Column Flotation : Theory and Practice

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ABSTRACT

Column flotation which employs a counter-current flow of slurry and air bubbles has proved to be a better alternative to the conventional mechanical cells for separation of minerals. Because of the distinct advantages of column flotation over mechanical cells, it is gaining wider acceptance in industry. Realizing the potential of column flotation, RRL Bhubaneswar also took initiative in the early sixties to develop column flotation technology for Indian ores. In the early stages, operation and design of columns were mainly based on experience. But with the increasing commercial installations, systematic investigations have been carried out by several workers. In this paper an attempt is made to review the development of column flotation for concentration of low grade ores. The basic principles and applications of column flotation have been described. The salient results obtained at RRL, Bhubaneswar have been highlighted.

Key Words : Column flotation, Theory & practice, Applications.

INTRODUCTION

Separation of valuable minerals from gangue is far from ideal in conventional mechanical cells. Column flotation, invented in the early sixties, proved to be a better alternative to the conventional cells. The main advantages of column flotation are : i) improved recovery, ii) higher grade, iii) lower capital and operating costs, iv) less wear and tear due to absence of moving parts and v) requirement of less floor space. Columns of varying design are in use all over the world[1].

Fig.1 shows a schematic diagram of flotation column. From an operational point, two main zones can be identified : i) collection zone, where feed entering 1-2 m below the top of the column flows down counter current to bubbles rising from a gas sparger near the bottom

of the column and ii) a cleaning zone, where the froth rising from the collection zone is washed of the entrained gangue by counter current wash water introduced at the top of the column. Finally, the washed froth overflows from the launder and is collected as the product while the tailings are discharged from the bottom. Commercial flotation columns can have either square or round cross-section and are generally upto 15 meters tall. Table 1 gives some of the early activities related to column flotation. Significant differences exist between the design and operating philosophies of mechanical cells and the flotation columns which lead to the difference in their performance. These are summarized in Table 2.

In the early stages, operation and design of the columns were mainly based on experience. With the increase in commercial installations several investigators particularly Dobby, Finch and co-workers[14-17] and Yoon and co-workers[18-20] carried out systematic studies on the design and operational aspects. It is now possible to carry out these operations on a more scientific basis.

In this paper an attempt is made to summarize the present status.

THEORETICAL BACKGROUND

Since there are no moving parts in the column the main operating variables are the flow rates : feed air, wash water, product and tailings. Column dimensions, bubble size, air holdup and the reagent dosages are the other important variables. To normalize the effect of flow rates in different sizes of columns, the superficial velocities, defined as the volumetric flow rates per unit area of cross section, are used. The normal ranges of these are given in Fig.1. Since the effect of reagent dosages are similar to those in conventional cells, they are not discussed in the paper. Another variable which is generally mentioned with reference to column operation is the bias rate which is the difference between the tailings rate and the feed rate. If the value is positive it is called positive bias and if it is negative it is called negative bias. Alternatively displacement wash ratio defined as the ratio of quantity of wash water to the quantity of water reporting to the concentrate.

As mentioned earlier, the column can be divided into two distinctively different zones : the collection zone and the recovery zone or the froth zone. Both of these need separate treatment.
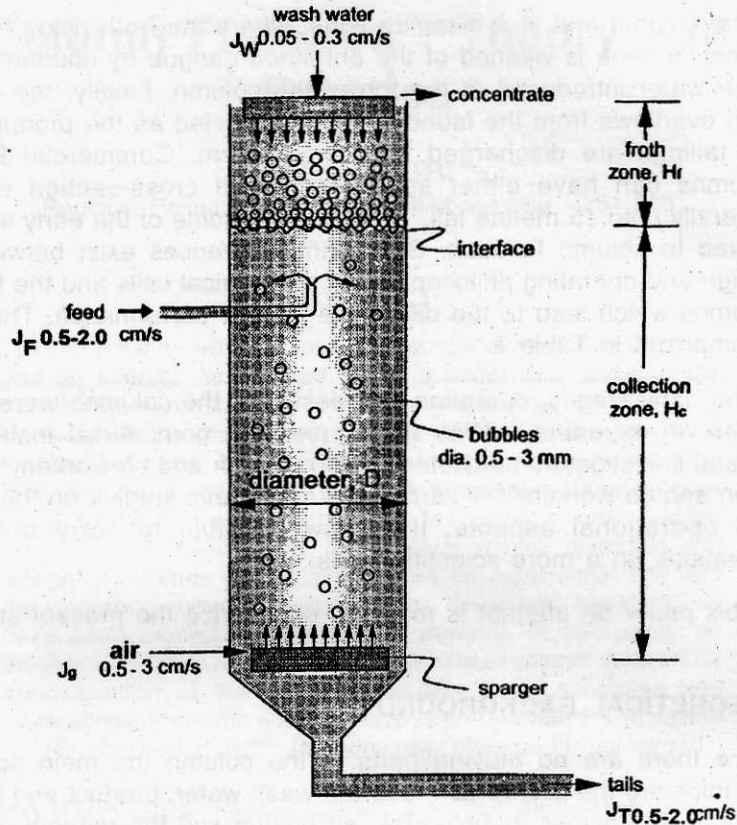
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Fig. 1 : Schematic diagram of flotation column

COLLECTION ZONE

In the collection zone the main factors affecting the recovery and grade are the bubble size and air hold up besides the flow rates.

Air Holding and Bubble Size

The volume fraction of liquid displaced by air is known as the air holdup, ϵ. The bubble size influences the hold up and the bubble surface available for carrying the values.

Except for clay type particles where viscosity effects dominate, in other cases slurry density and viscosity often have approximately equal and opposite effects on bubble rise velocity and therefore on holdup. It has been shown[21] that bubble loading may result in significant increase in holdup, the increase being less significant for finer bubbles.

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Table 1 : Early developments in column flotation

Year	Activity
1962	Invention of flotation column.
1963-67	Test work at iron ore company of Canada and Opemisaka Copper Mines (Quebec) on 0.45 m square column[2].
1966	First publication giving results of tests at Opemisaka Copper Mines[3].
	First publication from Regional Research Laboratory, Bhubaneswar[4].
1971	Paper in Russian on byproduct molybdenum recovery[2].
	Publication of R&D paper on graphite[5].
	Publication of R&D paper on concentration of molybdenum ore[6].
1975	Parallel testing of 0.45 and 0.9 m column at iron ore company of Canada[2].
1980	First commercial column at Mines Gaspe 0.51 m square column for Mo cleaning[7].
1984	First home made column 0.9 m dia at Gibraltar Mines for Copper Cleaning[8].
1986	Scale up at Mount Isa Mines for Pb-Zn flotation[9]. Commissioning of 3 stage circuit at Gibralta Mines for bulk Cu/Mo cleaning[10].
1987	Symposium on column flotation cell Trail B.C. Canada.[11].
1988	Column flotation' 88 SME/AIME,[12].
1990	Book 'column flotation of JA Finch and G.S. Dobby[13].

Effect of Gas and Liquid Rates on Hold up

According to Shah et al[22] the relationship between hold up and air superficial velocity defines the flow regime. The general trend is shown in Fig. 2.

It can be seen that the air hold up increase approximately linearly in the beginning and then deviates above a certain J_g. The linear section is characterized by uniform distribution of bubbles, nearly uniform in size, and is known as bubbly flow regime. This is the region of interest in

Table 2 : Comparison of operating mechanisms of conventional cells and flotation columns

	Mechanical cells	Flotation columns
1.	Similar to ideal mixers	Operate under conditions of plug flow with varying degrees of axial dispersion
2.	Air bubbles are formed by a rotating impeller	Air bubbles ore formed by passing compressed air/air slurry mixture through a bubble generator
3.	Relative velocity between air bubbles and mineral particles in negligible except near the impeller. Hence chances of collision ore reduced	Relative velocity between air bubbles and mineral particles is high through out the length of the column since they move counter current
4.	At any given time only a small fraction of the mineral particles is in the viscinity of air bubbles created. Thus effective residence time of particles is small compared to the total time of presence in the cell	Total length of collection zone is available for collision and attachment. Thus total residence time is effectively utilized
5.	The highly turbulent conditions promote i) detachment of once attached particles and ii) contamination of froth by entrainment of non floatable particles	The quiescent operation results in i) reduced possibility of detachment and ii) reduction in entrainment of gangue minerals in the froth
6.	Relatively large size bubbles not favorable in flotation of fine particles	Relatively smaller bubbles give higher surface and higher residence times.
7.		Addition of wash water further improves the grade of the product i) by pushing down the process water containing gangue mineral from going with the product and ii) washing down the coarse gangue particles carried over to the froth by entrainment.

column flotation. Above this air rate, hold up is characterized by large bubbles, rising rapidly displacing water and small bubbles downward. This region is known as the churn turbulent region and the operation will be unsteady in this region.

For a given flow rate of air, increase in counter current flow of water increases hold up as a result of relative decrease in bubble rise velocity. However, increase of J_l will decrease the maximum J_g for bubbly flow regime.
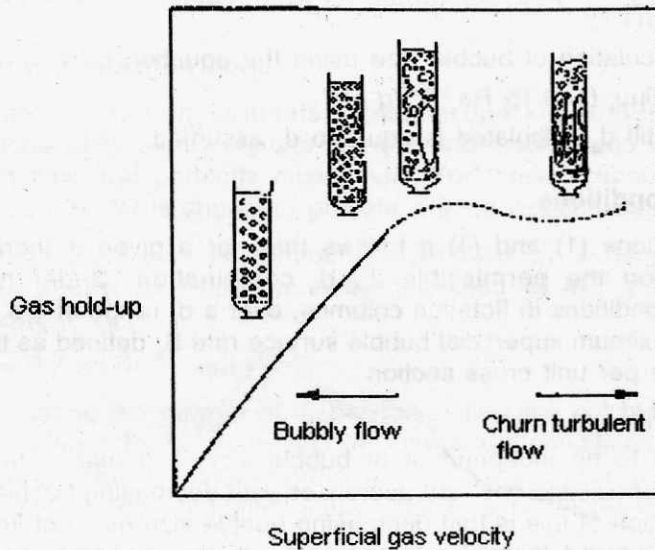

Fig. 2 : General relationship between gas rate and hold up

Addition of frother

Addition of frother up to a certain level has a pronounced effect of reducing bubble size, resulting in reduced bubble rise velocity and consequent increase in hold up.

Estimation of Bubble Size

It is difficult to measure the bubble size in operating columns. Based on laboratory studies, it is possible to estimate the bubble size using

drift flux analysis[23]. Accordingly to this method the data required are the hold up (and liquid and air rates J_l and J_g.

The steps involved are

I) assumption of a d_b value

ii) calculation of slip velocity (relative velocity) u_s from

$$u_s = (J_g/\varepsilon) + J_l/(1-\varepsilon) \tag{1}$$

iii) calculation of Reynolds number Re_s

$$Re_s = d_b \, u_s \, \rho \, (1-\varepsilon)/\mu \tag{2}$$

iv) calculation of the terminal velocity u_t

$$u_t = u_s \, /(1-\varepsilon)^2 \tag{3}$$

v) and calculation of bubble size using the equation

$$d_b = [18\mu u_t \, (1+0.15 \, Re_s^{0.687})/g \, \rho]^{0.5} \tag{4}$$

and iterate till d_b calculated is equal to d_b assumed.

Limiting Conditions

From equations (1) and (4) it follows that, for a given J_l there is a restriction on the permissible J_g, d_b combination. Under normal operating conditions in flotation columns, over a d_b range of 0.6 to 1.2 mm, the maximum superficial bubble surface rate S_b defined as bubble surface rate per unit cross section

$$S_b = 6J_g/d_b \tag{5}$$

S_b is found to be independent of bubble size[14]. It means that the maximum permissible gas rate decreases with decreasing bubble size. The implication of this is that decreasing bubble size may not improve solids removal rate. Instead column may be operated at higher J_g rates keeping the bubble size near the upper limit to improve solids removal rate.

Collecting of Particles

The fractional recovery of a mineral particle in the collection zone is given by

$$R_c = 1-\exp. \, (-k_c \, t_p) \tag{6}$$

for a first order rate process under plug flow conditions which is normally the case in laboratory columns

The first order rate constant k_c is given by

$$k_c = 1.5 \, J_g \, E_K/d_b \; = 1.5J_g E_C \, E_A/d_b \tag{7}$$

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assuming particle detachment to be negligible due to absence of mechanical agitation. Studies have shown that

$$E_c \propto d_p^m/d_b^n \qquad (8)$$

where m varies from 1-2 and n varies from 2.5-3 and E_A decreases with increasing particle size and increases with increasing particle density.

For column with internal sparger J_g and d_b are dependent, Equations (7) and (8) show the increasing J_g decreases k_c by increasing d_b and reducing E_c.

An advantage of external spargers over internal spargers is that J_g can be increased independent of d_b in the former to increase k_c.

Mixing in Collection Zone

Laboratory flotation columns typically operate under plug flow conditions while plant columns operate under conditions intermediate to plug flow and perfectly mixed flow. For these columns plug flow dispersion model is shown to provide a good working basis.

The axial dispersion is commonly quantified by a dimension less number known as Peclet number. Mankosa et al[19] proposed the equation

$$Pe = 0.7 \ (H/D)^{0.63} \ (u_l/J_g)^{0.5} \qquad (9)$$

for estimating the degree of dispersion in flotation columns. For plug flow conditions Pe is infinity and for fully mixed conditions Pe is zero. According to Eq. (9) dispersion in flotation columns can be decreased by increasing H/D, interstitial liquid velocity u_l or decreasing J_g.

Over the bubble size range relevant to column flotation, decrease of bubble size is reported to increase dispersion.

Particle Residence Time

Mean particle residence time reduces with increased particle size and increases with interstitial liquid velocity. It can be calculated from the following equations by iteration

$$t_p = t_l \ [J_t \ /(1-\varepsilon)]/ \ [u_{sp} + J_t \ /(1-\varepsilon)] \qquad (10)$$
$$\text{where } u_{sp} = gd_p^2 \ (\rho_p - \rho_{sl}) \ (1-\phi)^{2.7} \ /18\mu \ (1+0.15 \ Re_s^{0.687}) \qquad (11)$$
$$Re_p = d_p \ u_{sp}\rho(1-\phi)/\mu \qquad (12)$$
$$\text{and } \quad t_l = H \ (1-\varepsilon) \ / \ J_t \qquad (13)$$

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Location of Feed Point

Location of feed point is an important factor since it has a bearing on effectiveness of collection zone. Having a feed point in the lower portion is likely to result in short circuiting of solids to the tailings and also gives less residence time to the solid particles for effective collection. On the other hand having it too close to the interface is likely to disturb it. A compromise is to have the feed point about 2 meter from the top in commercial columns.

Effect of Mixing on Recovery

Recovery in a plug flow column with mixing can be calculated from the equation

$$R = 100 [1 - 4a \exp (Pe/2)/(1+a^2) \exp (a Pe/2) - (1-a^2) \exp (-a Pe/2)]$$

(14)

where $a = (1 + 4kt_p/Pe)^{0.5}$ (15)

and t_p is calculated from Equations (10-13)

As mentioned earlier, the Peclet number decreases as the column diameter increases and recovery would decrease unless t_p is increased. Increase of t_p means increase of column height which will result in change of H/D and consequently changed dispersion. Under these conditions t_p required for the same recovery will change. Due to interdependence of the variables, iterative process is needed to calculate the H or t_p required for a given recovery in commercial columns. Mankosa[19] et al have illustrated this effect by plotting the ratio of mean residence time required in the large column to that in the laboratory column as a function of column diameter for different flow conditions.

For a given residence time, increase of H/D ratio will also result in reduced volumetric flow rate (to maintain similar J_g) which means in overall reduction of collection of solids. Increase of gas rate generally results in improved recovery but lower grade of the product.

Bubble Generators

Bubble generators are termed as the hearts of flotation column. These can be divided into two groups : i) internal and ii) external. In the early stages of development only internal spargers are used but at present their use is limited to laboratory and pilot test units. The metallurgical performance of these two types of spargers are reported to be similar[24]. The advantages and disadvantage of these project are given in Table 3.

Table 3 : Advantages and disadvantages of different types of spargers

Advantages	Disadvantages
External spargers	
i. Less chances of plugging	i. Proprietary items and relatively costly
ii. On line maintenance	ii. Operation relatively complicated
iii. Control over bubble size	iii. Need other accessories like pump or high pressure compressor
iv. Long life	
Internal spargers	
1. Relatively cheap	1. On line maintenance not possible leading to production loss
2. Can be fabricated locally	2. Need to change once in 3 months
3. Operation is easy	3. Control of bubble size not possible
4. Require low pressure air	

Internal spargers of different shapes were in use. These include perforated pipes covered with perforated rubber or filter cloth, disk filter elements or inverted cone type covered with filter cloth, and porous metal spargers.

In case of the above type of spargers the bubble size is found to be related to the gas rate and relative areas of sparger and column R_s according to the relation

$$d_b = C (R_s J_g)^n \tag{16}$$

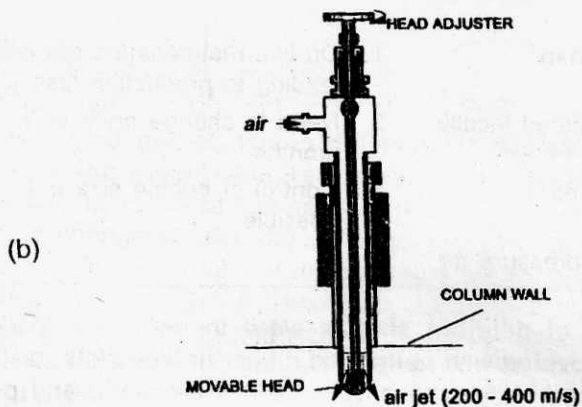where C depends on frother concentration for a given set up.

Typical examples of external sparger are USBM, Cominco, Minnovex and Microcel spargers (Fig. 3).
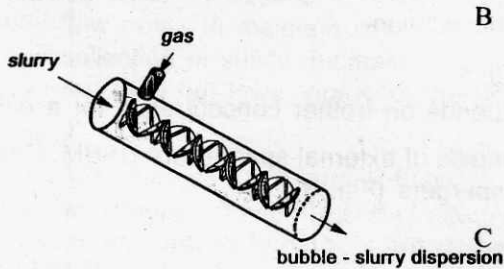
FROTH ZONE

The holdup of air in column froths is around 80%. Increase of J_g beyond a limit tends to increase hold up in collection zone and reduce the hold up in the froth zone with consequent loss of interface which
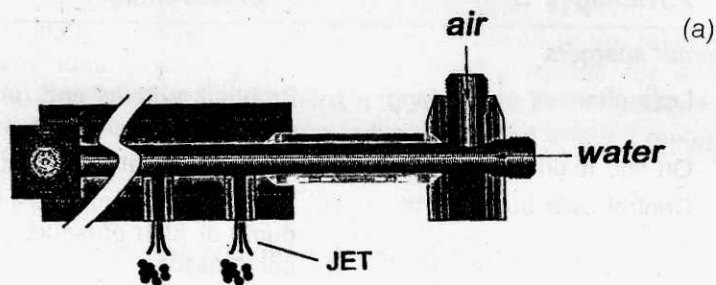
Fig. 3 : External spargers

(a) USBM/Cominco,   (b) Minnovex,   (c) Microcel

is not desirable for smooth column operation. In order to reduce the effect of entry of more feed water into the froth zone with increasing J_g more wash water needs to be used.

Plant experience indicates that froth depth has no significant effect on metallurgical results.

Wash Water

The use of wash water distinguishes the column froth from the conventional cell froth. The purpose of addition of wash water is i) to provide water necessary for the overflow of the collected solids into the launder and ii) to suppress the water coming from the feed from going along with the product in order to prevent the carry over of gangue minerals by entertainment.

Froth Dropback

Dropback from froth is important to calculate the overall recovery. Measurement of this is very difficult and the limited data available indicate that the froth drop back varies widely from about 20 % to 80 %.

The effect of different variables on the processes occurring in the flotation column were dealt with so far.

To summarize, the column performance is greatly influenced by a number of variables as shown in Table 4.

Now, the practical aspects of testing and design will be dealt with.

Table 4 : Influence of operating variables on column operation

Variable	Effected property
Air rate	bubble size, holdup, kinetics, carrying capacity, dispersion, product grade and recovery
Feed rate	bubble size, dispersion
Bubble size	holdup, kinetics, carrying capacity, dispersion
Wash water	entrainment
Particle size	residence time, kinetics
Viscosity	holdup, kinetics
H/D ratio	dispersion

Testing

Testing has multiple objectives

i) Demonstration of feasibility or amenability

ii) Determining the range of operating variables and parameter estimation

iii) Collection of engineering data for scale up

Amenability Tests

Amenability tests are carried out to establish grade-recovery curves for comparison against standard laboratory test results or existing plant performance. The variables generally studied are the residence time, % solids in feed and gas rate. Feed rates may be controlled using peristaltic pumps. Interface is maintained manually by adjusting tailings rate. A period of 3 residence times is normally allowed before collecting samples.

If the column gives superior results compared to those from the laboratory mechanical cell the inference is that column is better suited since laboratory mechanical cells often produce better results compared to the plant size cells.

Parameter Estimation

Rate constant

Generally the over all rate constant k (obtained in presence of froth) is measured instead of the collection zone rate constant K_c (assuming froth zone recovery to be 100%). For measuring this, the levels of other variables like air rate, reagent dosages which effect the rate constant should be fixed. Care should be taken to see that the air rate used is sufficient to keep it away from the fully loaded condition.

The overall rate constant k can be determined by varying the tailings rate in a long column (approx. 10 M long) or recycling the tailings in a short column. A disadvantage of the latter method is the possibility of surface modification due to repeated handling.

K the rate constant is estimated from the slope of ln (100-R) vs. residence time plot.

The collection zone rate constant k_c can be estimated directly by operating the column at high bias rate to eliminating the froth zone and maintaining a low level of recovery by entrainment.

Carrying capacity

Carrying capacity is defined as the concentrate removal rate in terms of mass of solids overflowing per unit time per unit column cross sectional area. It is shown that this can beestimated from the equation[25].

$$C_{max} = 0.049 \; d_p \rho_s \qquad (17)$$

Since this gives the upper limit where bubbles are fully loaded with mineral particles, the normal operating capacity should be below this and a reasonable estimate for the operating level is given by[25].

$$C = 0.03 \; d_p \rho_s \qquad (18)$$

The carrying capacity is experimentally determined by operating the column at a given retention time varying the feed solids rate (through feed percent solids) till the maximum in concentrate solids rate is achieved.

Hold up in the collection zone

A practical way of measuring air hold up is by using pressure transducers located at two different heights in the collection zone (Fig. 4). The hold up can be calculated from the equation

$$\varepsilon = 1 - \Delta P \, / \rho_{sl} \, g \Delta L \qquad (19)$$

To reduce the derivations in the estimated hold up, ΔP is measured over a section near the bottom of the column (above the air sparger) where the bubbles are expected to be only lightly loaded and the tailings density is used as an approximation to the slurry density within the region.
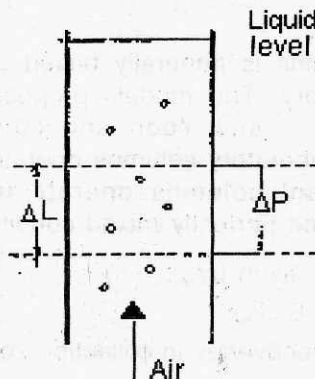

Fig. 4 : Measurement of gas hold-up

Interface between froth and collection zone

The location of froth slurry interface is normally carried out by the use of differential pressure measurement between two or more locations above the feed level.

Pilot plant testing

Pilot plants of 0.2 -1.0 diameter are constructed as an intermediate stage. The main objectives of the pilot plant are i) checking the results of amenability tests and the preliminary scale up data, ii) testing and evaluation of practical aspects and process control instrumentation and iii) operator training.

CONTROL

For stabilized operation and optimum performance control instrumentation is required. Among the different types of stabilizing controls used, the simplest one is to control the interface level by manipulation of tailings rate. In this system, wash water addition is manual with and no control over bias. A deep froth is generally maintained to dampen the effects of gas and bias rates. •

In an alternate method of control, wash water is manipulated to control the level and tailings rate to control the bias.

Both methods are reported to give similar metallurgical performance, but the former is relatively simpler.

Current information available leads inadequate understanding of the effects of air rate, hold up, bias, wash water rate and froth depth on metallurgical performance and it is difficult to suggest a general system of control instrumentation

SCALE-UP

Scale up of flotation columns is generally based on kinetic models using axial dispersion theory. The models proposed by Finch and Dobby and co-workers[13,26,] and Yoon and co-workers[18-20] are prominent among these. Laboratory columns operate under plug flow conditions, while the plant columns operate under conditions intermediate to plug flow and perfectly mixed conditions.

The over all recovery, R is given by

$$R = 100 \ R_c \ R_f \ / \ (1- \ R_c + R_c \ R_f) \tag{20}$$

where R_c and R_f refer to recoveries in collection zone and froth zone respectively.

The froth zone mechanisms are not fully understood, but indications are that the froth zone recovery may vary between 20-80% with an average of 50%.

For partially mixed flow condition, R_c is given by Eq. (14).

Column Diameter

The diameter of the column is estimated from the data on superficial velocity of feed and the carrying capacity.

Height of the Collection Zone

The height of the collection zone for a given recovery can be estimated from Eqs. (9-15). The dispersion equation (Eq. 10) indicates that increase of H/D decreases dispersion. For the same retention time, it is possible to increase H by reducing D. But varying column geometry causes other changes in other variables like particle velocity, bias and gas flow rates, besides the capacity which depends on the cross sectional area. It can be seen from the relationship.

$$Q = J_g \, V \, /H \tag{21}$$

where Q is volumetric air rate, increasing H at constant column volume results in lower air rate. This means increased bubble loading with increasing H/D rates. Beyond a point further increase in H/D may not be beneficial since the bubbles are already fully loaded. There is a practical limit to this ratio.

It is interesting to note that the performance of commercial plant is found to be superior to the one obtained by simulation using data from the laboratory and pilot plant test[9,27].

APPLICATIONS

Since the flotation column was tested in the sixties on iron ore and molybdenum, the first commercial application was replacement of a number of stages of cleaning in molybdenum circuit. Originally most of the applications were in replacing a number of stages of cleaning in molybdenum, lead-zinc circuits by column. Column flotation applications have increased covering roughing and scavenging also[28,29]. Even all column flotation installations are reported proving the versatility of columns.
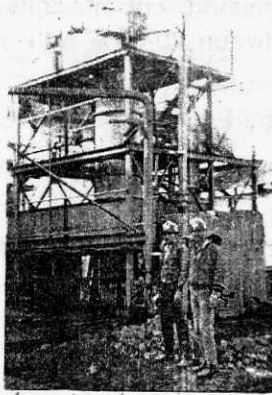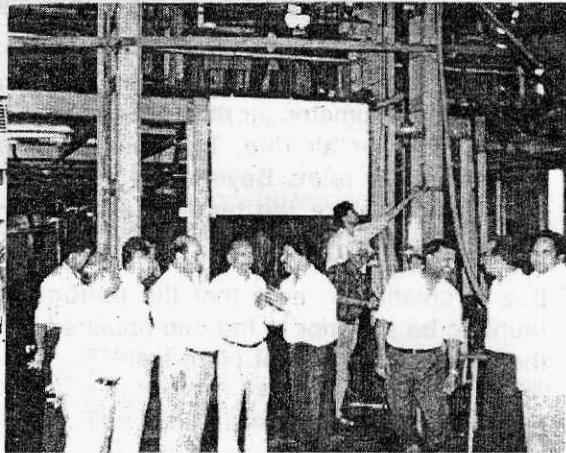
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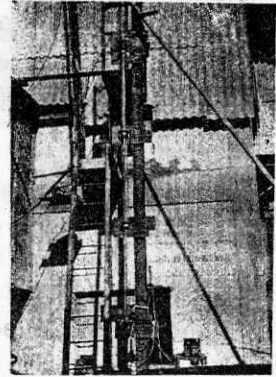
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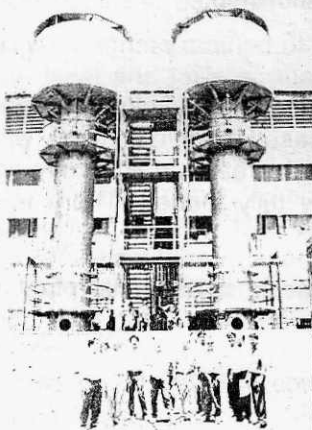
(c)

(d)

Fig. 5 : Some industrial Column Flotation projects of RRL Bhubaneswar (a)
1m dia Column, West Bokaro coaking coal washery, Tata Steel
(b) Molybdenite recovery at Rakha Copper concentrator (c) 1.75m dia Columns
in Zn cleaning circuit Dariba concentrator, Hindusthan Zinc Ltd. and
(d) Molybdenite recovery at Uranium Corporation of India Ltd., Jaduguda

COLUMN FLOTATION : REGIONAL RESEARCH LABORATORY, BHUBANESWAR

Realizing the potential of column flotation, the laboratory took initiative in the early sixties to adopt it to the Indian ores and to develop design capabilities. An inverted cone covered with filter cloth was used as the air sparger. A wide variety of materials graphite, coking coal, limestone, sillimanite, molybdenite, Zn-rougher concentrate were tested using columns ranging from 0.056 to 0.22 meters diameter. Based on the amenability tests carried out at the laboratory, a one meter diameter column to process 3-4 tones/hr of tailings of present flotation plant was set up at West Bokaro Coking Coal Washery of Tata Steel. The laboratory is also associated with the first indigenous effort in scaling up and operation of the columns in the zinc cleaning circuit at Dariba plant of Hindustan Zinc Ltd. Preliminary results indicate that the performance may be even better than the targets set in design. The laboratory also taken to some of the earliest publications on column flotation. Fig. 5 shows some of the industrial column flotation projects with which the laboratory is associated.

Nomenclature

C	Carrying capacity normal operating	Pe	Peclet number
C_{max}	Maximum carrying capacity	R	Overall recovery
D	Diameter of column	R_c	Collection zone recovery
d_b	Diameter of bubble	R_f	Froth zone recovery
E_A	Attachment efficiency	Re_b	Reynolds number of bubbles in swarm
E_c	Collision efficiency		
E_K	Collection efficiency	Re_p	Reynolds number of particle
g	Acceleration due to gravity	t	Mean residence time
H	Height of collection zone	t_l	Liquid residence time
J_B	Superficial velocity of bias	t_p	Particle residence time
J_F	Superficial velocity of feed	u_l	Liquid interstitial velocity
J_g	Superficial velocity of air	u_p	Particle interstitial velocity
J_l	Superficial velocity of liquid	u_s	Slip velocity between air bubble and water
J_{sl}	Superficial velocity of slurry		
J_T	Superficial velocity of tailings	u_t	Terminal velocity of air bubble
J_W	Superficial velocity of wash water	**Greek Letters**	
		$\in$	Air holdup
k	Overall rate constant	μ	Viscosity of water
k_c	Collection zone rate constant	μ_{sl}	Viscosity of slurry
ΔL	Distance between two points for measuring differential pressure	ρ	Density of liquid
		ρ_s	Density of solids
ΔP	Pressure differential between the two points	ρ_{sl}	Density of slurry
		ϕ	Volume fraction of solids in slurry

REFERENCES

1. Reddy, P.S.R., Kumar, S.G., Bhattacharya, K.K., Sastri, S.R.S. and Narasimhan, K.S., 1988. Int. J. Miner. Process, 24, p. 161.

2. Wheeler. D.A. Column flotation - The original column paper presented at the 87th Annual General Meeting of CIM-Van Coevur, 24th April 1985.

3. Wheeler, D.A., 1966. E&MJ 167 (11), p. 98.

4. Choudhury, G.S. Lakshmanan, C.M., Narasimhan, K.S. and Rao, S.B., 1966. The Explorer, p. 1.

5. Narasimhan, K.S, Rao, S.B. and Choudhury, G.S., 1972. E&MJ 173(5), p. 84.

6. Mathieu, G.I. , 1972, CIM Bulletin, 65, (271), 1972, p. 41.

7. Coffin, V.I., 1982. In : Procd. XIV International Mineral Processing Congress, Toronto, p. IV-21.

8. Mauro, F.L. and Grundy, M.R., 1984. In : Procd. CIM District Meeting, Kamloops, B.C.

9. Espinosa-Gomez, R., Johnson, N.W. and Finch, F.A., 1989, Minerals Engg. 2(3), p. 369.

10. Redfearn, M.A. and Egan, J.R., 1989. In : Procd. International Symposium on Processing of Complex Ores, G.S. Dobby and S.R. Rao (Eds.), Pergamon Press NV, p. 303.

11. Feasby, D.G. (Ed.), 1987, In : Procd. Column Flotation Cell Symposium, B.C. Canada, CANMET Ottowa.

12. Sastry, K.V.S. (Ed.), 1988, In : Procd. Column Flotation 88, SME/AIME, 12th Annual Meeting, Phonix, Arizona.

13. Finch, J.A. and Dobby, G.S., 1990, In : Column Flotation, Pergamon Press Oxford.

14. Finch, J.A. and Dobby, G.S., 1991, Int. J. Min. Process, 33, p. 343.

15. Dobby, G.S. and Finch, J.A., 1991, Minerals Engg., 4 (7-11), p. 911.

16. Finch, J.A. Uribe-Salas, A and Xu; M., 1995, In : Flotation Science and Engineering, K.A. Matis (Ed.), Marcel Dekker New York, p. 291.

17. Finch, J.A., 1995, Minerals Engg., 8(6), p. 587.

18. Mankosa, M.J., Adel, G.J., Luttrel, G.H, and Yoon, R.H., 1990, Mineral and Metallurgical Processing, Rajamani, R.K. and Herbst, J.A., (Eds.), Salt Lake City, USA, SME 35.

19. Mankosa, M.J., Luttrel, G.H, Adel, G.J., and Yoon, R.H., 1992, Int. J. Miner. Process., 35, p. 51.

20. Yoon, R.H, Mankosa, M.J. and Luttrel, G.H., 1993, In : Procd. XVIII International Mineral Processing Congress, Aus/MM, Sydney, Australia , p. 785.

21. Yianatos, J.B., Finch, J.A. Dobby, G.S. and Xu, M., 1998, J. Coll. Inter. Sci. 26(1), p. 37.

22. Shah, Y.T. Kelkar, B.G., Godbole, S.P. and Deckwer, W.D., 1982, AlchEJ 28 (3), p. 353.

23. Banisi and Finch, J.A., 1994, Minerals Engg., 7(12), p. 1555.

24. Huls, B.J. Lachance, C.D. and Dobby, G.S., 1990, Minerals Engg. 4(1), p. 37.

25. Sastri, S.R.S., 1986, Minerals Engg., 9(4), p. 465.

26. Falustu, M., and Dobby G.S., 1989, In : Procd. Complex Ores, Dobby, G.S. and Rao, S.R., (Eds.) C.I.M Halifex, Canada, p. 335.

27. Hall, S.T. and Averiss, S.B., 1988, In : Procd. Fine Particles, Plumpton, A. (Ed.), Can Inst. Min. Metall, p. 181.

28. Newell, A.J., Cantrell, R.A. and Dunlop, G.A., 1992, In : Procd. Extractive Metallurgy of Gold and Base Metals, Kalgorlie, Inst. Min. Met., p. 253.

29. Brewis,T., 1991, Mining Magazine, p. 383.