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Effects of the Particle Size Distribution on the Flotation Kinetics of Bituminous Coal

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ABSTRACT

The particle size distribution is an important parameter in the flotation process, which affects the floatability and therefore the flotation kinetics. This study aims at investigating the effects of the particle size distribution on the flotation kinetics of bituminous coal. For this purpose, a series of batch flotation experiments have been conducted in a rougher stage, and concentrates have been collected in different time periods. Then the particle size distribution for each concentrate was determined. Five flotation kinetic models were applied for the modeling of data obtained from the flotation tests using MATLAB (Matrix Laboratory) software. The relationship between the flotation rate constant, maximum combustible recovery and particle size were studied. The results show that the maximum flotation combustible recovery and flotation rate are obtained with an intermediate particle size (-250 +106 µm). Results of flotation tests fitted well to all five kinetic models. It is found that the first-order model with a rectangular distribution of floatability, provides the best fit to the experimental data obtained from the flotation processes among the tested models.

1. Introduction

Flotation is a physicochemical separation process based on the difference between surface properties of valuable minerals and gangues. Most important aspect of flotation is its kinetics. The flotation rate is measured by the recovery change of the floating material in the product of flotation per time unit and it is characterized by a rate constant and kinetics order [1, 2]. Flotation kinetics can be described using mathematical models which incorporate recovery and rate functions, since the flotation process is theoretically considered as a time-recovery process [3, 4]. Flotation kinetic models dominate almost all of the flotation conditions regardless of the ore type and characteristics as well as flotation cell configurations. In addition, applying the flotation kinetic models for variable pulp chemical conditions might be beneficial in the optimization of flotation circuits [5].

The flotation process involves the interactions of three phases (gas, liquid, and solid), often modeled using complicated mathematical relationships based on offline measurements or lab analyses. It is generally accepted that Zuniga in Chile [6] published

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the first paper in the field of flotation kinetics. He applied the differential equation of chemical reaction kinetics to calculate the flotation rate and observed that the flotation recovery was an exponential function of the flotation time. Various kinetic models are suggested to evaluate the flotation recovery from different aspects [7, 8]. The general form of a kinetic model can be written as Eq. 1:

$$\frac{dc(t)}{dt} = -kc^n \qquad (1)$$

The equation above was suggested by Arbiter (1951) for the experimental and industrial data in which c is the concentration of solid, t is time, k is the flotation rate constant, and n is the kinetic order [6].

Afterwards, numerous studies were reported about the kinetics of the flotation process [9-11]. The flotation kinetic models of quite a few flotation processes have been established based on the test data from batch flotation tests or industrial tests under reasonable operating conditions. The effects of flotation parameters including the particle size and size distribution, the type and dosage of reagent, the air flow rate, the pulp density, and the wash water rate on the flotation kinetics in a flotation cell or column were previously studied [3, 7, 12-14]. In the previous studies, the main focus has been on the impact of the individual operational conditions on the recovery of the flotation process. The size distribution of feed particles is one of the effective parameters in their floatability and thus the process recovery. Particles of different sizes have different flotation rates depending on the liberation degree of the ore (and thus the adsorption of chemicals on its surface) as well as its ability to collide with air bubbles. On the other hand, the pulp fed to industrial flotation cells contains a variety of minerals with different particle sizes, which in turn have effects on their floatability and recovery. In previous researches, studies have been conducted mainly on the floatability of size fractions separately. However, in this work, studies and the modeling of flotation kinetics have been conducted for a pulp containing a series of particles of different sizes in order to investigate the effect of the flotation of particles within different size fractions on each other.

Coal is a fossil fuel with a complex composition of organic and inorganic materials [15]. It can also be defined as a sedimentary rock [16, 17] which is a combustible mixture of plant-derived organic materials; so, it may include different physical and chemical compositions. Froth flotation is widely used in the process of separating the fine coal based on the difference between the hydrophobicity of coal and gangue minerals [18, 19]. The floatability of coal depends on different parameters such as the coal type or rank, coal handling procedure, mining method (strip mining or deep mining), oxidation time, etc. [18]. While bituminous coal used to produce coke is of high floatability, the low-rank sub-bituminous and oxidized coal floats poorly [20].

The present study is carried out in order to determine the kinetic parameters of the coal flotation and the particle size distribution of the coal concentrate collected in the flotation process. In addition, a major attempt of this paper was to discuss the differences between the flotation kinetics of various size fractions in the flotation process.

2. Experimental

2.1. Ore sample

The Iranian super-bituminous coal of

Ghouzlou region, which is located in North West of Iran, was used in this study. The quantity of the exploitable mineral of this mine is about 136000 tons, and the probable deposit in this region is estimated at 450000 tons. The calming environment of sedimentation in a flat topography, before the sedimentation, led to the formation of uniform layers of coal (the longitudinal extension of the layer was 800 meters and its width was 1600 meters). The hanging wall is made of a hard sandstone with a fine particle size sandstone with medium thickness of 4 meters and the foot wall of a coal coated layer that is made of argillite with an average thickness of 2 meters [21].

From the geologically structural point of view, three zones of continental, metamorphic and oceanic are observed in the area, located along the fault boundaries. The continental zone is covered by the platforms of the Precambrian-Paleozoic located in the Alborz-Azerbaijan (Soltanieh-Myshv) construction zone, the metamorphic zone is a part of the Sanandaj-Sirjan zone and consists of a set of Mica-schist, Quartzite, Ganesh and Amphibolite metamorphic rocks. The oceanic area, which includes a set of ophiolite rocks (Donite, Harzburgite and Lerzolite), marble and Amphibolite (Pale theca ocean survivors), is located alongside fault boundaries in the vicinity of other rock units [18].

2.2. Sample analysis

In order to provide a representative sample of the entire deposit, three samples from different sections of Ghozlou coal deposit were collected and mixed. Then a representative sample was selected. The analysis of the particle size distribution (PSD) has been done in the mineral processing laboratory of Urmia University. Also, flotation tests and ash analyses have been done in that laboratory. The results of the selected coal sample is presented in Table 1 and Figure 1. The ash content of the coal sample was 12 % on an air dry basis. According to Table 1, 19.33 % of the sample is smaller than 106 µm with an ash content of 19.08 %. It indicates that the coal sample contains large amounts of fine coal particles with a relatively high ash content.

2.3. Flotation test and flotation kinetic models

In the flotation experiments, kerosene and MIBC (Methyl Isobutyl Carbonyl) were used as the collector and frother respectively. The pH value of the pulp was measured using a pH-meter and it was adjusted to 6.5 using NaOH and HCl solutions. The temperature was fixed at 20 °C during the experiments.

Table 1

Particle size distribution (PSD) of the bituminous coal sample from Ghouzlou region.

Particle size (µm)	Weight (%)	Ash (%)	Cumulative weight of undersize (%)	Cumulative ash content of undersize (%)
(+850-1000)	7.22	8.70	92.78	8.70
(+500-850)	32.61	11.80	60.17	10.74
(+250-500)	21.70	11.20	38.47	11.11
(+106-250)	19.14	13.60	26.22	11.70
(+75-106)	12.25	17.80	19.14	13.19
(0-75)	7.08	21.30	0	19.08
Sum	**100**			**12.42**

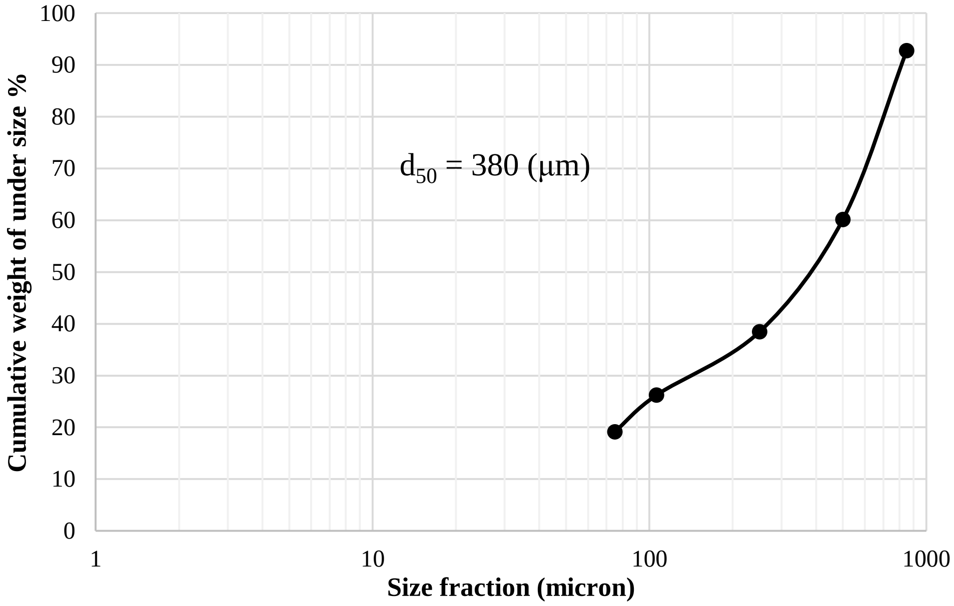


Figure 1. PSD of the coal sample–sample from the Ghouzlou region.

The flotation test was performed in a 1500 ml Denver flotation cell. In this test, 300 g of the coal sample has been mixed with 900 ml of tap water in the cell. The mixture was agitated for 120 seconds at an impeller rotation speed of 1800 rpm. Then, kerosene (3 ml) was added to the pulp and mixed for 120 s. Subsequently, MIBC (1 ml) was added to the pulp and mixed for 30 s. Then the air valve with the 5 L/min flow rate was opened and frothing was done for 200 s. The pulp level in the cell was kept constant during the operation by adding tap water.

Flotation concentrates were collected in sequential time periods of (0-20), (20-40), (40-60), (60-80), (80-120), and (120-200) s (Figure 2). All products including concentrates and tailings were subjected to the sieve analysis using 850, 500, 250, 106, and 75 (μm) screens, and all fractions were weighed and analyzed for the ash content. After obtaining the ash content, the flotation recovery was calculated according to the Eq. 2. The results are shown in the Table 2.

$$\text{Combustible Recovery }\% = \frac{W_c(100-A_c)}{W_f(100-A_f)} \times 100 \qquad (2)$$

where W_c is the weight of the concentrate (%), W_f is the weight of the feed (%), A_c is the ash content of the concentrate by weight (%), and A_f is the ash content of the feed by weight (%).

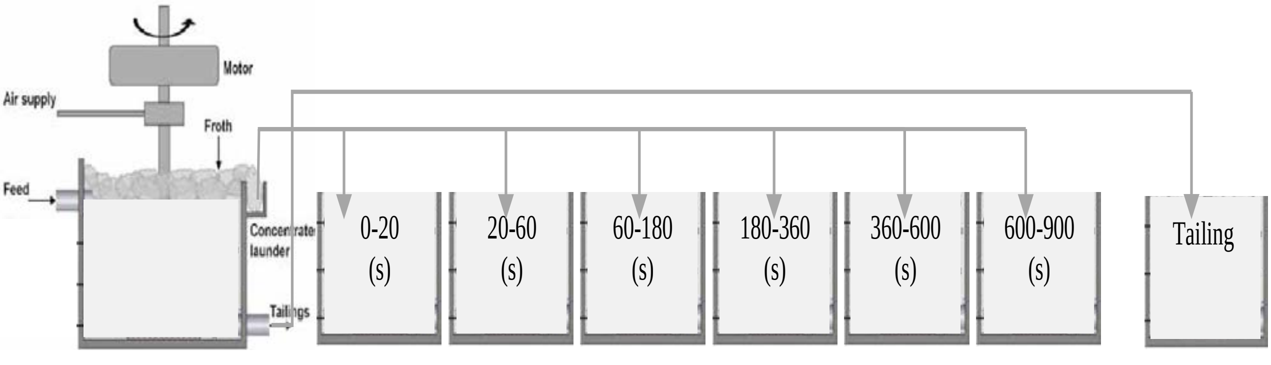


Figure 2. Schematic diagram of the procedure of flotation tests.

Table 2
The characteristics of the products of the flotation test.

Time (s)	Weight (g)	Ash (%)	Recovery (%)	Cumulative combustible recovery (%)	Cumulative Ash (%)
0-20	34.08	16.13	15.85	15.85	16.13
20-40	59.79	19.49	26.7	42.55	18.27
40-60	29.35	24.2	12.34	54.98	19.68
60-80	28.11	21.32	12.27	67.25	19.98
80-120	29.39	25.23	12.17	79.42	20.83
120-200	13.63	34.71	4.93	84.35	21.81
Tail	**105.65**	**69.3**	**15.74**	**100**	**69.3**

As shown in Table 3, five different flotation kinetic models were selected to study the performance of the flotation process for various size fractions, The cumulative combustible recoveries for the concentrates of different size fractions and in time periods of 20, 40, 80, 120 and 200 s were fitted to five aforementioned kinetic models. Matrix Laboratory (MATLAB) software (Version 8.3) was used to simulate the flotation rate constant (k), and maximum combustible recovery (R_∞). The correlation coefficients (R^2) were calculated based on the non-linear least square optimization method. MATLAB is one of the most powerful and advanced numerical calculation softwares. Nonlinear least squares optimization has been widely used in the non-linear regression, curve fitting and optimization of nonlinear model parameters.

In the relations expressed in Table 3, R is the recovery at time t, R_∞ is the infinite recovery, t is the time and k is the flotation rate.

Table 3
flotation kinetic models used in this investigation [9, 10].

Series number	Name of model	Formula
1	Classic first order model	$R = R_\infty\left(1 - e^{-kt}\right)$
2	First-order model with rectangular distribution of floatability	$R = R_\infty \left\{1 - \frac{1}{kt}(1 - \exp(-kt))\right\}$
3	Improved gas/solid adsorption model	$R = R_\infty \left\{\frac{kt}{1 + kt}\right\}$
4	Second-order kinetic model	$R = \frac{R_\infty^2 kt}{1 + R_\infty kt}$
5	Second-order model with rectangular distribution of floatability	$R = R_\infty \left(1 - \frac{1}{kt}\left(L_n(1 + kt)\right)\right)$

3. Results and discussion

3.1. Kinetic parameters of flotation process

The cumulative combustible recovery at 20, 40, 80, 120, and 200 s with various size fractions in the flotation process was fitted to the five flotation kinetic models (Table 3) using MATLAB software. The flotation rate constant (k), the maximum combustible recovery value (R_∞) and The multitude correlation coefficients (R^2) were also calculated. The results are given in Figure 3 and Table 4. Figure 3 indicates that the results of the flotation experiment are in full compliance with all models introduced in the Table 3. Similar findings were also reported by other researchers about coal [19]. The maximum kinetic constant is 0.0267 (s^{-1}), concerned values of the retention time and recovery are 200 s and 88.23 % respectively.

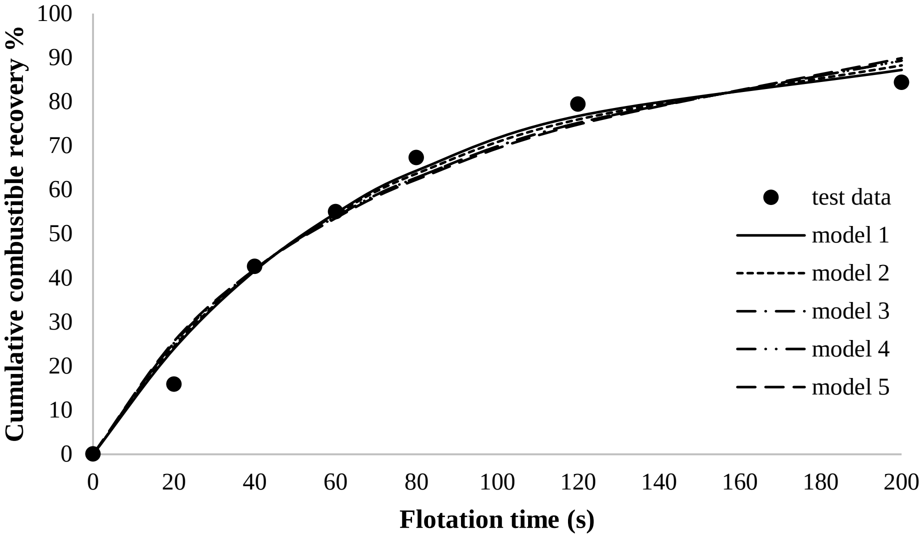


Figure 3. Comparison of five kinetic models fitted to the test data of the flotation process.

Table 4

Results of the non-linear regression of the data using first order kinetic models.

Model	R_∞	K (s^{-1})	R^2
Classic first order model	87.21	0.0151	0.9852
First-order model with rectangular distribution of floatability	88.23	0.0267	0.9962
Improved gas/solid adsorption model	89.33	0.0127	0.9749
Second-order kinetic model	89.33	0.0001	0.9749
Second-order model with rectangular distribution of floatability	89.89	0.0233	0.9715

3.2. Flotation kinetics of various size fractions in the flotation process

The flotation time-combustible recovery diagrams for various size fractions in the flotation process are shown in Figure 4. The combustible recovery increased initially and then decreased with an increase in the particle size, and the maximum combustible recovery was obtained at -250+125 µm size fraction. It indicates that the maximum combustible recovery is obtained at an intermediate particle size in the flotation process. Also according to Table 1, the ash content of 106-250 fraction is lower than other size fractions (except 850-1000). In other words, this size fraction is higher in grade. Similar findings were also reported by other researchers [19, 22, 23]. It is well known that the particle size is an important parameter in the flotation process, and a high process efficiency of froth flotation is typically limited to a relatively narrow particle size range (250-106 μm) [22, 24]. However, out of this range, the recovery drops significantly, whether it is at the fine or the coarse end of the size range [14]. The low combustible recovery of fine particles is mainly because of the poor collision and the attachment of the fine particles and air bubbles, while the reason for the same case about coarse particles is the high probability of the coarse particles and air bubbles being detached[14, 23, 25]. Furthermore, the non-selective entrainment of fine gangue particles, can also be a cause of the low combustible recovery of fine particles, since the fine particles in the feed of flotation tests have high ash content in this investigation (Table 1).

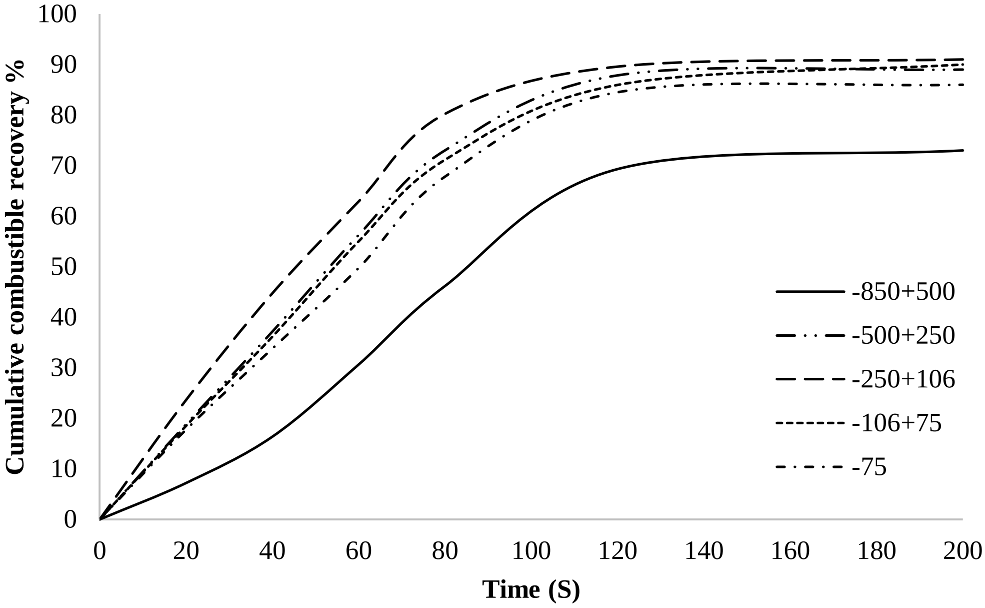
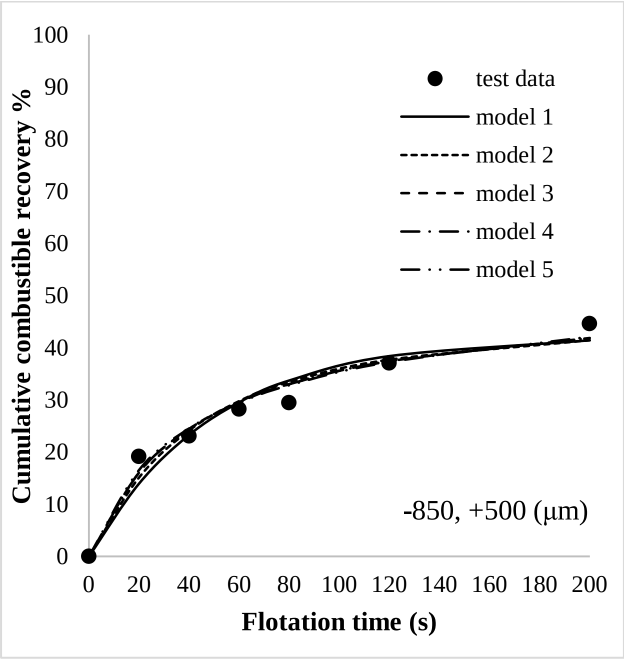
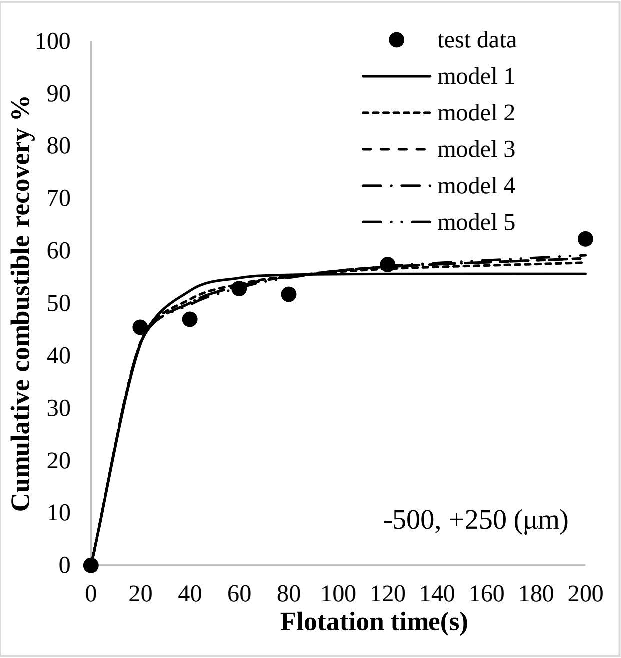


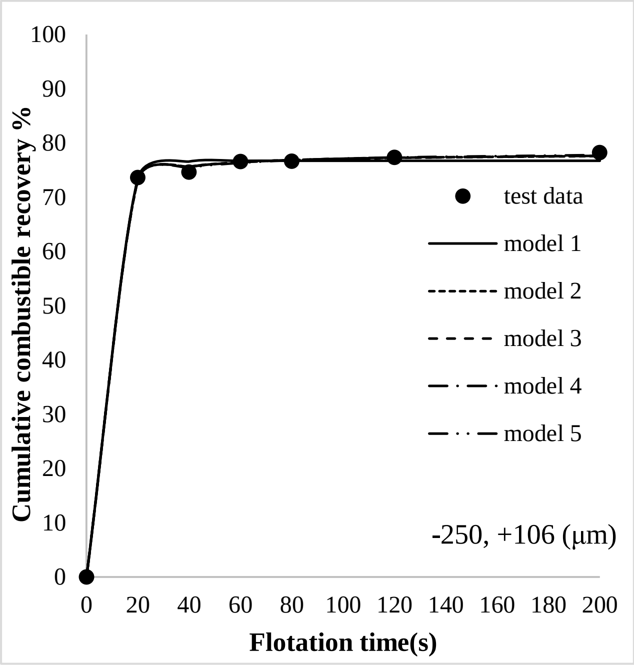
Figure 4. Cumulative combustible recovery for different size fractions in the flotation process.

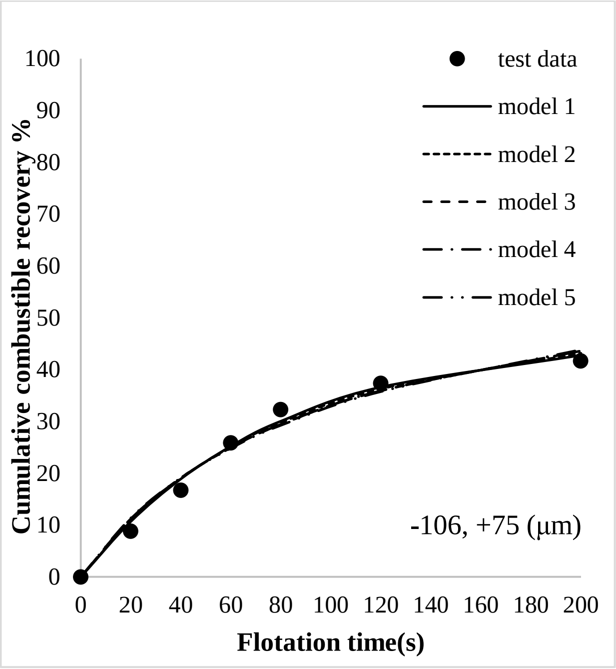
The cumulative combustible recovery at 20, 40, 80, 120, and 200 (s) with various size fractions was fitted to flotation kinetic models mentioned in Table 3 using MATLAB software. The flotation rate constant (k), maximum combustible recovery value (R_∞), and multitude correlation coefficient (R^2) were also calculated. The results are presented in Table 5 and Figure 5.

As shown in Table 5, the maximum R_∞ value of the flotation tests increased initially, reached a maximum and decreased afterwards because of fine size fractions in all of the models. The maximum R_∞ values were obtained with the (−250+106) μm size fraction. The results showed an excellent agreement with the trend of the variation of the combustible recovery as a function of size in Figure 4. Furthermore, k values obtained from all of other models exhibited the same trend of variation as that of the R_∞ values. Those results indicated that the maximum flotation rate constant was obtained at an intermediate particle size. The results were in accordance with previous studies [9, 19, 26-28]. The difference in kinetics constants (both k and R_∞) of various size fractions can also be explained by the combined effect of the collision and attachment/detachment sub-processes in the flotation process [29, 30]. Furthermore, the difference may be related to the physico-chemical properties of various size particles and hydrodynamic conditions in the flotation cell [14, 26, 28]. As shown in Table 5, the R_∞ value increased gradually from model 1 to model 5, while R_∞ values of models 3, 4 were the same. As shown in Table 5, the R^2 values for model 5 for the flotation tests with various size fractions have the largest values among the models that are used, which suggests that model 5 is the most reasonable description of the flotation process. It is suggested that the flotation process can be described with the first-order and second-order models, and the model 5 is the most reasonable one among the models tested.









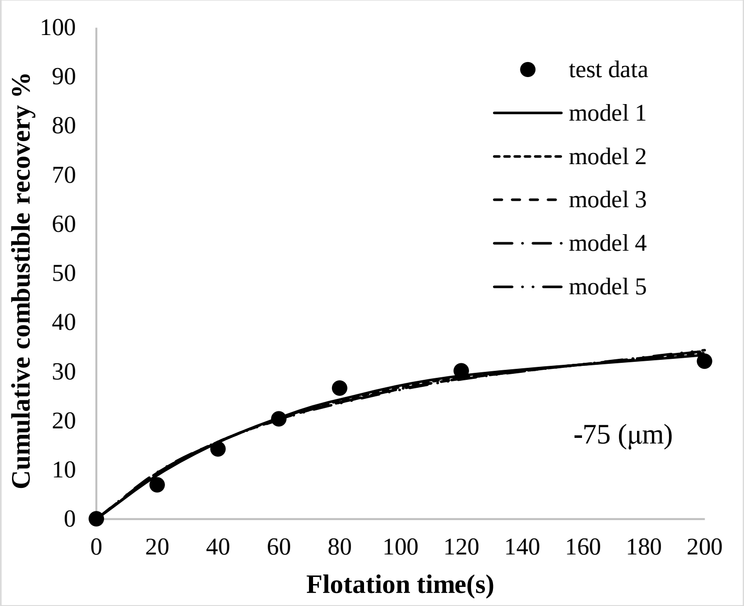


Figure 5. Comparison of five kinetic models fitted to the test data of various size fractions in the flotation process.

Table 5

Non-linear regression results for all models fitted to flotation results

Models	-850+500 µm			-500+250 µm		
	R_∞(%)	k (s^{-1})	R^2	R_∞(%)	k (s^{-1})	R^2
Classic first order model	42.18	0.0201	0.9300	55.58	0.0713	0.9591
First-order model with rectangular distribution of floatability	47.08	0.0416	0.9834	59.48	0.1695	0.9859
Improved gas/solid adsorption model	50.97	0.0230	0.9583	61.15	0.1127	0.9827
Second-order kinetic model	50.97	0.0005	0.9583	61.15	0.0018	0.9827
Second-order model with rectangular distribution of floatability	56.04	0.0471	0.9942	63.63	0.2886	0.9927

Models	-250+106 µm			-106+75 µm		
	R_∞(%)	k (s^{-1})	R^2	R_∞(%)	k (s^{-1})	R^2
Classic first order model	76.75	0.1576	0.9987	46.05	0.0132	0.9890
First-order model with rectangular distribution of floatability	78.10	0.7936	0.9997	55.07	0.0229	0.9977
Improved gas/solid adsorption model	78.19	0.7297	0.9997	64.21	0.0106	0.9814
Second-order kinetic model	78.19	0.0093	0.9997	64.21	0.0002	0.9814
Second-order model with rectangular distribution of floatability	78.65	2.960	0.9998	74.64	0.0190	0.9984

Models	<75 µm		
	R_∞(%)	k (s^{-1})	R^2
Classic first order model	35.31	0.0146	0.9842
First-order model with rectangular distribution of floatability	41.96	0.0255	0.9962
Improved gas/solid adsorption model	48.36	0.0120	0.9735
Second-order kinetic model	48.36	0.0002	0.9735
Second-order model with rectangular distribution of floatability	55.80	0.0219	0.9974

4. Conclusions

In this investigation, the difference in flotation rates of various size fractions of bituminous coal has been studied. According to the results, the experimental data obtained from the flotation processes is in full compliance with the first-order model with the rectangular distribution of floatability. The maximum kinetic constant among all models is 0.0267 (s^{-1}), which is related to the first-order model with the rectangular distribution of floatability. According to the influence of the particle size on the combustible recovery and flotation rate; the maximum flotation combustible recoveries and flotation rates were obtained with an intermediate particle size. On the other hand, the maximum recovery of 78.65 % was obtained at (−250+106) µm size fraction in the flotation process. In general, the flotation constant value and its recovery increased by decreasing the particle size from 850 to 250 microns and then decreased by decreasing the particle size.

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