Developments in Flotation Technology

Tülay TÜRK[1]*, Sultan GÖÇER[2], M. Kadir GÜNER[1],
Burakhan ERSOY[3], Enes KALYONCU[1], Gülay BULUT[1]

[1]*Istanbul Technical University, Faculty of Mines, Mineral Processing Engineering Department, 34469, Maslak, Istanbul, TURKEY*
[2]*Şişecam Glass Packaging, 16900, Yenişehir, Bursa, TURKEY*
[3]*Red Rock Minerals Mining Ltd. Şti., 06530, Çankaya, Ankara, TURKEY*
**Corresponding author email: turktu@itu.edu.tr*

A B S T R A C T

Flotation which has significant usage area in mineral processing is starting to gain a new role in a wide range of studies with technological improvements. Different mechanisms that are effective in flotation are influenced by many factors. Particle size, bubble size and water chemistry are some of the parameters which affects flotation recovery. As the days goes by, there is a need to float finer particles due to decreasing liberation size of the minerals. Moreover, bubble size needed to be optimized in order to float fine particles. Another crucial parameter which affects flotation is chemistry of water because of ions which are in water. In recent years, these parameters have become the most outstanding subjects of researches. Beside of these effective parameters in flotation processes, with technological developments and needs, flotation of rare earth minerals is a new area to be studied. In this context, new technological developments, their effects to flotation recovery and methods to enrich rare earth minerals by using flotation are investigated with the light of many studies.

Key words: *Flotation, Nano bubble, Water, Rare earth minerals, Flotation machines*

1. INTRODUCTION

Flotation is one of the commonly used methods in ore enrichment processes and has many application areas, and as the day goes by, the importance of flotation method is increasing due to the new needs. Over time, high grade mineral resources are transformed into low grade resources. Moreover, enrichment of fine particles formed by virtue of low grade ores can be perform with froth flotation more economically compared to other enrichment methods (Pattanaik and Venugopal, 2019). However, there is a need to float more complex and finer ores nowadays. In order to provide enrichment processes for these new type of ores, many researchers are studying on different aspects of flotation method.

One of the subjects of many studies is bubble size in flotation (Cho and Laskowski, 2002; Finch at al.,2008; Grau at al., 2005; Tao, 2005). Nanobubbles on flotation has become a popular topic of late. Besides bubble size as a parameter of flotation, another subject is water chemistry. Using fresh water or recycled water in flotation has an important effect in flotation recovery due to the ions that water consists. Many studies have been made about water chemistry and water re-use in flotation systems (Bıçak at al., 2012; Ikumapayi at al., 2012a; Ikumapayi at al., 2012b; Levay at al., 2001; Liu at al., 2013; Bulut and Yenial, 2016). On the scope of studies and developments, many valuable minerals came into consideration especially rare earth minerals. As a result of technologic improvement, beneficiation of Rare Earth Minerals has been gaining more importance. Nowadays Rare Earth Elements (REEs) are indispensable part of magnetic, phosphor, metal alloys, catalyst, ceramics, glass, polishing and defense systems industries. There are about 250 rare earth minerals in nature as carbonates, oxides, phosphates, silicates and halides. About 95% of the world rare earth resources occur in Bastnaesite, Monazite and Xenotime. Different methods are performed to beneficiate REE ores such as gravity and magnetic separation. In addition to above mentioned

methods, froth flotation has been gaining importance and academic studies have been increasing in this field. On the other hand, flotation machines have gained importance in the last 30 years especially in the industry. Thanks to flotation, we are able to classify, separate and enrich very small minerals. Less energy consumption, higher capacity, lower cost, very fine bubble diameter, ease of maintenance and repair etc. are expected from flotation machines (Bentli, 2001).

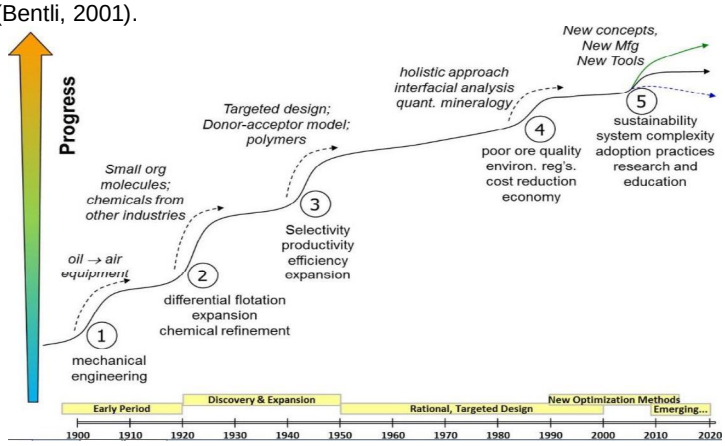


Figure 1. Historical progress of innovations (Nagaraj and Farinato, 2016)

The aim of this paper is to summarize new developments and studies about flotation parameters such as bubble size and water chemistry, flotation of rare earth minerals and technological improvements about flotation machines.

2. FLOTATION

Flotation is a method which separates minerals according to their surface features such as wettability. Moreover, in flotation, minerals with low wettability (hydrophobic) cannot float while minerals with high wettability (hydrophilic) float easily with the use of reagents (Dryzmala, 2007).

2.1. Flotation Parameters

In the flotation method, there are parameters such as pH, reagent type and amount, particle size and morphological properties of the particle that should be kept under control (Güven at al., 2015). Additionally to these parameters, bubble size, water chemistry and new machines are new considerations in flotation studies.

2.1.1. Bubble size (Nano bubbles)

Forming and separating a part of nano bubles from microbubbles during depressurization of saturated air (66.1 psi), in water (similar to DAF— dissolved air flotation) have been recently recognized in mineral processing community. Both micro- and nano-bubbles are generated in result of the depressurization followed by cavitation occurred, therefore, the procedure carried out that is simply waiting microbubbles to levitate and leaving the medium and having nanobubbles. The study where quartz particles were floated by both coarse bubbles with and without nano bubbles in Hallimond tube and in a Denver type cell with and without nanobubbles was examined (Calgaroto, Azevedo and Rubio, 2015). It was found that in smaller fraction size, coarse and nano bubles together yield higher recovery whereas, in coarser particle size, only coarse bubbles were ahead of nanobubbles in obtaining high recovery. The results were

concluded by the enhancement of fine/ultrafine particle capture and slower rising velocity and entrainment by the coarse bubbles in nanobubbles presence. In the mechanical cell, presence of nanobubbles provided about 3% higher recovery than that of without nanobubbles. Among the features of nanobubbles were also found that acting both as a second collector and an aggregating agent. Overall, higher contact angles and quartz fine aggregation in nanobubbles presence were thought to be the most significant phenomena. In a study of nanobubbles carried out on phosphate ore demonstrated that when nanobubble solution was added 50% volume of the cell in the conventional flotation, the recovery and the yield of the concentrate was higher than the other alternatives in the trials of charging frother and nano bubble solution into the cell (Pourkarimi, Rezai and Noaparast, 2017). Addition of nanobubbles had also positive effect on collecting light rare elements such as Ce, La and Nd into the concentrate than that of the conventional flotation in absence of nanobubbles. Similarly, the concentrate obtained in the presence of nanobubbles had also smaller size fraction than that of absence of nanobubbles. Moreover, the increased amount of nanobubbles resulted in more recovery increase and the smaller the nanobubbles were the better the results of the flotation were obtained. Usage of collector Flo-Y-S instead of MIBC in order to produce nanobubbles gave better and more selective outcomes (Pourkarimi, Rezai and Noaparast, 2017).

In a nutshell, nanobubble use in flotation increases the yield and recovery as they can collect smaller size particles along the way to upward and adhere the coarse bubbles. Their ability to aggregate fine particles altogether does also play an important part. Although there is still time to integrate nanobubbles to industrial level, the incoming studies might speed up the process.

2.1.2. Particle size

Throughout the years, as a well-known fact, application size of flotation is in range of 100-25 microns. However, in recent years, flotation of coarser and finer particles has become the center of attention.

According to one of the researches about flotation of coarse particles, recovery of coarser particles flotation can be increased by using submicron bubbles that are produced from hydrodynamic cavitation. Results of the research shows that recovery increased by 12 %. Moreover, the effect of the both nanobubbles and conventional bubbles in the same system are investigated and results demonstrate that flotation recovery increased. The reason of increased recovery is because of that nanobubbles are attached to surface of coarse particles and increased the hydrophobicity of the coarse particles. Beside the bubble size, the correlation of impeller speed and air flow rate with nanobubbles are also researched and air flow rate with the presence of nano bubles decreases its effects on recovery while flotation recovery is higher in lower impeller speed like 900 RPM in the presence of nanobubbles (Nazari et al., 2019). Another research focuses on machine properties to float coarse particles efficiently. In the presence of research, flotation cell that is used in the experiments is HydroFloat^{TM} fluidized-bed separator which has a advantage such as teeter bed that consists suspended particles with the help of countercurrent of water or different fluidized medium. Teeter bed assists the flotation recovery with its specific qualifications such as regulating optimum mixing condition, enhancing retention time, decreased detachment and raised probability of collision. Experiments are made with copper and gold samples. Outcome of the research is that copper sample is floated selectively in the size of up to 0,8 mm by using fluidized-bed flotation while gold sample had different recoveries at different sizes but have an overall recovery up to 98%. Results of the research shows that sulfide minerals can be floated by using HydroFloat in coarse fractions (Kohmuench et al., 2018).

2.1.3. Morphology

Morphological properties including surface shape and roughness parameters have been investigated recently in many researches (Ahmed, 2010; Güven et al., 2016; Güven, 2016;

Hassas et al., 2016; Rahimi et al., 2012; Rezai et al., 2010; Ulusoy and Yekeler, 2007; Ulusoy, Hiçyılmaz and Yekeler, 2004; Xia, 2017). Morphology, which has recently become the subject of research, is the area where the surface shapes of the grains are examined. The morphology is basically divided into two groups: shape factor and roughness (Güven et al., 2016). The shape factor is examined in four categories as roundness, flatness, elongation rate and relative length (Ulusoy, Hiçyılmaz and Yekeler, 2004).

In alumina flotation, one of the researches shows that both roughness and shape factor affects the flotation recovery. However, roughness has more effect at low concentrations while shape factor has more effect at high concentrations (Güven, 2016). In another study, flotation kinetics of quartz minerals, which are obtained from rod mill with high roughness and elongation ratio, are better than minerals that are obtained from ball mill (Rahimi et al., 2012). It is reported in different study that flotation recovery increases with the increasing surface roughness in quartz flotation (Rezai et al., 2010). Moreover, studies are made to investigate the effect of morphology to hydrophobicity by using calcite and barite minerals. As a result of this research, hydrophobicity ascends with high values of flatness and elongation ratio of grinded minerals (Ulusoy, Hiçyılmaz and Yekeler, 2004).

2.1.4. Water chemistry

Water consumption is one of the biggest challenges in mining activities. In flotation plants, different strategies are applied to circulate process water in a particular ratio between fresh and wastewater due to the high cost of production and transportation of freshwater. Therefore, usage of water in flotation plant can be classified as mixed of raw water and reused water. There are two categories of reused water, as internal reuse and external reuse. Internal reuse is a production of circulation of water in a dewatering system related to the concentrator such as recovered water from press filter or thicker overflow. The source of external reused is varied. It can be water in tailing pond or sewer water. Both internal and external reuse water can be treated or refeed process directly, the general flow of water in a mineral processing plant shown in figure 1 (Rao and Finch, 1998; Liu et al., 2013). The froth flotation is conducted surface interaction between mineral particle, chemical reagent and air bubble in a medium (mostly water). wastewater from processing activities is harmful to the environment because it contains both suspended solids and most contaminating toxic chemicals in solution, mostly flotation reagents and degradation products. These concerns make wastewater management is necessary because of not only economic but also environmental issues (Rao and Finch, 1998). Water controls mineral's hydrophobicity which is the essential parameter in flotation (Wills and Napier-Munn, 2006).

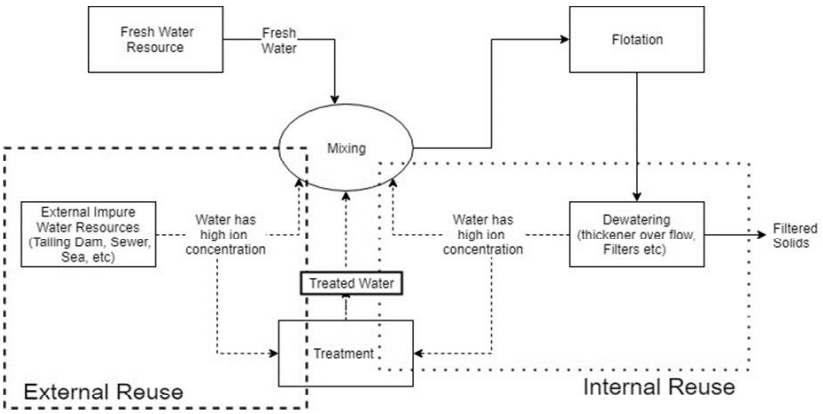


Figure 2. General Flowsheet of water circulation in a mineral processing plant (Liu et al., 2013; Rao, Finch, 1998; Michaux et al., 2018)

Michaux et al (2018), tried to digitalized modification of chemistry of water being processed when circulated fresh and waste water inside flotation plant. In that study, links between flotation performance and water priorities are investigated. Recirculation of water modifies the process water in case of viscosity, gas solubility and flotation kinetic. Ion concentration affects the viscosity of pulp in this way collision of rate between particle and bubble is affected. Pulp viscosity determines hydrodynamic condition of flotation in the flotation cell such as rate of collision between bubbles and mineral particles. High solution viscosity means a low collision rate, low flotation kinetics. (B. Michaux, et al., 2018). Wastewater contains generally SO42-, Cl-, F-, Mg2+, Ca2+, Na+, K+, sulphide, thiosalts, base metals, collectors, frothers, activators, depressants, colloidal materials (silicates, clays and iron hydroxides), and natural organic materials. (Muzenda, 2010). Moreover, ion concentration affects on gas solubility in water, high amount of ion concentration results in increased use of water molecules in the hydration of dissolved ions (Bulatovic, 2007), the presence of lower amount of water molecules dissolve the lower gases (Michaux et al., 2018).

The content of flotation water depends on chemical and mineralogical properties of ore, type of reagents, and raw water resource and also, climatic activities affect directly composition of water being processed. (Liu et al., 2013). Lui et al., classified two main parameters to cause of water quality variation, these are internal factor and external factor (2013). Grinding media employed influences redox potential and concentration of dissolved oxygen in the pulp. To illustrate, reduced steel grinding media decreased Eh and dissolved oxygen in the slurry after grinding (Grano et al., 1990). Ore oxidation and dissolution brings many particle into flotation medium. For example, in chalcopyrite flotation high pH is used to depress pyrite, thiosalts and Ca2+ are introduced into medium from ore. (Liu et al., 1993). Reagent addition is the other internal factor. It introduces inorganic and organic components into flotation water in the form of residue reagents, reaction by-products and impurities (Schumann et al, 2009), such as lime leads a increase of concentration of Ca ion (Raghavan and Hsu, 1984). Liu et al, emphasized "water internal use" as another internal factor in changing of water quality (2003). In these case, type of recirculation of water in the plant, reagent type and amount, type of dewatering operation and residence time of water in tailing dam is essential parameters.

Different kind of raw water resources is grouped in the external factor (Liu et al., 2003). In addition to main fresh water resources of the site, there can be other third-party water resources such as sea water, sewer water or tailing pond of another facility. Especially in recycled water, high calcium levels are often accumulated. Calcium ions can enter the dissolution of Ca-bearing minerals and the addition of lime as a pH modifier or as a pyrite depressant. Due to the oxidation of sulfur species, the process waters of many sulfur flotation plants also contain high sulphate concentrations Many studies have shown that recycled water contains high amounts of calcium and sulfate, increasing the selectivity or recovery of the remaining copper minerals (Bulut and Yenial, 2016).

Table 1. Effects of Water Constituent on Flotation (Liu et al., 2013)

	Abiotic Water Constituent	Biotic Water Constituent
Negative Effects	• Reduction of particle surface hydrophobicity by metal ions • Change of particle surface charge by metal ion • Inadvertent activation of unwanted minerals by metal ions • Slime coating on mineral surface • Interaction with flotation reagent	• Absorbing non-selectively on most sulfides • Decreasing hydrophobicity • Uncontrolled frothing
Positive effects	• Compression of electrical double layer • Formation of smaller bubbles	• Reducing reactive consumption • İncrease recovery in some cases

Ion flotation is also contemporary topic in flotation studies nowadays. Ion flotation can be alternative method for removing ions from waste water and then it is possible to re-feed flotation process as treated version. Polat and Erdogan applied ion flotation with anionic collectors SDS and cationic collector HTAB and observed that ion flotation has big potential to recovery metals such as copper, silver and zinc in a proper condition (2007). It can be possible to utilize from water has high amount ion concentration such as AMD by using ion flotation for future.

2.1.5. New Reagents

Nowadays, froth flotation has been facing great issues related to refractory complex ores and health, safety and environmental (HSE) aspects. The new preparation technologies for collectors such as xanthates and hydroxamates have been developed to prepare them in near atom economy under environmentally-friendly conditions, which is bound to offer a new and effective approach for support of their green manufacture and industrial upgrading. Green chemistry is an essential issue for preparation of flotation collectors. New collectors with "plane" configurations will be intensively designed and their special flotation performances will be gradually understood. Moreover, the rapid advances in computational toxicology of organic molecules can facilitate the recognition of collectors' poisonousness, and low toxic and biodegradable flotation collectors will be developed. Utilization of large doses of inorganic reagents in mineral industry not only leads to high cost but also increases the toxicity in the environment. Last research provides a new, environmentally friendly, biodegradable, and cost-effective flotation reagents such as collectors, depressant (Khoso et al.,2019; Liu et al., 2018). Many researchers have also attached great importance to the selection of suitable collectors for the flotation of the similar surface properties of minerals. The use of mixed collectors is considered a possible solution to this problem (Wu et al., 2018).

2.2. Flotation of Rare Earth Minerals

As a result of technologic improvement, beneficiation of Rare Earth Minerals (REMs) has been gaining more importance. Nowadays Rare Earth Elements (REEs) are indispensable part of magnetic, phosphor, metal alloys, catalyst, ceramics, glass, polishing and defense systems industries. Currently, China is the largest supplier in the world with a production of more than 95% of world's rare earth oxides (Suli et al., 2017). Global mine production of REEs was estimated around 170 kt of contained rare earth oxides (REOs) in 2018 (Liu, 2019).

There are about 250 rare earth minerals in nature in the form of carbonatites, oxides, phosphates, silicates and halides. Bastnaesite ($(Ce,La)CO_3F$) and Monazite ($(Ce,La,Nd,Th)PO_4$) are main REE bearing ores (Boulanger, Bazin, Turgeon, 2019) which about 95% of the world rare earth resources occur in these minerals and Xenotime as Miyawaki and Nakai (1996) (as cited in Yang et al., 2014). Also Cerium is the most abundant REE, which comprises more than copper or lead in earth's crust (Castor&Hedrick, 2006). Different methods are performed to beneficiate REE ores such as Gravity and Magnetic separation. In addition to abovementioned methods, froth flotation has been gaining importance and academic studies have been increasing in this field. Currently, flotation is most important beneficiation method to recover REMs (Yang et al., 2014). So regarding froth flotation applications in beneficiation of REE ores, fundamental parameters and issues were mentioned within the scope of this study.

Collectors are the most important reagents of flotation circuits in terms of selectivity, recovery and concentration grade. Considering that, variations of hydroxamates, fatty acids, dicarboxylic acids and organic phosphoric acids have been used in industrial and academic scale to make REE mineral particles hydrophobic and to improve abovementioned factors in beneficiation of REE ores, especially that of Bastnaesite, Monazite and Xenotime.

Fatty acids were used in beneficiation of REE ores initially due to their widespread availability, general usage in flotation and low cost (Jordens, Cheng & Waters, 2012; Anderson et al., 2016). But beside these advantages, fatty acids are unselective in beneficiation of REE ores, which this situation requires a large amount of depressants and high temperature as explained in next section to increase the selectivity (Liu & Wang, 2019; Anderson et al., 2016; Jordens et al. 2012). The negative effects of fatty acids mentioned previously and increased costs required new researches on alternative collectors to cope with these issues. For this reason, in 1980's, Pradip and Fuerstenau began studies on Bastnaesite ore from Mountain Pass, which they primarily focused on alkyl hydroxamates as an alternative of fatty acids (Anderson et al., 2019) and they reported that hydroxamate collectors were more selective than fatty acids (Karataş et al., 2017).

Table 2. Chemical Structures of Commercially Available Hydroxamates (Jordens, Zhiyong & Cappuccitti, 2016)

Hydrophobic Group	Chemical Formulation
Alkyl	8 carbon straight chain salt
	8 carbon straight chain acid
Aromatic	Benzoic
	Salicylic
	Naphthenic
	Styrene

Hydroxamic acids may be in one of two forms as in following figure, but only hydroxyamide is able to form chelates with metal cations (Jordens et al., 2012). Since REMs are semi-soluble in nature and form stable hydroxamate complexes, this situation makes them ideal for flotation with hydoxamates (Anderson et al., 2016).

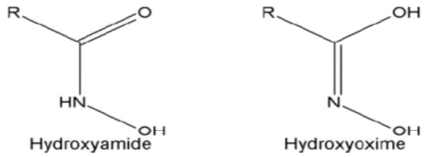


Figure 3. Two forms of hydroxamic acids

Apart from fatty acids and hydroxamates, different type of collectors was tested as well. For example, in a study carried out by Harada et al. to separate Monazite from Xenotime, dodecylsulfonate and dodecyl ammounium chloride were tested as alternative collectors. As a result of this study, approximately a monazite grade of 85% and 67% recovery were achieved (as cited in Anderson et al., 2016). In another study, Andrews et al. performed bench scale flotation on Australian heavy mineral sands containing Monazite and Xenotime using fatty acids, hydroxamate and phosphoric acid esters, which results showed that phosphoric acid esters were more selective, but highest recoveries were reached by using fatty acids. As for depressants, Barite, Calcite, Apatite, Tourmaline, Pyrochlore, Ilmenite, Quartz, Rutile, Zircon etc. are some of the gangue minerals in REE ore bodies, which makes the flotation difficult in terms of selectivity. As a compilation from academic studies sodium silicate, sodium hexafluorosilicate, lignin sulfonate, sodium fluoride, sodium carbonate, sodium sulfate, sodium oxalate and starches are typical depressants used in flotation of REMs.

Considering low cost, high availability and un-selectivity of fatty acids and relatively high cost and high selectivity of hydroxamates, these two collectors have drawn attention of researchers and mechanism behind REM flotation and related parameters have been investigated to increase efficiency and so that to reduce operation costs. Fuerstenau (1991), Houot et al. (1991) and Pavez et al. (1994, 1996) were on the opinion that main mechanism behind fatty acid and hydroxamate adsorption is chemisorption where the collector adsorbs onto mineral

at pH value where zeta potential is negative and so that collector molecules forms stable chelates with rare earth cations (as cited in Jordens et al., 2012; Karataş et al., 2017; Anderson et al., 2016; Yang et al., 2014).

Temperature is one of the most important parameter in beneficiation of REE ores. Pradip and Fuerstenau (1985) proposed that as the temperature is elevated, collector and mineral solubilities increase. So that selectivity increases since the rate of the collector adsorption onto mineral surface increases (as cited in Anderson et al., 2016). Also according to the study carried out by Pradip and Fuerstenau, as the temperature increases, the difference in free energy adsorption between Bastnaesite and Calcite/Barite increases and improved selectivity of octyl hydroxamate is achieved (Liu, Wang & Miller, 2019).

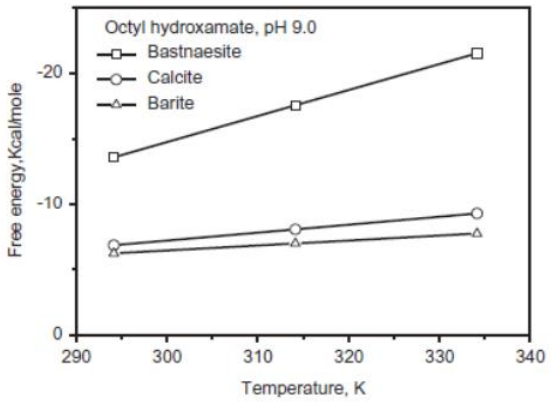


Figure 4. Standard free energy of adsorption of octyl hydroxamate on Bastnaesite, Calcite, and Barite as a function of temperature (Liu et al., 2019)

Also, in their study, Pradip and Fuerstenau (2013) showed that hydroximates are capable of producing higher grades at lower temperatures than required temperatures for fatty acids (as cited in Anderson et al., 2016).

The other important parameters in flotation of REMs are zeta potential and zero point of charge (zpc). As mentioned before, chemisorption occurs during the flotation of REMs between mineral surface and collector. For this reason, mineral surfaces must be negatively charged taking into consideration that flotation of REMs is achieved with anionic collectors (fatty acids, hydroxamate) and pH value is higher than zpc. According to Cheng (2000) and Houot et al. (1991), IEP values vary between 1.1-9.0 for Monazite and 4.6-9.5 for Bastnaesite (as cited in Jordens et al. 2012).

2.3. Machine Developments

Flotation machines have gained importance in the last 30 years especially in the industry. Thanks to flotation, we are able to classify, separate and enrich very small minerals. At the same time, the preference for flotation depends on machine properties and circuit arrangements, except for reagents and conditioning conditions within the industry.

Energy-saving aptitude high flotation and adequacy are two significant factors in the flotation process (Gui et al., 2014). In the production of flotation machines, they produce low cost and high capacity flotation cells. The aim of the flotation machines, which are still being developed today, is to increase flotation capacity and efficiency, to provide energy saving, to increase grain bubble collision, to produce fine bubble. Companies try to enhance flotation method with

the new developments in flotation machine technology and all the companies have common idea. Reducing plant footprint and power consumption, increasing flotation recovery, less expense to start up and run, longer operating life are the main targets of companies. New flotation methods and machines are producing with either combination of other machines or new mechanisms such as mixedROW™, TankCell®, SkimAir®.

In mixedROW flotation machine, which is produced by FLSmidth, is a combination of nextSTEP and WEMCO flotation cells by using their specific features. The mixedROW cells enhance bubble-particle attachment with optimal flow stream and forceful turbulence. According to company, this flotation cell acquires higher recovery, lower energy consumption and improved concentration grade in processing plants (FLSmidth, n.d.).

In TankCell and SkimAir flotation machines, which are produced by Outotec, have similar advantages with mixedROW flotation cells. In TankCell flotation machines, Float Force improves recovery while reducing the risk of sanding in the cell. The rotors and stators of TankCell have better resistance about wears than others. The role of SkimAir flotation cells in the process is different from other flotation cells. The SkimAir cells are positioned in underflow of hydrocyclone to catch the liberated, fast floating but coarse particles in order to increase total recovery and prevent overgrinding. This procedure can be used to both improve mill capacity and avoid slimes as a result of excess grinding (Outotec, 2017).

In order to obtain high yield and concentration in flotation enrichment, microchemistry properties such as surface chemistry, suspension balance, flotation machine design, circuit layout, hydrodynamic, kinetic phenomena and mechanical changes are effective. From a larger angle, a flotation machine: easy and fast installation, good air distribution, fine bubble production with new impeller design, fast foam removal thanks to design, automatic air and pulp level control, easy maintenance on temporarily stopped machines, possibility of repairing or replacing worn or corroded parts locally without removing the machine completely. If these targets are achieved, there will be significant gains in plant efficiency and efficiency. In addition, it is among the objectives of the machine manufacturers to produce economical and simple solutions to environmental problems.

3. CONCLUSION

Flotation is a separation method in which many parameters are effective together. The history of flotation is a record of over a century of impressive innovations, especially in the development of flotation chemistry and chemicals.

As in many other technology areas, flotation development has reached a plateau in the face of escalating industry challenges related to water and energy consumption, descent in the ore quality, economic uncertainty, and health, safety and environment aspect. Correspondingly, some prominent developments in flotation are summarized in this study. The development of flotation has been continuing for years and it is understood that many innovations in this field will increase according to the needs.

REFERENCES

Ahmed, M. M. (2010). Effect of comminution on particle shape and surface roughness and their relation to flotation process. International Journal of Mineral Processing, 94(3-4), 180-191.

Akar, A., (1985). “Cevher Hazırlama Tesis ve Dizaynı” Dokuz Eylul Universitesi Muh.-Mim. Fak. MM/MAD-85 EY 01, İzmir, s 271.

Anderson, C., Taylor, P. R. & Anderson, C. (2012). Rare Earth Flotation Fundamentals: A Review. IMPC 2016: XXVIII International Mineral Processing Congress Proceedings

Atak, S., (1990). "Flotasyon İlkeleri ve Uygulamaları" İTU Maden Fakultesi, İstanbul, s 148.
Bentli, İ., (2001). Flotasyon ve Flotasyon Makineleri. Dumlupınar Üniversitesi Fen Bilimleri Enstitüsü Dergisi, (002), 97-110.

Bıçak, Ö., Ekmekçi, Z., Can, M., Öztürk, Y. (2012). The effect of water chemistry on froth stability and surface chemistry of the flotation of a Cu–Zn sulfide ore. International Journal of Mineral Processing, 102, 32-37.

Boulanger, J-F, Bazin, C., Turgeon, K. (2019). Effect of Depressants and Temperature on Bastnaesite and Monazite Flotation Seperation from a Canadian Rare Earth Element (REE) Ore. Minerals, 2019, 9, 225, doi:10.3390/min9040225.

Bulatovic, S.M., (2007). Summary of the Theoretical Aspects of Flotation, Handbook of Flotation Reagents. Elsevier, Amsterdam, pp. 87–124.

Bulut, G., & Yenial, Ü. (2016) "Effects of major ions in recycled water on sulfide minerals flotation", Minerals and Metallurgical Processing, 137. Vol. 3, pp 137-143.

Calgaroto S., Azevedo A., Rubio J. (2015) "Flotation of quartz particles assisted by nanobubbles"

Castor, S. B., Hedrick, J. B. (2006), Rare Earth Elements, Industrial, 7th Edition, Society for Mining, Metallurgy and Exploration, Littleton, Colorado 769-792

Chelgani, S. C., Rudolph, M., Leistner, T., Gutzmer, J., & Peuker, U. A. (2015). A review of rare earth minerals flotation: monazite and xenotime. International Journal of Mining Science and Technology, 25(6), 877-883.

Cho, Y. S., Laskowski, J. S. (2002). Effect of flotation frothers on bubble size and foam stability. International Journal of Mineral Processing, 64(2-3), 69-80.

Drzymala, J., (2007), Mineral Processing, Foundations of theory and practice of minerallurgy, Oficyna Wydawnicza PWr, ISBN 978-83-7493-362-9 *www.ig.pwr.wroc.pl/minproc*, 269-385.

Finch, J. A., Nesset, J. E., & Acuña, C. (2008). Role of frother on bubble production and behaviour in flotation. Minerals Engineering, 21(12-14), 949-957.

FLSmidth (n.d.). mixedROW™ Flotation System. Retrieved from https://www.flsmidth.com/en-gb/products/flotation/mixedrow-flotation-cell

Grano, S., Ralston, J., Smart, R.S.C., (1990). Influence of electrochemical environment ion the flotation behaviour of Mt. Isa copper and lead–zinc ore. Int. J. Miner. Process. 30, 69–97.

Grau, R. A., Laskowski, J. S., Heiskanen, K. (2005). Effect of frothers on bubble size. International Journal of Mineral Processing, 76(4), 225-233.

Guangyi Liu, Jun Liu, Yaoguo Huang, Xianglin Yang, Hong Zhong (2018). New advances in the understanding and development of flotation collectors: A Chinese experience, Mineral Engineering, 118, 78-86.

Güven, O. (2016). Effect of Particle Morphology on Flotation. PhD Thesis, Department of Mineral Processing Engineering, 11.

Güven, Ö., Çelik, M. S., Drelich, J. W. (2015). Flotation of methylated roughened glass particles and analysis of particle–bubble energy barrier. Minerals Engineering, 79, 125-132.

Güven, O., Karakas, F., Kodrazi, N., Çelik, M. S. (2016). Dependence of morphology on anionic flotation of alumina. International Journal of Mineral Processing, 156, 69-74.

Harris, C.C., (1976), "Flotation Machines in Flotation" Gaudin Memorial Volume, SME AIME, V:2, pp 753-815.

Hassas, B. V., Calışkan, H., Güven, O., Karakaş, F., Cınar, M., Celik, M. S. (2016). Effect of roughness and shape factor on flotation characteristics of glass beads. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 492, 88-99.

Houqin Wua, Jia Tianc, Longhua Xub,c,, Shuai Fanga, Zhenyue Zhangd, Ruan Chid (2018) , Flotation and adsorption of a new mixed anionic/cationic collector in the spodumene-feldspar system, Mineral Engineering, 127, 42-46.

Ikumapayi, F., Makitalo, M., Johansson, B., Rao, K. H. (2012a). Recycling of process water in sulphide flotation: Effect of calcium and sulphate ions on flotation of galena. Minerals Engineering, 39, 77-88.

Ikumapayi, F., Sis, H., Johansson, B., Rao, K. H. (2012b). Recycling process water in sulfide flotation, part B: effect of H 2 O 2 and process water components on sphalerite flotation from complex sulfide. Mining, Metallurgy & Exploration, 29(4), 192-198.

Jordens, A., Cheng, Y. P., Waters, K. E. (2012). A Review of the Beneficiation of Rare Earth Element Bearing Minerals. Minerals Engineering, 41, 97-114, February 2013. Elsevier, 2012.

Jordens, A., Zhiyong, Y., Cappuccitti, F. (2016). The Application of Florrea 8920, A New Hydroxamate-Based Flotation Collector for the Flotation of Rare Earth Minerals. XXVIII International Mineral Processing Congress Proceedings.

Karataş, D., Karaağaçlıoğlu, İ. E., Eygi, M. S., Çelik, M. S. (2017). Flotation Chemistry of a Rare Earth Mineral:Bastnaesite. 17th Balkan Mineral Processing Congress Proceedings. ISBN: 978-975-7946-42-7.

Khoso, S. A., Gao, Z., Tian, M., Hu, Y., & Sun, W. (2019). Adsorption and depression mechanism of an environmentally friendly reagent in differential flotation of Cu–Fe sulphides. Journal of Materials Research and Technology.

Kohmuench, J. N., Mankosa, M. J., Thanasekaran, H., Hobert, A. (2018). Improving coarse particle flotation using the HydroFloat™ (raising the trunk of the elephant curve). Minerals Engineering, 121, 137-145.

Levay, G., Smart, R. S. C., Skinner, W. M. (2001). The impact of water quality on flotation performance. Journal of the Southern African Institute of Mining and Metallurgy, 101(2), 69-75.

Liu, L., Rao, S.R., Finch, J.A., (1993). "Technical note laboratory study of effect of recycle water on flotation of a Cu/Zn sulphide ore," Minerals Engineering, Vol. 6, pp. 1183-1190.

Liu, W. (2019). 2018 Industrial Minerals Review, Rare Earths. Mining Engineering, July 2019, 65-67

Liu, W., Moran, C. J., Vink, S. (2013). A review of the effect of water quality on flotation. Minerals Engineering, 53, 91-100.

Liu, W., Moran, C., Sue, W. (2003) "A review of the effect of water quality on flotation", Minerals Engineering, 92.Vol. 53, pp 91-100

Michaux, B., Rudolph, M., Reuter M.A., (2018), "Challenges in predicting the role of water chemistry in flotation through simulation with an emphasis on the influence of electrolytes" Minerals Engineering 125 pp 252–264.

Muzenda, E., (2010) "An Investigation into the Effect of Water Quality on Flotation Performance", International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering, 4(9), 562–566.

Nagaraj, D. R., Farinato, R. S. (2016). Evolution of flotation chemistry and chemicals: a century of innovations and the lingering challenges. Minerals Engineering, 96, 2-14.

Nazari, S., Chelgani, S. C., Shafaei, S. Z., Shahbazi, B., Matin, S. S., Gharabaghi, M. (2019). Flotation of coarse particles by hydrodynamic cavitation generated in the presence of conventional reagents. Separation and Purification Technology, 220, 61-68.

Outotec (2017). Outotec Flotation Technologies. Retrieved from https://www.outotec.com/globalassets/products/flotation/ote_flotation_technologies_eng_web.pdf

Pattanaik, A., Venugopal, R., (2019). Role of Surfactants in Mineral Processing: An Overview. DOI: 10.5772/intechopen.85947.

Polat, H., Erdogan, D., (2007), "Heavy metal removal from waste waters by ion flotation", Journal of Hazardous Materials 148 pp 267–273.

Pourkarimi Z., Rezai B., Noaparast M. (2017) "Nanobubbles effect on the mechanical flotation of phosphate ore fine particles "

Raghavan, S., Hsu, L.L., (1984). Factors affecting the flotation recovery of molybdenite from porphyry copper ores. Int. J. Miner. Process. 12, pp 145–162.

Rahimi, M., Dehghani, F., Rezai, B., Aslani, M. R. (2012). Influence of the roughness and shape of quartz particles on their flotation kinetics. International Journal of Minerals, Metallurgy, and Materials, 19(4), 284-289.

Rao, S., Finch, J. (1988) "A Review of Water Re-used in Flotation", Mineral Engineering, 2(1), pp 66.

Rezai, B., Rahimi, M., Aslani, M. R., Eslamian, A., Dehghani, F. (2010). Relationship between surface roughness of minerals and their flotation kinetics. In Proceedings of the XI International Mineral Processing and Technology Congress (pp. 232-238).

Schumann, R., Levay, G. Ametov, I., (2009), "The Impact of Recycling on Process Water Quality in Mineral Processing", Processing Water in Mining Conference, Perth, 2009, pp 79-86.

Suli, L. M., Ibrahim, W. H. W., Aziz, B. A., Deraman, M. R., Ismail, N. A. (2017). A Review of Rare Earth Mineral Processing Technology. Chemical Engineering Research Bulletin, 19(2017), 20-35

Tao, D. (2005). Role of bubble size in flotation of coarse and fine particles—a review. Separation Science and Technology, 39(4), 741-760.

Ulusoy, U., Yekeler, M. (2007). Floatability of Barite Particles with Different Shape and Roughness. Indian Journal of Chemical Technology, Vol. 14, 616-625.

Ulusoy, U., Hiçyılmaz, C., Yekeler, M. (2004). Role of shape properties of calcite and barite particles on apparent hydrophobicity. Chemical Engineering and Processing: Process Intensification, 43(8), 1047-1053.

Weiping Liu, Xuming Wang, Jan D. Miller (2019): Collector Chemistry for Bastnaesite Flotation-Recent Developments, Mineral Processing and Extractive Metallurgy Review, DOI:10.1080/08827508.2019.1647840

Wills, B. A., Napier-Munn, T., (2006) Mineral Processing Technology, seventh ed. Julius Kruttschnitt Mineral Research Centre.

Xia, W. (2017). Role of particle shape in the floatability of mineral particle: An overview of recent advances. Powder Technology, 317, 104-116.

Yang, X., Satur, J. V., Sanematsu, K., Laukkanen, J., Saastamoinen, T. (2014). Beneficiation Studies of a Complex REE Ore. Minerals Engineering, 71 (2015), 55-64. Elsevier, 2014.

View publication stats