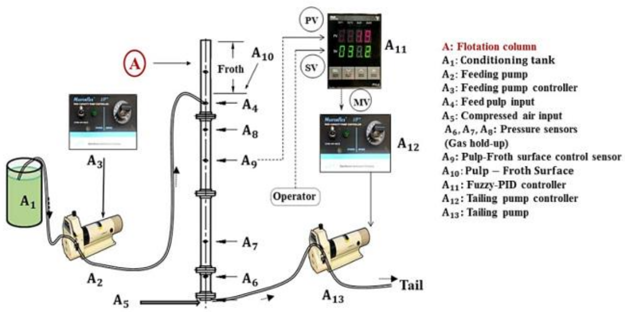

Figure 1. The schematic of the pilot scale column flotation device [11].

Table 1. The approximate analysis of coal sample.

Parameters	
Moisture	10%
Ash	33.6%
Volatile Matter	16.7%
Sulfur	0.99%

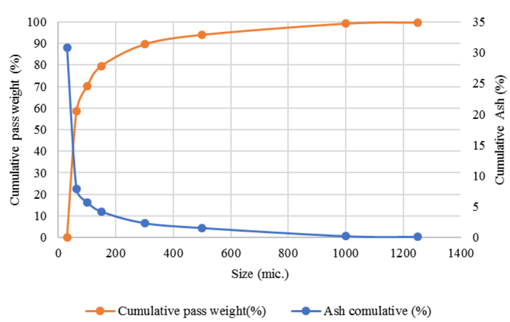

Figure 2. The ash fraction and weight in each coal particle size section.

26 experiments designed by the response surface method (RSM) and central composite design (CCD) were conducted using a pilot-scale column flotation device. The RSM method is a set of mathematical and statistical techniques used to develop, improve, and optimize new processes and products [7,12]. The most comprehensive applications of the RSM are in situations where several input variables potentially affect performance measures or process quality characteristics. The response surface method includes the experimental strategy to discover the process environment or independent variables, empirical statistical modelling to establish a suitable relationship between performance and optimization methods to find the values of the process variables that produce the desired response values [7].

For each test, 70 liters of pulp with a solid percentage of 5% (3.5 kg of coal) was prepared. The pulp was mixed with diesel collector and MIBC frother with a preparation time of 4 minutes. The pulp was pumped into the machine with a volume of 50 liters and then the air valve was opened. The overflow concentrate was collected from the device. The filter tailings and concentrate were dried and the ash content of each experiment was analyzed. The obtained results are presented in Table 2.

3. Results and Discussion

According to the analysis, the average amount of ash in the feed is 33.62%. This coal cannot be used for industrial purposes. To use this coal in industry, the amount of ash should be reduced to below 12%. The results presented in Table 2 were used to develop a linear model to predict the responses, i.e. weight recovery percentage and concentrate ash percentage in the column flotation process. The linear models that show the responses in terms of independent variables were determined as follows:

$$\text{Concentrate ash} = +6.13193 +0.000098C +0.008729F +0.000346A - 0.000148FR$$

$$\text{Recovery} = +24/08890 -0.002844C +0.037229F +0.001499A$$

which in the presented model are C= Collector, F= Frother, A= Air velocity, FR= Flow rate.

ANOVA statistical analysis was performed with the help of Design Expert application software. The results of the ANOVA linear model for the percentage of concentrate ash are presented in Table 3. According to the F=5.40 value of the model, it indicates the significance of the model. The value of P less than 0.05 shows that the expressions of the model are also significant, and according to Table 3, the amount of air entering the column flotation device is significant. The value of the model's adequate precision parameter, measuring the signal-to-noise ratio, was 7.69 for the percentage of concentrate ash, and a value greater than 4 indicates a sufficient signal to move in the design space.

In Figure 2, the impact of aeration rate in conjunction with the presence of a frother on the ash content of the coal concentrate is depicted. This figure clearly indicates that, while maintaining a constant frother dosage, an increase in the aeration rate is associated with higher air content, which leads to more coal ash particles being transported to the concentrate during flotation and with a rise in the concentration of ash percentage. This observation indicates that a higher air content, when combined with the frother, leads to an increase in the ash content of the coal concentrate.

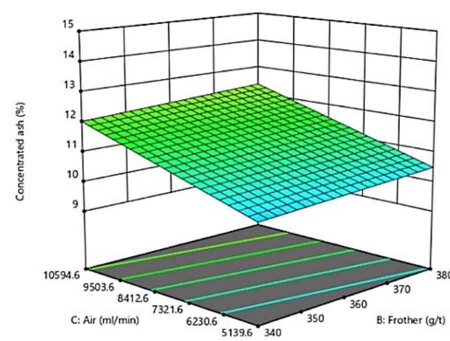

Figure 2- The diagram of the influence of the amount of air in the presence of frother on the percentage of concentrate ash.

Figure 3 presents the impact of the aeration rate, in the presence of a collector, on the ash percentage of the coal concentrate. The figure clearly demonstrates that, while maintaining a constant collector level, an increase in the aeration rate results in a higher ash percentage in the concentrate. This finding suggests that, under the specified conditions, increasing the aeration rate leads to a significant rise in the ash content of the coal concentrate. with an increased aeration rate, more air bubbles are generated, which can carry and attach to the ash particles, resulting in a higher ash content in the concentrate. Also, the increased turbulence caused by higher aeration rates can prevent the selective attachment of valuable coal particles to bubbles, leading to a higher concentration of ash in the concentrate. Furthermore, it should be noted that within the fixed aeration rate range, altering the collector level does not have a considerable effect on the ash percentage. This observation highlights the dominant influence of the aeration rate on the flotation process, which determines the ash content of the concentrate.

The results of the linear ANOVA model for weight recovery percentage are presented in Table 4. According to the F=3.67 value of the model, it indicates the significance of the model. The value of P less than 0.05 shows that the expressions of the model are also significant, according to Table 4, the amount of air entering the column flotation

Table 2. Experimental results.

Experiment	Collector dosage (g/t)	Frother dosage (g/t)	Air velocity (ml/min)	Flow rate (cm^3/min)	Concentrate ash (%)	Tailing ash (%)	Recovery (%)
1	900	340	5139.6	3000	11.54	69.03	52.25
2	1300	340	5139.6	3000	11.25	56.25	40.03
3	900	380	5139.6	3000	9.87	54.39	36.3
4	1300	380	5139.6	3000	9.32	57.99	34.63
5	900	340	10594.6	3000	12.1	74.47	47.27
6	1300	340	10594.6	3000	12.23	74.1	47.77
7	900	380	10594.6	3000	14.26	74.97	56.34
8	1300	380	10594.6	3000	12.65	69.04	52.22
9	900	340	5139.6	8400	9.44	68.23	39.15
10	1300	340	5139.6	8400	9.07	57.97	35.65
11	900	380	5139.6	8400	9.17	60.46	41.33
12	1300	380	5139.6	8400	10.46	68.99	45.92
13	900	340	10594.6	8400	11.16	64.89	52.72
14	1300	340	10594.6	8400	11.59	69.51	51.42
15	900	380	10594.6	8400	12.31	71.94	53.84
16	1300	380	10594.6	8400	13.31	69.41	52.59
17	700	360	7694.4	5400	11.91	68.66	42.3
18	1500	360	7694.4	5400	12.13	68.78	44.96
19	1100	320	7694.4	5400	11.89	67.61	47.09
20	1100	400	7694.4	5400	12.5	74.17	52.57
21	1100	360	2580	5400	11.13	66.59	51.07
22	1100	360	13075.1	5400	12.47	64.1	54.21
23	1100	360	7694.4	1200	10.46	72.16	40.28
24	1100	360	7694.4	10200	9.52	49.16	36.01
25	1100	360	7694.4	5400	9.25	53.39	36.38
26	1100	360	7694.4	5400	11.68	64.52	53.47

Table 3- The ANOVA results for the linear response surface model for ash concentrate.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	25.03	4	6.26	5.40	0.0038	significant
Air	20.87	1	20.87	18.00	0.0004	significant
Residual	24.35	21	1.16			
Lack of Fit	21.39	20	1.07	0.3623	0.8878	not significant
Pure Error	2.95	1	2.95			

Table 4- The ANOVA results for the response surface linear model for weighted recovery.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	412.38	3	137.46	3.67	0.0278	significant
Air	391.31	1	391.31	10.44	0.0038	significant
Residual	824.30	22	37.47			
Lack of Fit	678.27	21	32.30	0.2212	0.9545	not significant
Pure Error	146.03	1	146.03			

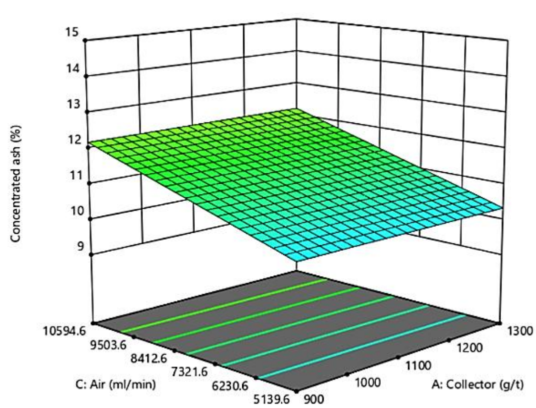

Figure 3- The diagram of the influence of the velocity air in the presence of the collector on the percentage of concentrate ash.

device is significant. The value of the parameter of adequate precision of the model, measuring the signal-to-noise ratio, was 6.55 for weight recovery percentage, which is greater than 4 and indicates a sufficient signal to move in the design space.

Figure 4 illustrates the influence of the aeration rate, in the presence of a frother, on the weight recovery in column flotation. The figure clearly demonstrates that, while maintaining a constant frother dosage, an increase in the aeration rate leads to a higher weight recovery. This finding suggests that, under the specified conditions, an elevated air content contributes to an increased recovery in the flotation process. This can be attributed to the improved attachment of particles to bubbles due to increased air dispersion, preventing particle settling, and facilitating the transportation of valuable particles through the froth.

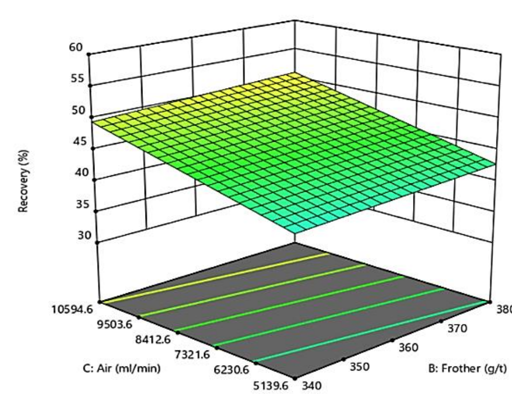

Figure 4- The diagram of the influence of the response level of the effects of the amount of air in the presence of frother on weight recovery.

Additionally, it should be noted that within the fixed aeration rate range, a slight increase in recovery is observed with an increase in the frother dosage. Increasing the frother dosage results in a greater formation of air bubbles in the flotation column. These bubbles can attach to the desired particles and improve the efficiency of flotation for particle recovery. This observation highlights the role of the frother in enhancing the flotation performance and the potential for improving recovery at a constant aeration rate.

Figure 5 shows the effects of the amount of collector and air on weight recovery. In this figure, an increase in weight recovery is observed with a fixed amount of collector and an increase in the amount of air.

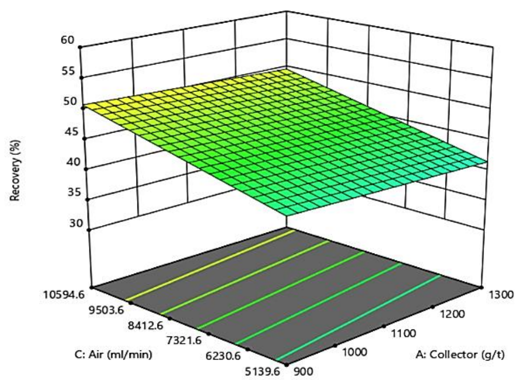

Figure 5- The diagram of the influence of the response level of the effects of the amount of air in the presence of the collector on weight recovery.

According to the simulation, it can be seen that with 900 (g/t) collector, 340 (g/t) frother, and an aeration rate increasing up to 10594/6 (ml/min), it is possible to recover 50.06% coal with 11.6% concentrate ash content. This amount of ash concentrate is suitable for steel factories.

For a constant air flow rate, increasing the flow rate against the pulp flow reduces the rate at which air bubbles rise, which increases the gas hold-up [13]. An increase in gas hold-up usually leads to a greater accumulation of air bubbles inside the cell, resulting in more collision between air bubbles with hydrophobic particles of mineral matter. In the modelling conducted, increasing the air flow rate results in an increase in both the amount of concentrate ash and the weight recovery of coal, due to higher gas hold-up in the column flotation cell.

Gas hold-up is directly proportional to bubble surface flux, which is strongly related to the flotation kinetic constant. The relationship between bubble surface flux and flotation kinetics was linear in the case of shallow bottom.

4. conclusion

The design of the experiment was done using the response surface method. A scheme for the effect of aeration rate on coal separation, as well as its modelling and optimization in pilot-scale column flotation was carried out. Mathematical equations related to the concentrate ash percentage and weight recovery were obtained using Design Expert software.

Raising the air velocity from 5139.6 ml/min to 10594.6 ml/min boosts the quantity of air bubbles, leading to a rise in gas hold-up. This, in turn, enhances the collision efficiency between air bubbles and particles.

According to the optimal values of fuel oil collector 900 g/t, MIBC frother 340 g/t and aeration rate 10594.6 (ml/min), a column flotation operation with a recovery of 50.06% and an ash content of 11/6% was obtained. The aeration rate had the greatest effect on the percentage of ash concentrate and recovery compared to the collector and frother.

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