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Fine, Coarse and Fine-Coarse Particle Flotation in Mineral Processing With A Particular Focus On The Technological Assessments

Ahmad Hassanzadeh 1,*, Mehdi Safari 2 and Duong Huu Hoang 3

1 Independent Scholar, Am Apostelhof 7A, 50226 Frechen, North Rhine-Westphalia, Germany; a.hassanzadeh@gmx.de
2 Centre for Minerals Research, Department of Chemical Engineering, University of Cape Town, Private Bag Rondebosch, Cape Town 7700, South Africa; saffari_mehdi@yahoo.com
3 Maelgwyn Mineral Services Ltd, Ty Maelgwyn, 1A Gower Road, Cathays, Cardiff, CF24 4PA, United Kingdom; dhoang@maelgwyn.com
* Correspondence: a.hassanzadeh@gmx.de; Tel.: +4917620666711 (A.H.)

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Abstract: After more than a century applying flotation to the mining industry, two completely different strategies have been introduced for processing purposes. One is the classical approach viz. grinding the ores to certain extend and floating them via conventional mechanical and recently pneumatic cells e.g. Jameson and Imhoflot™ cells. This strategy continuous because mines face up to declining cut-off grades, complex and poly-mineralized ores, and they require to achieve an acceptable degree of mineral liberation. The other school of mind deals with the coarse particle processes mainly owing to the low energy needs, that includes flash, fluidized bed and HydroFloat™ cells. The third and newest system proposes processing both fine and coarse sizes by flotation machines like oscillating grid flotation (OGC) and Reflux flotation cells. The present paper endeavours to critically evaluate these concepts from several points of view including existing technological elaborations, water and energy usages, kinetics and circuit design. Brief introduction of advanced technologies, along with their applications, were presented. It was revealed that the incorporation of coarse grinding apparatuses, mineralogical techniques together with the technologically applicable classification systems and adapted simulator tools are urgent needs for coarse flotation as the future requirements for mining industries. However, fine particle flotation may remain as the main focus of re-processing tailings dams.

Keywords: Flotation cells; fine and coarse particles; technological development; flotation kinetics; HydroFloat™ cells

1. Introduction

Froth flotation was undoubtedly the most innovative and mining saver in ore dressing in the 19th century [1]. Nevertheless, it did not last long that scientists recognized its limitations for extremely fine (<20 μm) and coarse particles (>150 μm) which have been remained as a long-standing unsolved issue in the mineral processing field [2]. From the early 20th century, many active industries applied the simplest solution to tackle this issue by increasing flotation cell size [3] with paying less attention to designing an efficient cell. This strategy has been a matter of argument over many years, which the present paper points this out by categorizing it into mainly two subdivision groups.
Generally speaking, three key points force the mining industries to coarse particle treatment containing I) drastic environmental consequences of wet tailings dams and acid mining drainage (AMD), II) losing precious materials in the coarse fraction sizes and III) enormous energy consumption (i.e., 2-4% global electricity usage) in comminution stages with less than 2% efficiency [4]. Although these concepts are well established, only a few technological developments have been appeared in mineral processing industries over the last decades. Microwave technology [5-6], high pressure grinding rolls (HPGR), and pneumatic type flotation cells are the major illustrations in this regard. The most recent industrial examples might be the commercialized rapid microwave and Nova Cell™. The former is the microwave (MW)-assisted grinding [7] which leads to a remarkable increase in material’s grindability, improvement of mineral liberation degree and reduction of the comminution energy over 30%. The latter is a developed flotation machine (Nova Cell™) shows saving in operating costs of grinding energy and media by 40% and 12% decrease in overall site operating cost [8].

In an industrial scale, up- and down-stream operating units (e.g. de-watering, grinding and classification) inevitably affect metallurgical responses of a flotation process. Thus, the efficiency of either coarse or fine particle treatment systems is inherently coupled with the performance of these units. For example, processing of rare earth elements (REEs) embedded in carbonate, fluorocarbonate, phosphate and fluorite deposits faces with massive challenges concerning their extremely low grades which leads to being ground finely for achieving a desirable liberation degree [9]. Poor recovery of fine particles is mainly related to the low frequency of collision between particles and bubbles (Zµs) [10-14], high specific surface area, high surface energy and most importantly low particle inertial force [15]. Technically speaking, to improve fine particles recovery in flotation, one must whether increase the particle size or decrease the bubble diameter. In this regard, the particle sizes can be enlarged by flocculants, while the small bubbles can be generated via dissolved-air flotation, induced-air flotation, hydrodynamic cavitation, electro-flotation and microbubble generators. The most common belief is creating an intense turbulent environment to increase particle-bubble collision efficiency (E), which is an extremely energy-consuming process [16-18]. Other than those, it was indicated at the OK Tedi plant that sulphidization by NaHS could improve copper recovery of fine particles (<20 μm) up to 3.4% [19]. Shear flocculation or high-intensity conditioning (HIC) is another technique used to upgrade the recovery of fines [20]. Mechanical vibration and the acoustic wave pre-treatments is also reported as a promising approach to enhance the recovery of fine fraction sizes up to ca. 3.5% by a cleaning effect on the surface of the minerals and generation of heterogeneous nucleation of microbubbles on the particle surfaces [21-22].

Some researchers worked on overcoming the challenges of fine and coarse particle flotation systems. Jameson [23] presented theoretical backgrounds regarding the main difficulties in recovering ultra-fine and coarse particles. He developed Concorde™ flotation cell and applied fluidization principles to upgrade recovery of ultra-fine (nickel sulphide and platinum ores) and coarse particles (galena) by a factor of ten. Recent advances in FLSmidth Inc. as a pioneer company in flotation processes can be classified into three groups as I) forced-air flotation machines (Dorr-Oliver) designed for recovering fine particles in terms of imposing high energy to these particles concerning their low inertia in tiring down the water film. II) induced-air flotation cells (Wemco) favourable for recovering coarse particles since these particles can be collected next to the surface and the travel distance to froth from the discharge lip is reasonably short. III) forced-air and induced-air cells (Dorr-Oliver and Wemco) in a circuit with the idea of recovering both fine and coarse sizes using a combination of the two technologies in the same row/bank or different flotation stages [24].

The present paper aims at introducing technological barriers that the froth flotation currently faces up with a particular focus on the identification of challenges and opportunities for treating coarse and fine particles.
2. Limitation of mineralogical approaches

Selection of fine or coarse particulate systems strongly requires a precise and appropriate mineralogy characterization approach. Recent developments indicated that X-ray computed micro-tomography (μCT) and mineral liberation analyzer (MLA) have been extensively utilized to characterize a variety of particle properties in the scope of process mineralogy for coarse and fine particle sizes, respectively [25]. The μCT is a non-invasive 3D technique that allows to image the distribution of minerals inside a sample while scanning electron microscopy-based methods like MLA and QEMSCAN (quantitative evaluation of materials by scanning electron microscopy (SEM)). It allows for a 2D quantitative analysis of mineral essays by combining backscattering electron (BSE) images with energy-dispersive X-ray spectroscopy (EDS) [26]. The low resolution (tens of microns) and the lack of chemical information have typically limited the application of μCT to identify and analyze fine particles. Nevertheless, it remains unclear how coarse a particle must be to be accurately measured by μCT [27].

From industrial perspectives, it is now possible to on-site measure particle characteristics in the range of 1-150 mm with a voxel resolution of approximately 100 μm at the sampling rate of 1 kg/min using high-speed X-ray computed tomography (HSXCT). Detailed information concerning the on-site measurements for coal washability, crusher plant products and pebble phosphates case studies can be found elsewhere [28-29]. Also, recent studies have manifested that the MLA and QEMSCAN cannot be applied in-situ and for coarse particle sizes [30]. For fine particles, it unavoidably suffers from a stereological bias along with a statistical dispersion in the light of the number of analyzed particles [31] which results in an overestimation of mineral liberation degrees. Moreover, there are natural uncertainties inherently linked to representativity and sample preparation shortcomings [32]. According to the raised assertions, there is an urgent need to tackle these issues related to either coarse or fine process mineralogies.

3. Fine or coarse particulate systems

Elephant curve is an explicit demonstration of the inefficiency of conventional flotation cells for recovering both fine and coarse fractions [33]. Figure 1 schematically illustrates the technological developments for raising either tail (via fine flotation systems, FFS) or trunk (by coarse flotation system, CFS) based on the energy consumptions [34].

Figure 1. An overview of existing flotation equipment based on energy consumption and particle size

3.1. Fine Flotation

In this section, technological and conceptual advances in FFS are briefly introduced. Other developments such as electro-flotation (EF) [35-37], carrier flotation [38] and reactive oily bubble systems [39-41] are not discussed in this paper. In this scope, one can find invaluable information in a manuscript presented by Farokhpay et al. [42]. Furthermore, two devices developed at the University of Newcastle, Australia i.e. Concorde cell™ [23, 43] and the Reflux Flotation Cell (RFC) [44] together with StackCell™ typically used for treating particles <150 μm (Eriez Manufacturing Co.) [1] are not included in this paper. They will be presented and discussed in details in a future study.

3.1.1. Pneumatic cells
Pneumatic flotation technology was originally developed in the 1970s by Bahr et al. [45] at the Technical University of Clausthal (Germany) and Simonis et al. [46] at the Technical University of Berlin (Germany) which the cell was so-called Bahr cell. The first research work was initiated in 1973 while the prototyped model was built up in 1978. It is well documented that the pneumatic flotation is more effective than the conventional cells in terms of recovering fine particles [47]. The pneumatic and traditional flotation cells differ concerning a requirement for compressed air and agitation, which consequences substantial energy saving in pneumatic ones [48]. Most recently, Safari et al. [49] pointed out this by reverse flotation of iron ore utilizing mechanical, oscillating grid and pneumatic cells. They manifested that the pneumatic flotation cell shows the best flotation performance for most operating conditions. Lima et al. [50] addressed the same concept by comparatively analyzing mechanical and pneumatic cells for quartz flotation. Two commonly used pneumatic flotation machines are Jameson™ and Imhoflot™ cells discussed as follows.

3.1.2. Jameson Cell

There have been about 350 Jameson Cells installed in a variety of coal (especially in Australian coal industry), metalliferous and industrial mineral application worldwide [51-52]. This type of flotation cell was used for upgrading final grade and increasing capacity issues of conventionally operated flotation cleaner circuits [53]. It was initially developed as a low-cost alternative to traditional column flotation cells for recovering fine particles. It was firstly installed at Mount Isa lead-zinc concentrator in 1988 and successfully recovered fine particles (<12 μm). Higher lead grade in concentrate (60%) was reported compared to the conventional cleaning circuit (51%). The Jameson Cell was successfully operated in the cleaning stage to treat the porphyry gold-copper ore in Minera Alumbrera Ltd in Argentina resulting in respectively gold and copper recoveries of about 80% and 90% for particles finer than 10 μm [54].

Technically, the cell works by closing the air inlet at the top of the downcomer while feeding the flotation pulp through the nozzle leads to the high-intensity particle-bubble contacting [55]. The feed is pumped into the downcomer through an orifice plate, and create a high-pressure jet where the plunging jet of liquid shears and entrains air [56]. It results in a rapid contact and collection of particles and bubbles in high mixing velocity and a large interfacial area, which ultimately consequences extremely short residence time. A vital privilege of this type of cell to the traditional mechanical cells is its faster kinetics rate. This relates to the gas holdup in a confined downcomer which is typically far higher than that of a conventional flotation vessel, reaching in some cases up to 60% [57]. However, the typical mean residence time (MRT) of a mechanical cell circuit is about 4-20 min for a rougher stage, depending on the mineral type and the number of cells in a bank, and up to 30 min for scavengers, while for a flotation column is in the range of 18 to 23 min, depending on the column design [58]. In this scope, Harbort et al. [59] reported a reduction in MRT of a mechanical rougher-scavenger circuit (17.9 min) and cleaner-scavenger circuit (30 min) down to 7.5 min and 2.5 min using Jameson cells with identical flotation performances.

3.1.3. Imhoflot™ cell

The history and development of Imhoflot™ pneumatic flotation cells are well documented in several technical reports [60-62]. The commercialization began in the early 1980s. From designing perspective, it differs from the conventional cells in that the particle-bubble collision takes place outside of the cell, within the aerator (called as a pipe flotation) [47]. Similar to HydroFloat™ and column flotation cells, it does not require compressed air and agitation, which provides the opportunity of saving a tremendous amount of energy compared to the traditional mechanical cells. The energy input goes more directly into the particle-bubble collision, rather than energy being used to maintain the pulp in suspension as in mechanical cells. The slurry is pumped with enough fluid energy to produce intensive aspiration of air and rapid dispersion for efficient particle-bubble collision [63]. The method of self-aspiration of Imhoflot™ flotation is based on the well-known venturi principal. However, the patented design has a complex system of nozzles, impingement plates and gas hold up mechanisms that generates a spectrum of fine bubble size. Maeqwyn Imhoflot™ flotation cell has three different types, i.e., vertically fed (V-cell), tangentially fed (G-cell) and another type called H-cell, which is similar to the G-cell. This type enables to introduce feed vertically via a separate
...distributor box located at the base of the tank. The design of the Imhoflot™ cell type depends on the particle size. The V-cell is generally used for the intermediate and coarse particle (i.e., 50-300 μm) flotation while the residence time is approximately 3 min. Imhoflot™ G-cell is favoured for very fine to intermediate-sized particles (i.e., <50 μm) with a very short residence time of approximately 1 min depending on the particle size, mineral characteristics i.e., mineral hydrophobicity, association, and liberation. The Imhoflot™ flotation cell including G-cell has been successfully applied to the mineral processing and recycling industries in the last two decades and practically demonstrated its capability in recovering ultra-fines. The application of a three stages Imhoflot G-Cell at a nickel operation plant in Europe showed its ability to recover approximately 30% Ni from the final tailings, predominantly in the <11 μm size fraction. Further, a two-stage Imhoflot G-Cell plant was established at a zinc operation to avoid losing fine intergrowth 7 μm particles. It recovered ca. 20% of the zinc from the final cleaner tailings [47].

3.1.4. Floc-flotation

As noted earlier, the principle issue related to poor floatability of fine and ultrafine particles is generally attributed to their low momentum and inertial force under conventional hydrodynamic and thermodynamic properties of flotation cells [64-65]. This leads to a low probability of E. and consequently, poor flotation kinetics rate constant [66-67]. Floc-flotation is a technique to aggregate the fine particles using a polymer flocculant, hydrophobic interactions and micro-organisms to obtain coarse-sized particles a.k.a. flocs to tackle those issues. There are many successfully reported achievements in a laboratory scale for coal [68], malachite [69], hematite [70], quartz and galena [71], calcite and talc [72]. However, yet only one unique industrial illustration operating since 1974 is Tilden nonmagnetic taconite concentrator located in the U.S.A. [73]. The main crucial aspect of this process is related to the type of polymer and low selectivity separation due to heterocoagulation and entrapment phenomena. More detailed information can be found elsewhere [74].

3.2. Coarse flotation

Few research studies showed approximately 2% improvement in the recoverability of coarse particles by distributing chemical reagents throughout the flotation circuit [75-77]. Nevertheless, coarse particle treatment by the conventional flotation machines is nearly impossible due to essential needs for a massive amount of energy for material suspension, high particle-bubble detachment probabilities, low retention time and limitations regarding the buoyancy force of the bubbles. The following section highlights two examples in terms of treating coarse fraction sizes, focusing on Flash flotation and HydroFloat™ technology.

3.2.1. Flash flotation

The flash flotation cell (SkimAir® Courtesy Outotec (formerly Outokumpu)) proposed in the early 1980s to flash off fast-floating liberated minerals of high value. It has been broadly used but not well understood for processing complex ores containing coarse (-212+38 μm) or free gold [78]. It was designed to avoid over-grinding of the valuable dense sulfide minerals in circulating load of primary milling circuits that allows floating coarse particles with high-grades in early flotation stages [79]. Technically, flash flotation enables a concentration plant to minimize over-grinding, enhance overall recovery, increase mill throughput and improve dewatering through shrinkages filter costs and diminishes final concentrate moisture. Its feed (up to 1800 tph) is normally the hydrocyclone underflow with high slurry % solids (up to 70%), which the flash flotation tailings recirculate into the grinding unit. One important privilege, which is often overlooked, is that the SkimAir® provides a buffer for the conventional flotation circuit to produce a more stable feed when the feed grade is highly variable. Another advantage of the flash flotation is the minimal contact time of particles with reagents and almost no conditioning stage prior to the flotation. Detailed description of the process of flash flotation was presented by Newcombe et al. [80].

3.2.2. Erize HydroFloat™ technology

HydroFloat™ is an aerated conical-shaped fluidized-bed (teeter-bed) separator which synergistically combines flotation with gravity/elutriation techniques enhancing the recoverability of middling (>150 μm), coarse (<2000 μm) and poorly liberated particles. In early 2000s, several proof-of-concept trials were carried out at laboratory and pilot scales (phosphate [81]) concerning its...
application for mostly sulfide type ores as well as potash (Canada), coal, vermiculite (U.S.A.), spodumene (Australia) and diamonds (Canada) [82]. The first full-scale industrial unit (3 m diameter) was commissioned at PotashCorp’s Rocanville potash mill to treat approximately 125 t/h of coarse tailings. It upgraded the potash recovery from approximately 50% to over 90% [83]. Mosaic’s South Fort Meade Mine [84] and PotashCorp’s Aurora beneficiation plant [85] were other successful examples. The initial sulfide mineral full-scale (3.4 m diameter) installation and operation was performed on rougher flotation tailings (-300+150 μm) of a copper ore at Newcrest’s Cadia Valley, New South Wales, Australia in 2018.

Practically, three zones within the vessel in a top-down design are as i) free settling phase with low solids concentration, ii) fluidized bed with nearly plug-flow mixing regime, and iii) dewatering zone with higher % solids (ca. 60%). This design induces floatability improvements by maximizing Zpb and particle residence time together with a minimization of axial mixing, particle-bubble detachment rate, turbulence and froth buoyancy restrictions [86]. One crucial advantage of the Erize HydroFloatTM to the conventional cells is extremely low (1%) necessity of mineral surface hydrophobization (>800 μm) and no agitation mechanism [87]. It also leads to not only reduction of capital and operating costs but also improves sustainability, tailings management and environmental aspects [88]. Most importantly, it shows an enormous drop-off of grinding energy consumption and 20-25% increase in mill throughput depending on the application.

3.3. Fine and coarse flotation

Typical overall flotation recoveries in many of mineral industries are between 80-90%, and as shown in previous reports [89, 90] virtually in all operating concentration plants, most of the losses are in particle sizes below 20 μm (50%) and above 150 μm (30–40%) fractions. The third ideology is to apply advance technologies allowed to float both these extreme sizes. As an example, considering copper alone, assuming an average loss of ~10%, the flotation loss described could amount to at least 1.5 million tonnes per year, with a cash value of $10 Billion. The real problem is that over 99% of what is mined in the precious metal industry is considered waste. Therefore, coarse particle flotation could allow mines to reject some waste earlier in the process before the fine flotation circuit, which might help to reduce capital and operating costs.

Each flotation cell is designed for targeting specific particle size range based on its hydrodynamic properties. It is a problem with both fine and coarse particle recovery that have been the focus of many subsequent novel cell developments. Most of these systems attempt to improve the fine or coarse particle recoveries. Therefore, it is good to have a flotation cell that floats both fine and coarse particles. The idea is that it would be part of a split circuit, presorted into coarse and fine, with technologies tailored to each. To float both size ranges, the following sections exemplify two vessels developed in bench-scale including oscillating grid cell (OGC) and reflux flotation cell (RFC).

3.3.1. Oscillating grid flotation cell

In the past two decades, a considerable amount of research has been undertaken in flotation, especially in the flotation cells. Research into flotation cells has focused on the development of new flotation cell technologies from a better understanding of the impact of cell hydrodynamics on the sub-processes of flotation. Several excellent studies into the effect of energy on flotation kinetics have been carried out in impeller stirred cells [91-95]. Investigations using this type of cell have a number of limitations such as the impeller influences particle suspension, bubble break-up and turbulence is highly inhomogeneous and anisotropic near the impeller [16, 96]. These limitations have resulted in the development of a novel flotation cell. The OGC was initially developed for the investigation of hydrodynamic parameters like energy input on flotation performance.

Energy input in a flotation cell is an important parameter which, if optimized, can increase the flotation rate [97, 98]. Safari et al. [99] investigates the effect of energy/power input on flotation kinetics in a novel oscillating grid flotation cell in lab scale. This study clearly demonstrates that optimal energy inputs for the flotation of fine and coarse particles differ significantly. For example, the apatite flotation results indicate that flotation rate constant for the finer particles (<38 μm) increases by around 200% with an increase in energy input from 0.1 to 2 W/kg. This is due to an increased bubble-particle collision/attachment. However, the flotation rate constant for the coarse particles (~650+150 μm)
decreases by over 900% over the same energy input range. This is because of improved bubble-particle detachment since the greater detaching forces lead to decreasing bubble-particle aggregate stability. The pilot OGC survey suggests that higher energy inputs are generally beneficial for the flotation of platinum ores as these consist predominantly of finer particles as observed in the flotation literature [100, 101].

The OGC experimental results in lab and pilot scale successfully showed that the effect of energy input on the flotation rate is strongly dependent on the particle size. The changes (increases/decreases) in the flotation rate with increasing energy input are very large for most of the conditions, indicating that this is an important parameter in flotation. The OGC results confirm the technical part behind most of the flotation cell designed so far. Safari et al. 2016b results showed why some flotation cells operate at high energy input and have high performance for fine particles; some flotation cells operate at low energy input and have high performance for coarse particles. The OGC was tested in the wide range of particle sizes up to 650 μm. The survey results clearly demonstrated that the OGC had a great potential to recover fine and coarse particles by optimizing the collision efficiency, attachment efficiency and stability efficiency for each particle size range and controlling the hydrodynamic parameters like energy input and bubble size.

3.3.2. Reflux flotation cell (RFC)

The RFC was initially developed for gas-liquid system and later for processing low pulp density coal slurries [102-104] showing the feasibility of extremely fast flotation [105]. This could be achieved by maximizing the kinetics of particle–bubble attachment, the bubble interfacial flux for particle extraction, and the rate of bubble–liquid segregation [106]. The maximization can be accomplished by two main features of the RFC. First inclines channels located below the main vertical section of the cell, causing to the enhancement of the bubble–liquid segregation rate, which is indeed an application of the Boycott effect [107]. The second is a multi-channelled downcomer used to deliver an extremely high flow rate into the flotation system under an excessive shear rate. A high volumetric flow rate combined with the narrow spacing within the channels generates a high shear rate, ideal for the formation of tiny bubbles and promoting collisions between the fine particles and the bubbles. Similar to the Jameson Cell, the RFC advantages a high gas hold up, leading to thin-film migration which may play a role in the particle collection [108]. Regarding the coarse size range of particles, high bubble concentrations generated by high feed fluxes at moderate gas fluxes allow for greater probabilities of particle-bubble re-attachment. Due to the excessive concentration of bubbles in the fluidized bed, any particles that detached from a bubble will immediately encounter another bubble and reattach.

5. Conclusions

Since the inception of froth flotation in 1905, numerous flotation machine designs have been proposed, particularly in the last 50 years. Traditionally, flotation has been performed in mechanically agitated tanks and the minerals processing industry has been particularly slow in its uptake of new cell technologies. For this purpose, the present work briefly highlighted the main concerns and advances in treating fine and coarse particles, focusing on flotation cells. A brief technical explanation, together with the historical background, was presented for each device. The primary reason for that was that the development and testing of new flotation cell designs might be costly and inherently risky to any mining company. Elaborations of mineralogical characterization techniques, which can precisely analyze the materials in extremely coarse and fine sizes seem urgent for the future of mineral processing. Also, classification equipment along with circuit designs adapted to the fine and coarse flotation require further studies in future works.

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