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P. Mavros[a]; N. K. Lazaridis[a]; K. A. Matis[a]; G. A. Stalidis[a]
[a] DEPARTMENT OF CHEMISTRY, LABORATORY OF GENERAL AND INORGANIC CHEMICAL TECHNOLOGY ARISTOTLE UNIVERSITY, THESSALONIKI, GREECE

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# A Study of Flotation Column Performance for the Recovery of Fine Particles

P. MAVROS,* N. K. LAZARIDIS, K. A. MATIS, and G. A. STALIDIS

LABORATORY OF GENERAL AND INORGANIC CHEMICAL TECHNOLOGY
DEPARTMENT OF CHEMISTRY
ARISTOTLE UNIVERSITY
GR-540 06 THESSALONIKI, GREECE



**Abstract**

The performance of a laboratory-scale flotation column has been experimentally investigated for the recovery of fine particles (−200 mesh). The column operation has been found to be exceptionally stable, and the solid particles (calcite) recovery to depend upon the pulp, gas, and washwater flow rates. An optimum performance can be achieved for a range of operating variables which depends upon the physical-chemical characteristics of the mineral system and also the geometrical features of the particular column in use.

## INTRODUCTION

Agitated flotation cells are widely used in the mineral processing industry for separating, recovering, and concentrating valuable particulate material from undesired gangue. Their performance is lowered, however, when part of the particulate system consists of fines, with particle diameters typically in the range from 30 to 100 μm.

As an alternative to agitated cells, bubble columns—used in chemical engineering practice as chemical reactors—were proposed for the treatment of fine particle systems. Flotation columns, as they came to be known, were "invented" back in the 1960s (*1, 2*) in Canada, and it seems that they were operating in China, too, by 1961 (*3*). The mineral industry

*To whom correspondence should be addressed.

was reluctant to adopt this new technology in the beginning; it thought it easier to deslime the ore prior to flotation. This, however, resulted in significant losses of valuable material (*4*).

The performance of the early columns proved equal or even higher than that of the conventional bank of flotation cells, due mainly to two factors: the long retention time of the solid particles and countercurrent flow and contact pattern, and the washwater added at the top of the froth. Their potential was recognized for the treatment of fine particles (*5, 6*).

This, and the need to process increasingly "difficult" ores, i.e. with low assays in the valuable material, as well as the need to minimize losses due to a decrease of resources availability, meant that flotation columns finally started becoming popular. Several companies have installed full-scale columns—e.g., in Canada, the United States, Chile, Australia, etc. (see the lists compiled by Moon and Sirois (*7*) and Finch and Dobby (*8*)—with equal or higher recoveries and higher grades than the replaced cells (*9*).

This renewed interest resulted in the need to study the fundamental phenomena occurring in the column (*10*), i.e., the hydrodynamics, the collision and collection processes, and the effects of process variables and geometrical features on column performance. The purpose of the present work was to investigate the performance of a laboratory-scale flotation column. Calcite ($CaCO_3$) dispersed in tap water was used as the particulate system, mainly for its ease of flotation; studies of its flotation behavior have already been reported (*11, 12*). In this work, calcite fines were used as the sole particulate material in order to determine the effects of process variables (gas and pulp flow rates, washwater addition, pulp density) on the rate of bulk flotation, i.e., total removal of the solids from the dispersion.



## EXPERIMENTAL

The experiments were performed in the laboratory in a column made of Perspex, having a height of 200 cm and an internal diameter of 2.5 cm, shown in Fig. 1.

The pulp was fed through a peristaltic pump (Watson-Marlow) at approximately two-thirds of the total height from the bottom of the column. The tailings were withdrawn from the bottom of the column with the help of another peristaltic pump (Masterflex), whereas the froth freely overflowed from the column top.

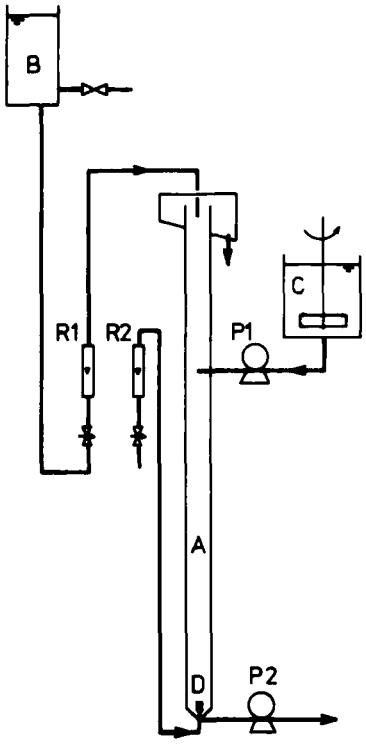


FIG. 1. Experimental set-up. A: Column. B: Constant-head water reservoir. C: Conditioning vessel. D: Gas diffuser. P1 and P2: Peristaltic pumps. R1 and R2: Rotameters.



Gas was introduced into the column at the bottom, just above the tailing's exit, through a small cylindrical sintered glass gas diffuser (Schott) of nominal porosity 160–250 μm. Washwater was fed into the froth at the top of the column from a constant head reservoir. The gas and washwater flow rates were continuously metered through calibrated glass rotameters.

The pulp consisted of carefully measured amounts of water and calcite, to which an amount of Acintol FA1 collector (kindly supplied by Arizona Chemical Co.) was added. The pulp (pH 7.2) was then conditioned in a stirred vessel at a stirring speed of 200 rpm. The addition of collector at a

rate of 800 g/ton and a conditioning time of 15 min was previously found to be sufficient for calcite pulps in tap water (*12*). In order to promote the froth structure and stability, a small amount of frother (pine oil) was also added to the pulp (0.002% w/v).

The calcite used in these experiments came from the Thessaloniki area (in Northern Greece) and was found to have the following chemical composition (w/w): CaO 50.84%, MgO 2.57%, $R_2O_3$ 0.81% (mainly Fe), $SiO_2$ 0.99%, loss on ignition 44.79%. It was crushed in a jaw crusher and finely ground in a pulverizer, with approximately 80% (w/w) of it in the range between 75 and 45 μm (see Fig. 2).

All experiments were performed in the following manner. Initially, the column was filled with tap water up to the required level. Washwater was allowed to flow and gas was bubbled through the column contents; both gas and washwater rates were carefully adjusted to the predetermined values.



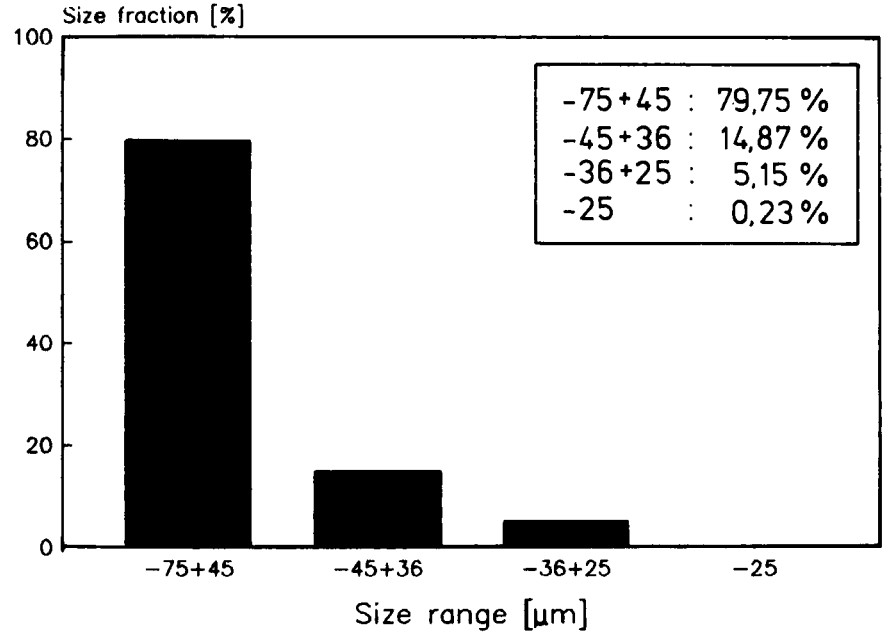


FIG. 2. Size distribution of calcite used in the experiments.

At time $t = 0$, the pulp-feeding pump was turned on and the tailings pump was continuously adjusted so as to keep the position of the collection zone-froth interface steady at a height of 150 cm. This allowed for a froth depth of 0.50 cm and, at the same time, a distance of 20 cm from the pulp entry point.

After enough time had elapsed for the column to achieve steady state, several samples were taken simultaneously by collecting both concentrate and tailings flows in separate vessels for 1 or 2 min; these were subsequently analyzed for their solids content. The recovery of calcite in the concentrate was calculated from the concentrate and tailings mass flow rates and the corresponding solids contents:

$$R = \frac{100 Q_C X_C}{Q_C X_C + Q_T X_T} \ (\%) \qquad (1)$$



## EXPERIMENTAL RESULTS

### Initial Stages

When the pulp started flowing into the column, the solid particles could be seen flowing downward frontwise against the rising bubbles. These were initially rather large but, as the surface-active reagents started dispersing in the liquid phase, they became smaller and smaller. Finally, a milky cloud was formed with solid particles and gas bubbles practically indistinguishable.

At the same time, a froth started building up on top of the liquid phase, initially consisting of rather large and unstable bubbles. The interface between the collection zone and the froth could be clearly distinguished, and while it was maintained steady by controlling the tailings rate, the froth rose slowly until, finally, it overflowed from the top of the column. At the same time the texture of the froth changed: the large bubbles, which formed a polyhedral froth, gradually gave way to smaller, heavily-mineralized bubbles, with the froth resembling the "aggregate froth" described by Schulze (*13*).

### Steady-State Operation of the Flotation Column

Figure 3(a) demonstrates that as soon as a concentrate flow was established, it remained practically stable. The same was true for the tailings

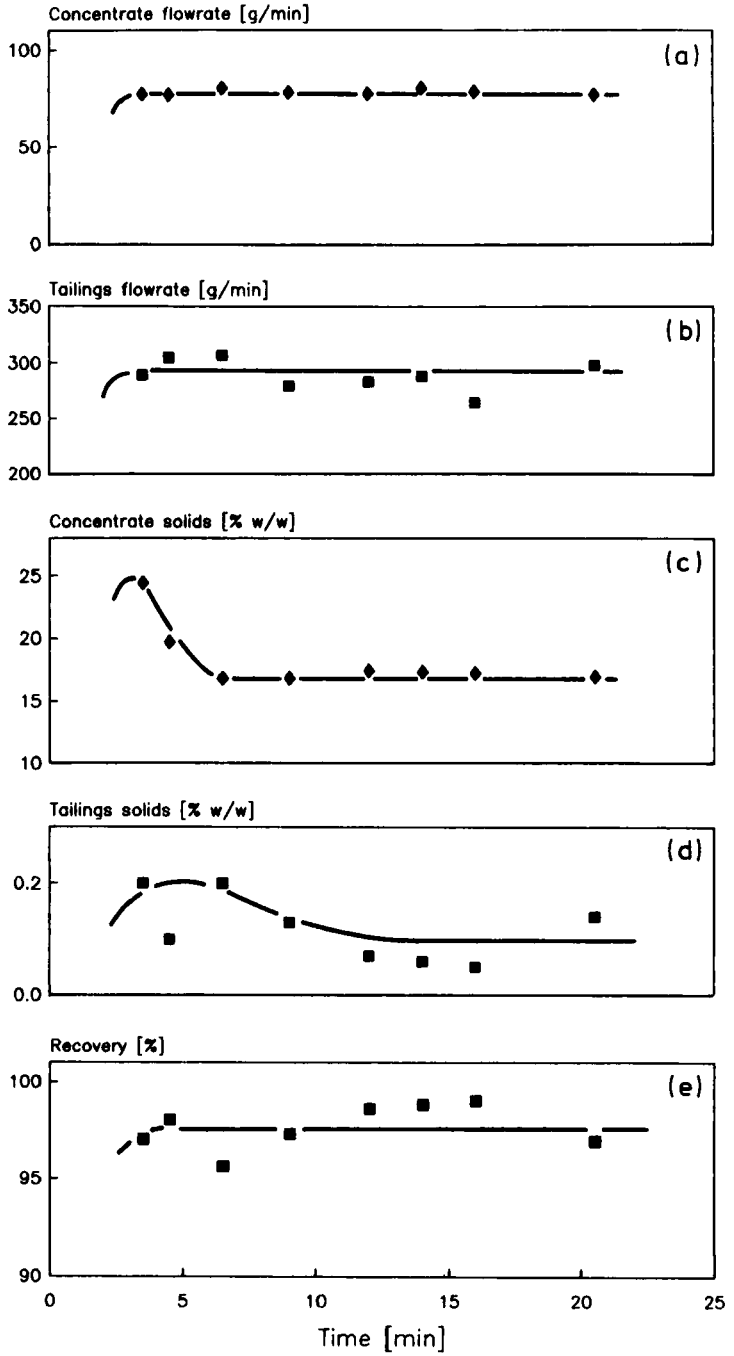


FIG. 3. Steady-state operation of the flotation column. $J_P = 0.88$ cm/s, $J_G = 0.68$ cm/s, $J_W = 0.34$ cm/s, $X_P = 5\%$ w/w.

flow—Fig. 3(b)—although some dispersion may be observed there. This is probably due to the fact that the stability of the column operation was maintained by controlling the tailings rate, which entailed that the tailings pump rate was practically continuously adjusted in order to maintain the collector zone–froth interface steady.

The time needed for achieving steady-state operation corresponded roughly to the time required for the solids front to travel to the bottom of the column. If $J_P$ is the superficial pulp velocity, which is defined as the nominal pulp velocity in the column and is given by

$$J_P = Q_P/A_C \tag{2}$$

and $L_C$ is the effective length of the collection zone (in this case, $L_C$ = 150 cm), then the nominal mean residence time of the pulp in the column is

$$\tau_P = L_C/J_P \tag{3}$$

which for a pulp flow rate of 267 g/min with a solids content of 5.1% (w/w) and a calcite density equal to 2.7 (*12, 14*) comes to $\tau_P$ = 170.5 s or 2.8 min, roughly the time observed experimentally. From Fig. 3 it may be clearly seen that allowing for at least $2\tau_P$ to elapse seemed sufficient in order to achieve steady-state operation.

It should be noted that the texture of the gas–liquid–solid mixture both in the collection zone and the froth depended upon the amount of solids in the pulp. Thus, at low solids contents, the froth structure was clearly different from that of the collection zone, allowing for an easy observation of the interface. However, as the concentration of solids in the pulp increased, this difference became less and less apparent until it was just perceivable. At this stage it was extremely difficult to control the column visually—in fact, the interface practically disappeared in several instances, which probably corresponds to the "loss of interface" as described by Finch and Dobby (*8*).

The amount of solids in the concentrate displayed an interesting feature: while it was initially high, it soon reached a lower steady concentration—Fig. 3(c). This may be attributed to the fact that during the initial rise of the froth, the bubble structure is unstable and the solids from the rupturing large bubbles accumulate on the lower ones, thus the froth that is initially discharged from the top of the column is heavily mineralized. With the establishment of a stable froth structure though, this process is terminated, the small-bubble froth is stabilized, and its solids content becomes steady.

The establishment of steady-state in the rate of concentrate flow and of its solids content meant that the recovery of calcite soon reached steady-state also, as may be seen in Fig. 3(e), and it also remained practically stable throughout the operation.

## Effects of Pulp and Gas Flow Rates on Calcite Recovery

After the initial dynamics of the column operation were investigated, the influence of various other parameters on the recovery of calcite was studied. In the subsequent figures the superficial velocities rather than the absolute flow rates are adopted, since this facilitates comparison of the performance for columns of varying diameters. Superficial velocities were calculated using Eq. (2) and the relevant flow rates.

As may be seen in Fig. 4, the effect of the gas and pulp flow rates depended upon their relative magnitude. Thus, at a low gas flow rate ($J_G$ = 0.68 cm/s), an increase in the pulp flow rate caused an initial rise of the concentrate rate and its solids content. At these low superficial velocities the recovery of calcite was almost 100%, indicating efficient column operation. A further increase of the pulp flow rate at this lower end of the gas flow rate range caused a decrease in the concentrate flow rate, thereby demonstrating a peak at approximately $J_P$ = 0.9 cm/s—Fig. 4(a)—beyond which operation of the column was no longer efficient, as seen in a drop of the calcite recovery—Fig. 4(c).

When the gas flow rate was increased, however—$J_G$ = 1.02 cm/s—this initial increase was barely perceptible, and at even higher gas flow rates—$J_G$ = 1.49 cm/s—a gradual decrease in column performance was actually observed, also at low pulp flow rates, with a sharp decrease in calcite recovery. This is probably due to a complex dependence of the mixing process upon the flow rates: at low pulp and gas flow rates, the phases are effectively mixed and the efficiency of the collision and capture of solids by the bubbles is high; at higher flow rates, though, the higher relative velocities result in less efficiency in the collection process and thus a decrease of the column performance is observed. This corresponds to the "flooding" situation reported by Dobby and Finch (*15*).

## Effect of Pulp Density on Column Performance

The effect of pulp density on calcite recovery is clearly demonstrated in Figs. 5 and 6: at low pulp densities, recovery was practically stable up to a solids content of approximately 10%, after which a sharp fall of the

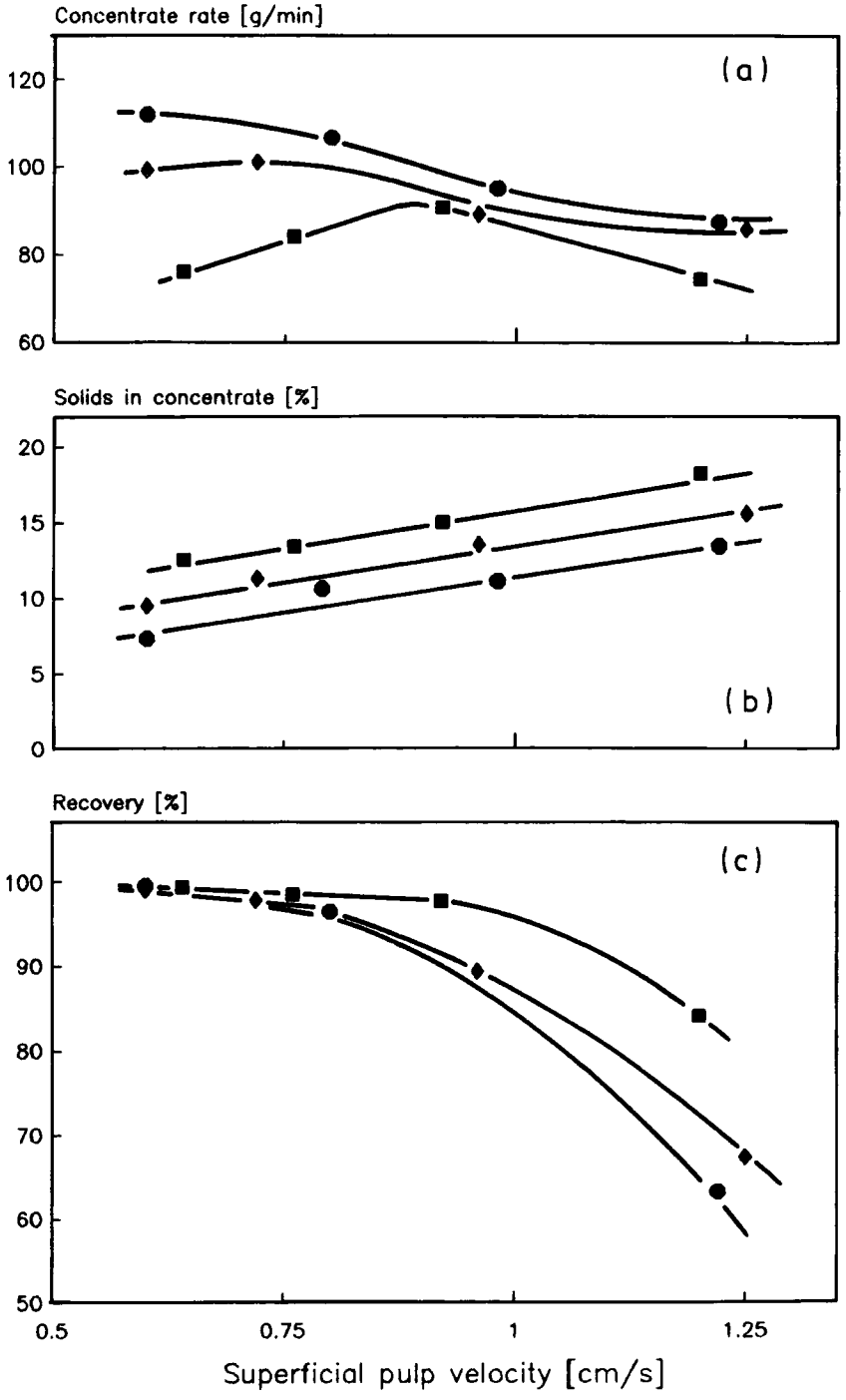


FIG. 4. Effect of the gas and pulp superficial velocities on the flotation column performance. ($J_W$ = 0.34 cm/s, $X_P$ = 5% w/w; $J_G$: (■) 0.68 cm/s, (♦) 1.02 cm/s, (●) 1.49 cm/s.

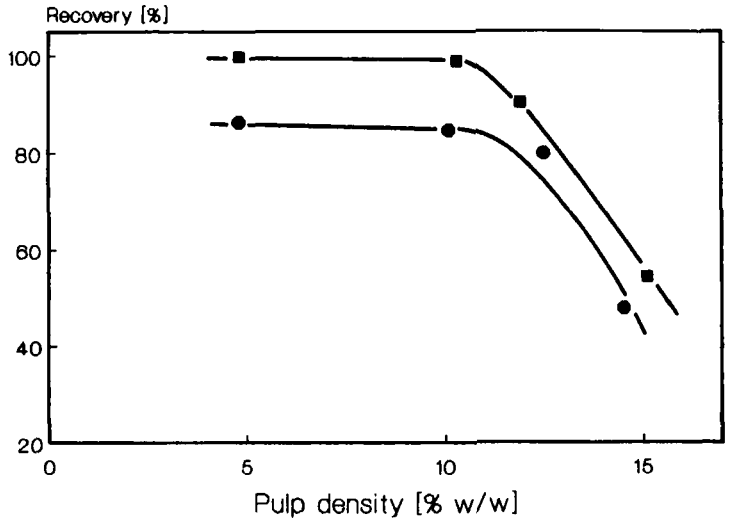


FIG. 5. Effect of the pulp density and pulp flow rate on the calcite recovery. $J_G$ = 1.02 cm/s, $J_W$ = 0.34 cm/s; $J_P$: (■) 0.84 cm/s, (●) 1.02 cm/s.

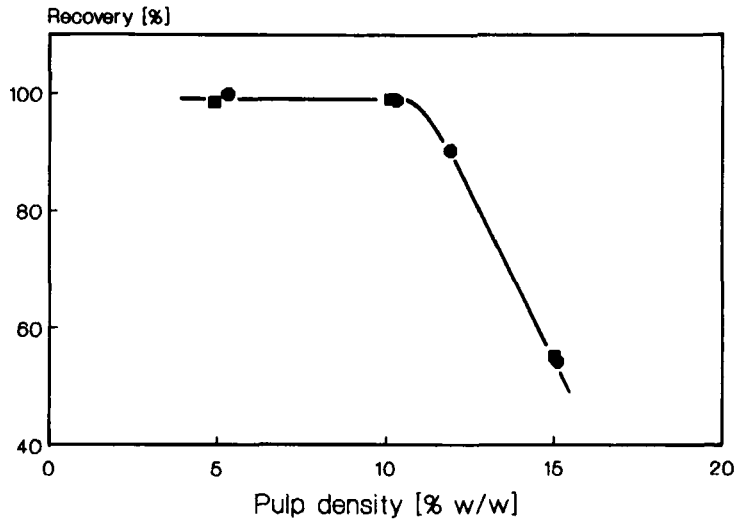


FIG. 6. Effect of the pulp density and gas flow rate on the calcite recovery. $J_P$ = 0.84 cm/s, $J_W$ = 0.34 cm/s; $J_G$: (■) 0.68 cm/s, (●) 1.02 cm/s.

recovery was observed. The additional effect of pulp and gas flow rates was also investigated. At a constant gas flow rate corresponding to an intermediate superficial velocity ($J_G$ = 1.02 cm/s), an increase in the pulp flow rate (from $J_P$ = 0.84 to 1.02 cm/s) caused a significant lowering of calcite recovery (Fig. 5). However, the effect of pulp density remained the same and, again, a sharp fall in recovery occurred when the solids content of the pulp rose above 10%.

On the other hand, at a constant pulp flow rate ($J_P$ = 0.84 cm/s), the increase in gas flow rate from $J_G$ = 0.68 to 1.02 cm/s had no further effect (Fig. 6), and the dependence of calcite recovery upon pulp density was practically identical for both gas flow rates.



## Effect of Washwater Addition on Flotation

Next, the effect of washwater addition was investigated. This is the main feature that differentiates the column from the mechanical flotation cell, and it is thought to be beneficial to overall column performance since it helps clean the froth from any entrained gangue while at the same time preventing water from the pulp flowing into the concentrate. In this way it was hoped that certain cleaning flotation stages could be gained.

The washwater stream is assumed to split into two streams: one is entrained together with the solids in the concentrate, while the remaining net downward flow is called the bias. The bias rate, $B$, may be calculated by subtracting the water flow rate in the pulp from the water flow rate in the tailings:

$$B = Q_T(1 - X_T/100) - Q_P(1 - X_P/100) \quad (4)$$

When $B$ is positive, there is more water flowing out of the column than has gone in with the pulp: the additional water is supplied by the "positive" bias—Fig. 7(a). If, however, the bias rate is negative, some of the pulp water has gone into the concentrate: this is potentially a source of concentrate contamination by gangue, which is undesirable—Fig. 7(b). Therefore, the aim of the operator should be to maintain a steady positive bias without, on the other hand, putting in too much washwater.

The amount of washwater flowing into the froth was altered from a low flow rate of 40 $cm^3$/min up to 100 $cm^3$/min (corresponding to a superficial washwater velocity of $J_W$ = 0.13 cm/s up to 0.34 cm/s). Its effect upon the bias rate is clearly illustrated in Fig. 7(c): at low superficial washwater velocities, it was found to be negative, whereas a flow rate of approx-

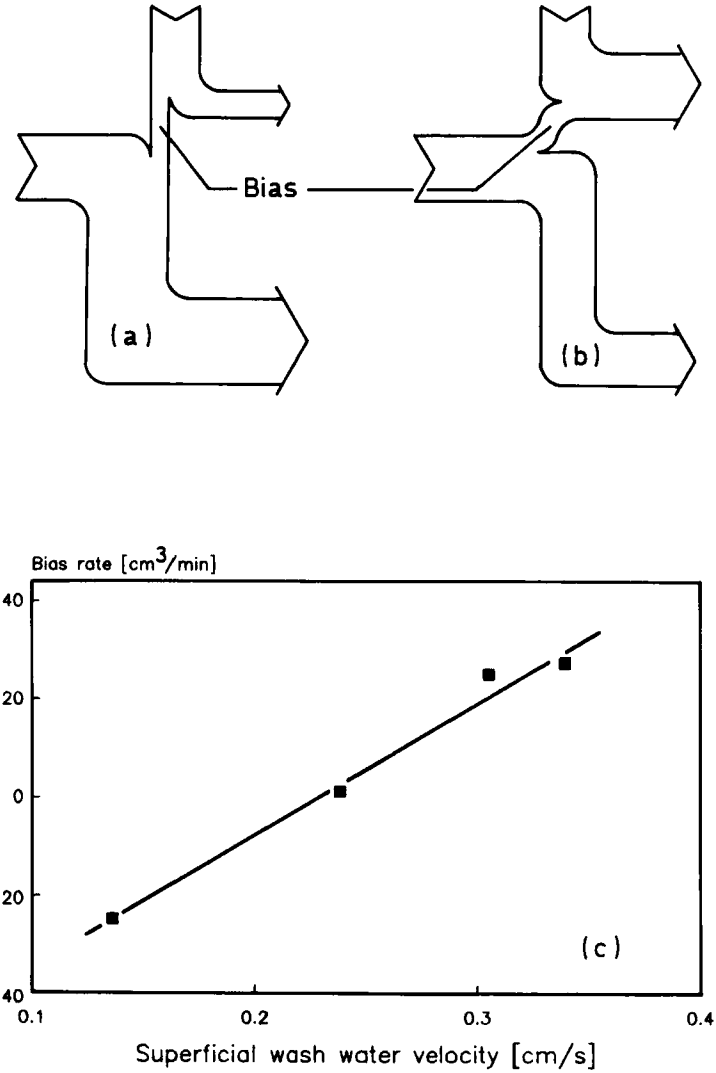


FIG. 7. Effect of the washwater flow rate on the bais rate. $J_P = 0.86$ cm/s, $J_G = 0.68$ cm/s, $X_P =$ 5% w/w.

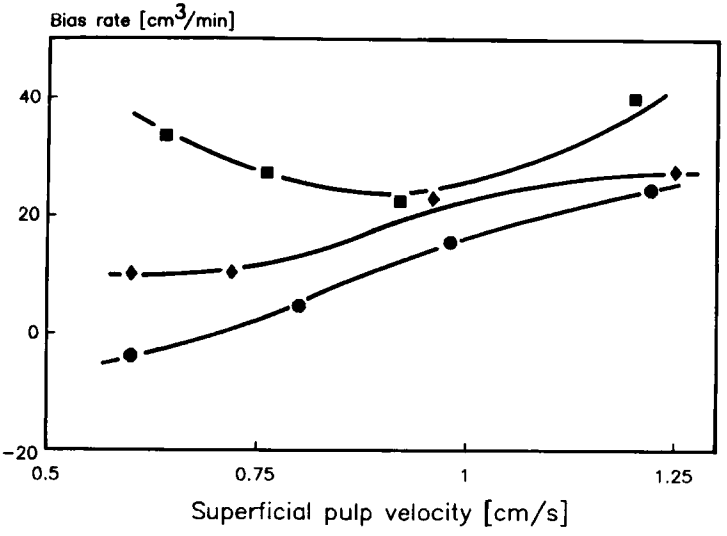


FIG. 8. Effect of the superficial pulp velocity on the bias rate. $J_W$ = 0.34 cm/s, $X_P$ = 5% w/w; $J_G$: (■) 0.68 cm/s, (♦) 1.02 cm/s, (●) 1.49 cm/s.



imately 70 cm$^3$/min of washwater ($J_W$ = 0.24 cm/s) was required in order to prevent the pulp water from flowing into the concentrate.

The bias rate was obviously a function not only of the washwater rate, but of the gas and pulp flow rates too, as is illustrated in Fig. 8. At a low gas flow rate ($J_G$ = 0.68 cm/s), an increase of pulp flow rate initially caused a decrease in the bias rate, reflecting a kind of "obstruction" or "flooding" due to the increased pulp flow rate, which is overcome by higher pulp flow rates (for $J_P > 0.95$ cm/s). At higher gas flow rates ($J_G$ = 1.02 and 1.49 cm/s), it seems that no such phenomenon occurs and the more pulp that flows into the column, the more washwater is allowed to flow downward, exhibiting a kind of entrainment. It is most interesting to observe that for low pulp flow rates, an increase of the gas flow rate caused a decrease in the bias rate; at the highest gas flow rate ($J_G$ = 1.49 cm/s), a negative bias was observed, denoting a flow of pulp water into the concentrate.

## DISCUSSION—CONCLUSIONS

The operation of a flotation column has been found to be straightforward. It attains steady-state in a relatively short time and this is main-

tained afterward by simply monitoring the collector zone–froth interface and controlling the tailings rate.

The amount of solids in the concentrate, the mass flow rate of the concentrate, and the recovery of calcite were a function of the various operating variables. An increase in both pulp and gas flow rates beyond a certain value essentially resulted in a decrease in the column performance, thus defining a region of variable values for which the performance of the column is optimum.

It is obvious, however, that the performance of the flotation column depends not only upon the above operating variables but upon several other parameters. For example, for the same mineral and for the same column, recovery is affected by the size of particles and the type of chemical reagents used for promoting the flotation process (collector, modifiers, etc.), froth stability (frother), etc.

The geometrical features of the column are of major importance. For example, a change in the diameter of the column will alter both the gas and liquid flow patterns, thus affecting the mixing process and, therefore, the flotation rate. An increased collection zone length increases the time spent by the solid particles in it, and thereby increases the probability of particles colliding with and adhering to a rising bubble. A deeper froth zone, on the other hand, means a longer time spent by the mineralized bubble rising against the washwater stream, thus resulting in more efficient cleaning from any entrained gangue particles.

Several workers have proposed models for describing the phenomena occurring in a flotation column (*16–21*). However, more work is required, mainly experimental, to provide the data necessary for correcting and validating these models and helping in the development of scale-up rules for designing flotation columns for the treatment of specific particulate systems.

Finally, column flotation might prove useful in the near future not only in mineral processing field but in emerging new technologies It could be used, for example, as an alternative to filtration or sedimentation for recovering fine particulate materials produced in dilute disperions (e.g., biotechnology, etc.).



## SYMBOLS

$A_C$ cross-sectional area ($cm^2$)
$B$ bias rate ($cm^3/s$)
$J_G$ superficial gas velocity (cm/s)

$J_P$ superficial pulp velocity (cm/s)
$J_W$ superficial washwater velocity (cm/s)
$L_C$ collection zone length (cm)
$Q_C$ concentrate mass flow rate (g/s)
$Q_P$ pulp mass flow rate (g/s)
$Q_T$ tailings mass flow rate (g/s)
$R$ recovery (%)
$t$ time (s)
$X_C$ concentrate solids content (grade) (% w/w)
$X_P$ pulp solids content (% w/w)
$X_T$ tailings solids content (% w/w)

## Greek Letters

$\tau_P$ pulp mean residence time (s)



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