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Proceedings

Editors:
Zoran ŠTIRBANOVIĆ
Milan TRUMIĆ

28-30 May 2025
Belgrade, Serbia

University of Belgrade,
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Original research article

THE EFFECT OF PARTICLE SIZE ON THE FLOTATION KINETICS OF RAW AND WASTE COAL

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ABSTRACT – This paper investigates the effect of particle size on the flotation kinetics parameters of raw and waste fine coal from anthracite mine "Vrška Čuka, Serbia. Based on batch flotation test data of coal, non-linear fitting was conducted by using MatLab for modeling first order flotation kinetics. The cumulative combustible recovery against flotation time were correlated using the Classical model. The coefficient of determination (r^2) values of the proposed model were from 0.9904 to 0.9998 for raw coal and from 0.9555 to 0.9980 for waste coal. The maximum values of the flotation rate constant (k) for both coals were obtained for the particle size fractions (-0.1+0.053) mm. The relation between flotation kinetics constant (k) with particle size (d_{sr}) was estimated through equations presented in the paper (Eq. 3 and 4).

Keywords: Coal, Particle size, Flotation, Kinetics, Classical model.

INTRODUCTION

Coal flotation is a very complex physico-chemical process and difficult to control. Coal flotation plays an important role in coal processing and is a widely used method in coal processing technologies for the separation of fine coal below 0.5 mm and in some cases even below 1 mm [2].

The coal flotation theory and parameters affecting the coal flotation performance are explained in detail by Polat [1] and Laskowski [3]. Generally, coal flotation is affected by a number of parameters [1, 3]. The most critical parameter affecting the stability of bubble-particle aggregates is the particles size [4]. Particle size has an important role in coal flotation as well as flotation kinetics. The effect of particle size on coal flotation kinetics is complex, and it has been described by Sokolovic and Miskovic (2018) [5].

Many studies have been conducted to determine the effect of particle size on coal flotation kinetics [2, 6–18]. A number of kinetic models have been developed and tested for the coal flotation process. In general, the best-fit kinetic model varies for different

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coal types and flotation conditions. Based on available literature, it is found that the coal flotation follows the first-order kinetics model [2, 5–18].

The flotation rate constant is strongly dependent on coal particle size. In recent years, studies showed that the highest flotation rate can be obtained over an intermediate particle size range while it decreases sharply for fine and coarse particle sizes.

The relation between flotation rate constant and cumulative recovery with particle size was found to be nonlinear [12]. Studies showed that the first-order kinetic model with a rectangular distribution of floatability gave the best fit to the flotation experimental data for coal with particle size between 37 and 375 µm [5]. Furthermore, the nonintegral-order equation fit the test data of fine coal with average particle sizes between 188 and 100 µm.

Additionally, the physical and chemical properties of coal are usually altered by the oxidation processes. The oxidation processes result in the formation of oxygen functional groups, such as carboxyl, phenol and carbonyl functionalities on coal surface [19], which reduces the hydrophobicity of coal as well as coal flotation kinetics [20]. This paper investigates the effect of particle size on the flotation kinetics parameters of raw and waste coal from anthracite mine "Vrška Čuka", Serbia.

EXPERIMENTAL

Materials

Coal samples of about 250 kg were collected from the anthracite coal mine "Vrška Čuka" in Serbia. The first representative samples were collected from raw coal and the second from the coal waste ponds. Raw coal (RC) was sampled as feed from the “BSRI-1200” dense-medium separator, with a particle size range of 0–25 mm. Waste coal (WC) was sampled from the coal waste ponds, with a particle size range of 0–1 mm. The raw coal sample was screened at 1 mm for particle size analysis and flotation kinetics tests.

Methods

Particle size analysis

The raw and waste coal samples were sieved to determine the particle size distribution. Wet sieving on sieves: 0.5; 0.2; 0.1; 0.053 mm was applied for determining the particle size distribution of both coal samples.

Laboratory sieve shaker Retsch AS200 was used with amplitude 2 mm for 25 min. After drying, the ash content was determined according to the SRPS ISO 1171 standard from 2014 at 815 ^{o}C. The particle size distribution wise ash content is shown in Table 1.

The particle size analysis results of raw and waste coal show a similar mass distribution by size fractions. The lowest ash content in both tested coal samples was recorded in the size fraction (-0.5+0.2) mm and was 14.54% and 29.60%, respectively.

From Table 1, it can be seen that fine size fractions below 0.053 mm are 26.19% for raw coal and 22.77% for waste coal. Higher ash content (about 53%) in waste coal designates the presence of slime and clay in this fraction.

Table 1 Particle size distribution and ash contents of raw coal (RC) and waste coal (WC) samples

Particle size fraction d (mm)	Raw coal (RC)				Waste coal (WC)			
	Internal values		Cumulative passing value		Internal values		Cumulative passing value	
	Weight (%)	Ash (%)	Weight (%)	Ash (%)	Weight (%)	Ash (%)	Weight (%)	Ash (%)
+0.5	23.52	20.98	23.52	20.98	23.96	31.84	23.96	31.84
-0.5+0.2	21.04	14.54	44.56	17.94	28.31	29.60	52.27	30.63
-0.2+0.1	13.94	16.88	58.50	17.69	14.91	35.73	67.18	31.76
-0.1+0.053	15.31	17.22	73.81	17.59	10.05	42.20	77.23	33.12
-0.053+0	26.19	22.31	100.00	18.83	22.77	53.23	100.00	37.70

Flotation tests

A laboratory flotation machine Denver D-12 was used for flotation kinetics tests with the impeller speed of 1250 rpm. All coal flotation tests were conducted with feed slurries at 10% solids (by weight). The pH was adjusted to 7.5. Kerosene (1000 g/t), tannic acid (200 g/t), sodium silicate (200 g/t), and pine oil (45 g/t) were used as reagents in this study. In each flotation kinetics test, the pulp was first agitated in the flotation cell for 3 minutes. After 2 min of agitation kerosene was added, and the slurry was mixed for 0.5 min, when tannic acid, sodium silicate, and pine oil were added and the slurry was stirred for additional 0.5 min. Air was introduced after the conditioning stage, and flotation concentrates were collected at 30, 90, 150, and 360 s. After the final froth sample was collected, the machine was stopped. The froth flotation concentrates and the tailings were filtered, dried, weighed, and analyzed. Ash content analyses were conducted for all samples. Following flotation kinetics tests, all concentrates were dry sieved. Size-wise ash analysis for the five particle size fractions, 0.5; 0.2; 0.1, and 0.053 mm were conducted for froth concentrates and the tailings. Based on the obtained results, the combustible recovery (R) of non-ash materials for each fraction were calculated by:

$$R = Y\,(100 - Ac) \,/\, (100 - Af) \qquad (1)$$

where Y is the percentage yield of the concentrate and A_c and A_f are the percentage ash contents in concentrates and feed materials, respectively [12].

Flotation kinetics

The yields for the individual particle size fractions were plotted as a function of flotation time. In this study, a classical first-order kinetics model, introduced by Zuniga (1935) [21], a given in Eq. 2, is used to obtain the parameters of k and R_∞ through fitting the flotation test data.

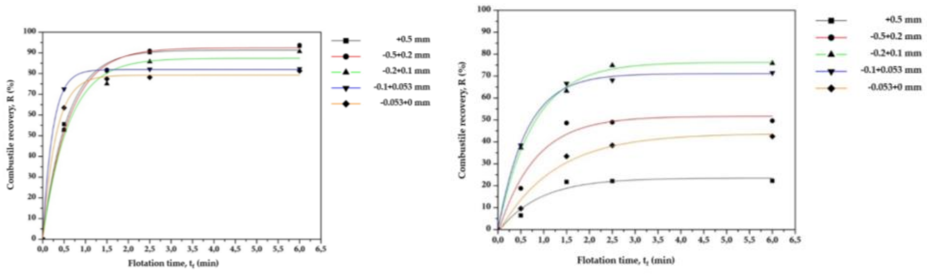
$$R = R\infty\,[1 - e(-\,k \cdot t)] \qquad (2)$$

where R_∞ is the ultimate (maximum) recovery of non-ash materials (%) at time, t is the cumulative flotation time (min), and k is the flotation rate constant (min^{-1}).

MATLAB tool was used to fit the first-order kinetics model to the flotation test results to obtain R_∞ and k values [22]. If the coefficient of determination (R^2) was higher than 0.8, Eq. 2 can be applied.

RESULTS AND DISCUSSION

The curves of flotation kinetics of different particle size fractions of raw coal (RC) and waste coal (WC) are shown in Figure 1.



a) b)

Figure 1 Cumulative recovery of different particle size fractions of a) raw coal (RC) and b) waste coal (WC) against flotation time

Using MatLab tools, the values of the flotation rate constant and other flotation parameters were determined for the first-order classical flotation kinetics model. The obtained values are shown in Table 2.

Table 2 Kinetics parameters generated by the first-order classical model for various size fractions of raw coal (RC) and waste coal (WC) samples

	Raw coal (RC)			Waste coal (WC)		
Particle size fraction d (mm)	k (min^{-1})	R_∞ (%)	r^2	k (min^{-1})	R_∞ (%)	r^2
+0.5	1.6848	93.37	0.9996	1.0584	23.55	0.9555
-0.5+0.2	1.8084	93.74	0.9942	1.2056	51.76	0.9746
-0.2+0.1	1.5017	90.68	0.9904	1.2877	76.26	0.9980
-0.1+0.053	4.2624	82.28	0.9998	1.4557	71.70	0.9960
-0.053+0	2.9839	81.29	0.9980	0.7786	44.06	0.9789

(r^2 – the coefficient of determination)

Based on the results presented in Table 1, it can be concluded that the ultimate (maximum) recovery of non-ash materials from raw coal decreases as the particle size decreases. Furthermore, the highest ultimate (maximum) recovery for raw coal is observed in the +0.5 mm size fraction, while the lowest recovery for waste coal occurs in the same size fraction.

Figure 2 shows the dependence of the flotation rate constant (k) on particle size, i.e. the mean diameter of a narrow size fraction (d_{sr}).

Figure 2 shows the flotation rate constant variation with particle size. As it can be seen from Figure 2, flotation rate constant (k), for raw coal, first increases sharply and then decreases, indicating an optimum particle size (about 0.1 mm), while for waste coal, flotation rate constant values are lower and increases slightly with increasing d_{sr}. The maximum flotation rate constant (k) values for raw and waste coal are 4.2624 min^{-1} and 1.4557 min^{-1}, respectively, for the particle size fraction of (-0.1 + 0.053) mm.

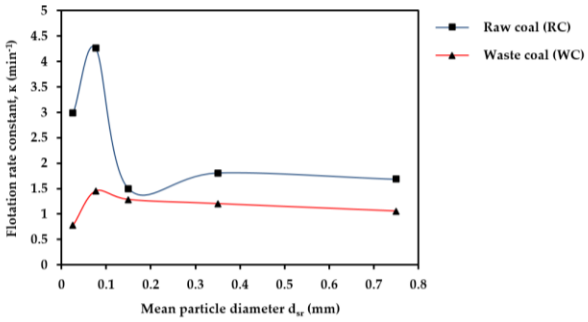


Figure 2 Dependence of the flotation rate constant on particle size of raw (RC) and waste (WC) coal

Using the MatLab tool, the values of the coefficients of determination were determined from 0.9904 to 0.9998 for raw coal and from 0.9555 to 0.9980 for waste coal. It can be concluded that the classical model well describes the first-order flotation kinetics. This model showed good applicability to experimental flotation data for both raw and waste coal. According to the results from Table 2 and Figure 2, the relation between flotation kinetics constant (k) with particle size (d_{sr}) was estimated through equations:

$$k_{rc} = (a + b \cdot d_{sr} + c \cdot d_{sr}^2)/(1 + d \cdot d_{sr} + e \cdot d_{sr}^2) \quad (3)$$

where: a = 2.728965; b = - 41.135466; c = 192.135603; d = - 18.675380; e = 102.500493

$$k_{wc} = a \cdot d_{sr} + b/d_{sr} + c/(d_{sr}^2) + d \quad (4)$$

where: a = - 0.1258396; b = 0.0451993; c = - 0.0014227; d = 1.1031061

The coefficient of determination (r^2) values for flotation kinetics constant for raw and waste coal were 0.9797 and 0.9911, respectively. Based on the observed trend, a proposed mathematical functions are a good fit for both coals.

CONCLUSION

The first-order classical model was applied as an effective tool for modeling the complex relation between the input and output variables in a coal flotation process. The r^2 values were obtained from 0.9904 to 0.9998 for raw coal and from 0.9555 to 0.9980, for waste coal, indicating a good relation.

The correlation between the flotation rate constant (k) and the mean particle diameter (d_{sr}) depends on the type of coal. The maximum values of the flotation rate constant (k) for raw and waste coal were obtained for the particle size fractions (-0.1+0.053) mm. The proposed mathematical models, given in Equations 3 and 4, provide a relationship between the flotation kinetics constant (k) and particle size (d_{sr}).

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REFERENCES

1. Polat, M., Polat, H., Chander, S. (2003) Physical and chemical interactions in coal flotation. International Journal of Mineral Processing, 72 (1), 199-213.
2. Brozek, M., Mlynarczykowska, A. (2013) An analysis of effect of particle size on batch flotation of coal. Physicochemical Problems of Mineral Processing, 49 (1), 341-356.
3. LaskowskI, J.S. (2001) Coal flotation and fine coal utilization, Elsevier, Amsterdam.
4. Polat, M., Arnold, B., Chander, S., Hogg, R., Zhou, R. (1993) Coal flotation kinetics-effect of particle size and specific gravity. In: Coal Science and Technology, 161-170.
5. Soković, J., Miskovic, S. (2018) The effect of particle size on coal flotation kinetics: A review. Physicochemical Problems of Mineral Processing, 54 (4), 1172-1190.
6. Panopoulos, G., King, R.P., Juckes, A. (1986) The effect of particle-size distribution on the flotation of two South African coals. Journal of the Southern African Institute of Mining and Metallurgy, 86 (5), 141-152.
7. Vanangamudi, M., Rao, T. C. (1986) Modelling of batch coal flotation operation. International journal of mineral processing, 16 (3-4), 231-243.
8. Vanangamudi, M., Kumar, S. S., Rao, T. C. (1989) Effect of fines content on the froth flotation of coal. Powder technology, 58 (2), 99-105.
9. Rao, T. C., Govindarajan, B., Vanangamudi, M. (1989) A kinetic model for batch coal flotation. Minerals Engineering, 2 (3), 403-414.
10. Mohns, C. A. (1998) Effect of particle size on coal flotation kinetics. Queen's University at Kingston.
11. Chaves, A. P., Ruiz, A. S. (2009) Considerations on the kinetics of froth flotation of ultrafine coal contained in tailings. International Journal of Coal Preparation and Utilization, 29 (6), 289-297.
12. Abkhoshk, E., Kor, M., Rezai, B. (2010) A study on the effect of particle size on coal flotation kinetics using fuzzy logic. Expert Systems with applications, 37 (7), 5201-5207.
13. Kor, M., Abkhoshk, E., Gharibie, K., Shafaei, S. Z. (2010) An investigation of the particle size effect on coal flotation kinetics using multivariable regression. 1 (1), 41-47.
14. Li, Y., Zhao, W., Gui, X., Zhang, X. (2013) Flotation kinetics and separation selectivity of coal size fractions. Physicochemical Problems of Mineral Processing, 49 (2), 387-395.
15. Xia, W., Xie, G., Liang, C., Yang, J. (2014) Flotation behavior of different size fractions of fresh and oxidized coals. Powder Technology, 267, 80-85.
16. Ni, C., Xie, G., Jin, M., Peng, Y., Xia, W. (2016) The difference in flotation kinetics of various size fractions of bituminous coal between rougher and cleaner flotation processes. Powder technology, 292, 210-216.
17. Bu, X., Xie, G., Chen, Y., Ni, C. (2017) The order of kinetic models in coal fines flotation. International Journal of Coal Preparation and Utilization, 37 (3), 113-123.
18. Liao, Y., Cao, Y., Liu, C., Zhao, Y., Zhu, G. (2017) Comparison of the effect of particle size on the flotation kinetics of a low-rank coal using air bubbles and oily bubbles. Journal of the Southern African Institute of Mining and Metallurgy, 117 (6), 561-566.
19. Sokolovic, J., Stanojlovic, R., Markovic, Z. (2012) Activation of oxidized surface of anthracite waste coal by attrition. Physicochemical Problems of Mineral Processing, 48(1), 5-18.

20. Sokolović, J., Stanojlović, R., Marković, Z. (2012) The effects of pretreatment on the flotation kinetics of waste coal. International Journal of Coal Preparation and Utilization, 32(3), 130-142.
21. Zuniga, H.G. (1935). Flotation recovery is an exponential function of its rate. Boln. Soc. Nac. Min., Santiago, Chile, 47, 83-86.
22. Brezani, I., Zelenak, F. (2010) MatLab Tool for Modeling First Order Flotation. http://www.mathworks.com/matlabcentral/fx_files/28703/2/content/html/Flotation_modeling.html.

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