PSG method for the simulation of carbon particles accumulation in the flotation process

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Abstract. Carbon agglomeration on the surface of gaseous bubbles in the flotation process has been modeled in this paper. The calculations were based on the PSG method and performed for five strictly defined size groups of carbon particles (M=5) for initial sizes 100-400 µm, and mixing energy $\varepsilon = 0.01$ $[m^2 s^{-3}]$. The analysis of the obtained results revealed that the process was much faster for particles with bigger initial size 300 and 400 µm. In this case the time needed for the removal of particles in particular size groups was shortest. It was observed for all analyzed cases that the process was most dynamic in the initial phase, whereas at the end of it the agglomerations considerably lowered because of the decreased number of particles in specific groups.

1. Introduction

One of the methods of separating gangue from coal is flotation. The optimal conditions of flotation depend on the concentration of solids in feed, temperature, ph of the solution, size of flotated grains, amount of introduced air as well as time and intensity of mixing. In the course of flotation the carbon particles are separated from the mineral part in the course of Surface phenomena taking place at the air bubble/particle division interface. The hydrophobic force makes the grain adhere to the gaseous bubbles. Heuristic models of flotation kinetics based on the stochastic approach to the process description taking into account the birth and death of flotation aggregates, are described by Brożek and Młynarczykowska [1-3]. The possible agglomeration of carbon particles on the bubble surface is usually analyzed theoretically or experimentally on aqueous models. One of the mathematical methods of agglomeration modeling is the Particle Size Grouping Method. Authors used this method in earlier works to describe agglomeration of nonmetallic inclusions in the process of liquid steel refining from nonmetallic inclusions during flotation [4-5].

2. PSG Method

The process of carbon particle agglomeration during flotation was simulated with the Particle Size Grouping (PSG) method. The algorithm is based on dividing particles into M groups. Each group
has a strictly defined size range, which is given and which is changed with the predefined coefficient [6]:

\[ R_V = v_k v_{k-1} = \text{constas} \] (1)

where:

- \( v \) – volume of particle (coal),
- \( k \) – index of a group.

If \( R_v = 2 \), the critical particle \( v_k \) was formed by two level-lower particles \( v_{k-1} \). Index \( k \) describes the number of smallest elements making up the particle. Hence the conclusion that with the agglomeration of particles representing two size-groups, e.g. \( k-l \) and \( k-l \), we can obtain a new particle with a size beyond this group. This new agglomerate is classified as \( k \) if its size exceeds the initial threshold of group \( k \), otherwise it belongs to group \( k-l \). This classification of particles affects the change of density of the groups, because:
- two particles form one particle, thus reducing the total number of particles,
- remaining in the group, a particle decreases the number of constituent elements.

If a collision of particles belonging to the interval \( i_{c,k-1} \) to \( k-l \) generates a particle \( k \), then the balance of the population can be calculated with the equation (2) [4-8]:

\[
\frac{dn_k}{dt} = \sum_{i=1}^{n} \xi_{i,k-1} (r_i + r_{k-1})^3 n_i n_{k-1} + \sum_{i=1}^{n} \zeta_{i,k} (r_i + r_k)^3 n_i n_k - \sum (1 + \delta_{ik}) (r_i + r_k)^3 n_i n_k \]

(2)

where:

dimensionless number density of size \( i \) particles are defined as:

\[ n_k = n_k/N_0 \] (3)

\[ t = 1.3a r_1^3 (\epsilon/\nu)^{1/2} N_0 t \] (4)

- \( N_0 \) – initial total number density of particles (m\(^{-3}\)),
- \( N_M \) – number of fundamental particles making up the biggest agglomeration,
- \( r_1 \) - radius of elementary monomers,
- \( t^* \) - dimensionless time of turbulence collision,
- \( n_i, n_{i-k}, n_k \) -number density of size \( i, i-k \) and \( k \) particles (/m\(^3\))
- \( \xi_{i,k-1}, \zeta_{i,k} \) – correction coefficient of particle density in a group,
- \( \nu \) – kinematic viscosity (m\(^2\)/s),
- \( \epsilon \) – turbulent energy dissipation rate (m\(^2\)/s),
- \( \alpha \) – agglomeration coefficient

\[ \xi_{i,k-1} = (v_i + v_{k-1})/v_k \] (5)

\[ \zeta_{i,k} = v_i/v_k \] (6)

\[ r_k = r_k/r_1 \] (7)

- \( i_{c,k-1} \) - size of a particle,
- \( v_i \) – volume of i-particle (m\(^3\)),
- \( \delta_{ij} \) – Kronecker’s delta (\( \delta_{ij} = 1 \) for \( i=j \), \( \delta_{ij} = 0 \) for \( i \neq j \)).

If \( k=3 \), then \( i_{k-1}=1 \), at \( R=2 \), the sum will consist of two elements, i.e. collision of particles \( k-2=1 \) and \( k-1=2 \), and the other one \( k-1 \) and \( k-1 \). Parameter \( \xi_{i,k-1} \) represents the fraction of total volume of two colliding particles, which tend to the volume of class „k“:
\[ \xi_{i,k-1} = \frac{V_{i} + V_{k-1}}{V_k} \]  \hspace{1cm} (8)

i.e. \[ \xi_{1,2} = \frac{V_{1} + V_{2}}{V_3} = \frac{3}{4} \] for \( R = 2 \) \hspace{1cm} (9)

and \[ \xi_{2,2} = \frac{2V_2}{V_3} = 1 \] \hspace{1cm} (10)

3. Results of calculations

The collisions of carbon particles during flotation were simulated based on data presented in table 1. The process was analyzed for a population consisting of particles representing the following size groups:

- 0.1 [mm] = 100 [µm]
- 0.2 [mm] = 200 [µm]
- 0.3 [mm] = 300 [µm]
- 0.4 [mm] = 400 [µm]

For calculation purposes, the assumed mixing energy was \( \varepsilon = 0.01 \text{ [m}^2 \text{s}^{-3}] \).

| Initial number of particles \((N_0) \text{ [/m}^3] \) | Agglomeration coefficient, \( \alpha \) | Viscosity of fluid \( \eta \text{ [m}^2 \text{s}^{-1}] \) |
|-------------------------------------------------|---------------------------------|----------------------------------|
| 5 000 000                                       | 1                               | \( 8.937 \cdot 10^{-7} \)        |

The results of calculation for particular variants was presented graphically; the effect of agglomeration was analyzed for a substitute time \( t^* \).

Figure 1. Results of calculations for a particle \( r = 100 \text{ [µm]} \).
Figure 2. Results of calculations for a particle $r = 200 \, [\mu m]$. 

Figure 3. Results of calculations for a particle $r = 300 \, [\mu m]$. 
The analyzed agglomeration of carbon particles does not mean that flotation takes place. In the process of agglomeration bigger particles are formed as a result of colliding smaller particles, in the course of which bigger particles are formed, the size of which (if exceeding threshold values) is classified in a different size group. It was assumed in the calculations that in the initial stage of the process the particles have only a given radius, e.g. 100 µm (fig. 1). As a result of mixing, the particles collide and new particles are formed in particular, successive size groups. It should be noted that the collisions take place between particles belonging to the same group and between different size groups. This signifies that the initial assumed number of particles $N_0$ does not change and stays constant during the simulation. However various groupings take place as the process (time) proceeds. The picture of changes of particles in particular groups presented in figures 1-4 illustrates the dynamics of carbon particles removal in the process of mixing a bath containing carbon particles. The process was observed to take place faster for bigger particles, e.g. 400 µm (fig. 4). In the analyzed case time $t^*$ required for the removal of particles belonging to a size group $n_1$ is 2 orders lower as compared to particles 100 µm – group $n_1$ (fig. 1). Characteristically, in all analyzed cases the biggest dynamics of the process was noted in the initial stage of the process, and were small in group 1 at the end of the process (fig. 1-4), which was caused by the decreasing number of particles in that size group. In this way the probability of occurrence of collision was also lower.

5. Conclusions
Coal flotation in view of mixing-induced agglomerates formation can be analyzed with the PSG method. The collisions cause the formation of bigger particles which are nor chemically bonded; their increase is solely a result of collisions. The assumed number of particles of a give volume remains unchanged over the agglomeration process, though this population is classified in particular size groups as the process proceeds. In the suggested solution only the dynamics of changes of particle size for the assumed mixing energy $\varepsilon = 0.01 \text{ [m}^2\text{s}^{-3}]$ and given particle sizes in group $n_1$ (100, 200, 300, 400 µm) are assumed. The process is definitely fastest in the case of bigger particles.
References

[1] Brożek M, Młynarczykowska A. Application of the stochastic model for analysis of flotation kinetics with coal as an example. *Physicochemical Problems of Mineral Processing*. 2006, 40, 31-44

[2] Brożek M, Młynarczykowska A. Analysis of kinetics models of batch flotation. *Physicochemical Problems of Mineral Processing*. 2007, 41, 51-65

[3] Brożek M, Młynarczykowska A. An analysis of effect of particle size on batch flotation of coal. *Physicochemical Problems of Mineral Processing*. 2013, 49, 341-356

[4] Kalisz D., Żak P L. PSG Method for Simulating of Al₂O₃ inclusions in liquid steel, *Acta Physica Polonica* A, 2016, 130.

[5] Kuglin K, Kalisz D. Effect of Energy Mix on the Phenomenon of Agglomeration of Non – Metallic Inclusion Particles in Liquid Steel, *Transactions of Foundry Research Institute*, 2017, 1

[6] Nakaoka T, Taniguchi S T, Matsumoto K, Johansen S T. Paricle – Size – Grouping Method of inclusion agglomeration and its application to water model experiments, *ISIJ Int.*, 2001, 41

[7] Higashinati K, Yamauchi K, Matsuno Y, Hosokawa G. Turbulent coagulation of particles dispersed in viscous fluid, *Journal of Chemical Engineering of Japan*, 1983, 16, 4

[8] Kalisz D, Zak P L, Kuglin K. Analysis of agglomeration of Al₂O₃ particles in liquid steel, *Archives of Metallurgy and Materials* 2016, 61, 4