https://doi.org/10.31713/m1306

MINERAL PROCESSING TECHNOLOGIES AND EQUIPMENT TO SEPARATE FINE/ULTRAFINE MINERAL VALUES. A REVIEW

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Abstract

In numerous cases of mineral processing, fine to ultrafine mineral particles are inevitably produced during the process of mineral liberation, with the percentage depending on the ore-grade. In case of low-grade ore, efficient liberation demands excessive grinding, as a necessity for efficient separation of fine-grained mineral value from gangue. Due to the peculiar properties of fine particles (physical, chemical), conventional processing methods have limited success or fail to separate the particles, especially at industrial level, because of the concomitant problems. As a result, mineral values of many commodities are lost to the tailings, e.g. phosphate, copper, tungsten, tin, sulfide minerals, iron, etc. With mining operations been shifted to the exploitation of even lower-grade ores, the problem of fine particles separation is expected to deteriorate.

The current paper deals with the innovation in equipment and processes developed to meet the problem of fine/ultrafine particles separation. Special emphasis is placed on physicochemical methods, which are mainly based on the improvement or modification of already known ones.

1. Introduction

Mining has been tightly bound with human history throughout centuries and highly contributed to the progress of humanity. Millennia years ago, Neanderthals used stone to make primitive tools and serve their elementary needs for living; in the relatively recent historic era, ancient Egyptians, Greeks, Romans and Incans used more sophisticated mining and processing technologies to extract and use mined materials, creating the corresponding civilizations and fabulous artifacts. Passing through the Industrial Age era that is characterized from the onset of the ability for mass production, the progress of human society has led to our modern times' demand that is characterized by bigger, faster, stronger and more products. The aforementioned clearly denote that human living, progress and civilization is based on natural resources. To see the importance of mining and related activities, let's imagine the impact of minerals on various sectors of daily use, such as building, household (appliances, cookware, decoration), transportation (cars, trains, planes, spaceships), communication (cell phones, radars, satellites), medicine (X-rays, robots, fine surgical tools), science, engineering, weaponry (although destructive), etc. What is the future trend? The staggering demand for primary raw materials will keep being even more increasing. Just consider where the advanced, and more sophisticated, technologies rely on (e.g., renewable energy equipment, sustainable energy generation, electric vehicles, just to mention some sectors of advanced engineering). What is the limit? Nobody knows, as humankind continuously sets new targets and expands its activities (e.g. into the Universe).

The aforementioned retrospect of human evolution and the emerging in the future clearly substantiate the strong dependence of human progress and economic prosperity on mineral commodities. To satisfy the continuously increasing demand in products, goods and services, there must be equal (or even higher) demand in mineral values, which leads to the extraction and processing of even larger tonnage of mineral raw materials. As the high-grade orebodies are gradually depleted, even lower-grade ones have to be extracted, followed by several problems. The major problem upon processing low-grade ore deposits is the fine particle size along with the concomitant inefficient processing and subsequent losses of mineral values to the tailings. The increased loss along with the deposition of even larger volumes of tailings in case of low-grade deposits render extraction and mineral processing more unsustainable processes than in usual cases [1].

Mineral value losses are encountered either as rejected waste (often called “extractive waste”) because of imperfect liberation from gangue or as lost fines because of inefficient separation.

The general term “extractive waste” collectively denotes waste and tailings. They are produced in billion metric tons every year from mining and processing operations and are deposited in Extractive Waste Facilities (EWF) as waste heaps or tailing dams, depending on their particle size and prior processing. The amount of waste depends on the grade of the commodity; for high-grade commodities (e.g., coal, bauxite, iron ore) its order is some kilograms per kilogram of product while it increases to several million metric tons per ton of product for low-grade or complex ores such as gold ores [2, 3]. To obtain a view, the amount of the total extractive waste generated in EU, in the period 2004-2014, roughly ranges between 550 and 750 Mt/year [4]; the estimation for the global extractive waste is over 100 billion metric tons per year [5]. Waste can be further categorized into “mine waste”, which is of no economic value and, consequently, rejected, as well as “mineralized mine waste”, which contains some quantity of mineral value and presents future potential economic prospects [6]. Consequently, every mineralized waste could be viewed as a potential, already-mined deposit and promising for mineral value recovery, after reprocessing [7-10]. This consideration necessitates proper liberation size, application of efficient reprocessing methods, high-grade product and positive overall economic outcome. Despite the wish for relatively coarse liberation size, the separation of mineral values from gangue in fine/ultrafine particle size is often inevitable because mineralized waste is usually a low-grade deposit.

When low-grade orebodies have to be extracted, the mineral value is usually disseminated as fine particles within the mass of gangue, because of the mineralogical texture of the orebody; consequently, the material has to be ground in very small particle size to obtain liberated particles. In this case, the entire process is designed to the ideal separation of the value from gangue. In fact, severe problems, because of the very small particle size, lead to inefficient separation with conventional separation methods and equipment, as these methods fail to obtain a concentrate of high grade and recovery in value [11]. As a result, considerable part of mineral values (tin, tungsten, phorphyry copper, sulfide minerals, iron ores, phosphate, etc.) is lost to the tailings [11, 12]. It is characteristic that approximately one-fifth of the world tungsten and one-half of Bolivian tin is lost as fine particles because common gravity methods fail to provide with a concentrate of increased recovery for such a fine particles size; one-third of the phosphate is discarded as slime in Florida phosphate industry, as the effort of their recovery should be uneconomic due to the excessive consumption of flotation reagents; one-tenth of iron ores explored in USA is discarded as slimes; similarly, losses for USA porphyry copper ores reach one-fifth while, even for sulfide minerals finely disseminated in the matrix, losses are so high as half of the value [12].

A lot of effort has been devoted on the role and influence of fine particles on separation methods, especially on flotation, which is the most proper method to separate particles of such a fine size [13-16]. Provided that it is important to reduce the loss of fine mineral values, the development of procedures and equipment to cope with the problem draws the attention of many workers, as the extraction of orebodies shifts to even lower grade deposits. Consequently, the improvement or modification of standard separation methods and the application of new techniques is a necessity for the processing of fine mineral particles.

The current paper reviews the progress achieved in separation methods (physical and physicochemical) and equipment to cope with the problem of fine particles separation.

2. Problems during fine/ultrafine particle separation

The generation of fine particles is inevitable in many operations of mineral commodities processing. In case of low-grade ores, the mineral value is found as finely disseminated particles due to its mineralogical texture; consequently, particle liberation is achieved upon grinding of the orebody to fine particle size. Although there are differences regarding particle size characterization, fine is usually characterized a particle in the size range of -100μm+20μm, very fine of -20μm+5μm, ultrafine of -5μm+1μm, and colloid the smaller than

1μm [17]. Very often, particles with grain size less than 20μm are commonly characterized as "slimes".

The characteristics of the ore deposits, especially the grain size of the mineral value in the ore, its dissemination in the mass of the deposit, and its association with the gangue minerals, highly determine the liberation size, the abundance of fine particles, the selection of efficient equipment, the proper separation method in some cases, and, consequently, the entire flow sheet of ore processing.

The major problems associated with the inadequate separation of fine particles are due to their following physical and chemical properties: small mass, high specific surface area, and high surface energy per unit area [11, 12, 17]. Regarding separation methods, the major problems related to these properties can be briefly summarized to the following:

- During separation with conventional gravity methods (jigging, flowing-film separation, etc.), the forces associated with water-flow dominate over those associated with gravity for fine/ultrafine particle size (less than 100 μm). Separation becomes progressively inefficient as particle size reduces while impossible for ultrafine particles. This fact renders the major share of mineral values irrecoverable by using gravity separation through conventional equipment.

- Magnetic separation is not efficient regarding the recovery of fine/ultrafine particles (less than 100μm), especially when feebly magnetic particles are involved. This fact has resulted throughout the years in their deposition into tailings and, consequently, loss of considerable volumes of fine/ultrafine paramagnetic mineral values (goethite, limonite, hematite, chromite, cassiterite, etc.).

- Common electrostatic separation methods are inefficient for fine mineral particles (-75 μm). This is mainly due to the small particle mass, influence of drag forces because of turbulence inside the chamber, as well as the difficulty of optimizing the residence time of the particles in the electric field, without affecting the other operating variables and setting parameters [18].

The problems regarding fine/ultrafine mineral flotation in conventional cells have been well substantiated [11-17]; these problems are mainly due to the small size of minerals and the concomitant effects, as well as to the hydrodynamic conditions prevailing in the cell. Flotation inefficiency for fine particles, especially for ultrafine size and below, is related to low probability of bubble-particle collision and adhesion, large bubble size, mechanical entrainment and entrapment, slime coating, higher flotation reagent adsorption, formation of dense froths and low process kinetics.

In the previous paragraphs, the major and most common problems encountered during fine/ultrafine mineral particles processing were delineated. Given that physical properties are inherent to minerals and the possibility for their modification is not always feasible, the efforts regarding physical separation methods have been mainly focused on the development of novel equipment.

As regards physicochemical separation of fine/ultrafine particles, the efforts have been focused on the following axes (a) development of novel equipment and (b) development of novel and more sophisticated procedures. In the next section, the equipment and procedures used to cope with the problem of fine/ultrafine mineral separation are reviewed.

3. Separation Methods

3.1 Physical Methods

3.1.1 Gravity Separation

As gravity circuits are much simpler than other (e.g. flotation) and mineral value (usually heavy) appears considerable density difference from gangue, the use of gravity circuits has been involved in many cases of fine/ultrafine particle separation. To efficiently treat fines and smaller particles, efforts led to innovative devices, which utilise centrifugal force to enhance the gravitational field. Centrifugal motion is usually applied along with pulsation, sluicing or oscillating motion. Such devices are the following:

Centrifugal Jigs. These devices incorporate the operating principles of jigging (pulsing action, water injection) along with centrifugal spinning motion. The ability of centrifugal jigs to highly increase the apparent gravitational field improves settling characteristics of fine particles and enhances the chance of their recovery. Separations of such fine particles as 38 μm with small density difference have been referred [19]. Kelsey jigs, which are the well-known, have been used both to separate various heavy minerals (zircon, rutile, cassiterite, wolframite, gold, tantalum and nickel minerals, etc.) at industrial level [20-23] and to recover fine heavies from tailings [24, 25].

Mozley Multi-Gravity Separator (MGS). This machine combines centrifugal motion of an angled rotating drum with oscillating motion; it can separate particles down to 10μm, because of the high "g" forces developed [19]. It has been employed to recover the corresponding heavy mineral from chromite, cassiterite and tungsten ores [26-28].

Knelson Concentrator utilises the combination of high centrifugal force, up to 60"g", and a back pressure force, arisen from injected water to form fluidised bed [29].

Falcon Concentrator separates through combination of centrifuge and sluicing; its operation under high "g" forces (from 50 to 200"g") permits the concentrator to efficiently separate both coarse and very fine particles (15 to 20 μm) [19, 30]. This concentrator has been used to recover very fine gold particles, and tantalum ore slimes [30, 31].

Flowing-film concentrators. The following concentrators are included in this class, which holds a significant share among gravity separators for very fine particles: Bartles-Mozley Multi – deck, Bartles Cross-belt and Duplex concentrator.

Bartles-Mozley Multi - deck concentrator is a semi-continuous device, based on the combination of flowing-film phenomena on a slightly tilted deck, which is also subjected to horizontal orbital motion to develop shear between heavy and light particles' bed. It consists of 40 fiberglass decks (tables) being arranged in two sections of 20 decks each, suspended by cables; each deck is riffled and connected by ½-inch plastic formers that define the pulp channel [32]. It is used for particle size between 100 and 5μm, but in case of gold and platinum separation it can reach down to 1μm [33].

Bartles Cross-belt concentrator has been used to separate chromite and cassiterite from light gangue of -100+5μm size [32]. It consists of an endless belt from PVC with a central longitudinal ridge. The belt has slight slopes from the ridge out to the sides. At the same time, the belt is subjected to orbital motion, which is imparted by a rotating weight [32].

Duplex concentrator has been used to recover cassiterite, tungsten, tantalum, gold, chromite and platinum from fine (-100 μm) feed [34]. It is comprised of two decks operating under slight tilt; the decks are used alternatively to provide continuous feeding, with one deck being fed and the other being discharged from the heavy product.

3.1.2 Magnetic Separation

In 1960s and 1970s, the development of Wet High-Gradient (or High-Intensity) Magnetic Separators (WHGMS or WHIMS) highly contributed in the recovery of fine weakly magnetic minerals and in the removal of color influencing contaminants from kaolin and other industrial minerals (e.g., kyanite, calcite, feldspars) in order to increase the whiteness and commercial value of the product [35-37].

With the subsequent development of high gradient superconducting magnetic separators (HGSMS) there was achieved an order of magnitude stronger field than ordinary ferromagnetic-core electromagnets and allowed industry to efficiently separate very fine weakly magnetic minerals as well as to refine kaolin [38, 39]. Further improvement of some features of the traditional Jones-type WHIMS resulted in high capacities and improved separation performances [40-43]. The innovations include: the orientation of the carousel, the utilization of 1-3 mm diameter rods as filamentary matrix, depending on feed size range and the establishment of pulsation in the separation zone through an actuated diaphragm.

3.1.3 Electrostatic Separation

Research efforts on fine particle separation resulted in the development of novel separators, mainly based on tribo-electrification [18, 43-46]; the separation on various mineral commodities proved successful [18, 43-49].

3.2 Physicochemical Methods

The physicochemical methods applied to cope with the problem of fine particles separation are primarily based on the combination or modification of known processes and sophisticated flotation equipment. Some of the methods are based on the principles of selective agglomeration process solely while others on the combination of selective agglomeration with another method, such as flotation or magnetic separation. The most popular methods are cited below.

3.2.1 Methods involving flotation

The inefficient separation of fine particles in sub-aerating flotation cells has been known since long time ago. In this respect, flotation devices of special design have been developed and installed in flotation plants to overcome the problem, among which column cells [50-56], jet (Jameson) cells [57], “Microcell” column [58] and reflux flotation cell [59].

Also, various flotation techniques such as, dissolved air flotation [60], electro-flotation [61], oil flotation, liquid-liquid extraction [62] and carrier flotation have been developed. Thus, despite the progress at lab and industrial scale, there still exist many items to be solved, especially in the size range -20 μm.

In electro-flotation, electrolytically generated fine bubbles (oxygen, hydrogen or both) are involved to efficiently float fine particles [61]. In liquid-liquid extraction and oil flotation (or emulsion flotation), oil droplets are introduced into flotation cell to collect hydrophobic particles. The droplets/particles aggregates are collected on the top of the cell as separate immiscible phase (liquid-liquid extraction) or with the aid of air-bubbles (oil flotation). The drawback of the methods seems to be the relatively high oil consumption [11]. Carrier flotation (ultraflotation or piggy-back flotation) is based on the flotation of fine particles as slime coating of coarser (carrier mineral). In industrial level, it has been applied to improve the brightness of kaolin via removing anatase impurities [63]. The major drawback of the process is high reagent and carrier mineral consumption; another drawback is the required separation of mineral value from carrier, if the mineral value is concentrated in the froth.

3.2.2 Methods involving hydrophobic agglomeration

Hydrophobic agglomeration is a general term used to denote clustering of hydrophobic particles in aqueous suspension, due to hydrophobic interactions between them under intensive agitation. It is considered to be an effective and potential technique for the separation of very fine mineral particles.

Hydrophobic agglomerates present variability regarding their size, strength, structure and properties, which depend on the applied agglomeration process, the prevailing conditions and the interaction forces. The most common processes involving hydrophobic agglomeration are [1]: shear-agglomeration (or shear-flocculation), agglomerate flotation/floc-flotation, oil agglomeration (or spherical agglomeration), various magnetic carrier methods, selective agglomeration/flocculation.

In shear-agglomeration the fine hydrophobic particles are aggregated under shear field provided by intense stirring to overcome potentially existing barriers [64, 65]. The resulting hydrophobic agglomerates are not always either large or compact, unless the particles are strongly hydrophobic or reagents are added to render particles hydrophobic or reinforce hydrophobicity. The separation of agglomerates is generally achieved through screening, sedimentation, magnetic separation or froth flotation.

Agglomerate flotation (or floc-flotation) combines hydrophobic agglomeration of fine particles followed by their flotation with air-bubbles [66-68]. The size of the agglomerates must not be very large so that flocs are able to float with air bubbles.

Oil (or spherical) agglomeration is established, when large amount of non-polar oil is added [69-71]. In this case, the pores of the agglomerates are filled with non-polar oil and they appear in the form of pellets. The function of oil is to bind, through oil bridges, the particles into agglomerates that are strong enough to be separated by mechanical means (e.g., settling or screening) from the rest of the slurry.

Various sophisticated techniques of magnetic separation have been involved in the separation of fine/ultrafine mineral particles, with the following being the commonest: i) <u>Magnetic carrier (magnetic coating)</u> that is based on the selective coverage of feebly- or non-magnetic minerals with a very fine ferromagnetic material to artificially provide the surface of non-magnetic minerals with magnetic properties, with or without collector; this is attained by controlling the surface properties of the mineral to be covered and of the magnetic material [72]. Magnetic coat is stronger when collector is used; the combination of collector and an immiscible oil phase results in heavier magnetic coating [73, 74]. ii) <u>Floc magnetic separation (magnetic seeding or selective co-agglomeration with ferromagnetic particles)</u> is encountered in various forms. When hydrophobicity has been established on particles with paramagnetic properties, the inter-particle bonds are tighter, as they are subjected not only to hydrophobic attractive forces but also to magnetic attractive ones [75]. In case of non- or poorly-magnetic minerals, the incorporation of ferromagnetic particles, indifferent of size, into the hydrophobic agglomerates increases the magnetic susceptibility of agglomerates or establishes it (magnetic seeding). iii) Alternatively, if a suspension is flocculated with a high molecular weight polymer in the presence of a ferromagnetic material, then co-flocculation is obtained either due to entrapment of ferromagnetic material within the flocs or co-adsorption of polymer both on mineral and magnetic material [76].

iii) Selective wetting by ferromagnetic laden oil is achieved if naturally hydrophobic or collector-hydrophobized minerals are contacted with ferromagnetic laden oil droplets. In this case, ferromagnetic oil tends to spread over their surface rendering them selectively magnetic; hence, their separation from hydrophilic, non-magnetic particles is feasible [77].

Fine/ultrafine particles can also be selectively separated through agglomeration/flocculation by adding polymeric flocculants in the fine particle suspension.

The first step includes dispersion of the suspension using proper dispersant. Subsequently, flocculant is added to selectively agglomerate the fine particles of the target-mineral into flocs. Consequently, the target-mineral is efficiently separated from fine gangues by settling, as flocs settle faster than dispersed particles [78].

The method has been applied for the selective separation of fine synthetic mineral mixtures at lab-scale only [79], because of its sensitivity to various physicochemical and mechanical factors.

As mineral/polymer flocs are not always hydrophobic in nature, selective flocculation is not regarded as hydrophobic agglomeration method.

4. Conclusions

As high-grade orebodies are gradually depleted, mineral extraction and processing are shifted to continuously lower grade ones. This fact results in finer liberation size, inefficient separation, high losses of mineral values and high volumes of waste/tailings. To make mineral extraction and processing more sustainable, fine/ultrafine particles have to be efficiently processed.

Common separation methods fail to process fine particles, as they are scheduled to treat coarse ones. Efficient processing can be achieved through the development of innovative equipment and sophisticated processing methods. Some of them have already been applied while other have to be improved.

Among them modified flotation equipment and hydrophobic agglomeration combined with another method (flotation, settling, magnetic separation) are promising ones but they must be further improved.

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