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Optimal structure of the connections of a flotation machine with three cells

Introduction

Flotation is a process of separating a mixture of particles differing in physicochemical properties. The properties of particles in the flotation process depend on the parameters under which the process proceeds (flotation reagents inflow rate, flow rate of aeration air, etc.). Flotation enrichment is therefore a complex process, influenced by many factors. In macroscopic terms, it is assumed that the quantity that amasses the effects of all significant factors that affect the flotation process is the flotation velocity coefficient k of particles. Thus the value of the k factor determines which particles pass onto the concentrate. This is analogous to gravity separation processes where the probability of a particle passing into the concentrate zone depends on that particle's specific gravity. In industrial practice the material subjected to the flotation process is non-homogeneous in terms of flotation properties. The values of the flotation velocity coefficient k of the material are characterized by a certain distribution. Therefore the feed may be described by a particle flotability distribution density function $f(k)$ (relationship between concentrate recovery and velocity coefficient of individual feed particles). Such characteristics may be useful when designing flotation systems.

In the design of flotation systems the amounts of products and their quality can be determined provided that the following data are available:

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- characteristics of the flotation system feed,
- mathematical models of the cell and of the bank of cells of the flotation machine,
- configuration of the flotation circuit.

The problems of optimizing the parameters of mineral flotation systems have been presented in numerous papers (Jovanović et al. 2015; Mehrotra and Kapur 1974; Pirouzan et al. 2014; Reuter and Van Deventer 1990; Schena et al. 1997; Yingling 1993a, Yingling 1993b). The mathematical description of these issues comes down mostly to maximizing (minimizing) the adopted criterion functions. An original method of solving these problems, where use is made of the so-called generalized characteristics of individual flotation machines, as well as the generalized characteristics of a flotation circuit, is discussed in other papers (Kalinowski 1997; Kalinowski and Kaula 2000; Kalinowski and Kaula 2010).

Fig. 1 shows sample characteristics of a system of flotation machines with three cells for a given separation coefficient $\mathrm{k_{roz}}$ (e.g. $k_{roz} = 1$). In ideal flotation (Fig. 1, curve 1), particles with a coefficient of flotation velocity k less than $\mathrm{k_{roz}}$ will not be included in the concentrate w_k, while particles with a coefficient of flotation velocity above $\mathrm{k_{roz}}$ will all be included in the concentrate (in Fig. 1 assumption is made that $w_k = 1$ is one hundred percent). Note that it is not possible to physically implement such a machine. Industrial systems mostly use flow flotation machines of series (cell to cell) structure (Fig. 1, curve 3). In this paper, we propose a structure of connections of a three-cell flotation machine, the separation characteristics of which are more similar to the ideal characteristics (Fig. 1, curve 2).

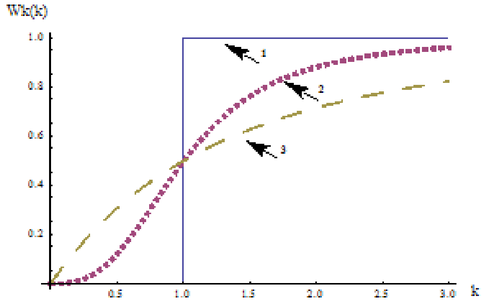

Fig. 1. Reference separation characteristics of three-cell flotation machines
1 – ideal separation, 2 – flotation machine of proposed structure,
3 – cell to cell flotation machine (commonly used)

Rys. 1. Poglądowe charakterystyki rozdziału flotowników trójkomorowych
1 – rozdział idealny, 2 – flotownik o strukturze zaproponowanej w artykule,
3 – flotownik szeregowy (powszechnie stosowany)

This shows that better results in raw materials enrichment, in technological and economic terms of flotation process assessment, are obtained in the case of connection structures of multi-cell flotation machines, the separation characteristics of which are more similar to the ideal characteristics.

Therefore, the adopted criterion of the optimum structure of connections within the flotation circuit was the maximum slope of the separation curve at the k_{roz} point:

$$\left.\frac{\partial W_k(k)}{\partial k}\right|_{k=k_{roz}} = \max \tag{1}$$

1. Distribution density function of flotation velocity coefficient

Under specified conditions the flotation feed is described by the density function of flotability distribution $f(k)$. A substantial amount of research work has been devoted to the problems of determining flotability spectra (Brożek and Młynarczykowska 2009; Fischera and Chudacek 1991; Imaizumi and Inue 1965, Kalinowski and Tumidajski 1995). Function $f(k)$ is determined indirectly by means of a mathematical model of the kinetics $m(t)$ based on concentrate mass components separated at discrete time intervals. The determined parameters of the kinetics model are also the parameters of the model of the density function of flotability distribution. This is because of the relationship between the $f(t)$ function and $m(t)$. Separation of the concentrate at time t follows the formula:

$$m(t) = M\left(1 - \int_0^{\infty} f(k)e^{-k\cdot t}dk\right) \tag{2}$$

↳ M – flotable mass of the feed.

The conducted studies (Kalinowski and Kaula 1995a, 1995b) have shown that dead time τ must be taken into account in flotation kinetics models. Including this parameter in the model provides the most accurate representation of flotation kinetics. The $f(t)$ function is determined from formula (2) by applying the inverse Laplace transform:

$$f(k) = L^{-1}\left\{1 - \frac{m(t)}{M}\right\} \tag{3}$$

↳ $L^{-1}\{\}$ – inverse Laplace transformation.

A triangular distribution of function $f(k)$ was proposed in paper (Kalinowski and Kaula 2013). A form of triangular distribution is shown in Fig. 2.

The parameters (k_1, k_2, k_3) of the triangular model were determined based on batch flotation experiments. Calculations were carried out for various air flow rates ($V_p = 10^{-5}$ m^3/s).

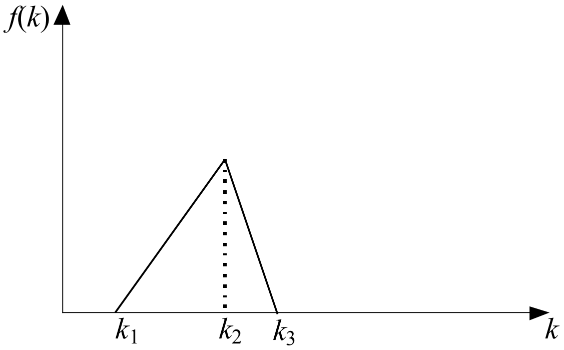

Fig. 2. Distribution of coal particles flotability $f(k)$ in the shape of a triangle
k_1, k_2, k_3 – parameters of the triangular distribution

Rys. 2. Rozkład flotowalności ziaren węgla $f(k)$ w kształcie trójkąta

2. Mathematical model of ash separation under the kinetics of the flotation process

The quality of the concentrate is determined primarily by the ash content in the concentrate. Based on batch flotation experiments on the mass of separated concentrate $m(t)$, the mass of ash $m_a(t)$ at time t can also be determined. Measurements of the masses $m(t)$, $m_a(t)$ and the parameters of the $f(k)$ function distribution enable the determination of the relationship between the distribution of ash content a_k in the concentrate and the flotation velocity coefficient k.

$$m_a(t) = M_a - M \int_0^\infty f(k) a_k(k) e^{-k \cdot t} dk \tag{4}$$

↳ M_a – mass of ash in the flotable part of the feed.

A mathematical model of ash separation during batch flotation at different air flow rates V_p was proposed (wherein $V_p = 10^{-5}$ m^3/s) (Kalinowski and Kaula 2016).

The effect of flotation velocity coefficient k on ash content in the concentrate $a_k(k)$ was expressed by means of a second degree polynomial with three coefficients (x_0, x_1, x_2).

$$a_k(k) = (x_2 \cdot k^2 + x_1 \cdot k + x_0) \tag{5}$$

The parameters of the model of ash mass separation $m_a(t)$ at time t are obtained by determining the integral (4) while taking into account the relationship (5) and distribution of $f(k)$. The detailed description of the batch flotation experiments and measurement data on separated mass of concentrate $m(t)$ and mass of ash $m_a(t)$ used for determining the parameters of the mathematical models were presented in paper (Kalinowski and Kaula 1995a). The values of the parameters of the triangular model of flotability distribution were taken from (Kalinowski and Kaula 2013). Parameters of the model of ash content in concentrate $a_k(k)$ were given in (Kalinowski and Kaula 2016).

3. Static mathematical models of the cell and of the bank of cells of the flotation machine

3.1. Static characteristics of multi-cell flow flotation machine

Recovery of the concentrate in a single-cell flow flotation machine (in a steady state) can be expressed in the form of the following formula:

$$W_k = \int_{k_1}^{k_3} \frac{\frac{k}{D_o}}{1+\frac{k}{D_o}} f(k)dk \tag{6}$$

Ash content in the concentrate may be represented by the following formula:

$$A_K = \frac{\int_{k_1}^{k_3} \frac{\frac{k}{D_o}}{1+\frac{k}{D_o}} a(k)f(k)dk}{\int_{k_1}^{k_3} \frac{\frac{k}{D_o}}{1+\frac{k}{D_o}} f(k)dk} \tag{7}$$

Recovery of the concentrate in a steady state of a three-cell flotation machine can be expressed in the form of the following formula:

$$W_K = \int_{k_1}^{k_3} \left[\frac{\left(1+\frac{k}{D_{oi}}\right)^3 - 1}{\left(1+\frac{k}{D_{oi}}\right)^3} \right] f(k)dk \tag{8}$$

Ash content in the concentrate may be represented by the following formula:

$$A_K = \frac{\int_{k_1}^{k_3} \left[\frac{\left(1+\frac{k}{D_{oi}}\right)^3 - 1}{\left(1+\frac{k}{D_{oi}}\right)^3} \right] a(k) f(k) dk}{\int_{k_1}^{k_3} \left[\frac{\left(1+\frac{k}{D_{oi}}\right)^3 - 1}{\left(1+\frac{k}{D_{oi}}\right)^3} \right] f(k) dk} \tag{9}$$

k – flotation velocity coefficient, s^{-1},

k_1, k_3 – parameters of the triangular flotability distribution $f(k)$,

D_{oi} – coefficient which characterizes the outflow of particles from the tailings zone of the i-th cell, s^{-1} (inverse of the mean residence time T_i of a particle in the flotation machine cell),

T_i – mean residence time of a particle in the i-th flotation machine cell, $T_i = \frac{V_{ai}}{\upsilon_{ai}}$, s,

V_{ai} – active volume of pulp in the i-th cell, m^3,

υ_{ai} – total pulp outflow rate from the i-th cell, m^3/s.

3.2. Proposed technological structure of the three-cell flotation machine

Fig. 3 shows the structure of connections in a three-cell flotation machine that ensures maximum slope of the flotation separation curve. In this arrangement the feed (N) is fed to

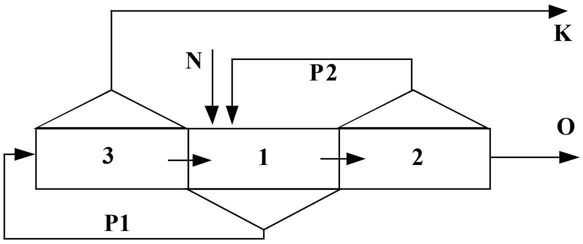

Fig. 3. Proposed structure of connections in a three-cell flotation machine

Rys. 3. Proponowana struktura połączeń maszyny flotacyjnej z trzema komorami the first cell (1) of the flotation machine, wherein the feed is separated into pulp and floated intermediate product (P1). Then the floated intermediate product (P1) is transferred to the third cell (3) and the obtained pulp is simultaneously transferred to the second cell (2) where separation into floated intermediate product (P2) and pulp takes place. Pulp from the second cell (2) are tailings (O), whereas the floated intermediate product (P2) is recycled to the first cell (1) of the flotation machine. At the same time the floated intermediate product (P1) in the third cell (3) of the flotation machine is separated into pulp (which is passed to the first chamber (1)) and floated concentrate (K).

The concentrate recovery rate in the flotation circuit is determined as the ratio of rate of concentrate particles (having a flotation velocity coefficient k) outflow from the circuit $xk_3(k)$ to the inflow rate of feed particles $x_N(k)$ under steady state conditions of flotation circuit operation.

$$Wk_3(k) = \frac{xk_3(k)}{x_N(k)} \tag{10}$$

Equation (10) may be determined from the balance of mass flow in the flotation circuit under consideration:

$$xk_1 = \left(x_N + xk_2 + xk_1(1 - w_3)\right) w_1 \tag{11}$$

$$xk_2 = \left(x_N + xk_2 + xk_1(1 - w_3)\right)(1 - w_1) w_2 \tag{12}$$

$$xk_3 = xk_1 w_3 \tag{13}$$

$$Wk_3(k) = \frac{xk_3(k)}{x_N(k)} = \frac{w_1 w_3}{1 - w_1 - w_2 + w_1 w_2 + w_1 w_3} \tag{14}$$

The total recovery (for all fractions $f(k)$) in the circuit may be determined from the following formula:

$$W_K = \int_{k_1}^{k_3} [Wk_3(k)] f(k) dk \tag{15}$$

Ash content in the concentrate may be represented by the following formula:

$$A_K = \frac{\int_{k_1}^{k_3} [Wk_3(k)] a(k) f(k) dk}{\int_{k_1}^{k_3} [Wk_3(k)] f(k) dk} \tag{16}$$

where:

$$w_i = \frac{\frac{k}{D_{oi}}}{1 + \frac{k}{D_{oi}}}$$

The parameters of the individual cells meet the following conditions (Kalinowski and Kaula 2010):

$$w_1 = w_2 \text{ and } w_3 = \frac{1 - w_1 - w_2 + w_1 w_2}{w_1} \tag{17}$$

The adopted values of $T_1 = \frac{V_{a1}}{\upsilon_{o1}}$ and $T_3 = \frac{V_{a3}}{\upsilon_{o3}}$ depend on technological properties of the flotation machines and on the adopted value of separation velocity coefficient k_{roz}. The value of k_{roz} is determined for the adopted criterion (qualitative, qualitative-quantitative). Various parameters of the flotation process, such as air flow rate, amount of flotation agent, level of suspension in flotation cell, provide differing characteristics of particle flotability density

Table 1. Example parameters of the flotation cells

Tabela 1. Przykładowe parametry komór flotacyjnych

k_{roz} [s^{-1}]	w_1 [%]	w_2 [%]	w_3 [%]	k_{roz}/D_{o1}	k_{roz}/D_{o3}	D_{o1} [s^{-1}]	D_{o3} [s^{-1}]	$T_1 = \frac{V_{a1}}{\upsilon_{o1}}$ [s]	$T_3 = \frac{V_{a3}}{\upsilon_{o3}}$ [s]
0.025	65	65	19	1.857	0.232	0.013	0.108	74.29	9.29
0.050	65	65	19	1.857	0.232	0.027	0.215	37.14	4.64
0.075	65	65	19	1.857	0.232	0.040	0.323	24.76	3.10
0.100	65	65	19	1.857	0.232	0.054	0.431	18.57	2.32

distribution (Fig. 2). Upon adopting k_{roz} (value between k_1 and k_3) an operating point of the circuit is selected (depending on adopted production requirements).

Table 1 lists example values of the set T_i parameters in relation to w_i and k_{roz}.

4. Results of simulation tests

Using formulae (15–16) quantitative-qualitative parameters of the circuit presented in Fig. 3 were calculated for the adopted feed. Calculations of the recovery W_K in the circuit and of ash content A_K were made with respect to the parameters w_i and k_{roz}. Static characteristics of quantitative-qualitative parameters of the three-cell flotation machine of the structure proposed herein were determined based on the results obtained (Fig. 3). Static characteristics of quantitative-qualitative parameters of the studied circuit are presented in Figs. 4 to 6. Calculation results on the graphs of recovery are given in relation to the flotable part of the feed (100% recovery corresponds to the maximum mass of the floated material). Each graph includes curves for three air flow rates.

Figs. 7 to 10 provide a comparative analysis of the static characteristics of the optimal circuit shown in Fig. 3 and of a typical three-cell flotation circuit of a cell to cell (series) structure. The “o” indexes in the figures indicate the circuit of optimal structure, while the “s” indexes indicate series (cell to cell) structure. Figs. 7 to 9 provide a comparison of the static characteristics for the subsequently increasing air flow rates (at a ratio of 1:1.5:3).

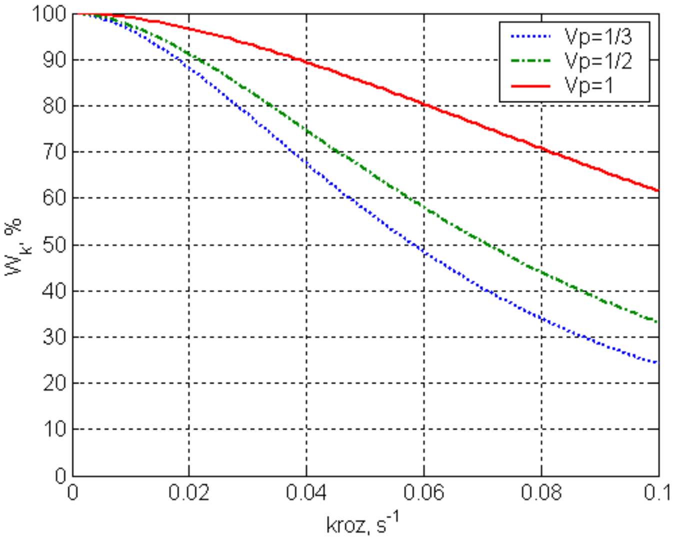

Fig. 4. Recovery of the flotable part vs. k_{roz} (for w_1 = 65%)

Rys. 4. Wychód części flotowalnej w funkcji k_{roz} (dla w_1 = 65%)

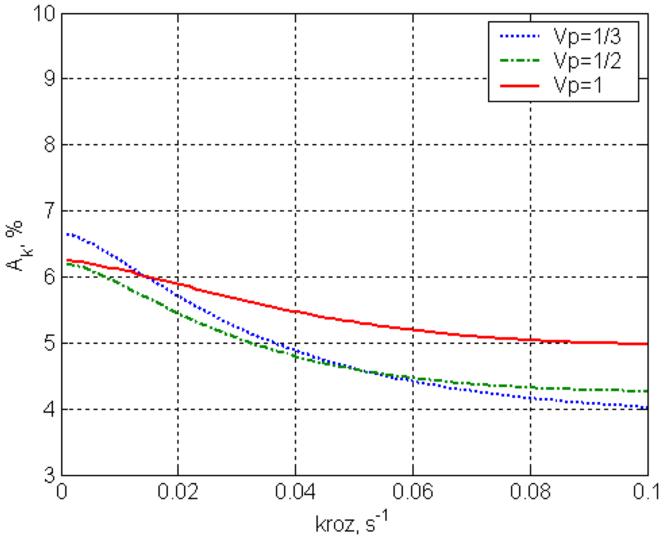

Fig. 5. Ash content of the flotable part vs. k_{roz} (for w_1 = 65%)

Rys. 5. Zawartość popiołu w części flotowalnej w funkcji k_{roz} (dla w_1 = 65%)

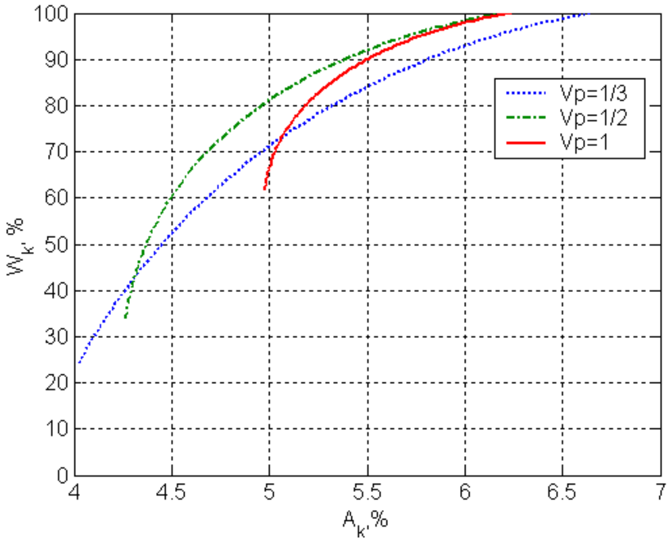

Fig. 6. Recovery of the flotable part in the three-cell flotation machine of proposed structure vs. ash content in the concentrate (for w_1 = 65%)

Rys. 6. Wychód części flotowalnej trójkomorowego flotownika o proponowanej strukturze w funkcji zawartości popiołu w koncentracie (dla w_1 = 65%)

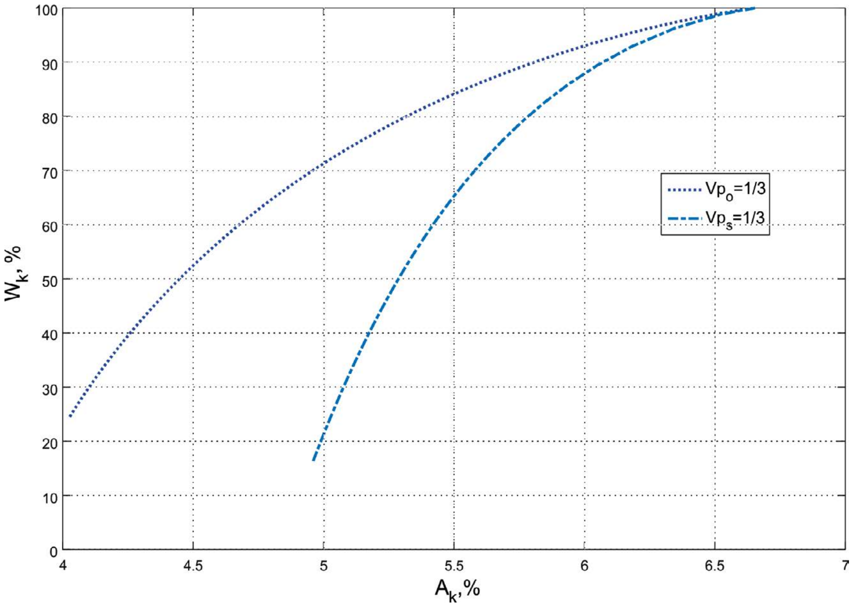

Fig. 7. Comparison of the static characteristics of the cell to cell flotation machine and optimal circuit at $V_p = 1/3$

Rys. 7. Porównanie charakterystyk statycznych układu flotownika trójkomorowego szeregowego i układu optymalnego przy $V_p = 1/3$

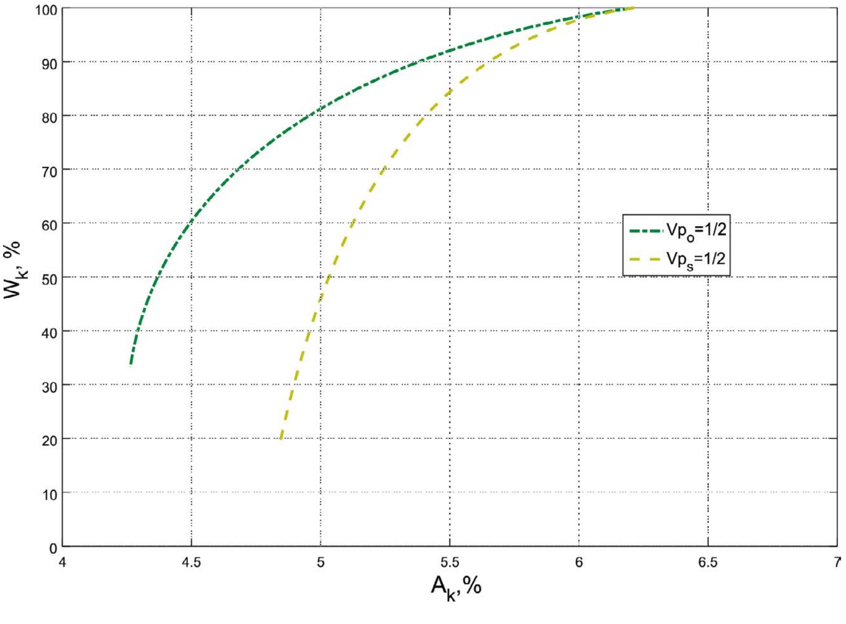

Fig. 8. Comparison of the static characteristics of the cell to cell flotation machine and optimal circuit at $V_p = 1/2$

Rys. 8. Porównanie charakterystyk statycznych układu flotownika trójkomorowego szeregowego i układu optymalnego przy $V_p = 1/2$

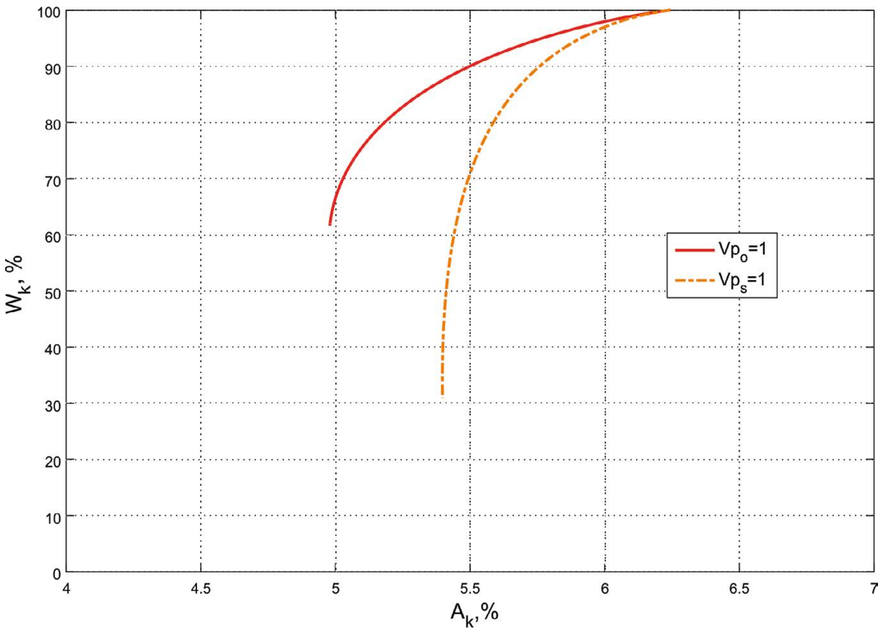

Fig. 9. Comparison of the static characteristics of the cell to cell flotation machine and optimal circuit at $V_p = 1$

Rys. 9. Porównanie charakterystyk statycznych układu flotownika trójkomorowego szeregowego i układu optymalnego przy $V_p = 1$

Fig. 10 presents a collective comparison of the static characteristics of the circuits discussed here.

Comparison between Figs. 7 to 10 shows that the recovery of the concentrate W_k (at set ash content in the concentrate A_k) is higher in the case of the proposed flotation circuit than in a three-cell flotation machine of a cell to cell structure. For instance, the recoveries of concentrates with ash content $A_k = 5\%$ are as follows: 82% for the proposed flotation circuit, 47% for the flotation circuit of a cell to cell structure (air flow rate $V_p = 1/2$). When comparing both circuits, one should note that a wide range of operating points is feasible for the circuit proposed here (depending on the adopted production requirements), which is not possible for the cell to cell flotation machine. For instance, it is not possible to attain very low values of ash content in the concentrate for a given recovery rate.

It should be noted, however, that in the case of lower quality requirements relating to concentrate production (higher ash content A_k in the concentrate), concentrate recoveries in the flotation circuits under consideration will be similar.

The study of the characteristics leads to an observation that there must be an extremum related to a specific air flow rate. Increasing the air flow rate increases the recovery rate (at specified ash content) only up to a specific flow rate (Fig. 6), upon exceeding which the recovery rate decreases. This applies to both structures of three-cell flotation machines.

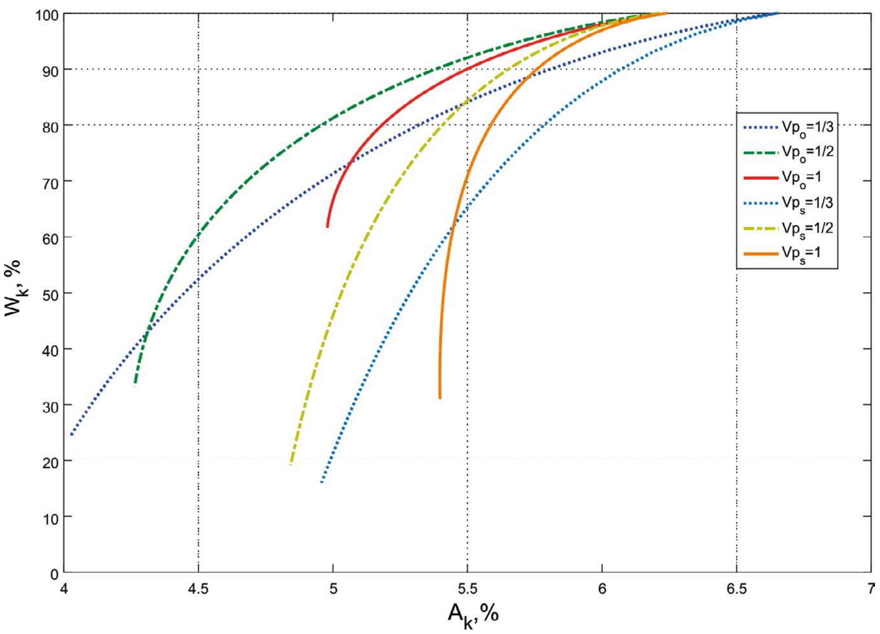

Fig. 10. Collective comparison of the static characteristics of the cell to cell flotation machine and optimal flotation circuit

Rys. 10. Porównanie zbiorcze charakterystyk statycznych układu flotownika trójkomorowego szeregowego i układu optymalnego

This indicates that the air flow rate has a significant impact on the quantitative-qualitative parameters of the circuit, and consequently also on the enrichment process.

In the example presented here, analysis was made for various air flow rates and fixed doses of flotation reagents. That analysis presented above may also be performed for other doses of flotation reagents. In such case the results of enrichment in the flotation circuit of the structure proposed here will also be superior to those obtained in the ordinary flotation circuits.

Summary

In a number of industrial embodiments flotation machines are of the cell to cell series configuration type. The flotation machine of a different structure proposed in this paper offers maximum slope of separation characteristics for a given separation velocity coefficient *k*.

The presented example shows that better results in raw materials enrichment (in technological and economic terms of flotation process assessment) are obtained in the case of connection structures of multi-cell flotation machines, the separation characteristics of which are more similar to the ideal characteristics.

The industrial application of the flotation circuit presented here differs from the existing industrial solutions in the structure of connections between flotation cells characterized by appropriate parameters.

It must be observed that the system of this type requires the use of control means to maintain appropriate mean residence times T_j of particles in the individual cells of the flotation machine.

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OPTYMALNA STRUKTURA POŁĄCZEŃ MASZYNY FLOTACYJNEJ Z TRZEMA KOMORAMI

Słowa kluczowe

współczynnik prędkości flotacji, funkcja gęstości rozkładu flotowalności ziaren węgla,
charakterystyki statyczne flotowników wielokomorowych,
optymalna struktura połączeń flotownika trójkomorowego

Streszczenie

Wzbogacanie flotacyjne jest procesem złożonym ze względu na wpływ wielu czynników na przebieg tego procesu. W ujęciu makroskopowym przyjmuje się, że wielkością która uwzględnia wpływ wszystkich istotnych czynników na proces wzbogacania, jest współczynnik prędkości flotacji k ziaren. W praktyce przemysłowej do procesu flotacji kieruje się materiał niejednorodny pod względem właściwości flotacyjnych. W związku z tym współczynnik prędkości flotacji k będzie się charakteryzował pewnym rozkładem. Nadawę można zatem opisać funkcją gęstości rozkładu flotowalności ziaren $f(k)$. Charakterystyki tego typu stosuje się przy projektowaniu i optymalizacji układów technologicznych flotacji. W artykule przedstawiono maszynę flotacyjną trójkomorową o określonej strukturze połączeń poszczególnych komór i sposobie doboru ich parametrów. Proponowany układ połączeń maszyny flotacyjnej trójkomorowej charakteryzuje się inną od szeregowej strukturą połączeń oraz ściśle określonymi parametrami każdej komory. Zdefiniowany sposób połączeń komór oraz odpowiedni dobór ich parametrów zapewnia maksymalne nachylenie charakterystyki rozdziału maszyny dla współczynnika prędkości k rozdziału. Prowadzenie procesu wzbogacania, w proponowanym układzie, umożliwia najdokładniejszy rozdział składników użytecznych nadawy.

Badania przeprowadzono metodami numerycznymi, gdzie podstawę stanowiły: opis analityczny układu połączeń trzech komór flotacyjnych rozpatrywany w stanie ustalonym, charakterystyka gęstości rozkładu flotowalności ziaren $f(k)$ oraz rozkład zawartości popiołu. Funkcję gęstości rozkładu flotowalności ziaren $f(k)$ określono na podstawie przebiegu kinetyki wydzielania się masy składników nadawy w procesie flotacji cyklicznej. Na podstawie wcześniejszych prac autorzy wykazali, że model rozkładu trójkątnego funkcji $f(k)$ dobrze charakteryzuje niejednorodność nadawy. Korzystając z rozkładu flotowalności ziaren, wyznaczono rozkład zawartości popiołu w zależności od zmian współczynnika prędkości flotacji. Następnie wyznaczono charakterystyki statyczne flotownika trójkomorowego. W końcowym etapie badań dokonano porównania efektów wzbogacania flotownika trójkomorowego szeregowego (o strukturze najczęściej spotykanej w przemyśle) z układem flotownika trójkomorowego o strukturze zaproponowanej przez autorów pracy.

OPTIMAL STRUCTURE OF THE CONNECTIONS OF A FLOTATION MACHINE WITH THREE CELLS

Keywords

flotation velocity coefficient, distribution density function of coal particles flotability,
static characteristics of flow flotation machines,
optimal structure of connections of a flotation machine with three cells

Abstract

Flotation enrichment is a complex process due to the influence of many factors on the course of this process. In macroscopic terms, it is assumed that the quantity that takes into account the influence of all important factors on the enrichment process is the flotation velocity coefficient k. In industrial practice the flotation process is followed by heterogeneous material in terms of flotation properties. Therefore, the flotation velocity coefficient k will be characterized by a certain distribution. Thus, the distribution can be described as the function of the density distribution of the particles flotability $f(k)$. Characteristics of this type are used in the design and optimization of flotation technological circuits. The paper presents a three cells flotation machine with a specific structure of connections of individual cells and the methods of selecting their parameters. The proposed circuit of the three cells flotation machine is characterized by a different connection structure and the specific parameters of each cell than the serial (cell-to-cell) flotation machine. The defined structure of connections between the cells and proper selection of their parameters ensures the maximum slope of the "separation characteristics" of the machine for the velocity coefficient k. Conducting the process of mineral enrichment in the proposed system enables the most efficient separation of the useful feed components.

The research was carried out using numerical methods, where the basis of the study was an analytical description of the connection system of three flotation cells being in a steady state, the distribution density characteristic of the particles flotability and the distribution of ash content. The distribution density function of the particles flotability was determined on the basis of the kinetics of the release of the mass of feed components in the batch flotation process. Based on previous work, the authors have shown that the heterogeneity of the feed is well characterized by the model of the triangular distribution function $f(k)$. Using the distribution of particles flotability, the distribution of ash content was determined in relation to the changes in the flotation velocity coefficient. In the final stage of the study, the effects of enrichment obtained in the three cells serial flotation machine (the most common industrial structure) were compared with those obtained in the three cells flotation machine circuit proposed by the authors.