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THE DISTRIBUTION OF THE FLOTATION RATE CONSTANT IN A SAMPLE
OF THE TWO-COMPONENT RAW MATERIAL

ROZKŁAD STAŁEJ PRĘDKOŚCI FLOTACJI W PRÓBCE SUROWCA DWUSKŁADNIKOWEGO

The flotation rate constant at the fixed hydrodynamic conditions in the flotation chamber is proportional to the probability of adhesion. This probability is, respectively, the function of the induction time which depends on the surface properties of the particle and reagents procedures.

The authors derived a formula for the distribution function of the flotation rate constant in the sample of the two-component raw material. When deriving, the analogy between the shape of empirical dependences of the flotation rate constant on the content of useful mineral in the particle and the coverage rate of the particle with a collector, and the theoretical dependence of the adhesion probability on the induction time. This analogy results from a sequence of several dependences. With the growth of the content of the mineral in the particle, the exposition rate of this mineral on the particle surface increases, the coverage rate of the particle surface with the collector grows, the induction time decreases, the adhesion probability goes up and therefore the flotation rate constant increases. Consequently, the distribution of the flotation rate constant in the sample will be analogical to the distribution of the content of a useful mineral. The distribution of content was derived according to the dispersive model of particle. This distribution is expressed by an incomplete gamma function, also called Pearson's function.

Key words: flotation rate constant, flotation kinetics, dispersive model, distribution function, incomplete gamma function

W ujęciu makroskopowym jako argument rozdziału przyjęło się w praktyce flotacji używać stałej prędkości flotacji. Stała ta przy ustalonych warunkach hydrodynamicznych w komorze flotacyjnej jest proporcjonalna do prawdopodobieństwa adhezji (wzór 7). Jak widać ze wzoru (5), prawdopodobieństwo adhezji, a przez to i stała prędkości flotacji, jest zależne od czasu indukcji, który jest funkcją własności powierzchniowych ziarna i reżimu odczynnikowego.

W artykule wyprowadzono wzór na dystrybucję rozkładu stałej prędkości flotacji w próbce surowca dwuskładnikowego. Wykorzystano podobieństwo kształtów między empirycznymi zależ-

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nościami stałej prędkości flotacji od zawartości flotowanego minerału w ziarnie (rys. 2) i stopnia pokrycia ziarna odczynnikami zbierającym (rys. 3) a teoretyczną zależnością prawdopodobieństwa adhezji od czasu indukcji (wzór 5 i rys. 1). Podobieństwo to wynika z następstwa kilku zależności. Ze wzrostem zawartości objętościowej minerału w ziarnie λ rośnie powierzchniowa zawartość tegoż minerału na powierzchni ziarna ω (wzór 9), rośnie stopień pokrycia powierzchni ziarna odczynnikami zbierającym g_c (wzór 10), maleje więc czas indukcji t_i (wzór 11), a przez to rośnie prawdopodobieństwo adhezji P_a (wzory 12) oraz stała prędkości flotacji k (wzór 14).

Wyrażenie (14) przedstawia zależność stałej prędkości flotacji od zawartości objętościowej flotowanego minerału w ziarnie. Rozkład stałej prędkości flotacji w próbce będzie więc analogiczny do rozkładu zawartości flotowanego minerału.

Funkcję rozkładu zawartości wyprowadzono na podstawie dyspersyjnego modelu ziarna, w którym liczba wprysnięć fazy rozproszonej (flotowanego minerału) w ziarnie o objętości V jest zmienną losową $s(V)$ mającą rozkład Poissona (wzór 18). Dystrybuanta tego rozkładu wyraża się przez niepełną funkcję gamma (wzór 20). Korzystając ze związku pomiędzy liczbą wprysnięć a objętościową zawartością fazy rozproszonej (wzór 21) uzyskuje się wyrażenie na dystrybuantę rozkładu zawartości flotowanego minerału w ziarnach nadawy (wzory 23 i 24). Odwrócenie funkcji (14) daje zależność zawartości fazy rozproszonej od stałej prędkości flotacji (wzór 25). Po podstawieniu tej zależności do wzoru (24) otrzymuje się dystrybuantę rozkładu stałej prędkości flotacji wyrażoną przez niepełną funkcję gamma. Wszystkie stałe występujące w tym rozkładzie mają interpretację fizyczną.

Słowa kluczowe: stała prędkości flotacji, kinetyka flotacji, model dyspersyjny, dystrybuanta rozkładu, niepełna funkcja gamma

1. Introduction

Every separation process, either the process of enrichment, of mechanical or hydraulic classification, is implemented according to a separation argument, specific for the given process. In the process in which the separation argument is constituted by the geometric properties of particles or their physical volume properties, such as density or magnetic susceptibility, the argument value is conditioned only by the particle structure and physical properties of its components. These properties cannot be modified without changing their chemical composition. The distribution of the separation argument in the sample, in the sense of distribution type and the values of distribution parameters, depends only on the size distribution function of the sample.

In the flotation process the particle flotation properties are determined by the surface properties of the particle whose value can be modified in a certain range by means of flotation reagents. However, the rate of modification of these properties is proportional to their primary values. Due to this, the type of distribution of flotation properties in the sample after treatment with flotation reagents will be the same as before treatment whereas the distribution parameters will change.

The flotation rate constant has been accepted to be used as a separation argument in the macroscopic approach. This value is defined in the equation of flotation kinetics whose first form (and most often applied so far) was proposed by Zuniga as an analogy of the equation of kinetics of the chemical reaction (Zuniga 1935):

$$\varepsilon(t) = 1 - e^{-kt} \quad (1)$$

where:

- $\varepsilon(t)$ — recovery of the useful component in the foam product after the time t of the process duration,
 k — flotation rate constant.

From equation (1) it is obtained:

$$k = \frac{1}{1-\varepsilon} \frac{d\varepsilon}{dt} \quad (2)$$

This is therefore the relation of the number of particles which were subject to flotation in a time unit to the number of free particles (which were not subject to flotation) in the flotation chamber in the moment t . The average value of the flotation rate constant is calculated by means of fitting the model dependence of the recovery of the useful component in the foam product on time, expressed by formula (1), to the empirical dependence.

Many models of flotation kinetics were proposed in the last several decades, both determinist and stochastic (Schuhmann 1942; Sutherland 1948; Beloglazov 1947; Kelsall 1960; Melkich 1963; Bushell 1962; Arbiter and Haris 1962; Panu 1965; Bodziony 1965; Inoue and Imaizumu 1968; Stachurski 1970; Kapur and Mehrota 1973; Siwec 1981; Geidel 1985; King 1982; Laskowski 1991; Yoon and Luttrell 1989; Yoon 1991; Jiang 1991; Yoon and Mao 1996). In these models the flotation rate constant is expressed by the probability of permanent mineralization of air bubbles. This probability is the product of three probabilities (Schuhmann 1942; Sutherland 1948):

$$P = P_c P_a (1 - P_d) \quad (3)$$

where:

- P_c — probability of collision between the particle and the air bubble,
 P_a — probability of adhesion of the particle to the bubble,
 P_d — probability of detachment of the particle from the air bubble.

The values of these probabilities depend on many physical and physicochemical factors. Starting from the first principles Yoon and Luttrell (1989) and Yoon and Mao (1996) derived the formulae for the above probabilities and presented the relation between these probabilities and the flotation rate constant:

$$P_c = \left(\frac{3}{2} + \frac{4\text{Re}^{0,72}}{15} \right) \left(\frac{R_p}{R_b} \right)^2 \quad (4)$$

$$P_a = \sin^2 \left\{ 2 \arctg \exp \left[- \frac{45 + 8\text{Re}^{0,72}}{30R_b \left(\frac{R_b}{R_p} + 1 \right)} \mu_b t_i \right] \right\} \quad (5)$$

$$P_d = \exp \left[- \frac{\gamma_{lv} \pi R_p^2 (1 - \cos \theta)^2 + E_1}{E'_k} \right] \quad (6)$$

$$k = \frac{1}{4} S_b P_c P_a (1 - P_d) \quad (7)$$

where:

- R_p — particle radius,
- R_b — bubble radius,
- Re — Reynolds number for the bubble,
- u_b — motion velocity of the elevated bubble,
- t_i — induction time,
- θ — contact angle,
- γ_{lv} — surface tension on the liquid-air boundary,
- E_1 — height of the energy barrier of the particle bubble interaction,
- E'_k — kinetic energy necessary to detach the particle from the bubble,
- S_b — area of air bubbles penetrating the area unit of the cross-section of the flotation machine.

As it appears from formula (5), the probability of adhesion as well as the flotation rate constant depend on the induction time. When the hydrodynamic parameters of the flotation system are fixed, the value of the flotation rate constant is affected by the induction time which, respectively, is the function of reagents procedure. This fact and the dependence of particle surface properties on the content of the useful component is the leading theme of this paper and will be used in the next part to derive the distribution of the flotation rate constant in the sample.

2. The relationship between the content of the useful component in the particle and the flotation rate constant

As it was revealed above, the flotation rate constant depends on many factors characterizing physical and geometrical properties of the particle. In mineral flotation by means of a selected reagent the flotation properties constitute the function of particle coverage rate with this reagent, depending on particle surface properties and the amount of reagent added to the system. The induction time is connected with the rate of particle coverage by the collector. The induction time decreases with the increase of the covering rate. Respectively, the induction time, as it results from formula (5), affects the adhesion probability.

Fig. 1 presents a dependence of adhesion probability on the induction time, drawn according to formula (5). The adhesion probability increases with the decrease of the induction time, i.e. the growth of coverage rate. The shape of this curve is convergent with the shape of the curve of dependence of the flotation rate constant on the content of

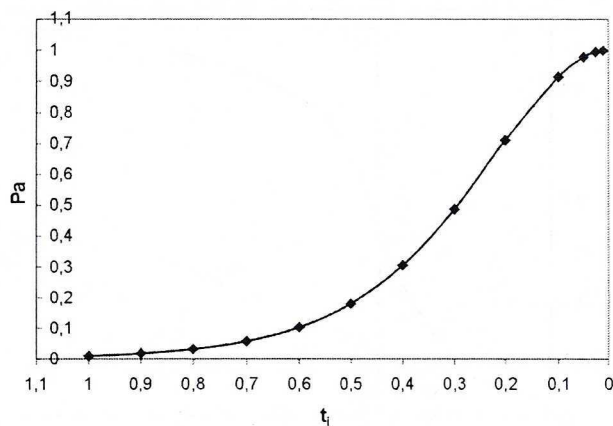


Fig. 1. Illustrative dependence of the adhesion probability (P_a) on the induction time (t_i)

Rys. 1. Poglądowa zależność prawdopodobieństwa adhezji (P_a) od czasu indukcji (t_i)

useful mineral in the particle and on the coverage rate of the surface by the collector. Fig. 2 and 3 present the dependences of the flotation rate constant on the weight content of hematite in particles and on the coverage rate of the particle by the collector (Bartlett and Mular 1974).

This convergence is explained in the following way. The surface properties of the particle depend on the exposition rate of the useful mineral on the particle surface which,

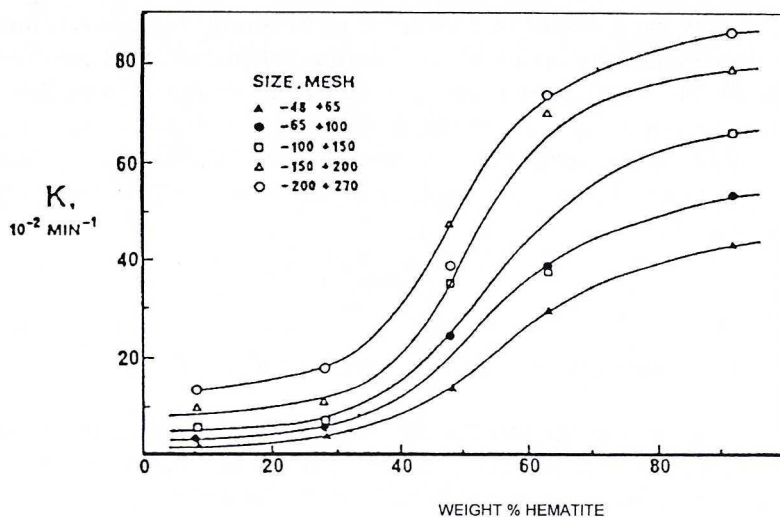


Fig. 2. Variation of the flotation rate constant (K) with average fractional hematite content for each particle size range (Bartlett and Mular 1974)

Rys. 2. Zmiany stałej prędkości flotacji K ze średnią zawartością hematytu dla różnych wielkości ziaren (Bartlett i Mular 1974)

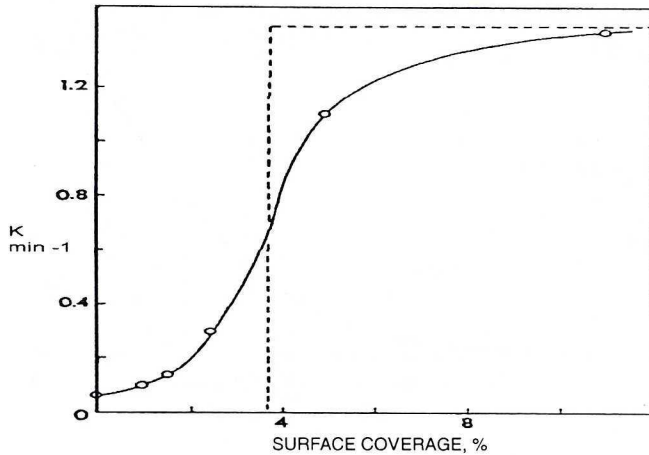


Fig. 3. Dependence of the flotation rate constant (K) on fractional surface coverage of collector. Results for 74–105 μm quartz particles and collector dodecylamine hydrochloride (Inoue and Imazumi 1968)

Rys. 3. Zależność stałej prędkości flotacji K od stopnia pokrycia powierzchni ziaren kwarcu 74–105 μm chlorowodorkiem dodecyloaminy (Inoue i Imazumi 1968)

respectively, depends on the content of this mineral in the particle. Therefore the following sequence of dependences exists. With the increase of content the rate of exposition of the useful mineral on the particle surface increases, the coverage rate of the particle surface by the collector increases, the induction time decreases, the adhesion probability grows and therefore grows the flotation rate constant. Therefore the distribution of the flotation rate constant in the sample will be analogical to the distribution of the content of useful mineral. If the inclusions of the dispersed phase (see Chapter 3) are distributed evenly in the volume of the spherical particle of radius R_p , then the total content of the dispersed phase in the sphere of radius r ($r \leq R_p$) and the infinitesimal thickness dr will be:

$$d\lambda = \lambda 4\pi r^2 dr \quad (8)$$

where:

λ — volume content of the dispersed phase in the particle.

If $r = R_p$, it can be assumed that the exposition rate of surface of the useful mineral (mineral of the dispersed phase) on the particle surface or, in other words, the surface content of the dispersed phase on the particle surface ω will be:

$$\omega = \frac{d\lambda}{4\pi R_p^2} = \lambda dr \quad (9)$$

It is therefore proportional to the volume content of the dispersed phase in the particle.

The coverage rate g of the particle with the collector is proportional to the surface content of dispersed phase:

$$g_c = c_1\omega + c_2 = c_3\lambda + c_2 \quad (10)$$

The constant c_2 in the above formula presents the coverage rate of the continuous phase with the collector.

As it was said above, the induction time decreases with the increase of the coverage rate. The convergence of the shape of curves of Fig. 1-3 contributes to the assumption that the dependence of the induction time on the coverage rate is of the form of a linear function:

$$t_i = c_5 - c_4g_c = a - b\lambda \quad (11)$$

where:

$$b = c_5c_3, a = c_5 - c_2c_4 \text{ and } \lambda \in [0,1].$$

Therefore the induction time decreases with the growth of the volume content of the dispersed phase in the particle. For the particles of the pure continuous phase ($\lambda = 0$) the induction time is a , whereas for the particles of the pure dispersed phase ($\lambda = 1$) the induction time is $t_i = a - b$.

Inserting expression (11) into formula (5) we can obtain the dependence of adhesion probability on the content of the dispersed phase in the particle:

$$P_a = \sin^2 \{2\text{arc tg} \exp[-A(a - b\lambda)]\} \quad (12a)$$

$$P_a = \sin^2 \{2\text{arc tg}[B \exp(Ab\lambda)]\} \quad (12b)$$

where:

$$A = -\frac{45 + 8\text{Re}^{0,72}}{30R_b \left(\frac{R_b}{R_p} + 1 \right)} \quad (13a)$$

$$B = \exp(-Aa) \quad (13b)$$

When the constancy of flotation conditions is assumed, the probability of collision for the particles of a narrow size fraction is constant. Then the changes of the flotation rate constant are conditioned by the changes of adhesion probability. Thus it can be written:

$$k = CP_a = C \sin^2 \{2\text{arc tg}[B \exp(Ab\lambda)]\} \quad (14)$$

where:

$$C = \frac{1}{4} S_b P_c (1 - P_d) \quad (15)$$

3. The distribution function of the flotation rate constant

Geidel (1985) and Laskowski (1991) dealt with the problem of distribution of the flotation rate constant. Starting from the exponential dependence of adhesion probability on the contact time, by means of the method of generalizations, they came to the conclusions that the flotation rate constant has a gamma distribution whose particular form is the exponential distribution.

As it was said in the previous chapter, the distribution of the flotation rate constant in the sample depends on the distribution of the content of the useful component. In this paper the distribution of the content of the useful component was determined according to the dispersive model of a particle (Brožek 1995b, c). In this model the multi-component raw materials are treated as a multi-phase system in which the phase denotes a part of the medium which is homogeneous from the point of view of physical and chemical properties (Cottrell 1964).

In the dispersive system there are a continuous phase and dispersed phases. The continuous phase constitutes a matrix for inclusions of the dispersed phase. In case of coal the continuous phase is constituted by the organic coal matter while the dispersed phases are the inclusions of the mineral matter. In case of ores the continuous phase is constituted by the waste rock while the dispersed phases are the inclusions of metal-bearing minerals.

In order to facilitate the derivation of the form of distribution of the content of the dispersed phase in the sample it was assumed that the dispersive system has two phases (continuous phase and one dispersed phase) while the dispersed phase is monodispersive. Let the particle volume of the narrow size fraction be equal V while the volume of a single inclusion be v .

Since the content of the dispersed phase changes from one particle to another, it is assumed in the dispersive model that the number of inclusions of the dispersed phase in the particle is a random variable $s(V)$.

There are two conditions which result from the very idea of the dispersive system and dispersion in general. They are fulfilled by the above mentioned random variable:

1. The sum of volumes of inclusions in every particle must be smaller than the particle volume, i.e. $s_i v < V (i = 1, 2, \dots, m)$, where s_i denotes the number of inclusions in the i -th particle while m is the number of particles in the sample.

2. The second condition results from the nature of the dispersion as such. At a sufficiently small element of the particle volume $\Delta V > v$, the probability of an event that there is only one inclusion in this element is proportional to ΔV with accuracy to infinitesimals of the higher order:

$$P[s(\Delta V) = 1] = n\Delta V + o(\Delta V) \quad (16)$$

where n is the average number of inclusions for a volume unit while $o(\Delta V)$ is an infinitesimal of the higher order than ΔV . The volume element ΔV is sufficiently little and the probability of finding two or more inclusions in this element is negligible little, i.e.

$$P[s(\Delta V) > 1] = o(\Delta V) \quad (17)$$

Moreover:

3. The probability of appearance of a determined number of inclusions in the particle depends only on its volume V . It means that when the particle volume is constant, the probability of appearance of a determined number of inclusions is constant.

4. The numbers of inclusions in respective particles are independent random variables. The random variable which fulfills the above four conditions has Poisson's distribution (Fisz 1967). Respectively, the probability that there are s inclusions in the particle of volume V is expressed by the formula:

$$P_v(s) = \frac{(nV)^s}{s!} e^{-nV} \quad (18)$$

Expression (18) present a fraction of a general number of particles in which the number of inclusions equals s , or the volume yield (frequency of occurrence) of particles of the number of inclusions s .

The distribution function of the number of inclusions equals:

$$F_v(s) = P(S \leq s) = e^{-nV} \sum_{p=0}^s \frac{(nV)^p}{p!} \quad (19)$$

The distribution function of Poisson's distribution is expressed in the following way by the gamma function (Gradstein and Ryzik 1971):

$$F_v(s) = \frac{1}{\Gamma(1+s)} \int_{nV}^{\infty} e^{-t} t^s dt = I(nV; 1+s) \quad (20)$$

where:

- $\Gamma(1+s)$ — gamma function,
- $I(nV; 1+s)$ — Pearson's function (Firkowicz 1970).

Pearson's function is also known as the incomplete gamma function.

The number of inclusions in the particle is connected with the volume content of the dispersed phase by the following dependence (Brożek 1995a):

$$s = h\lambda \quad (21)$$

while

$$h = \frac{V}{v} = \text{const.}$$

The product nV represents the average number of inclusions in the particle of volume V . Therefore, analogically as in formula (21):

$$nV = h\Lambda \quad (22)$$

where Λ is the average volume content of the dispersed phase in a sample. After substituting dependences (21) and (22) into formula (20) we obtain the expression for the distribution function of the volume content of the dispersed phase:

$$F_v(\lambda) = I(h\Lambda; 1 + h\lambda) \quad (23)$$

Formula (23) was derived at the assumption of monodispersivity of the dispersed phase. This assumption was made to facilitate the combining of distribution parameters with the properties of raw material and the sample.

After these remarks a generalization can be made and hypothesis can be proposed that the following Pearson's function constitutes the distribution function of volume content of the polydispersive dispersed phase:

$$F_v(\lambda) = I(H\Lambda; 1 + H\lambda) \quad (24)$$

while Λ presents the average volume content of the polydispersive dispersed phase in the sample, whereas H , analogically as h , is a constant connected with the size of particles and inclusions.

From formula (14) an inverse dependence, i.e. the content of the dispersed phase in the particle in the function of the flotation rate constant will be:

$$\lambda = \frac{1}{Ab} \ln \left[\frac{1}{B} \operatorname{tg} \left(\frac{1}{2} \arcsin \sqrt{\frac{k}{C}} \right) \right] \quad (25)$$

Substituting this dependence to formula (24) we obtain the required distribution function for the flotation rate constant:

$$F_v(k) = I \left\{ H\Lambda; 1 + \frac{H}{Ab} \ln \left[\frac{1}{B} \operatorname{tg} \left(\frac{1}{2} \arcsin \sqrt{\frac{k}{C}} \right) \right] \right\} \quad (26)$$

In the above distribution all the included constants have a physical interpretation by sample properties or physicochemical conditions occurring in the flotation chamber. The values of constants a and b can be obtained from dependence (11) while constants A and B from dependence (13). Constant H is connected with the size distribution function and can be determined from the density or magnetic susceptibility distributions in the sample (Brożek 1995 b, 1995 c). The value of constant C is obtained from fitting the model distribution function (26) to the empirical distribution function. In this constant, as it results from formula (15), there are probabilities of collisions P_c , detachment P_d and the area of air bubbles S_b crossing the area unit of the cross-section of the flotation machine. The values P_d and S_b can be determined from the investigations of flotation kinetics (Brożek et al. 2003) and size distribution function of air bubbles. Therefore, knowing of the value of constant C enables the probability of collision P_c to be calculated. This is, of course, the average value of this probability because it depends, according to formula (4), on the hydrodynamic conditions in the flotation chamber (Re) and on the dimensions of particles and air bubbles (R_p and R_b), subjected to flotation.

Consequently, both the sizes of particles and air bubbles have determined distributions in the flotation of natural mineral mixtures.

Summing up, it can be said that dependences (14) and (26), derived in this work, can be used for the analysis of a given flotation system and influence of physical and physicochemical parameters on the flotation results.

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