RECENT DEVELOPMENTS IN FLOTATION FOR THE BENEFICIATION OF LOW-GRADE FINELY DISSEMINATED ORES

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Abstract

Rapid increase in consumption rate of metals and minerals over the last few decades and consequent depletion of mineral resources have necessitated the effective utilization of low-grade finely disseminated ores. The utilization of such reserves and recycling of metallic waste can help to maintain an adequate supply of minerals to meet economic and strategic needs of our nation. Since the yield of low-grade ores is generally very low, the technology/ process should be efficient to make it cost effective. Recent equipments like flotation column and Jameson cell which are basically designed to float fine particles are energy efficient. Selective reagents are being designed for the separation of individual minerals from complex assemblage. The necessity of biodegradable and eco-friendly reagents is highlighted. In the present paper, recent developments in flotation cells and beneficiation of low-grade ores was presented and discussed. Beneficiation of low-grade barite sample from Mangampet deposit was conducted both by direct flotation using oleic acid and reverse flotation by cationic collector. Production of barite concentrate assaying less than 1% silica by reverse flotation was demonstrated. Similarly, limestone concentrate assaying 97% of $CaCO_3$ and less than 1% SiO_2 was achieved by reverse flotation process. The viability of flotation process for up-gradation of siliceous iron ores was also studied and discussed.

INTRODUCTION

A rapid increase in consumption rate of metals and minerals over the last few decades and consequent depletion of mineral resources has necessitated the effective utilization of low-grade finely disseminated ores that are abundantly available. The effective utilization of such low-grade ores may help to maintain an adequate supply of minerals to meet economic and strategic needs of our nation. Though India is endowed with rich mineral deposits, the availability of same to future generations becomes very restricted if we exhaust at the present rate. The life indices of some of the minerals are shown in Table 1.

Table 1: Life Indices of some important minerals (Source: Department of Mines, Govt. of India)

Mineral	Total resources as per UNFC*(million tonnes)	Life Index(Years)
Bauxite	3289.817	204
Copper	1394.426	220
Lead & Zinc	522.580	82
Gold	90.289 (primary) & 26.121 (placer)	240
Iron ore	14630 (haematite) & 10619 (magnetite)	104
Chromite	213.063	47
Magnesite	337.882	603
Manganese	378.569	113
Limestone	175828.914	364
Rock phosphate	305.309	94

*United Nations Framework Classification

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From the data shown above, it is evident that lead, zinc, chromium, phosphate and iron ore reserves exhaust by the turn of this century. Thus it is necessary to utilize lean grade finely disseminated ores besides recycling of metallurgical waste. Due to recent increase in prices, the cut-off grades are reduced. For example, the cut-off grade for estimating the haematite resources has been considered as 55% Fe and above. The present technological developments are aimed to utilize banded magnetite quartzite (BMQ) and banded haematite quartzite (BHQ) where the Fe content varies from 30-40%. The Kudremukh Iron Ore Company Limited (KIOCL) is an example of success in exploiting lean iron ore deposits at a profit by employing a combination of sophisticated mechanized opencast mining on a large scale, an automated beneficiation plant and a pipeline based slurry transport system.

The occurrence of valuable minerals in a finely disseminated form necessitates fine grinding for liberation and subsequent separation. In certain cases considerable quantity of ore is discarded as fines and slimes. In the case of iron ore, nearly 50% is wasted as fines generated either at the time of mining or during conversion of lumps into calibrated lump ore. Because of loss in mineral values in the fine size range, considerable interest is growing in developing new processes for the recovery of fine particles. One of the most widely used techniques in processing fines is froth flotation. At the same time, the problems associated with fines in flotation are complex.

PHYSICO-CHEMICAL CHARACTERISTICS OF FINES

The specific surface becomes large and the mass becomes small as the particle size is reduced. Due to small mass and momentum of fine particles they may be carried in to the froth after getting either entrained in the liquid or mechanically entrapped with particles being floated. When such particles are of gangue minerals, the concentrate grade will be affected. The large specific surface area of the particles increases the adsorption capacity of the reagents. Thus high quantity of reagent is required to make the fine particles to float. Under such circumstances sufficient reagent may not be available for the flotation of larger particles that leads to decrease in recovery. Increased dissolution of fine particles may introduce undesirable impurities in to solution affecting collector mineral interactions. The leached metal ions are expected to cause unintentional activation of undesirable minerals or depression of desired minerals in the system.

As the particles become colloidal in size, long range intermolecular forces and electrical double layer forces dominate and control the interaction of a particle with other particles or bubbles in a suspension. The slime coating is also affected by long range intermolecular forces similar to those that determine the interactions between a bubble and particle. The details of the physico-chemical interactions on flotation are discussed earlier (1-2).

Various techniques like carrier flotation, oil flotation, agglomerate flotation/shear flocculation (3), electroflotation (4-5), vacuum floatation, column flotation, Jameson flotation cell have been developed to separate valuable particles from gangue. Though the techniques were proved to be effective for the separation of fine particles, only column flotation and Jameson cell were implemented on commercial scale. The present paper deals with the principles and development of flotation column, dual extraction column, oscillatory baffled column and Jameson Cell.

COLUMN FLOTATION

The concept of counter current contact between the downward flowing slurry with rising air bubbles forms the basis of column flotation. Original column concept is due to Boutin and Trenblay (6) and Boutin and Wheeler (7). The column can be divided into cleaning zone and recovery zone as shown in Fig 1. The conditioned mineral pulp is fed through a side inlet which is located about one-third of height from the top. The mineral particles encounter rising air bubbles while settling down by gravity action through the recovery zone, where the continuous phase is mineral pulp. Fine air bubbles are generated through sparger located at the bottom of the column. The continuous collision between the air bubbles and mineral particles ensures the flotation of hydrophobic minerals. The mineralized bubbles after reaching the cleaning zone, where the continuous phase is froth, encounter a blanket of cleaning water, so that no process water enters in froth. Finally the clean froth is discharged through launder system. The

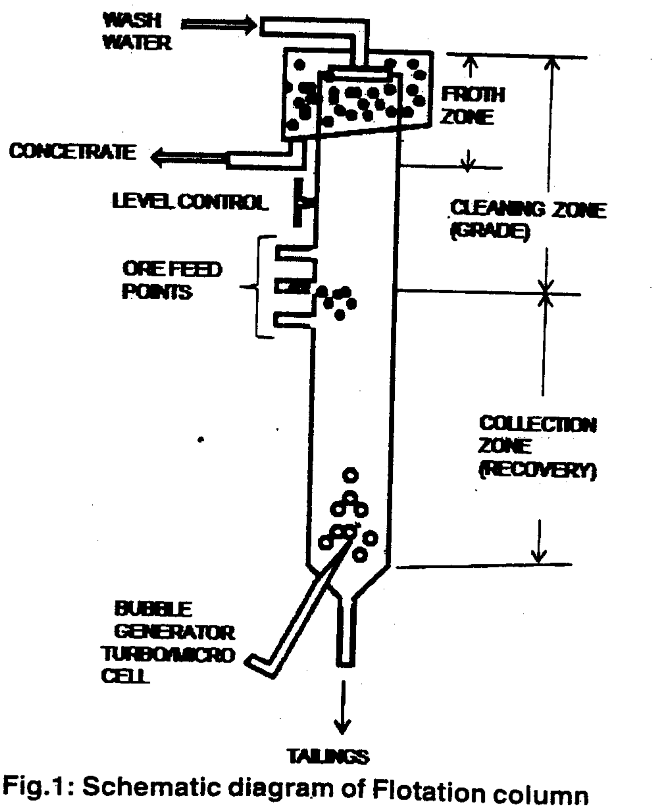

Fig.1: Schematic diagram of Flotation column

throughput is mainly determined by the cross sectional area of the column, while the length of recovery and cleaning zones determines the recovery and grade of the froth product respectively. Since there is no mechanical mixing, quiescent conditions prevailing inside the flotation column provide many opportunities for collision allowing the flotation of weakly hydrophobic minerals. The mineral particles move through the flotation column in a plug-flow mode. All particles invariably pass through the column of fine air bubbles rising from the bottom of the column in plug-flow mode. Therefore every particle and air bubble spends all its residence time very productively, making the effective residence time equal to the nominal residence time.

The merits of the column flotation include better grade and recovery, low operating cost and small floor space. The absence of turbulence at the interface of the column minimizes the chance of physical entrapment of unwanted gangue particles. The wash water mechanism helps in cleaning the entrapped gangue particles.

Bubble generation: Two different bubble generation technologies viz. Turbo type and Microcel type are widely known. Turbo type is a high pressure, low shear external bubble generator originally developed at the US Bureau of Mines. A mixture of air and water are injected under high pressure through injection tubes with distributed nozzles. Bubble size is controlled by manipulating air and water pressure, air and water ratio and frother addition in the water line if required. The details of the bubble generation are shown in Fig.2. The microcell type is low pressure and high shear bubble generator which is developed at Virginia Polytechnic Institute, USA. The sparger consists of one static online mixer and a centrifugal pump as illustrated in Fig.3. The slurry from the bottom of the column is sucked and pumped again to the column through the in-line static mixture where air and slurry are mixed under high shear conditions to create the bubble dispersion in the column. Frother is added to control the average bubble size if required. The gas hold up is very high (20-25%) in microcel system compared to Turbo type (15%). Since the bubble flux is high in Microcel system, it can be used during rougher stage flotation and also to boost the recoveries of low grade ores such as gold ores. The Turbo system requires additional water which invariably dilute the reagent regime in column whereas there is no such dilution of reagents with Microcel system as it utilizes the slurry water. The static mixer will wear out quickly and needs to be frequently replaced due to high shear action. Further, the bubble generator is sensitive to frother dosage and over a period of time switch over to negative bias.

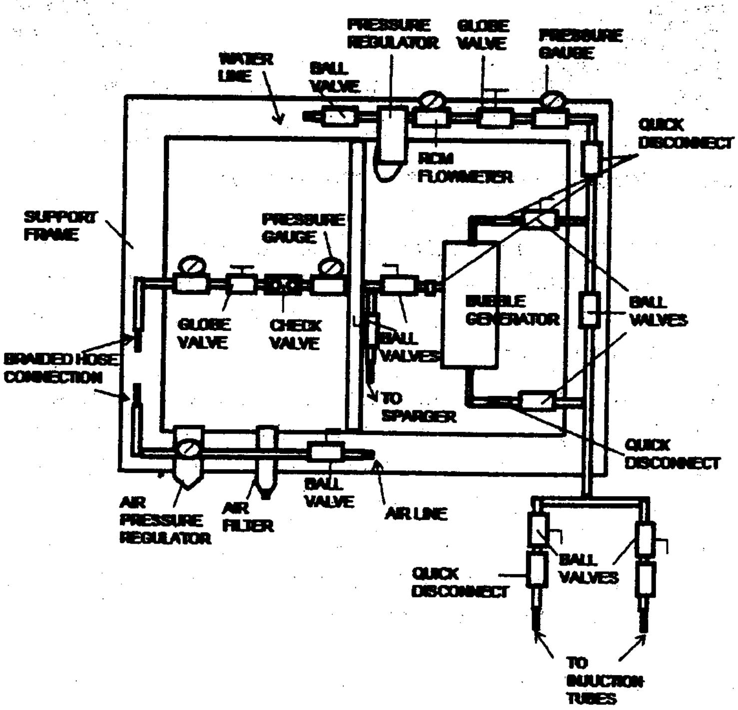

Fig.2: Schematic arrangement of Turbo-Type bubble generator

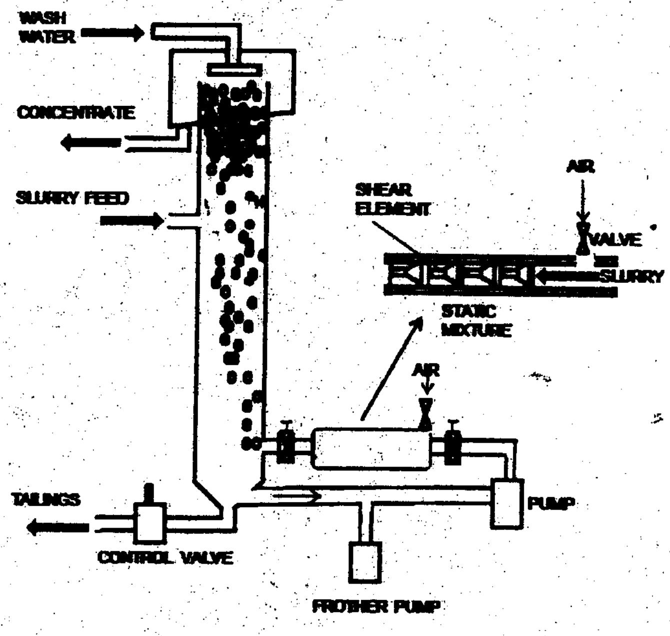

Fig.3: Schematic arrangement of Microcel bubble generator

NML Madras Centre has initiated the development of column flotation research since 1990. Initially laboratory column was developed, demonstrated and extensively field tested in the flotation circuits of various mineral industries. After gaining enough confidence and experience, fully automated semi-commercial flotation column was designed, fabricated and utilized to generate necessary data for scale-up (Fig.4).

Based on the scale-up data generated, commercial plants were commissioned for the beneficiation of sillimanite and limestone for Indian Rare Earth Limited and M/s Calpro Mineral

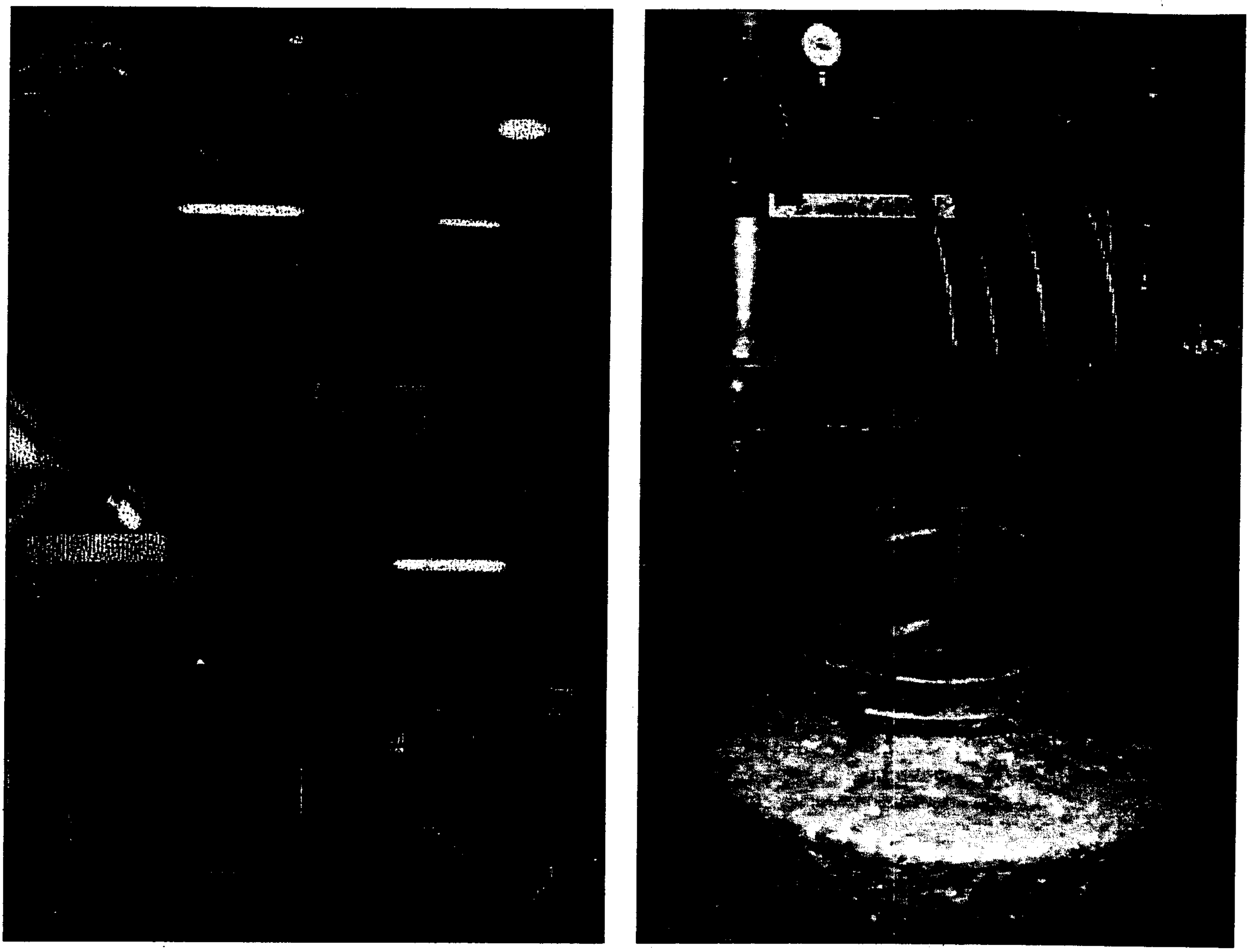

Fig.4: Photograph of pilot size flotation column, Bubble generator & Froth launder

technologies respectively. Detailed studies on the beneficiation of fluorspar, copper ore, lead and zinc ore, gold ore, iron ore, limestone and sillimanite by column flotation (8-15) shows definite advantage over conventional flotation cells in achieving better recoveries and grades. The salient features of the above mentioned studies are:

- Acid insolubles in copper concentrate remained as high as 11% inspite of two-stage cleaning by conventional flotation. Whereas high grade copper concentrate with less than 4% acid insolubles was achieved in single stage column cleaning.
- Lead sulphide concentrate assaying above 70% were achieved in a two-stage column cleaning Similarly zinc concentrates assaying 55% Zn were obtained in a single stage column cleaning where as it took four-stage cleaning by conventional cells.
- It was demonstrated that fluorspar concentrates assaying 97% of CaF_2 could be produced by adopting three column configurations in the place of several stages of cleaning by conventional cells.
- Gold concentrates assaying 50 ppm of Au was achieved by using flotation column as rougher cum cleaner cell. Whereas concentrates assaying 10 ppm of Au were generated by conventional cells.
- Iron ore concentrates assaying around 2% AL and silica that are suitable for direct reduction process could be obtained by flotation column.

In general column flotation technology was proved to be more effective to achieve high quality concentrate with minimum cleaning stages.

OSCILLATARY BAFFLED COLUMN

The cell is based on standard column design but employs a novel agitation mechanism where a series of baffle plates are oscillated sinusoidally through the fluid (16). This type of agitation is expected to produce a more evenly distributed shear rate in the cell and allows the effect of agitation on particle bubble contact to decouple from gas dispersion effects. An oscillatory baffled column (OBC) consists of a cylindrical column fitted with equally spaced orifice plate baffles down its length. A schematic diagram of OBC is shown in Fig.5. It consists of conventional flotation column agitated by an oscillating baffle cage. The baffle cage made up of orifice plates are oscillated by a piston and cam located above the cell. The piston is driven by variable speed motor and has an adjustable yoke to vary the oscillation amplitude. When the fluid is travelled through the baffle constriction, toroidal vortices are formed behind the baffles.

The moment the fluid starts to decelerate; these vertices are swept in to the centre of the baffle cavity by the jet of incoming fluid. The vortex then begins to weaken and acts as an obstacle to

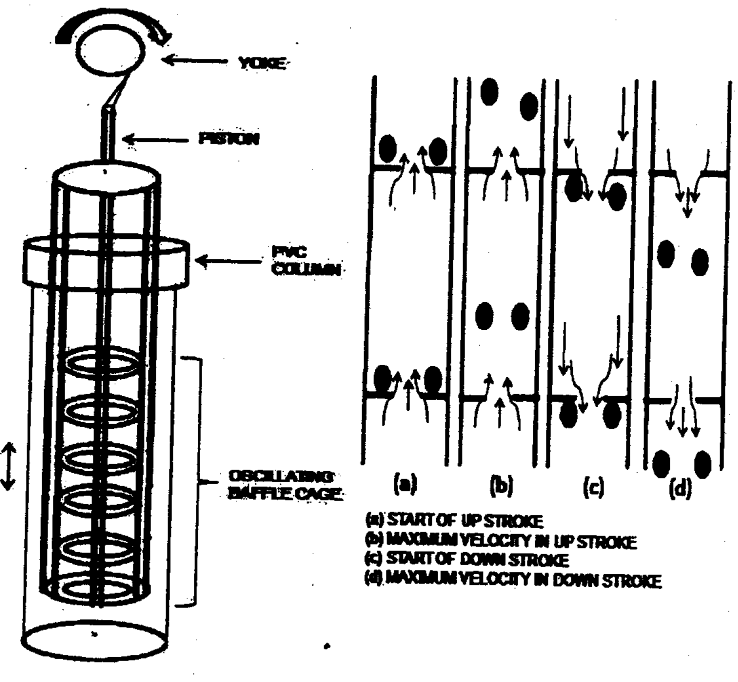

Fig.5: A schematic diagram of Oscillatory Baffled Column and mechanism of mixing (Reference 16)

ncoming jet of fluid during the down stroke. This type of flow nas been shown to give uniform mixing in each inter baffle zone and cumulatively along the length of the column. The OBC technology was found to be successful particularly in bio-fermentation and flocculation where the performance of he process is sensitive to shear rate.

Flotation of quartz using amine as collector was evaluated by OBC technology (16). The results show that the flotation rate constant was up by 60% for fine particles below 30 microns. In the case of coarse particles the rate constant was up by 30-40% compared to standard flotation column. The results were attributed to the unique hydrodynamics rather than flotation chemistry effects.

DUAL EXTRACTION COLUMN

The dual extraction column (DEC) principally resembles column flotation but differs in terms of height and bubble injection (Fig.6). It is a high efficiency flotation device which handles slurry feeds with wide particle size. The DEC combines low capital and operating costs. Designed for high through put with unique bubble generator to offer the advantages of low power and water

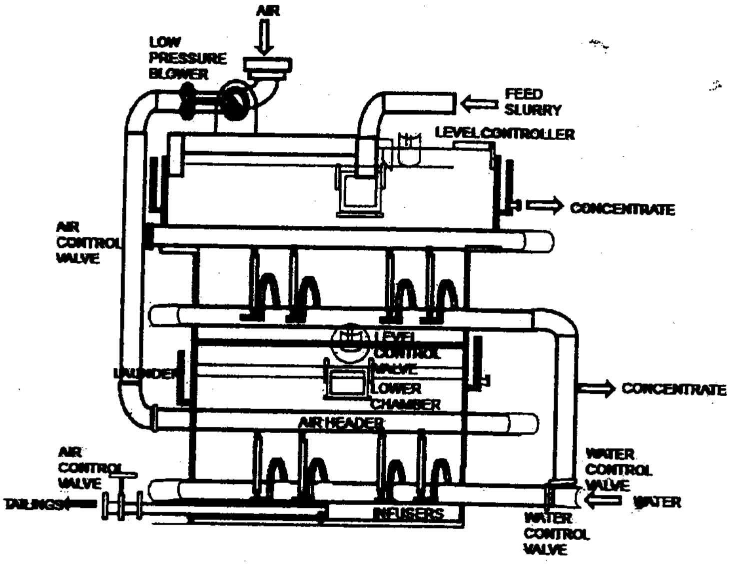

Fig 6: Schematic diagram of Dual Extraction Column (http://www.maxflot.com)

usage and operates as a rougher and scavenger in one unit. The DEC is anti choking and restarts immediately after the power or plant outage. Since height of the DEC is comparatively small, it is useful to separate minerals with faster flotation kinetics. It was proved to be effective in reducing the coal ash from 30% to below 10%. Separation of silica and alumina from iron ores by reverse flotation process was tried using pilot scale flotation column and DEC. Iron ore concentrates assaying 67% Fe and <2% SiO_2 and Al_2O_3 could be obtained with a recovery of 85-90% by single stage column flotation (17). The effectiveness of DEC in removing the gangue was observed to be comparatively poor.

JAMESON CELL:

The Jameson cell is a high intensity flotation cell and it was developed by Professor G.J.Jameson of the university of Newcastle in 1980's. The first cell was installed at Newlands Coal handling and flotation plant in 1990 to treat coal slimes.

Presently more than 250 cells were installed all over the world for various applications through Xstrata Technology. The conditioned mineral slurry is pumped through an orifice at the top of the downcomer (Fig.7). The liquid jet thus formed plunges vertically downwards in to the downcomer. The free jet impinging on the surface of the bubbly mixer in the downcomer serves to entrain air in to the downcomer by jet surface entrapment and film entrapment. The introduction of the conditioned feed in to the low shear region of the downcomer reduces the probability of aggregate break-up. The downward velocity of the bubble liquid mixer in the downcomer is chosen such that all bubbles have to descend and emerge in to a reservoir at the bottom of the downcomer. The reservoir acts as a disengagement zone allowing the aerated particle aggregates to float to the surface to form a sludge layer. The sludge overflows the reservoir in to a launder while the tailings are sent to the next stage in the process.

The process is particularly effective for the separation of coal (18) and also low density hydrophilic materials like algae (19).

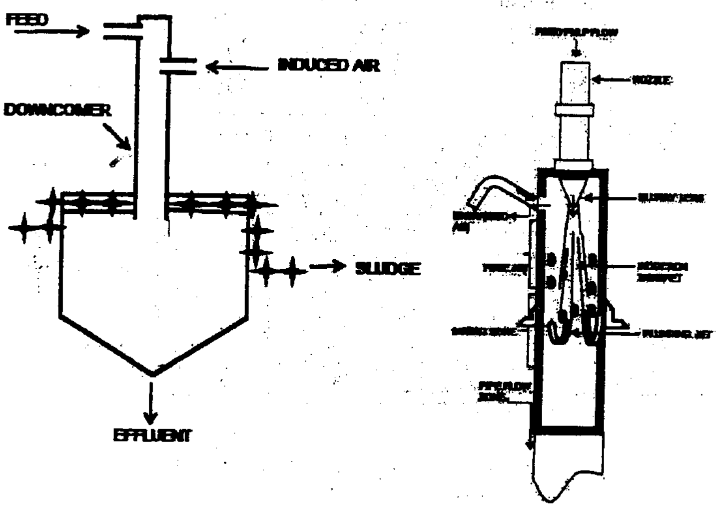

Fig.7: Schematic diagram of Jameson flotation Cell and Downcomer

The key difference with mechanical flotation cell and flotation column are;

- A high shear jet creates a high intensity mixing zone, producing a swam of fine bubbles rapidly mixing with particles.
- The fine air bubbles enables high solid loading per air bubble and thus high froth carrying capacity.
- Most of the particle-bubble interactions occur in the downcomer zone. The cell is required only for the separation of froth from slurry. Unlike columns, no large collection zone is needed and no need for the residence time calculations of conventional cells.
- The Jameson cell has no moving parts and thus low maintenance costs.
- It uses no external air supply hence further reduction in operating costs
- Simple and powerful mechanism. Provides consistent bubble size distribution for consistent performance.
- Simple scale-up to large machines. Capacity varies from 80 m^3/h to 3000 m^3/h feed.
- Filtration is better due to high recovery both fines and coarse particles with good rejection of unwanted fines.
- The Jameson installation is typically 40-60% of the foot print of conventional flotation cells and less than 30% of the height of column cells.

REVERSE FLOTATION

In reverse flotation gangue minerals are floated and valuables are depressed. When the proportion of gangue minerals is relatively less and comprises mainly of quartz and silicates, it is advantageous to beneficiate these gangue minerals by using cationic reagents as collectors. Furthermore, selective flotation of oxides in the presence of silicates is difficult because multivalent cations present in pulp may adsorb on negatively charged SiO_2 which facilitate the adsorption of anionic collector. Silicates are extremely water avid and pose high negative charge due to oxygen. It has been established that pure quartz cannot be floated with anionic collector. On the other hand, quartz can be easily floated by cationic collectors. Commonly used cationic collectors in froth flotation are amines having 12-18 carbon atoms in the chain. Example laurylamine ($C_{12}H_{25}NH_2$). Since the solubility of amines is low, they were converted to hydrochlorides and/or acetates to make them more soluble in water. Unsaturated hydrocarbon chains may also be present to increase the solubility of higher molecular weight collectors. Secondary and tertiary amines are used when a greater surface activity is required and even quaternary salts such as cetyl tri-methyl ammonium bromide is used in certain specialized flotation circuits. In general the amines are readily converted to ammonium ion in acid medium

$$R\text{-}NH_2 + H^+R\text{-}NH_3^+ \longrightarrow R\text{-}NH_3^+$$

The cation thus formed is readily adsorbed on negatively charged surface by electrostatic interaction. The cationic collectors are attractive because of their insensitivity towards hard water salts, low consumption, less induction time and high contact angles.

Low-grade barite from the Mangampet area and limestone from salem ware beneficiated by reverse flotation using cationic collector. High grade barite concentrates of barite assaying 98.7% of $BaSO_4$ and limestone assaying 97% of $CaCO_3$ suitable for high end applications were produced. Based on the success achieved during pilot plant trials, commercial size flotation column was designed and commissioned at Salem for the production of high grade CaCO3 concentrate suitable for paper and paint industry and also for poultry feed.

M/s Indian Barytes and Chemicals Limited, Chennai are also establishing commercial flotation column at Mangampet for high grade barite production. In the case of direct flotation, collector will be coated on the surface of the $BaSO_4$ and $CaCO_3$ particles making the products unfit for many applications. Whereas in reverse flotation, the cationic collector will be coated on gangue minerals making the final product free from chemical contamination. Thus the reverse flotation can be adopted to produce high grade concentrates without surface contamination.

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