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POTENTIAL ADVANCES IN FLOTATION BY USING WATER JETS

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Some mineral processing problems are not yet satisfactorily solved by the current technology, especially those based on the use of mechanical energy for comminution and separation. The use of mechanical energy has certain inherent drawbacks such as wear of machinery components and limitation in the speed of moving parts to avoid risk of failure under the severe working conditions encountered in the industrial processes. Waterjet can contribute to overcoming such disadvantages since it allows to transfer energy without contacts between solid materials (no wear) and it is suitable for generating high velocity streams in air or in water even at relatively low pressures. The potential benefits of waterjet technology are particularly interesting in flotation where the size and speed of the air bubbles, that depend on the shear velocity induced by agitation, are a critical aspect for the optimization of the separation results (recovery and selectivity) and the reduction of the running cost items (wear and energy consumption).

keywords: waterjet, flotation, coal flotation, comminution

1. INTRODUCTION

The possibility of taking advantage of the power of water in mining and mineral beneficiation is known since early times, although only very few instances of the application of this technology can be found in the industrial practice. In Spain Romans used to disintegrate the gold-bearing soft formations by means of water streams forced to flush down the slope of the hills against the ore (*ruina montium*). The flow of suspended particles was then allowed to settle along appropriate channels where heavier gold particles could be separated by gravity from the washed-away barren

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sand.

Much later, the same principle has been employed for digging the ore during the *gold rush* as well as for coal production in underground mines, using low pressure, high flowrate monitors.

More recently, attempts were made for winning hard rocks by means of high pressure water cannons, although the productivity was poor due to the discontinuity of the operation.

Today the interest in waterjet technology is considerably increased and widely expanded owing to the development of suitable systems capable of generating a variety of jets for specific applications in different fields of science and engineering.

The performance of the jet can be enhanced by the addition into the water stream of suitable components like, for instance, soluble polymers for improving the coherence of the jet over longer distances, and/or abrasives for increasing the erosion capability when cutting hard materials. Accordingly, a water jet can represent an efficient tool, alone or in combination with other actions of different nature (mechanical, chemical, thermal, electric) for piercing, drilling, cutting, kerfing, milling, fracturing, crushing, and cleaning any kind of solid material, to the characteristics of which the jet can be properly tailored, as well as for carrying, stirring, emulsifying, aerating, breaking, and blending multiphase mixtures.

2. STATE OF THE ART IN FLOTATION

2.1. PROBLEMS ENCOUNTERED WITH CURRENT TECHNOLOGY

Froth flotation is the dominating mineral beneficiation technique and has achieved great commercial success. This process has also found many applications in other industrial fields where physical separation of materials is needed like, for instance, water cleaning and decontamination, elimination of foreign materials from molten metals, and so on.

However, its process efficiency is often limited to a narrow particle size range of approximately 10-100 μm (Tao, 2005).

It is a well known fact that separation performance of traditional flotation machines gradually deteriorates as particle size decreases, resulting in a poor recovery, unsatisfactory quality of the product and a high specific consumption of energy and reagents, when very finely ground materials, let's say below few microns, are treated.

2.2. BUBBLE POPULATION FEATURES

The formation of air bubbles into the pulp is the necessary requirement for the development of the flotation process. Collection efficiency increases if the bubbles are well dispersed into the cell meaning that, for a given volume of injected air, bubble size should be as small as possible at the moment of their generation, merging later then into larger bubbles due to coalescence phenomena for the uplift of attached mineral particles.

From the analysis of the conditions governing the dispersion of the bubbles in flotation cells with mechanical agitation it emerges that their average size decreases if: i) the surface tension at the liquid-gas interface increases, ii) a more intense turbulence into the liquid phase is achieved and iii) air is injected into the pulp at higher velocity (Klassen and Mokrousov, 1963).

Studies on the effects of the gas phase have shown that in flotation, like in other gas-liquid mass transfer processes, the rate of mineral recovery is intimately linked to the bubble size distribution in the flotation vessel.

It is widely recognised that particle-bubble collision, attachment and detachment, bubble collapse, insufficient buoyancy action for heavier floatable particles and the undesired mechanical draw of gangue slimes are the most critical steps in the flotation process. All these aspects require a careful knowledge and control of the hydrodynamics in the flotation cell.

A scientific approach to the problem enables to meet the growing need to design larger and more efficient flotation cells to treat the lower grade and more finely disseminated ores that are currently being mined in the world.

2.3. AVAILABLE KNOWLEDGE

2.3.1. IMPORTANCE OF BUBBLE SIZE

Many researchers have been dealing with the problem concerning air bubble generation and hydrodynamics into flotation cells.

It is generally agreed upon that the scant flotation recovery of very fine particles is mainly due to the low probability of bubble-particle collision, while the main reason for poor flotation recovery of coarse particles is the high probability of detachment of particles from the bubble surface. Fundamental analysis indicates that use of smaller bubbles is the most effective approach to increase the probability of collision and reduce the probability of detachment (Tao, 2005). The same statement has been made by other authors.

It has been experimentally proven that the degree of aeration of the pulp in the form of small bubbles increases linearly with the relative velocity of the two interacting fluids (air and water) whereas it is inversely proportional to the so-called capillary elasticity, i.e. the ratio between surface tension and bubble diameter.

While a reduction in surface tension always plays an outstanding role in the process, on the other hand it is also clear that, at equal surface tension, a good dispersion chiefly depends on the shear friction between the liquid and the gaseous phase, i.e. on the degree of turbulence right in the region of bubble formation.

The amount of friction, strictly related to the transfer of momentum, is given by the well known general equation:

$$F = A \, \mathrm{K} \, (-\Delta \mathrm{V})^2, \tag{1}$$

where F is the friction force, A the contact surface, K a constant, ΔV is the equilibrium velocity, i.e. the difference between the actual velocity of one of the phases at a given point and that which would theoretically be reached under the same conditions if it were in a state of steady flow with the other phase (Loncin, 1961).

Further confirmation of the importance of bubble size distribution can be found in a comparison study of column flotation technologies for cleaning Illinois coal: generation of small bubbles can be promoted by increasing the shear rate of the fluid at the bubble nucleation site.

In the same study it is underlined that the addition of larger amounts of frother in order to further reduce bubble size can be detrimental to selectivity as a result of increased water recovery from the pulp to the froth. Therefore, reducing bubble size by increasing the shear rate should be regarded as a better choice in terms of selectivity, although this alternative could result in a somewhat higher energy consumption (Honaker, 1994).

The successful achievements of column flotation technology especially in the case of fine particles is due to the fact that the external bubble generators used in column flotation produce smaller bubbles with higher degree of uniformity than conventional flotation cells. Consequently, a significant increase in the rate of coal recovery from the pulp can be achieved owing to the larger overall amount of bubble surface area for a given aeration rate, available for the capture of floatable particles.

2.3.2. HYDRODYNAMICS OF MULTIPHASE FLOW IN THE CELL

Different concepts have been developed in the attempt to improve the chances of bubble-particle attachment. For example, one approach utilizes a complete froth column. Other techniques utilize packing or baffles to reduce turbulence, thereby, decreasing the probability of a particle escaping without bubble contact. The use of self-induced air and the generation of uniform microbubbles are novel concepts of other column technologies.

Ahmed and Jameson (1985) reported an almost one-hundred-fold increase in the rate of fine quartz flotation when the average bubble size in their batch flotation cell was reduced from 655 to 75 μm, and Yoon and Luttrell (1989) showed theoretically that the probability of contact between particles and bubbles in flotation varies as the inverse of the bubble size raised to a power of between 1 and 2.

An obvious consequence of any attempt to enhance the probability of collision between the air bubbles and the particles is that the retention time required to achieve a high recovery decreases considerably even 2 to 3 times less, like in the case of the

Jameson Cell. The overall carrying capacity of the froth in ton/hr of product increases accordingly (Honaker, 1994).

2.3.3. MODELLING THE FLOTATION PROCESS

From the above it emerges that a careful study of bubble features is of a paramount importance for the optimization of flotation performance.

To this end a number of models have been proposed. However, the traditional approach to modelling gas dispersion in mechanical flotation cells has generally not involved micro-properties such as bubble size distribution, but has rather dealt with macroscopic properties of the system.

A more sophisticated attempt to describe the bubble population balance in both the space and time domains allows to predict the Sauter mean bubble diameters in a mechanical flotation cell which is treated as two separate, statistically homogeneous zones: the impeller zone and the bulk tank zone (Sawyerr et al., 1998).

Balance functions for the rates of bubble breakage, coalescence, recirculation and inlet-outlet events are proposed based on classical chemical engineering research in two- and three-phase fluid mixing systems.

The reliability of mathematical models can be better assessed with the assistance of observation techniques capable of sizing accurately a large number of bubbles. A technique consisting in exposing a stream of bubbles to a progressive scan camera has been used to study the effect of several physical and chemical variables on bubble size in laboratory scale flotation cells (Grau, 2006).

2.3.4. EFFECT OF TURBULENCE

Experimental results of a research aimed at purifying molten aluminium indicate that turbulence may enhance the flotation rate of non-metallic inclusions to bubbles significantly. Possible flow phenomena responsible for such effects are investigated. Only the smaller eddies contribute to an enhanced turbulent deposition of inclusions whereas the eddies in the spectrum larger than the bubble diameter can only displace the bubble.

The bubble size and the collection conditions at the bubbles may change considerable with rotor speed. Turbulence may increase the collection efficiency by more than 100-fold compared to laminar conditions (Gammelsæter et al., 1997).

The hydrodynamic conditions prevailing in the flotation cells can be modified mainly by altering the impeller speed and aeration conditions, as well as the frother concentration.

The aeration rate has a profound impact on bubble generation because the bubble size increases with an increase of the air flow rate entering the flotation cell. The aeration rate seems to determine to a large extent the size, shape and behaviour of the aerated cavities formed behind the blades of the rotor of the cell.

The U.S. Bureau of Mines examined the influence of turbulence on the fine bubble flotation of fine-sized (minus 40 micrometer) galena in order to improve flotation efficiency. While improved flotation response was obtained with intense agitation, the effect of bubble size was small. These results matched the model's predicted response for fine particle flotation (Spears and Jordan, 1989).

2.3.5. EFFECT OF FROTHER ADDITION

With increasing frother concentration, the degree of bubble coalescence decreases, while at a particular frother concentration, known as the critical coalescence concentration (CCC) bubble coalescence is totally hindered. The experimental results also indicate that frothers appear to affect the break-up process or bubble generation. (Grau, 2006)

At frother concentrations beyond CCC, bubble size is no longer determined by coalescence but depends on the sparger geometry and hydrodynamic conditions.

The results show that probability of collection increases rapidly with decreasing bubble size, and the values are in good agreement with the theoretical collision probabilities predicted from Weber and Paddock's analysis (Yoon and Luttrell, 1989).

Coalescence can be prevented at frother concentrations exceeding the critical coalescence concentration (CCC). The foamability tests indicate that stability of foams under dynamic conditions is determined by bubble coalescence (Cho and Laskowski, 2002).

The ultimate size of bubbles in a flotation cell is an outcome of competing processes: coalescence of bubbles and adsorption of the surfactant on their surface. Formation of highly developed initial interface due to break-up of the gas phase is an indispensable condition for stabilizing bubble size at a lower size level (Kondrat'ev and Bochkarev, 1998).

2.3.6. INSIGHT INTO THE MECHANISM INVOLVED IN FLOTATION

The basic mechanism of gas dispersion under highly turbulent conditions has been dealt with by a number of researchers. In mechanically agitated, aerated vessels, such as flotation cells, air introduced into the cell accumulates in low pressure cavities behind the impeller blades and bubbles are sheared off the cavities by the impeller's rotation (Tatterson, 1991). These bubbles are further broken under the turbulent conditions in the impeller region and are then dispersed throughout the cell by the pumping action of the impeller. In the bulk region of the cell, bubble motion is controlled by the surrounding fluid circulatory motion and by the bubble's inherent buoyancy. Bubbles in this region may collide and coalesce, re-circulate back to the impeller region, or rise out of the cell. The equilibrium bubble size distribution in the cell is ultimately dictated by all the events taking place in the cell, in particular by the relative rates of bubble breakage and bubble coalescence in the cell.

Investigations into bubble coalescence reported in the literature have isolated the coalescence rate by eliminating the contribution of bubble breakage to the equilibrium bubble size distribution. This has been done either by employing very quiescent bubble columns where the rate of bubble breakage was negligible, or by sparging bubbles into the system that were too small to be broken up by the impeller.

It is evident that both coalescence and breakage are complex, interdependent phenomena that are influenced by the instantaneous state of the system, in systems such as the mechanical flotation cell, where both bubble breakup and coalescence are taking place.

3. WATERJET POTENTIAL IN FLOTATION

3.1. LABORATORY EXPERIMENTS

3.1.1. STARTING POINT OF THE RESEARCH

As pointed out above, poor results are generally achieved in the treatment of slimes using conventional methods. Since fine size fractions below 0.5 mm can together represent a significant portion of the plant's feed, the development of suitable technologies for an efficient recovery of their valuable mineral content may give a considerable contribution to the economic balance of the beneficiation process. Froth flotation can be regarded as the most attractive technique for treating such slimes.

In order to create the most favourable conditions for the full development of collection and separation mechanisms, a new approach has been devised and tested, according to which agitation is produced using high velocity water jets generated through a suitable nozzle configuration (Carbini et al., 1996; 1998; Chudacek et al., 1997).

In mechanically agitated conventional flotation cells impellers are used for creating the conditions for achieving the highest differential velocity between the liquid and the gaseous phases, thus enhancing the pulp aeration. There the differential velocity is that established at the rim of the rotor between the incoming air and the layer of stirred water (Ciccu and Kursun, 2010).

However, in spite of using suitable devices like a facing stator with the goal of improving the effect, differential velocity commonly achieved in mechanical cells does not exceed few metres per second.

On the basis of these considerations, the possibility of applying a different concept in the attempt to increase substantially the differential velocity was an intriguing opportunity to investigate.

Collection efficiency improves if the bubbles are well dispersed into the cell meaning that, for a given volume of injected air, bubble size should be as small as possible at the moment of their generation. Then controlled coalescence into large bubbles can ensure sufficient buoyancy while avoiding rupture phenomena due to thinning of the interface film.

To this end, the chances offered by waterjet seemed very attractive for a number or reasons such as

- possibility of generating a high velocity water streams, at least one order of magnitude higher than with mechanical impellers, even at relatively low pressures,
- high turbulence into the vessel owing to the feasibility of producing a number of superimposing whirls by suitably modifying the arrangement of the nozzles,
- smaller initial bubbles issuing from calibrated holes right below the waterjet nozzle,
- even distribution of the bubbles inside the vessel (Fig. 1).

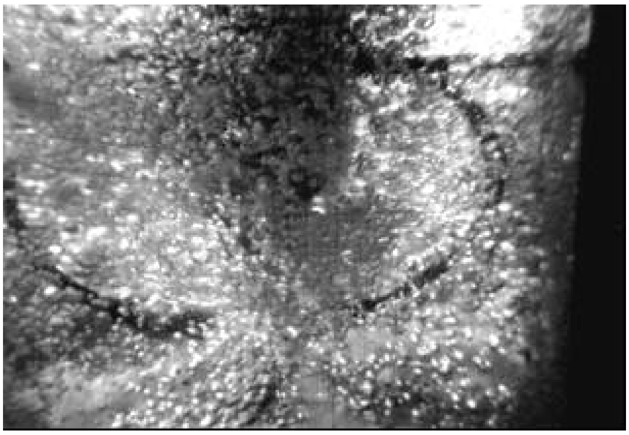

Fig. 1. Features of bubble produced with waterjet agitation

A high-velocity water jet is capable of carrying a considerable power (up to some hundreds of kW) concentrated in a small space (less than 1 mm^2). When this beam of energy is injected into a vessel filled with still water the shear velocity can be very high, by at least an order of magnitude greater depending on the hydraulic parameters (pressure and flowrate).

3.1.2. LABORATORY EQUIPMENT

A prototype of the waterjet-agitated flotation cell named ‘Hydrojet’ has been designed and built. It consists of a cylindrical vessel, about 10 dm^3 in volume provided with a hemispherical bottom screen for the discharge of the reject through a central outlet. Froths are eliminated through a chute in the upper section of the cylindrical body (Carbini et al., 1998).

The efficiency of the flotation process depends highly on the initial contact between the air bubble and the mineral particle. To enhance this contact, the nozzle arrangement inside the flotation cell has been devised to achieve good mixing between the suspended solids and the dispersing air. A sketch of the laboratory equipment is shown in Fig. 2.

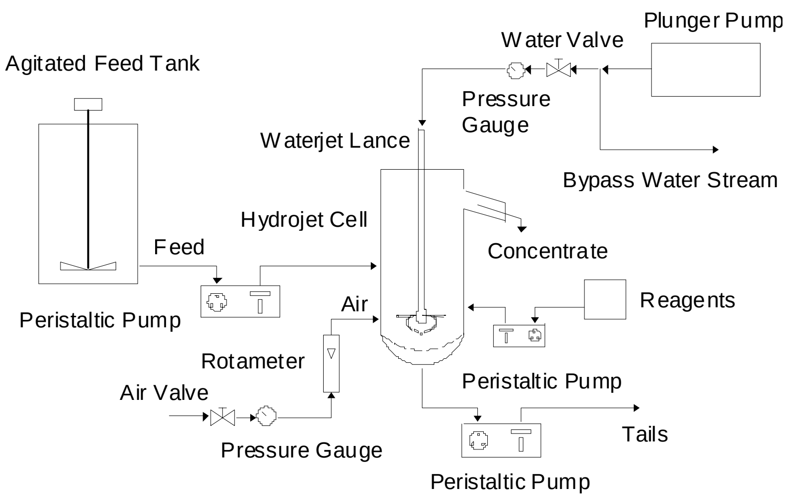

Fig. 2. Sketch of the Hydrojet cell laboratory equipment

3.2. RESULTS

3.2.1. PROOF OF THE HYDROJET CONCEPT

Parallel series of flotation tests have been carried out with waterjet or with a conventional impeller (M&M), using the same cylindrical cell under common experimental conditions for the unbiased comparison of the results. Experiments were made on samples of a run-of-mine coal, a barite crude ore and a sphalerite sample with quartz gangue.

3.2.2. COAL FLOTATION

The high-rank coal utilised for the flotation tests, coming from the Walsum mine (Germany) was dry ground to below 0.3 mm. The kinetics of the process with waterjet or with mechanical agitation was studied by varying the solids feed rate. Technical results (fuel recovery and quality of the separation products) as a function of residence time are summarised in Fig. 3. Recovery with waterjet is considerably higher than that achieved with mechanical agitation. Results are better using only two jets, although the quality of the product is slightly worse. For achieving the same recovery a 2.5-fold longer residence time is needed with mechanical agitation (Agus et al., 1998).

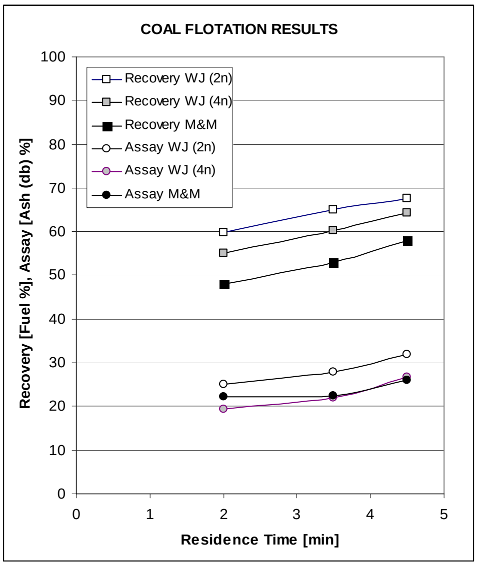

Fig. 3. Rougher flotation of Walsum coal. Fuel recovery and ash content in the product versus residence time. Frother concentration (MIBC) was 9.7 g/dm^3

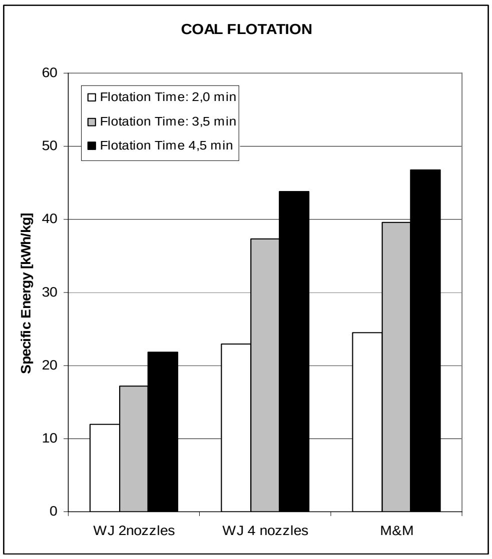

Fig. 4. Specific energy consumption in coal flotation experiments

A further advantage offered by the Hydrojet cell is a considerable reduction in energy consumption, as shown in Fig. 4, where specific energy per kg of recovered coal is represented at variable residence time. Compared with the conventional cell, specific energy with four 0.3 mm jets is almost the same but it becomes less than half if only two jets are used, which is also the most favourable condition for separation (Carbini et al., 2007).

3.2.3. FLOTATION OF INDUSTRIAL MINERALS

The sample used for the experiments, dry ground to below 0.2 mm, contained about 45% $BaSO_4$, the main gangue components being limestone, silica and iron oxides. Results of rougher flotation are summarised in Fig. 5.

The following aspects are worth underlining:

– $BaSO_4$ recovery with waterjet is somewhat higher than that achieved with mechanical agitation at any dosage of collector, although with lesser evidence than for coal (Carbini et al., 1998)
– $BaSO_4$ content in the concentrate is slightly higher with waterjet in spite of using half the power
– results do not improve by doubling the jet flowrate using four 0.3 mm nozzles instead of two at equal pressure
– the presence of an optimum value for pressure can be identified around 9 MPa for the laboratory model, although it can be higher for larger cells.

The above findings are of great interest for the future development of the concept and the improvement in the design and operation of waterjet cells.

3.2.4. SULFIDE FLOTATION

The zinc sulphide ore used for the new series of experiments originates from a Sardinian mine and averages about 9.5 % Zn, ground to below 0.2 mm.

In order to put into a better evidence the expected advantages achievable by using water jets, flotation tests have been carried out using the same cylindrical vessel, hosting the waterjet nozzle head (Hydrojet cell) or the conventional impeller (Minemet), under common experimental conditions concerning the reagents used and their dosage, the solids feed rate and mass concentration, the residence time (3.5 min) and the air flow rate

Results of the comparative tests between Minemet and Hydrojet cell carried out according to the above described procedure are summarised in Fig. 6, where Zn recovery and Zn grade of the rougher concentrated are plotted against air rate.

It is worth underlining that both Zn recovery and Zn concentrate grade with the Hydrojet cell are well higher (by more than 10 percent points, and by about 2-3 points, respectively) than those achieved with mechanical agitation at any pulp aeration conditions, while the metal loss in the tailings is significantly lower (by at least 2 points).

All the curves are almost parallel showing that the difference in results is essentially due to the kind of agitation. This achievement fully corroborates the results already obtained with coal and barite and further confirms the superior flotation selectivity when using waterjet.

It seems that optimum operating pressure is around 8-10 MPa, giving a jet velocity at the nozzle of about 100 m/s. An increase in pressure beyond that level at equal hydraulic power using smaller nozzles does not appear very profitable. However it is likely that higher pressure will be needed in the scale-up of the system.

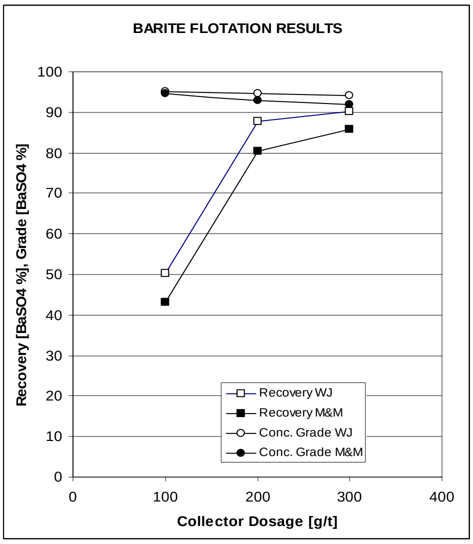

Fig. 5. Rougher flotation recovery and concentrate grade with water jet and with mechanical agitation as a function of collector dosage

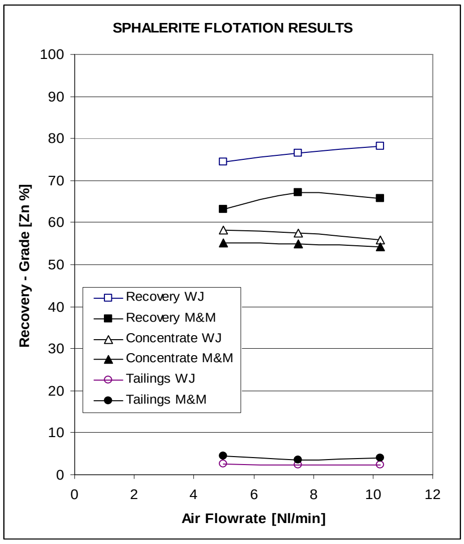

Fig. 6. Rougher flotation recovery and concentrate grade with water jet and with mechanical agitation as a function of collector dosage

3.3. DISCUSSION

Based on the outcome of the experimental tests, the following considerations can be drawn concerning the scientific explanation of the observed results.

3.3.1. GRADE OF THE PRODUCT

The quality of the floated products is always better when waterjet is used for agitation and bubble generation for coal, sulfide and barite ores. It is believed that this is due to the more favourable size distribution of the bubbles (mean value and dispersion parameter). In order to support this statement in a quantitative way it should be necessary to characterize the bubble features with suitable measurements. For this purpose, a specific research project has been undertaken at the University of Cagliari using the Particle Image Velocimetry (*PIV*) optical technique, that allows to measure displacement with time (and hence the velocity) of individual particles starting from a sequence of images taken at very small time intervals.

Floatable mineral particles are uplifted only if buoyancy prevails over the attached weight. If particles are well liberated by comminution, selectivity should be good irrespective of bubble size. However, this is not true for mixed particles: provided that the attachment strength is sufficient, a single large bubble will carry a particle even if the gangue component largely prevails, thus polluting the product, whereas this is avoided in the case of small bubbles that may attach to the same particle, making flotation more selective, especially for coarser particles.

3.3.2. FLOTATION RECOVERY

The higher recovery, observed in the experiments with waterjet agitation, can be explained by the fact that bubble-particle collision probability is enhanced because the bubbles are smaller (and hence much higher in number for a givel overall air flow), faster and much better distributed inside the cell than in the case of mechanical agitation. Moreover larger bubbles are more likely to break before reaching the froth layer, thus loosing the attached particles. The use of a suitable number of nozzles conveniently placed in the inner space of the cell allows to optimise bubble distribution by multiplying the generation points while avoiding the backwards draw of the bubble stream towards the rotor where an air vortex is formed.

3.3.3. THROUGHPUT CAPACITY

Owing to faster development of collection mechanism, a shorter flotation time is needed for achieving a given recovery level when resorting to waterjet for bubble generation. This is a considerable advantage concerning the economic issues of a beneficiation process.

3.3.4. ENERGY CONSUMPTION

In spite of the fact that waterjet is generally regarded as an energy consuming technology, specific energy required in this particular application is relatively low. In fact, for attaining a shear velocity tenfold higher than the peripheral velocity of conventional rotors, a relatively low pressure is needed, thus limiting the overall hydraulic power of the jets per unit volume of the flotation vessel. Wear is also quite insignificant due to the absence of components subject to consumption in presence of abrasive minerals.

3.3.5. CONCLUDING REMARKS

Separation performance of available flotation machines gradually deteriorates as particle size decreases, resulting in low recovery, unsatisfactory quality of the product and a high specific consumption of energy and reagents. The use of water jets generated at moderate pressure can be considered as a suitable way for improving the required conditions for the full development of flotation mechanisms, especially in the case of very finely ground ores.

The following advantages can be predicted with the further improvement and the industrial scale-up of the technology, compared to conventional methods:

- more favourable bubble features
- efficient control of the agitation pattern by optimising the nozzle arrangement and using fan jets
- higher recovery and better separation selectivity especially for the fine particle sizes
- less energy consumption using lower pressures
- reduced wear (no rotating parts are involved)
- expected higher capacity per unit volume of the cell owing to faster flotation kinetics
- waterjet can be the base for the design of a new sparger device in column flotation.

4. CONCLUSION

A jet of water issued at high velocity from a calibrated nozzle can be used in a variety of applications owing to its unique capability of carrying a high power concentrated in a very small space. The potential is considerably increased by the possibility of incorporating a load of abrasive particles into the jet. However, although this technology is still applied in many fields of rock and stone engineering (excavation, slotting, cutting, drilling, surface finishing) no commercial instances can be found in the areas of mineral comminution and separation. This is due to the high level of maturity reached by conventional methods and equipment, the use of which enables the efficient solution of most mineral processing problems. However waterjet can offer new opportunities for improving the performance of conventional machines on one side as well as for designing and implementing new solutions.

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Niektóre problemy występujące w przeróbce kopalin jak dotąd nie są rozwiązane przez obecnie stosowane technologie, zwłaszcza te oparte na użycie energii mechanicznej. Stosowanie energii mechaniczna ma wady takie jak zużycie części maszyn oraz ograniczona prędkość części ruchomych z powodu unikania ryzyka awarii w wyniku trudnych warunków pracy. Strumienie wodne mogą przyczynić się do przezwyciężenia tych trudności poprzez transfer energii bez kontaktu pomiędzy częściami wykonanych z materiałów stałych (brak tarcia) i są one wygodne dla generowania wysokich prędkości strumienia powietrza oraz wody przy względnie niskich ciśnieniach. Możliwe korzyści ze stosowania strumieni wodnych mogą mieć miejsce zwłaszcza we flotacji, gdzie rozmiar i prędkość pęcherzyków powietrza zależy od prędkości ścinania wywoływanej agitacją jako krytyczny aspekt optymalizacji wyników separacji (uzysk i selektywność). Pozwoli to także na redukcję rosnących kosztów zużycia części oraz oszczędność energii.

słowa kluczowe: strumienie wodne, flotacja, flotacja węgla, rozdrabnianie