Metallurgical performance of column and mechanical flotation as a rougher circuit in sphalerite ore flotation with %solid and frother dose variation

S Oediyani¹,³*, A Muttaqin¹,²,³, D Haryono¹,³, R F Suwandana¹,³

¹Laboratorium Material Maju dan Tomografi, Universitas Sultan Ageng Tirtayasa, Gedung Center of Excellence (CoE) 2 Lt. 4, Jl. Jenderal Sudirman Km. 3 Cilegon, Banten, Indonesia 42435
²Pusat Penelitian dan Pengembangan Teknologi Mineral dan Batubara, Jl. Jend. Sudirman No.623, Wr. Muncang, Kec. Bandung Kulon, Kota Bandung, Jawa Barat 40211
³Jurusan Teknik Metalurgi, Fakultas Teknik, Universitas Sultan Ageng Tirtayasa, Jl. Jenderal Sudirman Km. 3 Cilegon, Banten, Indonesia 42435

*Email: s_oediyani@untirta.ac.id

Abstract. Column flotation is commonly used in cleaner circuits at the ore beneficiation industry. However, this research wants to apply the column to the rougher circuit as an alternative to the mechanical flotation due to its energy efficiency which is 80% more efficient. This research was conducted using column and mechanical flotation cells to observe their metallurgical performance as a rougher circuit. The feed is sphalerite ore at size -140+230# with variables of % solid 7.5; 10; 12.5; 15 and doses of frother 20; 30; 40; and 50 ppm. Reagents used include OrePrep, Potassium Amyl Xanthate 500 g/ton, copper sulfate 500 g/ton, and soda ash 500 g/ton. Flotation process is carried out 5 minutes for conditioning and 10 minutes for aeration. The results obtained the recovery value and grade. The results from the experiment, it can be concluded that the recovery obtained by mechanical is superior, and for column flotation grade is superior. In the variation of solid percent and frother dose, recovery increases to the maximum point and then decreases because no significant effect after maximum point. The recommended variables for mechanical flotation are 12.5% solid and 50 ppm frother dose, because the recovery worth 75.462%. For column flotation, 15% and 40 ppm, obtain the highest recovery 53.439%.

1. Introduction

Sphalerite (ZnS) is one of the minerals belonging to sulfide minerals with one of its properties, which is naturally having relatively high hydrophobicity. Sphalerite is also usually naturally bound to impurities that are classified as strong hydrophilic, so that with this difference in hydrophobicity the process of separation is suitable for sphalerite ore by using flotation (1). Flotation is a process of mineral separation based on differences in the ability of adhesion of particles to air bubbles. This process is complex because it includes interactions between mineral particles, air bubbles, reagents, water and the flotation machine so that the process of floating mineral particles occurs. Based on the regulation of Energy and Mineral Resources Ministry of Indonesia no. 5 of 2017 states that the levels
for zinc concentrate to be exported have a value of ≥ 51%. For this reason, it is necessary to beneficiate the sphalerite ore in order to meet these requirements.

Flotation in the mineral processing industry is a process of concentration, and usually flotation within the scope of the industry is not only carried out in one stage of the process but rather several stages of the process which have their respective functions to obtain the targeted concentrate levels. Usually called a flotation circuit which includes 3 stages of the process namely rougher, cleaner, and scavenger. The rougher circuit with its input in the form of fresh feed or ore has a function to maximize recovery, the cleaner circuit with concentrated input from the rougher circuit has a function to get the target grades, and the scavenger circuit with the tailings input from the two previous circuits has a function to maximize gain valuable minerals that are still left in the tailings. Initially each of the circuits used a mechanical flotation cell system, but in a yahyaei research in 2006 it tried to replace mechanical flotation with column flotation on a cleaner circuit, because mechanical flotation has several disadvantages that affect process efficiency, namely high energy consumption, high operating costs, and difficult footprints and controls. After the application of column flotation on the cleaner circuit in yahyaei research, it was found that energy consumption decreased by 83%, operating costs by 76%, and separation efficiency increased by 7% (2).

Industrial-scale flotation columns are generally cylindrical with a height of 9-14 m and a diameter not exceed than 2 m. Ore in the form of slurry is feed from the top of column (about 2/3 the height of the column), flowing countercurrently with air bubbles produced by the sparger. Hydrophobic particles will attach to the bubbles, and move up to the top of column and form a froth zone. Hydrophilic particles will be left in the water and removed as tailings. The interaction between particles and air bubbles takes place in a zone called the collection zone. In addition, column cells have wash water to eliminate entrainment particles that carry over into the froth zone. Over the last few decades the concept of column cells has slowly been recognized (3). In the flotation circuit, the rougher circuit is used to obtain as many valuable minerals as possible and a cleaner circuit to increase grades of valuable minerals in the concentrate. Column cells are the most suitable cells for cleaner circuits, because their high selectivity results in higher levels of acquisition (4). Another advantage of column flotation is that it can produce thicker and more stable bubbles formation, so that a relatively higher recovery is obtained because it uses a taller cell and a smaller surface area than the column compared to conventional flotation cells (5). Fuerstenau et al., Considered column cells as an advantage for some reasons, namely column cells can provide better separation because column cells can obtain better recovery without reducing grades, require less capital and also lower operational costs than mechanical cells. In addition, column cells are also more adaptable to automatic control (6). Jena et al., stated that column cells can reduce amount of stages in operations and able to handle finer feeds (7). The number of collectors needed in a column cell is lower than a mechanical cell, and its construction and design is also simpler. The basic difference between column flotation and mechanical flotation is that column flotation does not have an agitator. Air bubbles in the column flotation are generated from the air flow through the sparger (1). Meanwhile, the mechanical flotation cell mechanism uses an agitator to produce air bubbles. In flotation circuits, mechanical flotation is generally used in rougher circuits because the mineral floatation mechanism is valuable in finding a high recovery, correspond with the function of the rougher circuit. However, mechanical flotation has several deficiencies, one of which is in terms of energy consumption. Mechanical cells consume 100-200 watts/volume. Meanwhile, column cells consume 20-30 watts/volume, or about 80% more efficient (8). These deficiencies led to the idea of applying column flotation cells to the rougher circuit as an alternative to mechanical flotation cells. So, by applying column cells to replace mechanical cells commonly used in rougher circuits, as well as the success of column cells applied to cleaner circuits in yahyaei research. Therefore, the use of column cells in the rougher circuit has the potential to increase the efficiency of the metallurgical performance and reduce production costs.

In previous research, column flotation cells were applied to a cleaner circuit and monitoring was carried out using an electrical capacitance volume tomography (ECVT) in the collection zone area to provide better results in imaging objects. However, this research is based on the application of column
flotation in the rougher circuit with the aim of getting better %recovery than conventional flotation cells in the rougher circuit, so, in the future column flotation can be applied to the rougher circuit then can be monitored using ECVT. To do this research, mechanical or conventional flotation is needed as a comparison of column flotation, because basically mechanical flotation is used in the rougher circuit.

2. Experimental Methods

2.1. Sample Preparation
In this preparation stage sphalerite ore is prepared so the parameters are suitable to be carried out the flotation process, the first to do is comminution with the grinding method using a rod mill, in order to smooth the particle size in order to increase the degree of liberation as in Figure 1. after that do the sieving using a multilevel screen with a size of 100; 140; 230 # until you get the size -140+230#. Oversize +100# will be crushed again. With the best grinding parameters, 25 steel balls, 40 minutes grinding time, and 2 kg feeds succeeded in getting the desired fraction with the most mass of 550 grams from 2 kg feeds. After that, do washing and drying to reduce the slime contained in the ore. Finally, in the preparation phase, a coning-quartering method was used for all flotation feeds and samples for the initial characteristics of XRD and XRF.

![Figure 1. (a) Rodmill (b) Sieving.](image1)

2.2. Flotation Process Rougher Circuit
The main process stage wherein applying column flotation and mechanical flotation on the rougher circuit such as Figure 2. to compare metallurgical performance with the same scope and the same conditions, namely 5 minutes conditioning; variation of oreprep dose 20; 30; 40; and 50 ppm; variation of %solid 7.5; 10; 12.5; and 15%; PAX, Na2CO3 and CuSO4 500 ppm; aeration time of 10 minutes. Different parameters are the air flow rate at the 2.5 L/minute on column flotation and 1200 rpm agitator speed at the mechanical flotation. The products are in the form of concentrates and tailings and then carried out drying and sampling again for the final characteristics with XRF.

![Figure 2. (a) Mechanical flotation (b) Column flotation.](image2)

3. Result and Discussion
Before the flotation process was carried out, the sphalerite and quartz samples were characterized to determine the compounds and elemental content respectively using the X-ray diffractometer (XRD)
and X-ray fluorescence (XRF) methods. Data from XRD testing are compounds contained in the ore. The data is in the form of graphs with certain peaks according to the compounds characterized. The XRD reading method uses PANalytical X’Pert High Score Plus software. The top pattern of the sphalerite sample is shown in Figure 3. From the picture, it appears that the dominant mineral is sphalerite (ZnS) with galena (PbS), pyrite (FeS2), and quartz (SiO2) associations. XRD data obtained prove that the sample used is true sphalerite ore, because sphalerite generally in nature is often found to bind to FeS2, PbS, CuS, and SiO2 in the deposit. (Wills, 2016).

The elements contained in the ore are analyzed using Portable X-Ray Fluorescence Oxford X-MET 5100. XRF analysis is used as quantitative data to calculate %recovery. In the sample raw material of sphalerite ore, the Zn content was 25.78% and the S content was 10.95%. In the sphalerite sample there are also other dominant elements such as Fe of 15.06%, Pb of 7.67%, and Si of 27.83%, which can be seen in table 1.

![Figure 3. Results of XRD analysis of sphalerite.](image)

Table 1. XRF feed analysis results

| Elements | Zn (%) | S (%) | Si (%) | Fe (%) | Al (%) | Pb (%) | Cu (%) | Mg (%) | Lain |
|----------|--------|-------|--------|--------|--------|--------|--------|--------|------|
| Zn       | 25.78  | 10.9  | 27.8   | 15.06  | 2.3    | 7.67   | 1.35   | 5.77   | 3.32 |

3.1. Preliminary Experiments

Preliminary experiments on column flotation for three phases namely, bubbles, water, and sphalerite were carried out within 5 minutes for the conditioning phase and 10 minutes for the aeration stage using particle size -230+325#, the flow rate is 2.5 l/min, variations of frother dose 10; 20; 30; 40 & 50 ppm, and 7.5 %solid. This is done to find out whether the column flotation process is going well, and to find out whether column flotation can separate valuable minerals from their impurities. The results obtained from the three phase experiment are shown in Figure 4.
It can be concluded from Figure 4b that the graph of the three-phase trial results proves that column flotation can separate valuable minerals and mineral gangue, as evidenced by the relatively high %recovery. Not only from the graph, from Figure 5a in the process of technical operation also shows that the phenomenon of bubble formation by frother can occur. The phenomenon that occurs in the froth zone, namely when valuable minerals are carried by bubbles and are held in the froth zone before falling into the concentrate outlet can be seen in Figure 4a.

3.2. Effect of Frother Dose and Solid Percent on Recovery and Grade of Mechanical Flotation

Recovery, which is one of the metallurgical performance parameters used as main data for comparison of mechanical flotation and column flotation processes. Frother doses are varied at 20, 30, 40, and 50 ppm. The flotation process (aeration) using a D-12 denver mechanical flotation cell lasts 10 minutes using an agitator rotation speed at 1200 rpm. Flotation feed in the form of 1.2-liter slurry with a variation of %solids 7.5; 10; 12.5; and 15%. Reagents other than frother, i.e. pH regulators (Na₂CO₃), activators (CuSO₄), and collectors potassium amyl xanthate (PAX) are added at a dose of 500 g/ton of feed at the conditioning stage. Conditioning duration is 5 minutes. Na₂CO₃ (soda ash) serves to maintain the slurry alkalinity in the range of 8-13 so that the xanthate collector is relatively stable (9). Copper ions from Cu²⁺ replace zinc ions on the surface of the sphalerite to optimize the performance of xanthate, producing metal-xanthate that is stable and difficult to dissolve. When compared with other types of xanthate, potassium amyl xanthate (PAX) provides a greater hydrophobicity effect because it has a longer carbon chain (C5) (1). Recovery and grade as a function of frother dose are shown in Figure 5 and the function of %solid is shown in Figure 6.
Figure 5 shows the maximum conditions achieved at a frother dose of 40 ppm, and there are some that have not yet found the maximum conditions, then the tendency decreases with increasing frother doses according to the theory (10). This phenomenon is caused by critical coalescence concentration (ccc) in the frother. CCC is the maximum point when the frother can no longer reduce the bubble size due to coalescence. When it reaches the ccc point, the frother no longer has a significant effect which causes coalescence or the phenomenon of small-sized bubbles unite into large-sized bubbles that are more easily collapse so that recovery decreases. The same thing happens with the addition of %solid when the addition no longer significantly influences after reaching its maximum condition, there is a maximum point that is at 12.5% solid percent. In Figure 6 that happens after the maximum conditions are achieved is the bubble overloading phenomenon shown in Figure 7 which causes recovery to decrease or no longer have a significant effect, with an increase in solid percentage, the number of particles carried and attached to the bubble also increases as much. Therefore, it causes the bubble overloading phenomenon so that the particles fall back and recovery decreases (11).

**Figure 7.** Bubble overloading phenomenon (12).

All of the variable combinations, the highest recovery was achieved at a %solid condition of 12.5% and the highest dose (50 ppm) resulted in a recovery of 75.462%. For the highest Zn grade obtained from the condition of 12.5 %solid and 30 ppm frother dose that is, 40.2%. In this case the Zn content still cannot meet the ESDM PERMEN requirement of ≥ 51%. Therefore, it is necessary to do further stage, that is circuit cleaner to reach the desired grade.

### 3.3. Effect of Frother Dose and Solid Percent on Recovery and Grade of Column Flotation

One of the objectives of this study is to determine the maximum effect of the flotation process variables in increasing recovery and grades of sphalerite ore. The same is done in mechanical flotation also done in the column flotation process with a solid percent variation of 7.5; 10; 12.5; and 15% and the variation of the frother dose are 20, 30, 40, and 50 ppm, with a slurry volume of 1 L and volume in the column cell is 1.7 L, and a constant air flow rate for each variable is 2.5 L/min. The products in the form of concentrates and tailings are produced from a combination of these 2 variables and are used as the main data for metallurgical performance calculations and compared with mechanical flotation. The function of frother dosage and percent solid against metallurgical performance is shown at the graphs in Figures 8 and 9. The increase in the pulp density will result in the decrease of recovery. It is caused by the fact that the increase in the pulp density results in the growing number of particles in the pulp and consequently in the growing resistance when the bubble-particle aggregates travel upwards to the froth. Under such conditions detachment of particles from the bubbles is easier (13). This may be also due to the reduction in selectivity due to increasing pulp density which increased non selective solids entrainment and bubbles-particles detachments(13). The most selective results and the lowest entrainment were obtained at the lowest solid concentration due to lower amount of water that was transferred to the froth (14).
Based on Figure 8, the higher addition of the frother dose, the recovery value tends to increase or the acquisition obtained is higher, and there is also a maximum value of the addition of the frother dose. At 7.5 and 12.5 % solids from the graph do not yet have a maximum dose, for 15% solids have a maximum dose is 40 ppm, for 10% solids have a maximum dose is 30 ppm and more than that have a significant tendency to reduce the recovery value. After getting the maximum value of addition the dose no longer have a significant increase. This is due to the saturated concentration of frother which causes the addition of the dose does not greatly affect the formation and reduction of bubble size and another frother influences.

From all of combinations of variables, the highest recovery was achieved in the condition of 15 % solid and 40 ppm frother dose resulted in recovery of 53.439% with 37.1% Zn content. For the highest Zn levels obtained from the condition of 15% solid and 30 ppm frother dose that is, 39.6%. The grade obtained has a tendency to be inversely proportional to the recovery value, when the recovery value is high, it can be seen from the graph that the grade value has decreased. Factors that cause high or low Zn levels, one of which is the thickness of the froth zone, can be seen in Figure 10.

The recovery by entrainment decreases with the increased dilution of the pulp and the froth height, and increases with increased agitation, rate of aeration, and froth stability. Also, it decreases with increasing particle size and its density, and depends on the particle shape, with lamellar shape particles being more easily entrained(15). The thick froth zone causes the residence time of entrainment particles to be longer in the froth zone and allows wash water to be removed before entrainment particle is carried to the outlet concentrate because entrainment particles that like water will be attracted to the flow of wash water that falls from the top side of column.

The effect of solid percent on column flotation, which is along with the addition of values will increase recovery to the maximum point and after that no longer has a significant effect. That is because when the percentage of solids gets higher the amount of minerals in slurry will increase, and
small-sized air bubbles cannot float valuable minerals onto the froth surface because they are too heavy or have exceeded bubble carrying capacity which causes bubble overloading (12). In addition, the cause of the decrease after passing the maximum point at 15 %solid is more fast the slurry viscosity, the bubble rise velocity decreases. This is caused by, the more particles are carried and the longer the aggregate is raised up to reach the froth zone, causing the flotation kinetics to be longer or residence time in the cell much longer. This phenomenon causes the process to be stopped before all valuable minerals are lifted to the concentrate because the aeration time which is only 10 minutes is not enough to lift all the valuable particles, it may take more than 10 minutes to be able to lift all the valuable minerals thus reducing what's left in the tailings. This phenomenon is characterized by the darkness of the column flotation collection zone in the 10th minute. A high percent solid value can also make the flotation process difficult or even impossible.

3.4. Comparison of Metallurgy Performance of Column Flotation and Mechanical Flotation

The purpose of this research is to determine whether effective that column flotation is applied to the rougher circuit by looking at metallurgical performance when compared to mechanical flotation that has been approve commonly used on rougher circuits. The best tendency of each flotation cell for recovery and grade compared to the results is shown in Figures 11 and 12.

![Figure 11](image1.png) ![Figure 12](image2.png)

**Figure 11.** Graph of comparison column flotation with mechanical flotation with % solid effect on recovery and grade.  **Figure 12.** Graph of comparison column flotation with mechanical flotation with the effect of frother dose on recovery and grade.

Based on Figures 11 and 12 it can be concluded that the acquisition obtained is higher mechanical flotation than column flotation. Meanwhile, the resulting grade is superior to column flotation. It can be seen in the graph that the tendency obtained is in accordance with the previous research literature namely research (16) that the % grade has a tendency that is inversely proportional to the % recovery in the effect of the percent solid added. It can be concluded that column flotation is still not in accordance with the function of the rougher circuit which seeks the highest grade because it is still not better to mechanical flotation. The cause of column flotation cells is still not getting high recovery, the main cause is indeed the flotation cell mechanism, namely the column flotation system is more selective for lifting valuable minerals which makes the mass of concentrate is not too high and the mechanism depends on the thickness of the froth zone and the performance of wash water which cause %grade on column flotation is higher (17). Mechanical flotation can get high recovery, because mechanical flotation cells are more suitable at a high ratio of %solid due to good particle dispersion and perfect mixing due to conditions created by agitators (18). In column flotation it does not have agitator which makes it less superior in high %solid conditions less superior than mechanical flotation, but in low %solid with 7.5 and 10 %solid column flotation some recovery values are superior compared to mechanical flotation.

The cause of mechanical flotation has a high %recovery due to the influence of the zones formed and the cell mechanism that supports it to obtain high grades and is still effective at high viscosity of
slurry. The turbulent zone in mechanical flotation with its agitator system causes a large amount of valuable particle mass to be lifted thus increasing %recovery because it can circulate high %solid under suspension but not too selective which causes many impurities to be carried to the concentrate (18). In contrast to column flotation where fluid flow is very influential on the increase in recovery, along with increasing flow rate to certain conditions a flow transition phenomenon from laminar (bubbly flow regime) to turbulent (churn-turbulent regime) (3), so that at certain conditions the flow rate value needs to be maintained so that the separation process occurs optimally. The increase in recovery along with the laminar flow can be explained according to the statement C.M. Goodall that in laminar conditions the bubble size is relatively smaller. The small bubble size causes the possibility of particles to fall (detachment) to be lower. This is because bubbles become more stable to be able to rise to the surface carrying particles so that recovery increases. Unlike the case when turbulent flow, it will cause bubbles to become unstable. This bubble instability results in the possibility of a bubble coalescence phenomenon and increasing bubble size, so that many particles undergo detachment and recovery decrease (19). Thus, the churn-turbulent flow regime is undesirable in processes that target high recovery. But in the process of column flotation with a flow rate of 2.5 L/min, the gas holdup formed still shows the churn-turbulent flow regime even though it is not too large. Maybe this is also one of the causes of column flotation recovery not being able to get the highest results (20).

4. Conclusion

Based on the comparative research of the metallurgical flotation performance that has been done, it can be concluded that for column flotation, solid percent affects the recovery and grade. As the solid percent value is added, recovery increases to the maximum point. After reaching the maximum point, adding value no longer has a significant effect. The maximum condition occurs in different percent solids, namely 10 and 12.5%. However, when the percentage of solid is too large at 15%, the addition of value no longer has a significant effect on condition 20; 30; and 50 ppm. But in the condition of a 40 ppm frother dose, the maximum point cannot be found. Meanwhile, the grade tendency will decrease after passing the 10% point of percent solid. For variable dose of the frother also affects the recovery value and grade, with the same tendency as the percent solid. The maximum condition occurs at frother doses of 30 and 40 ppm. When the frother dose is 50 ppm it will reduce the recovery value because it no longer has a significant effect. At the solid percent conditions of 7.5 and 12.5% the maximum point has not been found. The recommended variable to use based on this experiment is 15% solid under 40 ppm frother dose conditions because it gets the highest recovery value of 53.439%.

For mechanical flotation, solid percent affects the recovery and grade, which is same as the percent solid on column flotation. The maximum condition occurs at 12.5% solid, both at condition 20; 30; and 50 ppm. But in the condition of a 40 ppm frother dose, the maximum point cannot be found. Meanwhile, the grade tendency decreases if the solid percent is too high, such as 12.5 and 15% solid. The recommended variable to use based on this experiment with the condition of a 40 ppm frother dose and 12.5% solid has the highest recovery value is 75.462%. Then, for the dose of the frother also affects the recovery value and grade. The effect is the same as solid percent. The maximum condition occurs at 40 ppm frother dose after that will reduce the recovery value in several percent solid conditions, but in the 12.5% solid condition the maximum point cannot be found. Meanwhile, the grade tendency decreases at high frother doses such as 50 ppm.

The metallurgical performance comparison of the two flotation cells is divided into recovery and grade, for the recovery values obtained from the graph are superior to mechanical flotation. Whereas, the grade is superior to column flotation, which shows that the rougher circuit which functions to find recovery as high as possible is still mechanical flotation, which indicates less effective column flotation if applied to the rougher circuit. However, if in the search for high grades of the function of the cleaner circuit, column flotation is more effective if used on that circuit.
Acknowledgement
This research is granted by Ministry of Research and Technology of Indonesia. Special gratitude also appreciated to Advanced Materials and Tomography Laboratory of Sultan Ageng Tirtayasa University and Puslitbang TekMIRA which have provided the necessities during the research process.

References
1. Wills BA, Finch JA Chapter 12 - Froth Flotation In: Wills BA, Finch JA, editors Wills’ Mineral Processing Technology (Eighth Edition) Eighth Edi Boston: Butterworth-Heinemann; 2016 p. 265–380.
2. Yahyaei M, Banisi S, and Javani H Replacing mechanical flotation cells by a flotation column at the pilot plant of the Sarcheshmeh copper mine. Sep Sci Technol 41 3609–3617.
3. Finch JA, Dobby GS Column flotation 1990
4. Hurdeyal R A Comparison between Column and Mechanical Cell Performance in Platinum Flotation In fulfilment of the degree Masters in Engineering 2012
5. Smith RJB. Experimental Studies on Column Flotation Cell. Int J ChemTech Res. 2012;4(3):1198–202.
6. Fuerstenau MC, Han KN. Principles of Mineral Processing. Society for Mining, Metallurgy, and Exploration, Inc. 2003. 1-586 p.
7. Jena MS, Biswal SK, Das SP, Reddy PSR. Comparative study of the performance of conventional and column flotation when treating coking coal fines. Fuel Process Technol [Internet]. 2008;89(12):1409–15. Available from: http://dx.doi.org/10.1016/j.fuproc.2008.06.012
8. Wang LK, Shammas NK, Selke WA, Aulenbach DB Flotation Technology Humana Press 2011 (Handbook of Environmental Engineering)
9. Roy K-M Xanthates In: Ullmann’s Encyclopedia of Industrial Chemistry Weinheim Germany: Wiley-VCH Verlag GmbH & Co. KGaA; 2000.
10. Finch JA, Nesset JE, Acuña C. Role of frother on bubble production and behaviour in flotation. 2008;21:949–57.
11. Luo X, Feng B, Wong C, Miao J, Ma B, Zhou H. The critical importance of pulp concentration on the flotation of galena from a low grade lead – zinc ore. Integr Med Res [Internet]. 2015;5(2):131–5. Available from: http://dx.doi.org/10.1016/j.jimr.2015.10.002
12. Uribe-Salas A, de Lira-Gómez P, Pérez-Garibay R, Nava-Alonso F, Magallanes-Hernández L, Lara-Valenzuela C. Overloading of gas bubbles in column flotation of coarse particles and effect upon recovery. Int J Miner Process. 2003 Sep;71(1–4):167–78.
13. Amin R, Abdelkhaled MA, Ibrahim SS, Yehia A. Statistical Design of Column Flotation Parameters for Beneficiation of Egyptian Oil Shale Statistical Design of Column Flotation Parameters for Beneficiation of Egyptian Oil Shale. 2018;
14. Wei T, Peng Y, Vink S. SC reagents in stabilizing froth in coal flotation. Int J Miner Process [Internet]. 2016; Available from: http://dx.doi.org/10.1016/j.minpro.2016.01.005
15. Ore K. Kaolin Ore. 2017;1–13.
16. Stephani Y. Monitoring proses flotasi kolom pada bijih sphalerite menggunakan kamera dengan variasi persen solid dan laju alir udara terhadap recovery. 2018;
17. Massinaei M, Kolahdoozan M, Noaparast M, Oliazadeh M, Yianatos J, Shamsadini R, et al. Froth zone characterization of an industrial flotation column in rougher circuit. Miner Eng [Internet]. 2009;22(3):272–8. Available from: http://dx.doi.org/10.1016/j.mineng.2008.08.003
18. Al-Fariss TF, El-Nagdy KA, Abd El-Aleem FA, El-Midany AA. Column versus mechanical flotation for calcareous phosphate fines upgrading. Part Sci Technol. 2013 Sep;31(5):488–93.
19. Goodall CM, O’Connor CT Residence time distribution studies in a flotation column. Part 2: the relationship between solids residence time distribution and metallurgical performance. Int J Miner Process. 1992 Oct;36(3–4):219–28.
20. Yan X, Shi R, Xu Y, Wang A, Liu Y, Wang L, et al Bubble behaviors in a lab-scale cyclonic-static micro-bubble fl otation column 2016