Analysis of the Gas Phase in Flotation Process. Part 1: Experimental Determination of the Volume of Air Bubbles in the Pneumo-Mechanical Flotation Machine

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Summary

Problem of bubble mineralization, representing the most important flotation stage and resulting in measurable outcomes described by flotation concentrate yield, is of a key importance research problem from practical point of view. Most of publication in the literature refer to the global study on the impact of selected factors (size of the bubbles, the particle coverage ratio with flotation reagents, hydrophobic properties of particles) on the results of flotation. A decisive role in this process is played by dispersive properties of the gas phase, which is the main factor affecting the results of upgrading process, defining the operation conditions of the flotation machine or the degree of aeration of flotation pulp. The paper presents the results of the assessment of the influence of selected physical parameters on the size of air bubbles generated in the working chamber of pneumatic-mechanical type of flotation machine. The variables, directly related to the size and the way the dispersion of air bubbles, were the dispensed amount of air and the number of rotor's rotation at fixed physicochemical conditions. These parameters were determined in order to characterize the dispersion of air in the two-phase liquid-gas. The study was carried out on the unique device, with using video recording techniques and image analysis.

Keywords: flotation, bubbles dispersion, bubble size population

Introduction

The results of the flotation process course are determined by a number of factors of a random character, like: collision of single particle with air bubble, adhesion of particle to the surface of bubble and detachment process. Due to the random nature of these factors it is only possible to talk about the probability of occurrence of a specific event, affecting the speed of the process course and thus a constant speed of flotation process (Brożek et al., 2003). Many models, linking the speed of flotation course with the phenomena occurring in the flotation cell and conditioning it from the physical and physicochemical factors affecting the flotation, can be found in literature. Therefore investigations over the impact of various factors on the kinetics of flotation are equivalent to study the impact of these factors on the value of flotation speed. Indeed, this volume is of a macroscopic character and should contain any information about the qualitative and quantitative influence of the parameters investigated on the upgrading process (Yoon and Luttrell 1989, Varbanov et al. 1993, Yoon and Mao 1996, Brożek et al. 2003, Brożek 2010, Saramak et al. 2012). Based on heuristic considerations and full stochastic model, it is possible to specify the values influencing the constant of flotation speed of the first order, to estimate the intensity of subprocesses of adhesion and detachment in specific physicochemical and hydrodynamic conditions in the flotation cell (Brożek and Młynarczykowska 2005, 2006, 2010, 2012).

From a practical point of view the most important stage of flotation is the process of mineralization of air bubbles, it is therefore an important research problem. In the literature, most of investigations refer to the study over the impact of selected factors (size of the bubbles, the degree of covering the particle surface with flotation reagents, hydrophobic properties of particles) on the results of flotation. There are relatively few works based on heuristic analysis of basic phenomena occurring in flotation, and more precisely, during the process of bubble mineralization.

Crucial role in this process play dispersive properties of the gas phase, which is a key factor affecting the upgrading process results, specifying the operation manner of flotation machine or the degree of aeration of flotation pulp. The characteristics of the gas phase in a flotation chamber consists of: the volume and distribution of air bubbles generated in the flotation cell, the volume of gas flowing through the cross-sectional areas of the chamber per unit time (Jg [m/s]), the volumetric concentration of gas in the flotation cell (εg [%]) and the stream of surface bubble flowing through the cross-sectional area of the flotation chamber per unit time (Sb [1/s]).

Bearing in mind that the process of the air bubble mineralization, that is a formation of stable aggregates of flotation, is a necessary condition for the occurrence of flotation process, the properties of the gas phase are of essential importance in this process.

The above considerations are the basis for empirical verification of characteristics of the gas phase in the flotation process at variable physicochemical and hydrodynamic conditions in the working chamber of flotation machine.

The article presents the results of the assessment of the influence of selected physical parameters on the size of air bubbles generated in the chamber of pneumatic-mechanical type of flotation machine. The dispensed amount of air and number of rotations of the rotor at fixed physicochemical conditions, were the variables directly related to the size and the way of air bubble dispersion. The study was limited to the execution of direct measurements only in designated sectors of the working chamber due to its symmetrical structure. The experiment was carried out on a unique testing device utilizing visual techniques of image recording and analyzing, allowing for counting the population of generated air bubbles together with simultaneous analysis of indicated size parameters, like: Feret's diameter, circumference, surface area of the object. The above parameters were determined to characterize the dispersion of air in the two-phase liquid-gas system.

Testing equipment

The tests were carried out in the Laboratory of Instrumental Methods in Department of Environmental Engineering and Mineral Processing, Faculty of Mining and Geoengineering, AGH University of Science and Technology in Krakow, using the testing device (Fig.1) developed within the framework of the research project KBN No. 4 T12A 035 30/2009, under the leadership of the Author of this paper. The testing equipment consists of: flotation machine of pneumo-mechanical type with the working chamber and the automatic control system, vacuum pump, cylinder with compressed air, video recording system consisting of a digital camera with Nikon lens, flash strobe DRELOSCOP 3009 lamp, the "Luba Tube" system and control device with suitable software (Malysa et all, 1999a). Flotation machine has the ability to automatically con-

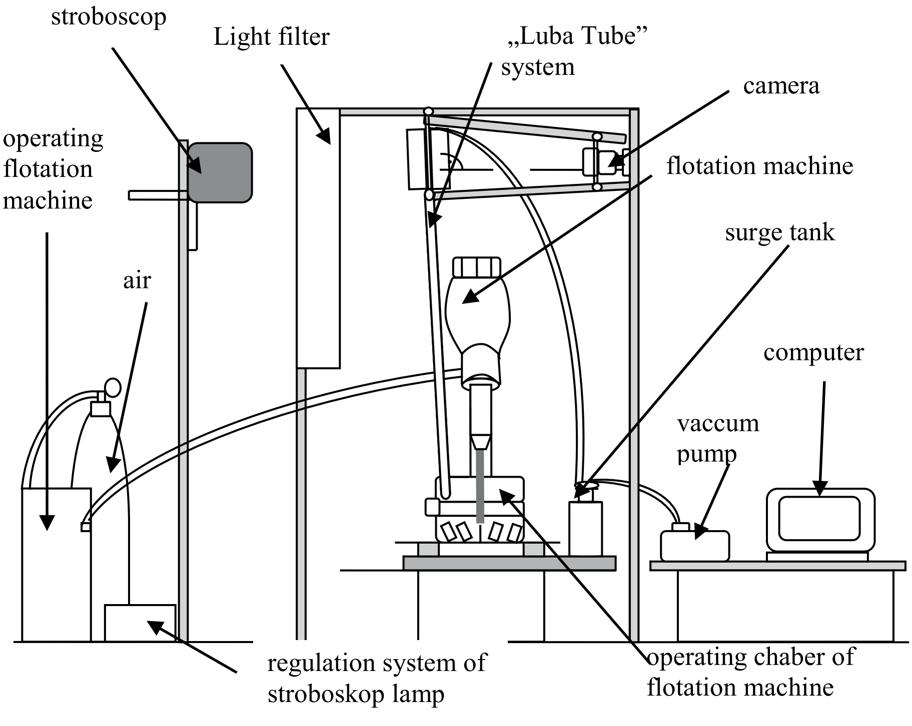


Fig. 1. The scheme of the research

Rys. 1 Schemat stanowiska badawczego (Nyrek A., Oleksik K., 2014) trol the air flow rate, the number of rotation of the rotor, the rotational speed of the scraper, to maintain a constant level of liquid or flotation pulp, by means of suitable professional software.

The measurement methodology

The proper execution of the experiment required filling with water of flotation machine working chamber with using the "Luba Tube" system, to which the liquid was sucked in by the vacuum pump working continuously during the course of investigations. Based on a number of preliminary analyses, there were determined final range of operating parameters of flotation machine like rotation of the rotor and fixed air flow for physico-chemical conditions.

There were also worked out the optimal work parameters of the image recording system, that guarantee obtaining the proper quality of images for further analyses. Testing of the gas phase were carried out in distilled water, the surface tension of which on the border of water-air phase was 72.75 mN /m in temperature 20°C. Air bubbles in the working chamber of flotation machine are produced from the gas stream. Large air bubbles flowing from the pipe are broken down by a rotor blades into a number of smaller bubbles. The bubbles generated in given hydrodynamic conditions were discharged from the specified area of flotation cells through the "Luba Tube" system, and directed to the registration chamber, under observation of digital camera lens. Video recording the image of flowing air bubbles was subject to further processing with using an image analysis software, to isolate a series of individual images and to determine the parameters characterizing the size of the gas bubbles.

Video recording time was 6 minutes, which was sufficient to estimate the changes in the size

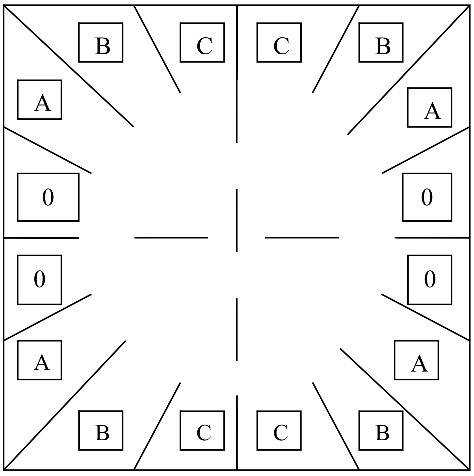
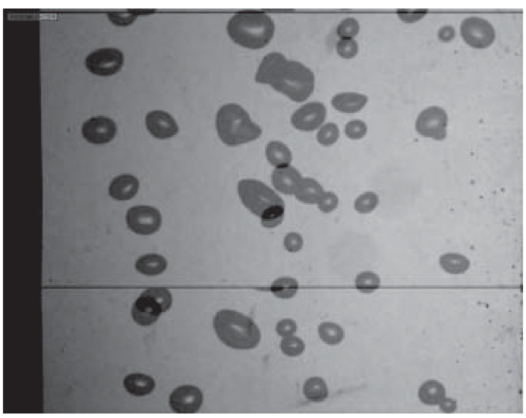


Fig. 2. Elevational view of the flotation cell with distinguished measurement sectors.

Rys. 2. Rzut pionowy komory flotacyjnej z wyznaczonymi sektorami pomiaru.

a)



b)

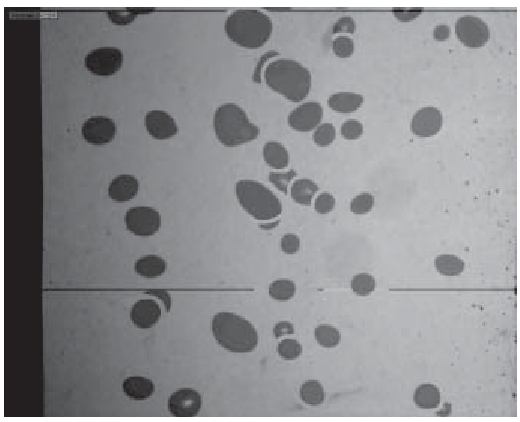


Fig. 3. Sample image selected for analysis before and after the technical adjustment (rotor speed 1000 rpm, air flow rate 240 dm^3/h)

Rys. 3. Wybrane próbki obrazów do analizy przed i po ustawieniach technicznych (prędkość wirnika 1000 obrotów na minutę, wskaźnik przepływu powietrza 240 dm^3/h)

Tab. 1. Results for the „0" sector

Tab. 1. Wyniki pomiarów dla celi pomiarowej „0" komory flotacyjnej

Section „0"							
Q = 24 dm^3/h, ω = 1000 rpm				Q = 240 dm^3/h, ω = 1350 rpm			
	Surface area [mm^2]	Feret's diameter [mm]	Perimeter [mm]		Surface area [mm^2]	Feret's diameter [mm]	perimeter [mm]
mean value	1,318	1,001	3,341	mean value	5,03	2,303	8,256
standard deviation	2,253	0,822	2,846	standard deviation	4,127	1,05	4,142
standard error	0,059	0,022	0,075	standard error	0,162	0,041	0,162
95% confidence interval	0,116	0,042	0,147	95% confidence interval	0,318	0,081	0,319
99% confidence interval	0,153	0,056	0,193	99% confidence interval	0,418	0,106	0,42
measurements number	1449	1449	1449	measurements number	650	650	650
Min.	0,045	0,234	0,734	Min.	0,107	0,37	1,136
Max.	17,76	4,755	15,923	Max.	24,131	5,543	25,556

of Feret's diameter, the surface and circumference of bubbles, and what constitute a reference to the conditions of implementation the laboratory tests for mineral flotation.

Due to the symmetrical construction of the flotation cell, the sectors, indicated in Figure 2 and denoted as 0, A, B, C, were distinguished. A stream of generated air bubbles was led out from these sectors. The results of ¼ of the chamber can be applied to the entire working area of the flotation chamber.

Image analysis

Having obtained the registered image flow of air bubbles in a flotation cell, single images were firstly extracted from the film. The amount of single frames in each sector varied from 180 to 400, but for standardization purposes the number of images to be analyzed will be limited to 200. Images with highest quality were then selected, however the technical correction of image quality was necessary before the final image analysis, because the software operates on the basis of a fixed grayscale. In the case of the overexposed photos, too light bubbles would not be included in the bubble surface or the overlapping bubbles could be accounted as a single bubble.

An adequate preparation of images is a very important stage of the research, as can be seen on the sample images (see figure 3a and 3b). They represent air bubble images recorded under identical conditions but measured in various stages of preparation for the final analysis.

During the pre-selection of the experimental material it was also included the recording time of each frame, for purposes of further direct results comparison. Quantitative and qualitative analysis was conducted for images recorded at time t_0=1 sec., t_1=5 sec., t_2=10 sec. etc, that is, for the time interval equal to 5 seconds. As a result of the above selection, 40 images of each cell were selected, which, after technical adjustment, were analyzed by means of professional software.

Experimental results analysis

Tables 1–4 show the results of measurements for four sectors of flotation chamber (that is: 0, A, B, C). The total volume of the chamber was 1 dm^3. Tests were carried out for variable air flow (Q) at two value levels: 24 dm^3/h and 240 dm^3/h at a fixed speed of the rotor (ω) 1350 rpm (for the section 0) 1000 rpm (revolutions/minute), for sections A, B, C, respectively. An increased speed of rotor for air bubble flow measurement in section 0 were dictated by the results of preliminary experiments.

A thorough analysis, presented in accordance with the above measurement methodology, was carried out for each section, at given operating parameters of flotation machine. This allowed for determination of the quantity and quality (Feret's diameter, circumference, surface area), of the air bubbles generated in the working chamber of the device. In the tables, in addition to the computed characteristics of the gas phase in the flotation cell, there were also presented statistical characteristics, generated by the image analysis software (mean, standard deviation, standard error, 95% and 99% confidence interval, number of measurements, minimum and maximum value).

Tab. 2. Results for the „A" sector

Tab. 2. Wyniki pomiarów dla celi pomiarowej „A" komory flotacyjnej

Section „A"							
Q = 24 dm^3/h, ω = 1000 rpm				Q = 240 dm^3/h, ω = 1000 rpm			
	Surface area [mm^2]	Feret's diameter [mm]	Perimeter [mm]		Surfach area [mm^2]	Feret's diameter [mm]	Perimetert [mm]
mean value	2,333	1,553	5,244	mean value	6,649	2,814	9,743
standard deviation	2,094	0,748	2,575	standard deviation	3,46	0,74	2,707
standard error	0,048	0,017	0,059	standard error	0,077	0,017	0,06
95% confidence interval,	0,094	0,034	0,116	95% confidence interval,	0,151	0,032	0,118
99% confidence interval,	0,124	0,044	0,152	99% confidence interval,	0,199	0,043	0,156
measurements number	1901	1901	1901	measurements number	2008	2008	2008
Min.	0,062	0,282	0,852	Min.	0,284	0,601	1,939
Max.	15,682	4,469	15,347	Max.	29,114	6,088	22,441

Tab. 3. Results for the „B" sector

Tab. 3. Wyniki pomiarów dla celi pomiarowej „B" komory flotacyjnej

Section„B"							
Q = 24 dm^3/h, ω = 1000 rpm				Q = 240 dm^3/h, ω = 1000 rpm			
	Surface area [mm^2]	Feret's diameter [mm]	Perimeter [mm]		Surfach area [mm^2]	Feret's diameter [mm]	Perimeter [mm]
mean value	2,479	1,673	5,645	mean value	5,976	2,656	9,122
standard deviation	1,924	0,598	2,13	standard deviation	3,317	0,746	2,753
standard error	0,066	0,02	0,073	standard error	0,088	0,02	0,073
95% confidence interval,	0,129	0,04	0,143	95% confidence interval,	0,174	0,039	0,144
99% confidence interval,	0,169	0,053	0,187	99% confidence interval,	0,228	0,051	0,189
measurements number	860	860	860	measurements number	1406	1406	1406
Min.	0,176	0,474	1,503	Min.	0,464	0,768	2,542
Max.	14,332	4,272	15,126	Max.	20,82	5,149	22,516

Tab. 4. Results for the „C" sector

Tab. 4. Wyniki pomiarów dla celi pomiarowej „C" komory flotacyjnej

Section „C"							
Q = 24 dm^3/h, ω = 1000 rpm				Q = 240 dm^3/h, ω = 1000 rpm			
	Surface area [mm^2]	Feret's diameter [mm]	Perimeter [mm]		PSurface area [mm^2]	Feret's diameter [mm]	Perimeter [mm]
mean value	3,251	1,844	6,186	mean value	8,978	3,268	11,265
standard deviation	3,03	0,846	2,932	standard deviation	4,472	0,867	3,386
standard error	0,102	0,028	0,098	standard error	0,126	0,024	0,095
95% confidence interval,	0,199	0,056	0,193	95% confidence interval,	0,247	0,048	0,187
99% confidence interval,	0,262	0,073	0,254	99% confidence interval,	0,325	0,063	0,246
measurements number	890	890	890	measurements number	1262	1262	1262
Min.	0,125	0,398	1,302	Min.	0,775	0,993	3,228
Max.	17,806	4,761	16,041	Max.	31,481	6,331	52,095

The air bubble population, generated in the section 0, for the flow rate 24 dm^3/h is as much as twice larger than for increased aeration of the flotation chamber. Bubble sizes are small and their average size is 1.318 mm^2, Feret's diameter is equal to 1 mm, while the average circumference of the bulb equals 3.341 mm. The ten times larger gas flow at simultaneous increase of the rotor speed, caused in reduction of the air bubble population of more than a half, together with the increase of average values of the surface area, Feret's diameter and circumference of bubbles, which eqal respectively: 5.03 mm^2, 2.303 mm and 8.256 mm. For the other sections, the measurements were carried out at fixed rotor speed (1000 rpm) and for two levels of air flow rate: minimum - 24 dm^3/h and the maximum - 240 dm^3/h.

In the section A, regardless the operating parameters of the flotation machine, the amount of generated air bubbles were similar. The differences can be seen in the calculated values of the average area of the air bubbles generated at the minimum flow rate of 24 dm^3/h, which equals 2.333 mm^2, while the maximum flow rate is equal to 6.649 mm2, that

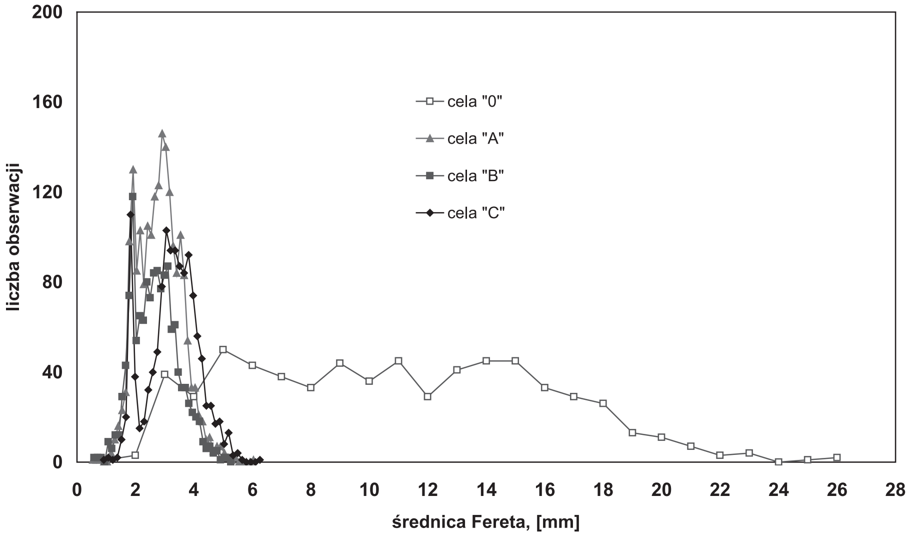


Fig. 4. Value changes of bubbles Feret's diameter for air flow 240 dm^3/h

Rys. 4. Zmiany wartości średnicy Fereta pęcherzyków powietrza dla przepływu gazu 240 dm^3/h

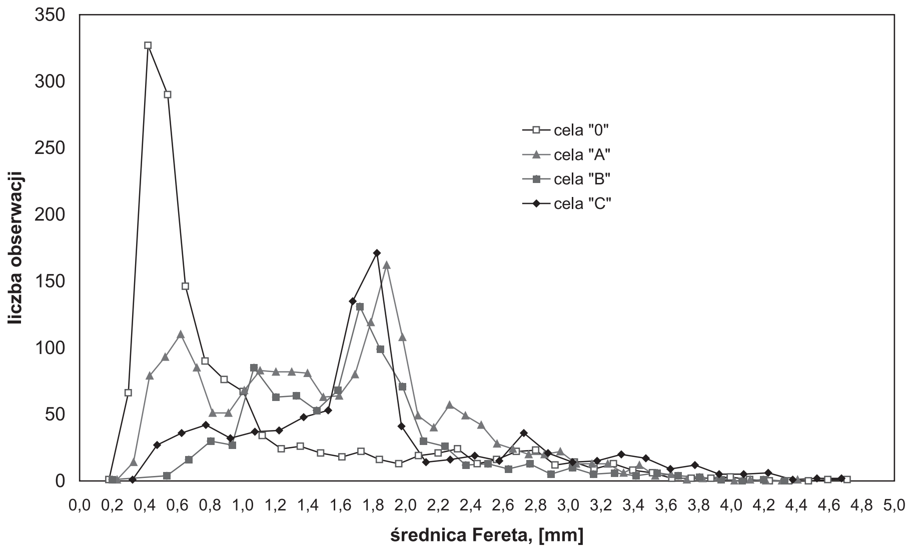


Fig. 5. Value changes of bubbles Feret's diameter for air flow - 24 dm^3/h

Rys. 5. Zmiany wartości średnicy Fereta pęcherzyków powietrza dla przepływu gazu 24 dm^3/h isthree times larger. With an increase in air flow rate, the average value of Feret's diameter and circumference of air bubbles, have also increased (Table 2).

Analyzing the results for Section B it can be seen that the values, calculated for the bubbles generated at maximum flow rate are approximately two times greater than the values for flow rate 24 dm^3/h. It was also confirmed by a significant difference in numbers of bubbles in the stream. Significant discrepancies can be seen in minimum and maximum values of the air bubbles generated at the different aeration of flotation chamber: bubble surface at minimal aeration equals 0.176 mm, while for maximum aeration the minimum bubble surface is 0.454 mm. A similar case occurs in both the minimum and maximum values Feret's diameter and circumference of the bubble.

In section C, similarly as for the results obtained for section B, it can be seen that with the lower aeration, the lower generation of air bubbles with small values Feret's diameter area and circumference, is observed. Since the flotation machine working chamber has a square cross-section, divided on 16 symmetric parts (Fig.1.), it is possible to assess the impact of the measuring section position on the obtained results. Results of measurements show that under the same operating parameters of flotation machine, bubbles are larger and more numerous in the sections, which are located in the corner of the chamber. This is confirmed by the analysis of the results obtained for Sections B and C, which have comparable population and size of air bubbles. In the section B at the air flow rate 24 dm^3/h and 1000 rpm of rotor speed, average values are as follow: 2,479 mm^2 of surface area, Feret's diameter of 1,673 mm and a circumference of 5,64 5mm, while for Section C average dimensions are larger and equal: surface area 3.251mm^2, Feret's diameter1.844 mm and circumference of bubble: 6.186 mm. In an analogous manner, values obtained for maximum air flow rate, are distributed.

In Figures 4 and 5 the change in the size of Feret's diameter for analyzed series of individual sections of the flotation chamber, were presented. At fixed conditions of maximum aeration of chamber and maximum rotation of the rotor, the most bubbles reach a size from the range of 1.8-4.0 mm, which means that the generated bubbles are stable and have a stable shape close to a sphere. The largest range of at a small population was obtained for bubbles in section “0”, which means that this sector of the working chamber was supplied by small portion of poorly dispersed air. The results obtained for minimum air flow rate at fixed speed of the rotor indicate on a dispersions of two separated groups of population versus the surface area of bubbles, which can be observed on the graph as a peak. A significant number of micro-bubbles, with Feret's diameter in the range of 0.2-0.8 mm and half less of bubbles with Feret diameter of 1.5 to 2,1 mm, were generated.

It should be noted that for the stream of bubbles analyzed in section 0, and A, the number of observations was large (360 and 905, respectively), which means that just this number of bubbles was of this dimension. The above results show that in the given measurement conditions, many microbubbles is generated, which potentially do not have a chance to create a permanent flotation aggregates, but may be subject to a process of coalescence.

Summary and conclusion

1. Increasing the rotational speed of rotor results in reduction of air bubbles size, but at the same time increases their number.
2. Increasing the air flow rate has an effect of increasing the size of bubbles at the fixed speed of the rotor.
3. Aeration influences the shape of the air bubbles. In the case of lower aeration the bubbles are of a smaller size, but they also have a more spherical shape, and with greater aeration ratio their dimensions increase, but their shape is more irregular.

The presented experimental technique and measurement methods are an excellent tool to study the properties of the gas phase during the flotation process. It also can be used for analysis and simulations of other phenomena that take place in a flotation cell with mechanical agitation, such as the study of the gas flow streams for different construction solutions.

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Literatura - References

1. *Brożek M., Młynarczykowska A., Turno A., 2003. The relationships between deterministic and stochastic models of flotation. Archives of Mining Sciences, 48, 3, p. 299–314.*
2. *Brożek M., Młynarczykowska A., Turno A., 2003. The distribution of the flotation rate constatnt in a sample of the to-component raw material. Archives of Mining Sciences, 48, 3, p. 521–532.*
3. *Brożek M., Młynarczykowska A., 2005 Distribution of adhesion rate constant in the coal sample. Acta Metallurgica Slovaca, 10, 1, p. 127–135.*
4. *Brożek M., Młynarczykowska A., 2006 Application of the stochastic model for analysis of flotation kinetics with coal as an example. Physicochemical Problems of Mineral Processing, 40, p. 31–44.*
5. *Brożek M., 2010. Probability of particle-bubble collision in pneumo-mechanical flotation cell. Archives of Metallurgy and Materials, 55, 1, p. 293–304.*
6. *Brożek M., Młynarczykowska A., 2012. The distribution of the flotation rate constatnt in a sample of the to-component raw material. Archives of Mining Sciences, 57, 3, p. 729–740.*
7. *Nyrek A., Oleksik K., 2014. . Determination of the size of air bubbles in steady state conditions using a flotation machine image visualization techniques. (Dissertation Engineering)*
8. *Saramak D., Mlynarczykowska A., Krawczykowska A., 2012. Influence of a high-pressure comminution technology on effectiveness of copper ore flotation processes. Archives of Metallurgy and Materials, 59, no. 3, p. 731–740.*
9. *Malysa K., Cymabalisty Ng S., Czarnecki J., Masliayah J., 1999a. A metod of vizualization and characterisation of aggregates flow on inside a separation. Part 2. Composition of bitumen air aggregates. International Journal of Mineral Processing, 55, p. 189–202.*
10. *Woodburn E.T., King R.P., Colborn R.P., 1971. The effect of particle size distribution on the performance of a phosphate flotation process. Metallurgical and Materials Transactions B, 2, p. 3163–3174.*
11. *Varbanov R., Forssberg E., Hallin M., 1993. On the modelling of the flotation process. International Journal of Mineral Processing, 37, p. 27–43.*
12. *Yoon R.H., Mao L., 1996. Application of extended DLVO theory, IV. Derivation of flotation rate equation from first principles. Journal of Colloid and Interface Science 181, 613–626.*
13. *Yoon R.H., Luttrell G.H., 1989. The effect of bubble size on fine particle flotation. Mineral Processing and Extractive Metallurgy Review 5, p. 101–122, p. 751–756.*

Analiza fazy gazu w procesie flotacji. Część I: Eksperymentalne określenie ilości pęcherzyków powietrza we flotowniku pneumatyczno-mechanicznym

Problem mineralizacji pęcherzyków, będący najważniejszym etapem flotacji i uzyskujący wymierne efekty widoczne przez wydajność koncentratu, jest kluczowym tematem badań z praktycznego punktu widzenia. Większość publikacji na ten temat nawiązuje do ogólnych badań sprawdzających wpływ wybranych cech (rozmiar pęcherzyków, stosunek pokrycia cząsteczek z odczynnikami flotacyjnymi, hydrofobiczne właściwości cząsteczek) na wyniki flotacji. Decydującą rolę w procesie odgrywają właściwości rozpraszające w fazie gazu, które są głównym czynnikiem wpływającym na wyniki wzbogacania procesu, definiowanie warunków operacyjnych maszyny flotacyjnej oraz na stopień napowietrzenia pulpy flotacyjnej. Artykuł przedstawia wyniki określające wpływ wybranych fizycznych parametrów na rozmiar pęcherzyków powietrza, które tworzą się we włączonej komorze pneumatyczno-mechanicznego typu maszyny flotacyjnej. Zmienne, które bezpośrednio powiązane są z wielkością i sposobem dyspersji pęcherzykow powietrza, były wartościami podzielonymi na ilość powietrza oraz liczbę obrotów w wirniku przy określonych warunkach fizyko-chemicznych. Parametry zostały tak określone, aby dobrze opisać właściwości dyspersji powietrza w dwóch fazach płynu – gazu. Badania przeprowadzono przy pomocy specjalnego urządzenia z użyciem technik nagrywania wideo oraz analizą obrazu.

Słowa kluczowe: flotacja, dyspersja pęcherzyków, rozkład wielkości pęcherzyków