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Kinetic modelling of flotation column and Jameson cell in coal

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Abstract: Physical enrichment technologies can be used worldwide in various coal washing plants to enrich up to 500 µm particle size. Conversely, coals smaller than this are discarded as waste, causing storage and environmental issues. In this regard, studies on coal below 500 µm in Turkey have recently acquired attraction. The Jameson flotation cell and flotation column, which have many uses worldwide but are not used throughout the plant in Turkey, were used to investigate the separation possibilities of coals below 500 µm. In the study, the flotation column and Jameson cell performances for three different particle sizes (-500+300, -300+212 and -212+106 µm) were compared. For the first time, both machines operated in a negative bias condition. In addition, the flotation kinetics of the machines were modelled with some critical operating parameters. Models illustrating the main and multiple effects of the parameters were developed using the data derived from the experimental results, and the models were statistically significant at the 95% confidence level. In the experiments performed with both flotation machines, the flotation rate increases with the decrease in particle size in general. According to the results, the velocity increase in the Jameson cell was 0.0050-0.0075 min^{-1} compared to the flotation column in the experiments performed in the size range of -500+300 µm, and the flotation rate constant increased approximately twice. In the size range of -212+106 µm, the difference became larger, and the flotation rate of the Jameson cell increased up to six times with a difference of 0.0450-0.0500 min^{-1}.

Keywords: coarse particle, flotation column, Jameson cell, kinetics, particle size

1. Introduction

It has gained importance to develop environmental policies and carry out studies that lead to zero waste in all occupational groups worldwide. When evaluated within this framework, mining is essential because it is one of the processes that produce a high amount of waste. Mining wastes are in the category of wastes that should be evaluated due to environmental effects and waste storage costs. Environmental laws in Turkey also impose severe restrictions on mining waste. These restrictions also apply to coal, which harms the environment and causes enormous costs for companies. For this reason, the enrichment/recovery of coals below 500 µm, which cannot be enriched with conventional methods (spirals, jigs, heavy medium separation, etc.), gains great importance.

The most effective method for enriching low-rank fine-sized coals is flotation. The researchers conducted coal flotation tests in order to acquire the best results (Aktas and Woodburn, 1995; Kowalczuk et al., 2011; Mohanty and Honaker, 1999; Sahbaz, 2013; Sahbaz et al., 2013). According to these investigations, coal flotation performance and coal characteristics vary depending on chemical and machine parameters. Kinetic models have developed concerning micro phenomenon in flotation based on these parameters. Kinetic models are frequently used to analyse batch flotation data and evaluate parameters such as flotation chemicals and machine operating parameters. (Xu, 1998). Machine modelling using these characteristics is critical for pilot/industrial investigations, simulation, and plant design (Chander and Polat, 1995). It is seen that the most suitable model for the flotation process was the classical first-order kinetic model among the various model. The first kinetic model for the flotation process was developed by García-Zuñiga (1935). The model assumes that the particle–bubble collision rate is first-order in terms of particle number and that the bubble concentration in the system remains constant (Sutherland, 1948).

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The following expression can be used to calculate the first-order kinetics Eq. (Polat and Chander, 2000; Tsai, 1985):

$$R = R_{\infty}[1 - e^{-kt}] \tag{1}$$

where R is the percentage recovery of combustible matter, k is the first-order rate constant [s^{-1}], t is the flotation time [s], and R_{∞} is the maximum recovery.

As stated in Eq. (1), the traditional first-order model describes flotation kinetics using two parameters: maximum recovery and first-order rate constant. Using a simple model fitting and regression analysis approach, parameters for any feed material may be easily calculated from experimental data presented through the recovery-time curve.

The ultimate recovery is influenced by chemical factors like collector dose, whereas the first-order kinetic rate constant is heavily influenced by physical process variables such as feed particle size, gas flow rate, and power input (Nguyen and Shulze, 2003). The particle size is the most important factor influencing the flotation kinetics and hydrodynamics, hence, the metallurgical results (Yianatos and Bergh, 1991). Numerous research has examined the relationship between flotation kinetics and particle size in the mechanical flotation of coal (Abkhoshk et al., 2010; Bahrami et al., 2020; Li et al., 2013; Ni et al., 2016; Polat et al., 1993; Sahu et al., 2021; Zhang et al., 2013).

The low mechanical cell flotation success of coarse particles causes the bubble to detach from the particle due to the centrifugal force caused by the rotational movement of the bubble-particle aggregate entering the turbulence area (Schulze, 1984; Ata and Jameson, 2013). With the use of air-stirred flotation machines (Flotation column, Jameson cell), the range of floatable particle sizes expands (Nicol, 2001). Numerous research has examined the connection between buoyancy and both machines for coarse particles (Bedekovic, 2016; Cowburn et al., 2006; Fahad et al., 2022; Kowalczuk et al., 2011; Ling et al., 2017; Vapur et al., 2010). This is important in the flotation of coarse or partly floating particles. However, using negative bias to reduce or eliminate the froth thickness will result in fast flotation of coarse particles (Soto, 1989). Positive bias has been used in both machines in research studies; negative bias has not been extensively studied. Therefore, negative bias in coarse coal flotation is expected to improve flotation performance. There is no extensive study on the negative bias, and researchers have operated both machines with positive bias in their studies. The flotation efficiency of coarse particle materials has been observed to significantly increase in flotation investigations carried out with negative bias in flotation columns (Oteyaka and Soto, 1995; Soto, 1992). According to Ucar et al. (2014), colemanite samples with a size between 150 and 38 μm had improved flotation efficiency when the Jameson cell was operated in a negative bias condition. Therefore, it becomes crucial that the negative bias enhances the flotation kinetics of coarse particles.

This work explored the enrichment of low-rank coals smaller than 500 μm, which cannot be enriched efficiently by traditional procedures, using the flotation column and the Jameson cell. As a result, the most favourable conditions for the recovery of coals that generate environmental difficulties have been proposed. Despite the fact that there is numerous research on the kinetic characteristics of flotation cells in the literature, there is no comprehensive study on the kinetic properties of the Jameson cell and the flotation column in negative bias conditions. This research aims to create models by determining the characteristics that affect the kinetics of both machines with negative bias. Also for the first time, the combination of important parameters such as collector dosage (chemical one), bias (operational one) and particle size (physical one) have been modelled and compared for two different machines in terms of kinetic.

2. Materials and methods

2.1. Material

The coal sample used in the experiments was obtained from the Şahinköy lignite quarry belonging to Akcelik Mining Company in Tekirdağ province. The sample was initially crushed to -20 mm in the Ore Preparation Laboratory of Kutahya Dumlupınar University using a jaw crusher. The sample was then crushed in a closed circuit using a roller crusher to a size of -500 μm. The sample was sieved through 300, 212, and 106 μm sieves and divided into three size groups: -500+300, -300+212, and -212+106 μm. For flotation studies, samples in each size group were homogeneously separated and stored in a deep freezer. The substance contains 47.1% ash and 1.51% sulphur, according to the analysis results of the lignite coal with high ash content.

2.2. Method

2.2.1. Flotation experiments

A flotation column and a Jameson cell were used in the flotation tests. The kinetics of both machines were assessed in the tests employing size groups of -500+300, -300+212, and -212+106 µm. Flotation column experiments were carried out on a 5230 mm high and 60 mm diameter column made of plexiglass. Fig. 1 shows a schematic of the column flotation unit. In the Jameson cell experiments, the cell with a 200 mm separation tank with an 1800 mm long and 15 mm diameter downcomer was used. The nozzle diameter of the tool is 4 mm (Fig 2).

Washing water was not used because it was operated with negative bias in both flotation systems. The feed flow rate was changed for three different bias velocities by keeping the tailing flow rate constant. Bias is the difference between the tailing flow rate and the feed flow rate and is the parameter responsible for the formation of the froth zone (there is a froth zone with a positive bias). The bias is generally negative in the flotation of coarse particles (Mohanty and Honaker, 1999; Oteyaka, 1993; Patwardhan and Honaker, 2000). Using Eq. 2, it is possible to find the bias rate in the cell:

$$J_b = \frac{Q_a - Q_b}{A_c} \tag{2}$$

where J_b is bias rate (m/s) and A_C represents the cell cross-sectional area (m^2).

Concentrates were taken at different times to determine the flotation rate constant. The remaining material in the flotation machine and the feed tank is taken as tailing.

In the flotation process, kerosene (10 kg/t, 20 kg/t and 30 kg/t) was used as a collector, and Aerofroth 65 (AF-65) was produced by Cytec company, which was a polyglycol type as a frother (20 ppm). In addition, sodium silicate (500 g/t) was used to suppress the clay in the sample. All experiments were carried out using tap water.

It was aimed to carry out the experiments with parameters in optimum conditions as much as possible since the study was carried out to compare the flotation kinetics of both machines. For this reason, before starting the kinetic experiments, a series of optimization experiments were carried out, and the levels of the parameters were determined accordingly.

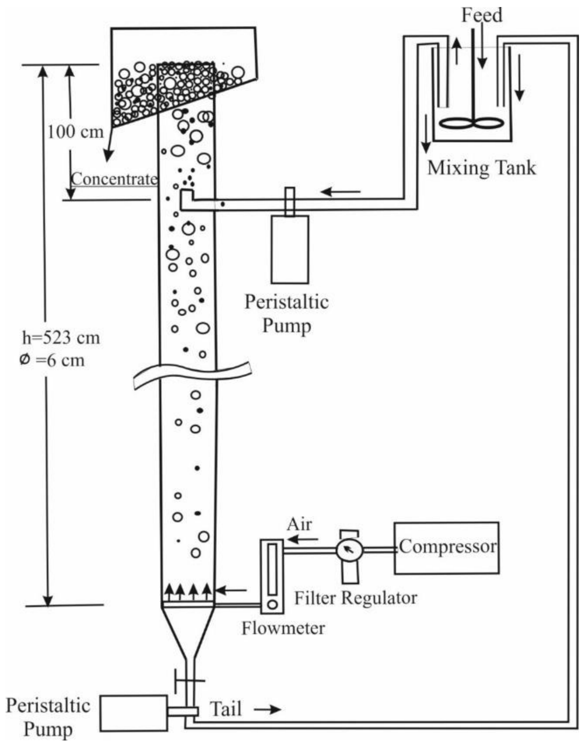

Fig. 1. Flotation column schematic diagram

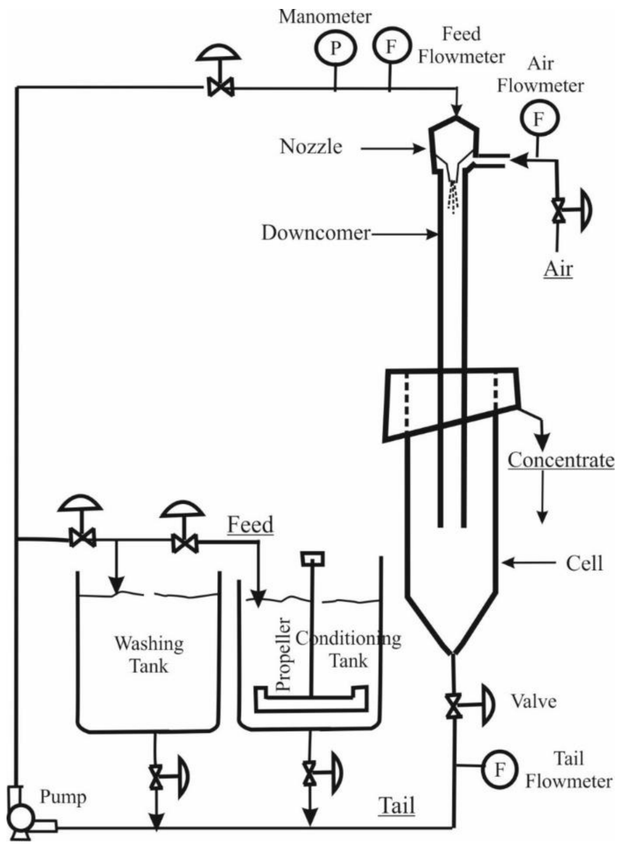

Fig. 2. A schematic view of the Jameson cell setup

Table 1. Test conditions used in the flotation column

Parameters	Values
Solid ratio (%)	10
Feeding flow (Q_b) (dm^3/min)	1.42, 1.47, 1.52
Tailing flow (Q_a) (dm^3/min)	1.25
Conditioning time (t) (min)	2+7 (Depresant+Collector)
Flotation time (min)	0-1, 1-3, 3-5, 5-8
Hold-up (%)	10
Air flow rate (dm^3/min)	1.5

Table 2. Test conditions used in Jameson flotation

Parameters	Values
Solid ratio (%)	5
Feeding Flow (Q_b)	6.00, 6.38, 6.55
Tailing flow (Q_a) (dm^3/min)	5.08
Conditioning time (t) (min)	2+7 (Depresant+Collector)
Flotation time (min)	0-1, 1-3, 3-5, 5-8
Hold-up (%)	39

2.2.2. Experimental design and modelling

Experiments were carried out according to 2^3 full factorial experimental designs. Twelve experiments were conducted for each flotation machine, eight at low and high levels and four at medium levels, which are independent variables such as particle size, bias rate and collector amount. Flotation kinetics was taken as the dependent variable. The factors, levels and values for 2^3 experimental designs are given in Table 3.

Table 3. Variables and their levels

Parameters	Units	Low (-1)	Midpoint (0)	High (+1)
Collector Amount – Q_C	g/t	10000	20000	30000
Particle Size - d	µm	-212+106	-300+212	-500+300
Bias Rate – J_b	cm/s	0.10	0.13	0.16

The upper level in the design matrix was labelled "+1," while the lower level and mid-point were labelled "–1" and "0," respectively. From the actual values (X_{actual}), the following Eq. was applied to generate coded units (X_{coded}).

$$A_{coded} = \frac{X_{actual} - X_{mean}}{X_{Low}\ or\ X_{High} - X_{mean}} \tag{3}$$

where X_{high} is any factor's maximum value, X_{low} is its lowest value, and X_{mean} is half the sum of the low and high values. The flotation rate constant was chosen as a response in the study. The major effect of any factor is the change in response that occurs when the variables' levels are changed. The following Eq. (Montgomery, 2009) may be used to compute it:

$$Main\ effect\ of\ factor\ X = \left(Average\ response\ at\ X_{high}\right) - \left(Average\ response\ at\ X_{low}\right) \tag{4}$$

It's also crucial to uncover interaction effects, which arise when the difference in response between levels of one factor isn't the same at all levels of the other factors. This effect can only be discovered by employing Eq. 5's statistical design (Montgomery, 2009).

$$Interaction\ effects\ of\ X_1 and\ X_2 = \left(Average\ response\ at\ X_1 X_{2high}\right) - \left(Average\ response\ at\ X_1 X_{2low}\right) \tag{5}$$

A cube may geometrically depict a full factorial 2^3 design with four base points. Responses can be put in the corners and the X, Y, and Z axes represent factors A, B, and C, respectively. The origin is the cube's centre, and each cube side corresponds to two units, +1 and -1. Design Expert 10.0.6 statistical software determined the main and interaction effects with a 95% confidence interval. The Fisher test and probability values were employed to assess the data stat statistically. The F and p-values were used to compare the outcomes in this analysis. The model significance is indicated by the F-value. It's used to figure out how to navigate the model in the design space. The parameter effect on a response is proportional to the F_{value}. Furthermore, the p_{value} values are used to determine the usefulness of the parameters, with a p-value of less than 0.05 indicating that the model terms are significant at the 95% confidence level.

Eq. 6 was used for this determination in eight experiments (Montgomery, 2009).

$$NoE = 2^k \tag{6}$$

The number of experiments is NoE, and the number of variables is k. Additional four trials were run at the base level to provide statistical significance and assess the variance (σ^2) and error. Eqs 7 and 8 (Kelebek et al., 2008) yield the variance of the primary and interaction effects:

$$Variance\ (Effects) = \frac{4\sigma^2}{2^k} \tag{7}$$

$$Calculated\ main\ or\ interaction\ effects / [Variance(Effects)]^{0.5} \geq t_{3.0.025} \tag{8}$$

The primary and interacting terms of the model (regression Eq.) can be stated as follows:

$$Y = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_{12} AB + \beta_{13} AC + \beta_{23} BC + \beta_{123} ABC \tag{9}$$

where Y is the response (flotation rate constant), and β is the main and interaction term coefficients.

2.2.3. Kinetic calculation

It can be plotted with a recovery-time curve to find the flotation kinetics by batch experiments (Yuan et al., 1996). Thus, the following Eq. expresses the velocity Eq. for batch flotation experiments.

$$\frac{dC}{dt} = -kC^n \qquad 10)$$

Here, C is the amount of floating particles, n is the order of the Eq., k is the flotation rate constant, and t is the time. After n = 1 is valued, first-order flotation kinetics are obtained by integrating and rearranging Eq. 10 (Arbiter and Harris, 1962).

The Eq. shows the natural logarithm of 1 minus fractional recovery for each size fraction as a function of time (min) by integrating both sides of the Eq.. This represents the simplest form of first-order kinetics with an analogy to chemical kinetics (Arbiter and Harris, 1962), which was judged to be adequate for comparing the performance of collecting data. The recovery was calculated for the coal flotation by the use of Eq. 11:

$$R = \frac{C \times (100-c)}{F \times (100-f)} \times 100 \tag{11}$$

where C; is the amount of floatable product (%), c is; the ash content of floating material (%), F; is feed amount (%), and f is the ash content of the feed (%).

3. Results and discussion

3.1. Determination of flotation rate constant

In this study, the enrichment of coal below 500 µm, which is difficult to recover with conventional separation machines, was investigated with a flotation column and Jameson cell. Due to the potential use of the machines in Turkey, kinetic models have been empirically presented for the first time for certain parameters (particle size, collector amount and bias rate). Thus, the potential uses of the machines in the industrial dimension were tried to be evaluated.

With the help of the values obtained from the experiments with the flotation column and Jameson cell (Fig. 3), the flotation rate constants were determined from the slopes of the graphs drawn against ln(1-R) depending on the concentration recovery times. For both machines, the maximum rate constant was obtained in the size range of -212+106 µm. According to Gaudin et al. (1931), particles of various sizes had different flotation kinetics under the same chemical conditions. They claimed that the ideal particle size for coal flotation is usually less than 1 mm, while the highest recovery of copper minerals is in the size range of 20 and 100 µm, and phosphate minerals are in the range of 60 and 200 µm. According to Zhang et al. (2013), the highest flotation rate constant obtains in the size range of -250+150 µm in the study conducted on six kinetic models and various size fractions, except for the first-order flotation kinetic model. In the experiments performed with both flotation machines, the flotation rate increases with the decrease in particle size in general (Table 4) because of the detachment as mentioned by Tao (2005) and Trahar (1981).

When Fig. 3 is analysed on a machine basis, it is seen that the flotation rate constants obtained from the Jameson cell are higher due to the generation of the fine bubble, the hydrodynamic properties, the energy due to the high shear forces occurring at the top of the downcomer, and the lower residence time in the machine (Harbort et al., 2002; You et al., 2017). In the experiments performed in the -212+106 µm size group, the highest rate constant value was obtained with 0.9686 R^2 and 0.0128 min^{-1} in the flotation column, and 0.0632 min^{-1} with 0.9841 R^2 in the Jameson cell. Thus the velocity increase in the Jameson cell was 0.0500 min^{-1} more compared to the flotation column, and the flotation rate increased by six times. In the experiments performed in the coarsest particle size group (-500+300 µm), the velocity increase in the Jameson cell was 0.0075 min^{-1} more than in the flotation column, and the flotation rate constant increased approximately twice. In addition, changing the collector amount in the flotation column did not cause any change in the performance of the machine (Table 4).

3.2. Statistical results

2^3 design matrix of the experiments is given in Table 4. These results were analysed using the F Test (Table 5). Thus, the effects of the experimental parameters, which are the independent variables, on the flotation rate constant (dependent variable) were tested at the 95% confidence interval.

Table 5 shows the impact of particle size, collector quantity, and bias rate parameters on the rate constant in the flotation column and Jameson cell tests. At the 95% confidence interval, the empirical models obtained from the trials in both the flotation column and the Jameson cell were significant, according to Table 5. Fisher-Test F values and flotation kinetic p values are listed in Table 5. Model F values of 7.48 and 51.89 for the flotation column and Jameson cell, respectively, are noteworthy. This finding demonstrates that empirical kinetics models (Eqs. 12 and 13) from experiments can be utilised to forecast outcomes.

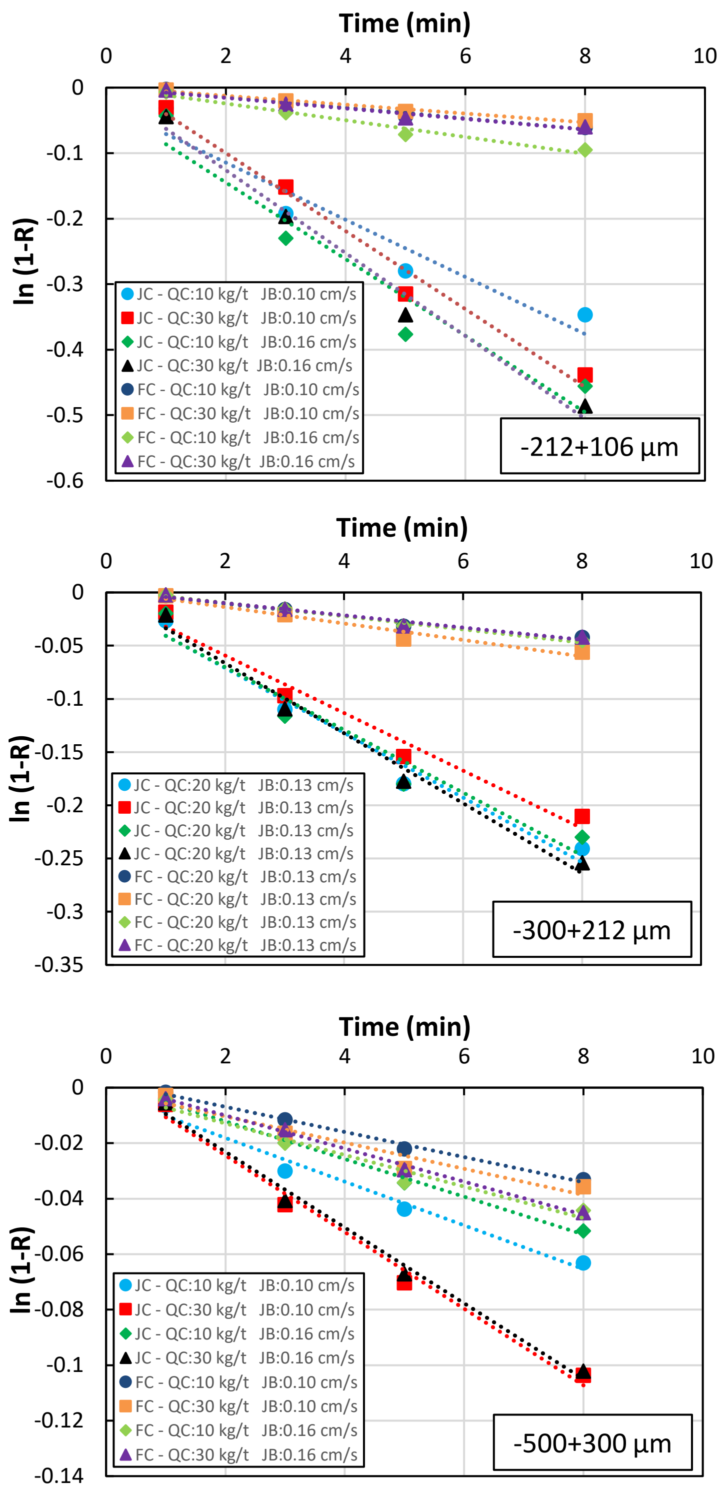

Fig. 3. First-order flotation kinetics of flotation with different particle sizes of column and Jameson cell

The flotation rate is highly dependent on particle size (Trahar, 1981). The impact of particle size on coal flotation kinetics has been the subject of numerous investigations. Studies have generally shown that the maximum flotation rate may be achieved throughout a range of intermediate particle sizes, whereas it decreases for fine and coarse particle sizes. In order to compare the flotation kinetics of different size fractions of bituminous coal using rougher and cleaner flotation processes, Ni et al. (2016) conducted flotation studies. Using Matlab software, six alternative flotation kinetic models were used to model the outcomes of the flotation tests. In the rougher flotation experiments, the reported flotation rate constants for size fractions of -500+250, -250+125, -125+74, -74+45, and -45+0 μm were 0.0585,

Table 4. First-order flotation rate constant and R^2 value of kinetic experiments

Collector amount (g/t)	Particle size (μm)	Bias Rate (J_b)(cm/s)	Flotation column: Flotation rate constant (k)(min^{-1})	Flotation column: R^2	Jameson Cell: Flotation rate constant (k)(min^{-1})	Jameson Cell: R^2
10000	-212+106	0.10	0.0084	0.9775	0.0436	0.9143
10000	-212+106	0.16	0.0128	0.9686	0.0585	0.9253
30000	-212+106	0.10	0.0068	0.9787	0.0595	0.9811
30000	-212+106	0.16	0.0081	0.9590	0.0632	0.9841
20000	-300+212	0.13	0.0077	0.9574	0.0270	0.9692
20000	-300+212	0.13	0.0057	0.9721	0.0304	0.9713
20000	-300+212	0.13	0.0062	0.9866	0.0329	0.9831
20000	-300+212	0.13	0.0058	0.9698	0.0295	0.9405
10000	-500+300	0.10	0.0042	0.9841	0.0079	0.9711
10000	-500+300	0.16	0.0057	0.9607	0.0068	0.9936
30000	-500+300	0.10	0.0047	0.9374	0.0138	0.9866
30000	-500+300	0.16	0.0060	0.9957	0.0136	0.9902

Table 5. Results of change analysis of flotation column and Jameson Cell flotation rate constant.

Factor	Flotation Column: F Value	Flotation Column: p-Value Prob>F	Jameson Cell: F Value	Jameson Cell: p-Value Prob>F
Model	7.48	0.0352	51.89	0.0009
Q_C	3.76	0.1244	11.35	0.0281
d	29.88	0.0054	341.55	< 0.0001
J_b	8.99	0.0400	3.06	0.1550
Q_C-d	6.27	0.0665	0.64	0.4690
Q_C-J_b	1.35	0.3092	1.09	0.3563
d-J_b	1.05	0.3643	4.05	0.1144
Q_C-d-J_b	1.05	0.3643	1.50	0.2881

0.1096, 0.1030, 0.0673, and 0.0382 s^{-1}. According to the findings, intermediate particle sizes produced the highest flotation rate constant in rougher flotation applications. In a rougher process, the size fraction of 250+125 µm produced the maximum combustible recovery of 87.15% and a rate constant of 0.1096 s^{-1}; in a cleaner process, the size fraction of 125+74 µm produced 95.65% and 0.1423 s^{-1}. Three coal size fractions were the subject of a study by Li et al. (2013) that examined the flotation kinetics and separation selectivity. They used the Matlab program to calculate the values of R_∞ and k. The flotation rate constants for particles with sizes of -500+250, -250+75, and -75+0 µm were 3.52, 2.47, and 2.17 s^{-1}, respectively. Using a laboratory flotation column, Bedekovic (2016) investigated the impact of particle size, air flow rate, and pulp density on combustible recovery and ash content. Five different coal size fractions were used in the tests: -450+400, -400+300, -300+200, -200+100, and -100+63 µm. The combustible recovery is higher for coarse particles as particle size increases. According to the test's p-level, a linear relationship between particle size and concentrate ash content ($p = 0.008$) and the combustible recovery (0.0015) was found to be significant. It is clear that particle size has a substantial impact on both machines' trials when the primary effects of the parameters are evaluated (Table 5). The p-value was less than 0.0001 for the Jameson cell, while this was 0.054 for the flotation column.

The presence of the froth zone in the system depends on the bias value. If the bias rate is negative, there is no froth zone. In flotation studies with negative bias in flotation columns, significant increases were found in the flotation efficiency of coarse particle minerals. Soto (1992) stated that the froth region is a barrier for coarse particles and made an effective coarse phosphate flotation in the negative bias. Oteyaka and Soto (1995) proposed a model for coarse particle flotation in negative bias. Bias was measured at a rate of 0.13 cm/s during the investigation. The studies with three different biases were taken to have a midpoint bias rate of 0.13 cm/s. In this study, it was found that changing the bias rate generated considerable variations in the performance of the flotation column, whereas changing the bias rate had no effect in the Jameson cell studies. In flotation column studies, the bias rate is significant with a p-value of 0.04, while in Jameson cell experiments, the bias rate is insignificant with a p-value of 0.155. (Table 5).

Although the coal structure is hydrophobic, the degree of hydrophobicity changes due to the presence of active hydrophilic groups and porous structures on the coal surface (Laskowski, 2001). Hydrocarbons like kerosene, diesel, and fuel oil have long been utilized in coal flotation because they increase the hydrophobicity of coal. This situation is due to the fact that these oily collectors can withstand stronger aggregate-breaking force fields from turbulent flows inside the flotation cell, increasing coal fine recovery (Zhang et al., 2020; Chen et al., 2022). Although researchers widely use kerosene in coal flotation, they did not find its effect on flotation sufficient. Naik et al. (2005) investigated the effects of kerosene, MIBC and sodium meta silica on fine coal flotation using 2^3 experimental designs and optimized the chemicals. In the experiments, it was seen that all three chemicals had a positive effect on the yield, but kerosene and MIBC had an adverse effect on the grade. In addition, in the study where the effects between parameters were determined, it was determined that the MIBC-kerosene interaction had a negative effect on the flotation performance. The depressing effect of MIBC on some kerosene-coated particles is the cause of the negative kerosene and MIBC interaction on recovery. Due to the activation of a group of high ash coal particles rather than low ash coal particles, this interaction has a detrimental impact on grade. According to Kelebek et al. (2008), dodecyl amine was more important as a collector than kerosene, and pH value also had a major impact on interactions between dodecyl amine and coal surface. The change in the amount of collector level in the 95% confidence interval substantially influenced the Jameson cell studies (p = 0.0281) but was insignificant in the flotation column experiments (p = 0.1244) (Table 5).

Fig. 4 shows the response surface graphs illustrating the interaction effect of parameters on the flotation rate constant. Fig. 4 (a) shows that as the collector amount in fine particle size increases, the flotation rate constant increases. The amount of collector and the change in bias rate have little effect on the flotation rate constant, and it is statistically negligible, as shown in Fig. 4 (a). Although an increase in the bias rate in coarse particle flotation has no effect on the flotation rate, an increase in the bias rate in fine particle flotation boosts the flotation rate. Using the data obtained from the experiments, the model giving the flotation rate constant for the flotation column was determined, as seen in Eq. 12.

$$\begin{aligned} \mathrm{k} = {} & 6.84167\mathrm{E}-003 - 6.87500\mathrm{E}-004Q_c - 1.93750\mathrm{E}-003\mathrm{d} + 1.06250\mathrm{E}-003J_b \\ & +8.87500\mathrm{E}-004Q_c\mathrm{d} - 4.12500\mathrm{E}-004Q_cJ_b - 3.62500\mathrm{E}-004\mathrm{d}J_b + 3.62500\mathrm{E}-004Q_c\mathrm{d}J_b \end{aligned} \tag{12}$$

The change in pulp flow in the downcomer decreases the particle's residence time and increases flow without changing air velocity. With the increase of the flow rate, the rate of the particles coming to the concentrate also increases, so the flotation rate also increases (Harbort et al., 2003). In the experiments, the residual flow rate was kept constant, and the change in the bias rate was achieved by changing the feed flow. In general, the flotation rate of all experiments increases as the bias rate increases from 0.10 cm/s to 0.16 cm/s. As seen in Fig. 4 (b), the flotation rate constant increases with the increase in the amount of collector and the decrease in particle size in the Jameson flotation cell, and it takes its highest value with 0.0632 min^{-1} (Fig. 3) under the conditions of where high bias is used. The flotation rate constant rises with the amount of collector added at a bias of 0.10 cm/s. The flotation rate constant in the coarse size increased from 0.0068 min^{-1} to 0.0136 min^{-1} at a bias rate of 0.16 cm/s with the addition of more collectors. In the flotation of fine particles, this rise can reach 0.0595 min^{-1}, whereas in the flotation of coarse particles, it can reach 0.0138 min^{-1} at a bias rate of 0.10 cm/s. It was determined that the amount of collector and particle size were the most effective parameters on the flotation rate constant. Regardless of the importance of the change in bias rate, it is seen that the flotation rate

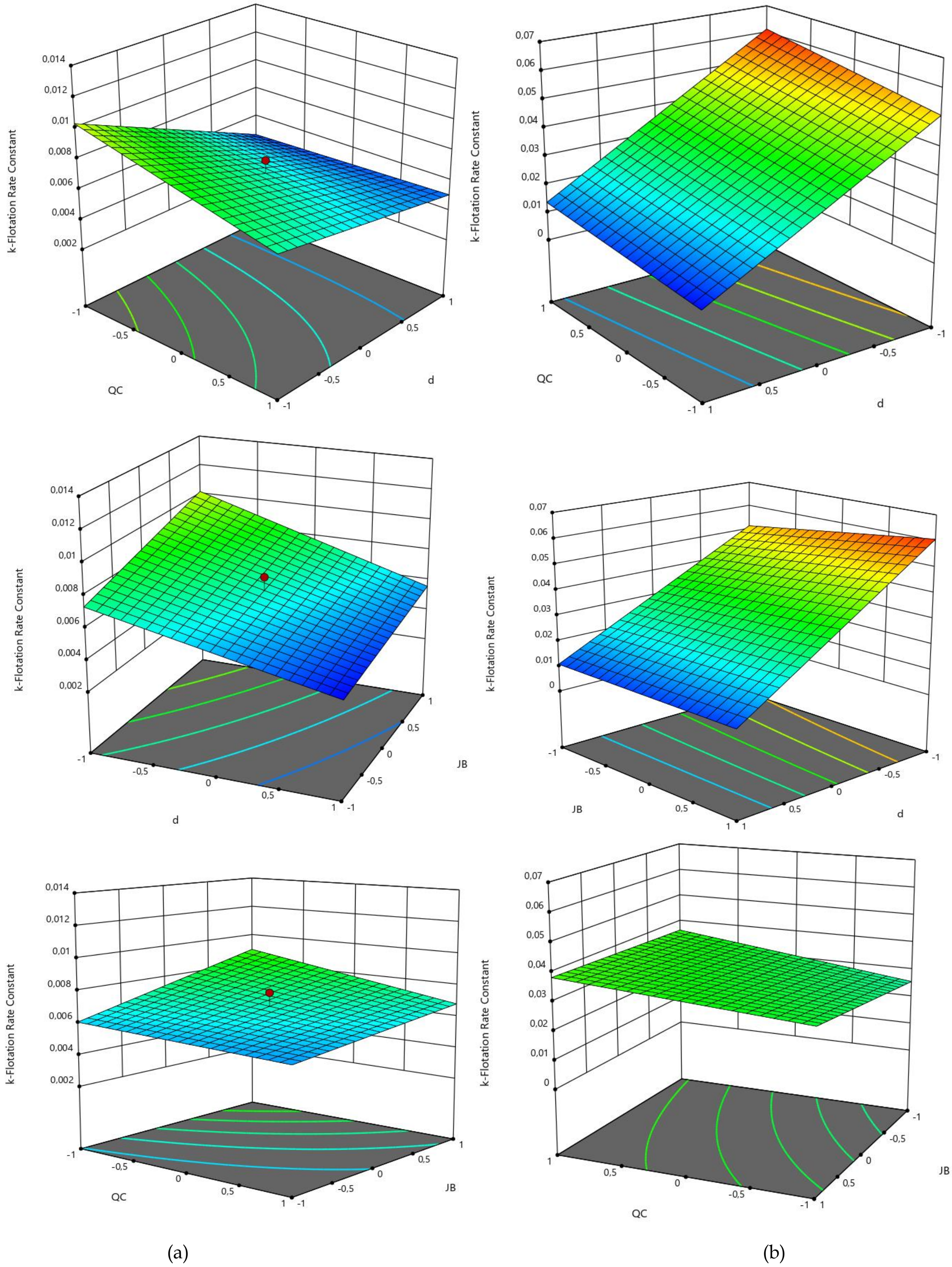

Fig. 4. The effects of the dual effects of Collector Amount-Particle size, Collector Amount-Bias, and Particle size-Bias on the flotation rate constant of the flotation column (a) and Jameson cell (b).

increases as the particle size decreases and the interaction effect between the collector amount and bias rate are statistically insignificant. The model describing the effects of collector amount, particle size and bias rate on the flotation rate constant in the experiments performed in the Jameson cell is given in Eq. 13.

$$\mathrm{k} = 0.032225 + 4.16250\mathrm{E} - 003Q_c - 0.022838\mathrm{d} + 2.16250\mathrm{E} - 003J_b - 9.87500\mathrm{E} - 004Q_c\mathrm{d} - 1.28750\mathrm{E} - 003Q_cJ_b - 2.48750\mathrm{E} - 003\mathrm{d}J_b + 1.51250\mathrm{E} - 003Q_c\mathrm{d}J_b \quad (13)$$

When the study is examined as a whole, $\Delta k = k_{\mathrm{Jameson}} - k_{\mathrm{colon}}$ value in size range of -212+106 µm varies between 0.450-0.500 min^{-1}. While this value is 0.0225-0.0250 min^{-1} in size range of -300+212 µm, the result is 0.0050-0.0075 min^{-1} in size range of -500+300 µm.

The most effective parameter on flotation kinetics in both machines, according to these findings, is particle size. The Jameson cell appears to be suited for quick flotation compared to machines modelled for the first time in negative bias.

4. Conclusions

The effects of particle size, collector amount, and bias rate on the flotation rate constants were determined for the flotation column and the Jameson cell with negative bias in this study, which used lignite coal with a high clay component. 2^3 full factorial experimental designs were used in the experiments.

Models illustrating the main and numerous effects of the factors were generated using the Design Expert 10.0.6 statistical program for the flotation rate constants established from the data collected from the test results. At the 95% confidence interval, the models developed in the study were statistically significant. When the models created according to the ANOVA results were examined, it was determined that the R^2 value in the Jameson cell was higher than the flotation column and the difference between the Adj R^2 value was less. Therefore, it can be explained that the model created for the Jameson cell is highly representative of the real experimental results. The terms that are insignificant in the 95% confidence interval and the effects of the terms included in the model remain weak model. The particle size revealed the strongest effect among the independent variables forming the model. As a result of the evaluation made with the F-Test, the final versions of the flotation kinetic models in the flotation column and Jameson cell with negative bias are given below.

$$k_{column} = 6.84167\mathrm{E} - 003 - 1.93750\mathrm{E} - 003\mathrm{d} + 1.06250\mathrm{E} - 003J_b + 8.87500\mathrm{E} - 004Q_c\mathrm{d}$$

$$k_{Jameson} = 0.032225 + 4.16250\mathrm{E} - 003Q_c - 0.022838\mathrm{d}$$

The flotation rate increases with the decrease in particle size in general in both flotation machines' experiments. Because the bias rate increased, the increase in the flotation rate was even greater. When compared to the flotation column, the velocity in the Jameson cell rose roughly twofold in the -500+300 µm size group, reaching 0.0075 min^{-1}. The difference was even greater in the -212+106 µm size group, with the Jameson cell flotation rate increasing up to six times with a difference of 0.0500 min^{-1}. Furthermore, adding more collectors to the flotation column did not affect the response variables.

These results show that the Jameson cell has great potential to be used in coal waste removal applications and environmental issues points of view.

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