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MIXING IN FLOTATION COLUMNS. IV: EFFECT OF INTERNAL COLUMN STRUCTURE ON LIQUID-PHASE MIXING

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ABSTRACT

The effect of vertical baffling, of the type and number of gas spargers and of the presence of packing material on the mixing process in a flotation column has been experimentally investigated. The presence of vertical baffles was found to accelerate considerably the liquid flow, leading to an almost complete mixing of the collection zone. Multiple gas spargers had also a similar effect, whereas the use of a bed of packing, made of short cylindrical glass tubes, effectively abated the mixing. Thus, packing seems the only means of altering the column internals in order to reduce the liquid-phase mixing. The mixing process seems to be related to flow instabilities generated at the gas spargers and possibly to gas- and/or liquid-phase inlet maldistribution. Copyright ©1996 Elsevier Science Ltd

Keywords
Column flotation; mixing; modelling

INTRODUCTION

The performance of flotation columns is directly affected by the gas-, liquid- and solid-phase flow pattern inside the collection zones. The counter-current contact of the gas with the solid-liquid phase effectively brings into contact the phases, allowing for collisions and eventual adhesion of the hydrophobic particles on the rising gas bubbles. It is obvious that, although a certain amount of turbulence is necessary to achieve the required contact, too much turbulence and mixing may result in the disruption of the particle-bubble bonds and their detachment, reducing the process efficiency.

The large diameters favoured by constructors and plant operators, reaching almost 4 m, result in an aspect ratio—i.e., the ratio of column height to diameter—of approximately 4-5. However, the increase in column diameter, keeping its height constant, leads to an increase in the degree of mixing, as already experimentally observed [1,2]. Therefore, it would possibly be beneficial to modify the internal structure of the collection zone, in order to abate the mixing process.

In this work, an experimental program was devised in order to study the effect of modifications on the mixing of the liquid phase; this comprised the alteration of some of the column internal features, like:

- the presence and position of vertical baffles, separating the collection zones into distinct regions,
- the number of gas spargers, or
- the presence of packing material

and the determination of the effect of these changes on the residence time distribution of the liquid.

EXPERIMENTAL APPARATUS AND PROCEDURE

All experiments were performed in a column having a diameter (d_C) of 11 cm and a initial liquid height (h_{L0}) of 150 cm. Liquid was fed at approximately 20 cm below the free liquid surface and was withdrawn from the bottom of the column. Gas was fed through a sparger. Calibrated rotameters were used to monitor and control the flow of the two streams; a U manometer was also used to determine the gas pressure just before the sparger, in order to calculate the volumetric gas flow rate.

Gas superficial velocities (u_G) varied within the range [0.49 .. 2.09], while the liquid superficial velocities (u_L) varied from 0.42 to 1.37 cm/s; thus, both u_G and u_L were typical of the conditions encountered in flotation columns, in contrast to bubble columns, where much higher (especially for gas) velocities are usually applied.

A small volume—usually 1-2 cm^3—of 3M KCl was introduced into the liquid stream just before the feed to the column; the conductivity of the outflowing stream was determined by a conductivity cell (cell constant $k = 1.0\ cm^{-1}$) connected to the column liquid outlet, and the conductivity readings were collected on a personal computer through a 12-bit A/D data acquisition card. Time-conductivity data were subsequently transformed into time-concentration data and used to determine the RTD. The results presented in this work were performed in triplicate and the mean RTD was determined in each case.

RESULTS AND DISCUSSION

Baffling

The alteration of the column interior with some kind of internal structure, like baffles, internal draught tubes or plates, among others, is often used in the chemical process industries to modify their hydrodynamic characteristics: gas and/or liquid flow pattern, gas hold-up [3-10]. Baffles are sometimes horizontal, and they are often used in conjunction to mechanical agitation in each of the compartments created by the baffles to enhance the gas-liquid intermixing.

In flotation columns, vertical baffles may be more appropriate in order to avoid the disruption of the particle-laden bubble mobility. The use of vertical baffles has been investigated by (among others) Miszczak [11], Moys [12] and Xu [13]; Rice *et al.* [14] used also conical 3-D baffles with a major horizontal dimension. Recently, the residence time distributions obtained in a plain column were compared to the RTDs obtained in a column with a single vertical baffle [15]; an intensification of the mixing process was observed, with the column behaving almost as a single well-mixed vessel. The addition of another baffle, separating the collection zone into four regions, had no additional effect on the mixing process.

In this work, the effect of a single vertical baffle on the RTD was further investigated. For these experiments, a different liquid feeding position was chosen (Figure 1; series "F"), distributing the incoming liquid downwards at the axis of the column; the vertical baffle was positioned 11.0 cm above the gas sparger and extended up to 11.0 cm (one column diameter) below the liquid feed tube. In the previous experiments [15], the feeding tube was connected so as to be flush with the inside wall of the column (Figure 1; series "A").

Figure 2 illustrates the results obtained with the baffled column (Figure 1; series "G") and compares them to the unbaffled column data. The plain-column RTD (indicated as series "F") yielded a simple Gaussian profile; a series of theoretical profiles was generated using the following equation :

$$E_\theta = \frac{N(N\theta)^{N-1}}{(N-1)!} \exp(-N\theta) \tag{1}$$

and the best-fitting number of well-mixed zones (N) was determined by determining the minimum of the sum of squared deviations :

$$\text{best fit} = \min\left\{\sum \left(E_{\theta,\text{theor}} - E_{\theta,\text{exper}}\right)^2\right\}$$

where E_θ is a function of the dimensionless time (θ) and the number of zones-in-series (N). Thus, the collection zone was found to correspond to a series of 5 well-mixed stages, through which the liquid moves as it flows towards the bottom of the column.

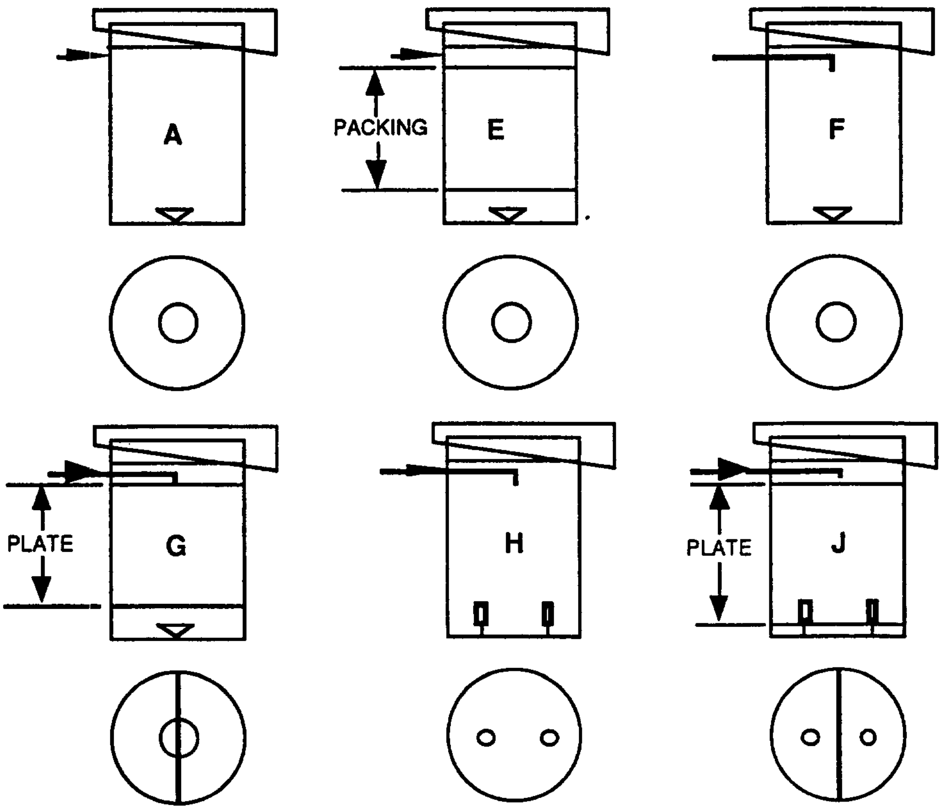


Fig.1 Experimental setup of the flotation column for RTD measurements; d_C = 11.0 cm; h_{L0} = 150.0 cm.

It has been theoretically postulated [16] that the number of stages may be estimated from the column aspect ratio, i.e., the ratio of the column height vs. the column diameter [see ref. [17] for a discussion of various related models]; in the present case, the aspect ratio was ($h_L : d_C = 150.0 : 11.0$) $\approx$ 14, which is almost double the number of stages determined by fitting of the profiles, indicating that mixing is more considerable than expected in the collection zone, possibly due to the strong interaction of the countercurrent gas and liquid flows.

The addition of the vertical plate seems to have caused an even more drastic mixing of the column contents, reflected by the RTD profile. After an short initial delay, necessary for the tracer to reach the exit of the column, the tracer concentration oscillated briefly (seen in expanded form in Figure 2B) and then followed the exponential decay, which is characteristic of the single, well-mixed vessel. Since the simple, zones-in-series model is not a realistic representation of the main flow in the baffled column, a different model was considered, which consists of a closed loop comprising a number of well-mixed zones (Figure 3a); liquid feed enters the loop at its top-most zone and leaves from the middle of the loop (bottom zone). This model has two adjustable parameters, the number of zones (N) and a recycle parameter, to account for the volumetric flowrate of the upward liquid flow.

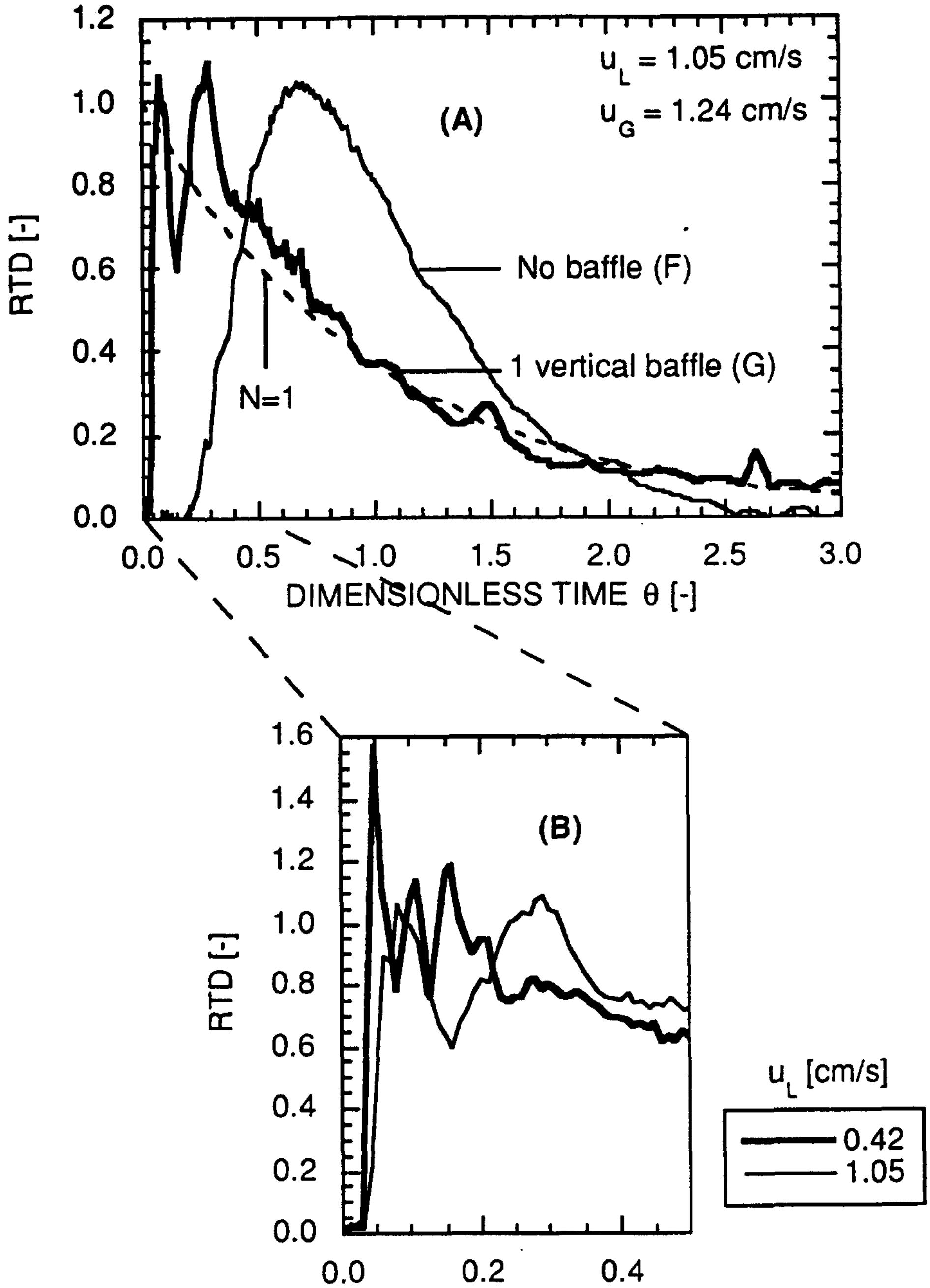


Fig.2 (A) Effect of a single vertical baffle on residence time distribution. (B) Magnification of top figure for $\theta \leq 0.5$, showing more pronounced internal flow recirculation at low liquid superficial velocities.

The model predictions (Figure 3) show the initial oscillation for an intermediate value of the recycle parameter. These results—which are used here only to provide an insight about the flow structure—imply that the presence of the baffle induces a strong recirculation, and a further intensification of the mixing process; this is consistent with the results obtained by Moys *et al.* [12]. It is also interesting to note that, although their recommendation that a space is left free just above the sparger—for the flow to redistribute freely—was kept, this did not seem to reduce the liquid-flow acceleration.

The effect of the gas and/or the liquid volumetric flow rate on the RTD was studied in some detail by increasing u_G and/or u_L (Figure 4), but neither increase seemed to have any particular discernible effect on the mixing process.

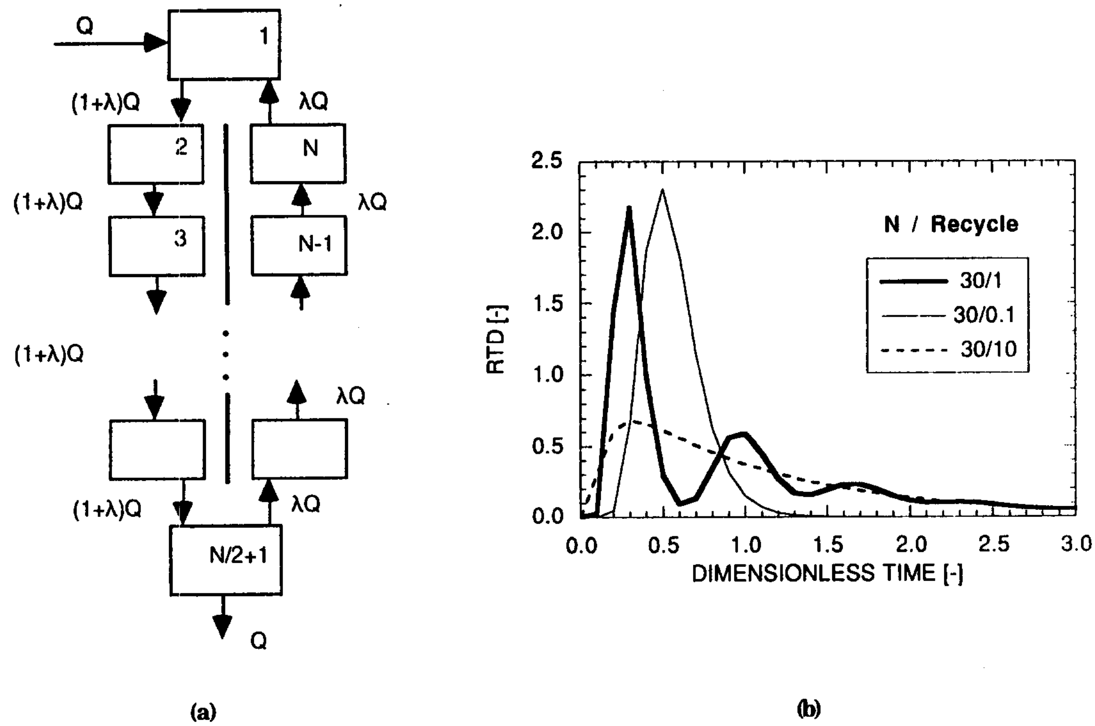


Fig.3 Effect of gas (top; A) and liquid (bottom; B) flow rate on RTD in a flotation column with a single vertical baffle.

It should be noted that the enhanced mixing of the liquid phase may not be due solely to the presence of the baffle; its vertical alignment or the column alignment, or the position of the outlet of the pulp-feeding tube may also cause liquid-flow maldistribution and contribute to this phenomenon; however, given the major pattern change seen in the RTD profiles due to the presence of the baffle itself, studying of the effect of such details was not undertaken, since this would be out of the scope of the present investigation.

Gas Spargers

Since the agitation of the phases in a flotation column is provided by the counter-current contact of the two phases, it is conceivable that the type and position of the gas sparger may affect the flow pattern inside the flotation column as well as the mixing process.

Spargers employed in chemical vessels are usually metal tubes or plates with a small number of relatively large holes, but when there is a need for small bubbles, as for example in flotation and especially in columns, porous spargers have been favoured. The spargers themselves may be rigid or made of a flexible material, e.g., of rubber, fabric or filter cloth [18–22], which is itself beneficial, since spargers from such material tend to clog less [13].

In this work, the effect of the sparger form and position of the sparger has been studied, in conjunction with the presence of a vertical baffle: either a single large porous disk, or two cylindrical porous spargers were fitted at the bottom of the column. The large single plate had a diameter of 60 mm, while the two gas diffusers had a diameter of approximately 13 mm and a height of 20 mm. Both the plate and the twin diffusers had a porosity of G4, corresponding to a maximum pore diameter of 10–16 μm. The set-up was tested with (series "J") and without (series "H") the vertical baffle, which for the twin spargers extended down so that its lower edge was below their base.

Figure 5A illustrates the effect of the sparger type—single or twin—on the column RTD, when no baffle is inserted in the collection zone. The presence of the two sources of bubbles seems to intensify the mixing process, with the RTD profile moving towards the single well-mixed vessel profile. The insertion of a vertical baffle (Figure 5B) results in an considerable enhancement of the liquid circulation in the column; with the profiles for the two types of spargers becoming practically indistinguishable and close to the single well-mixed vessel profile. The effect of the baffle insertion on the column RTD for the twin gas spargers is better seen in Figure 5C, where the circulation enhancement due to the presence of the baffle is more pronounced.

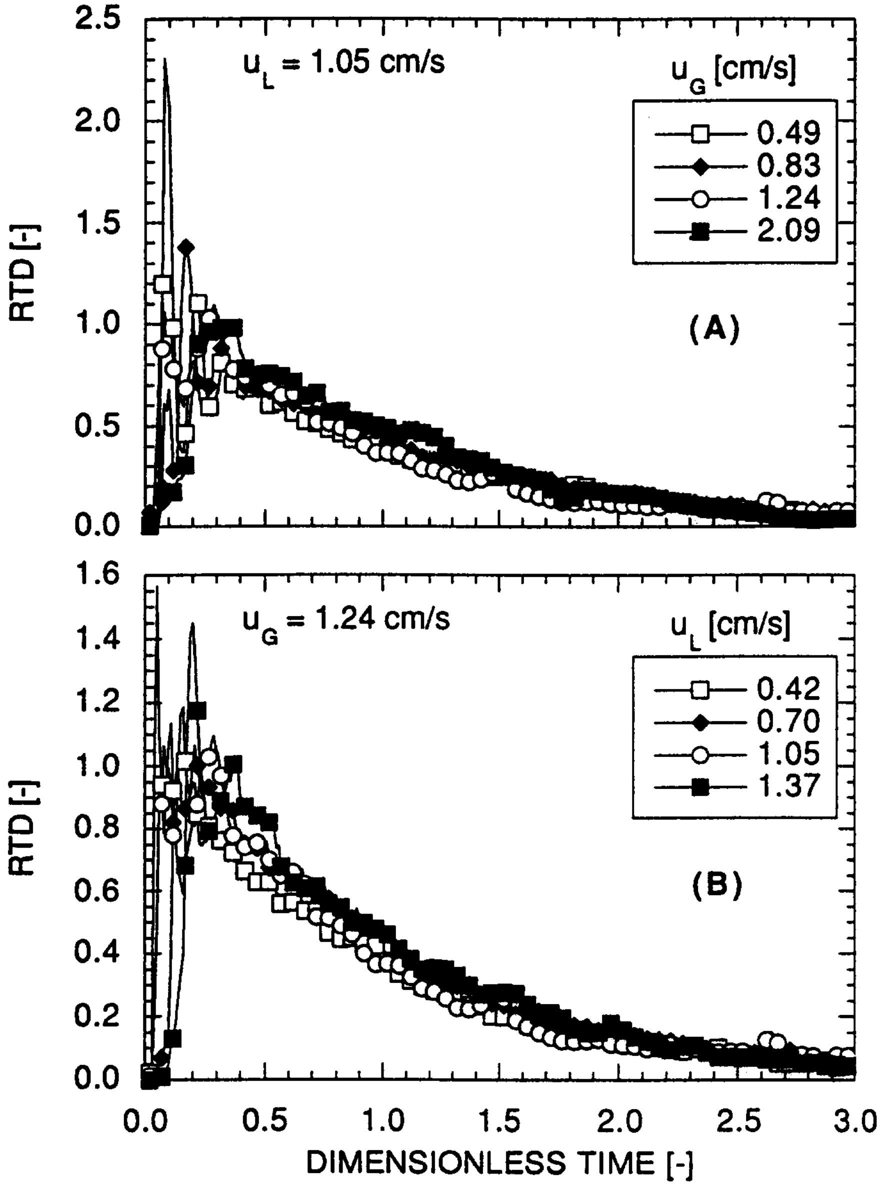


Fig.4 Comparison of effect of vertical baffling and/or single/twin sparger on column RTD; u_L = 1.05 cm/s, u_G = 1.24 cm/s.

The mixed zones-in-series with backflow model (Figure 6A) [1,9,23,24] was used to analyse the results for the single and twin spargers; the best-fitting parameter values—i.e., the number of well-mixed zones (N) and the backflow parameter (λ)—were determined by generating theoretical profiles and fitting them to the experimental ones using Eq. 2. The theoretical profiles were obtained by establishing the appropriate O.D.E.s corresponding to the number of zones (N), and integrating them using a Runge-Kutta routine for a range of λ values.

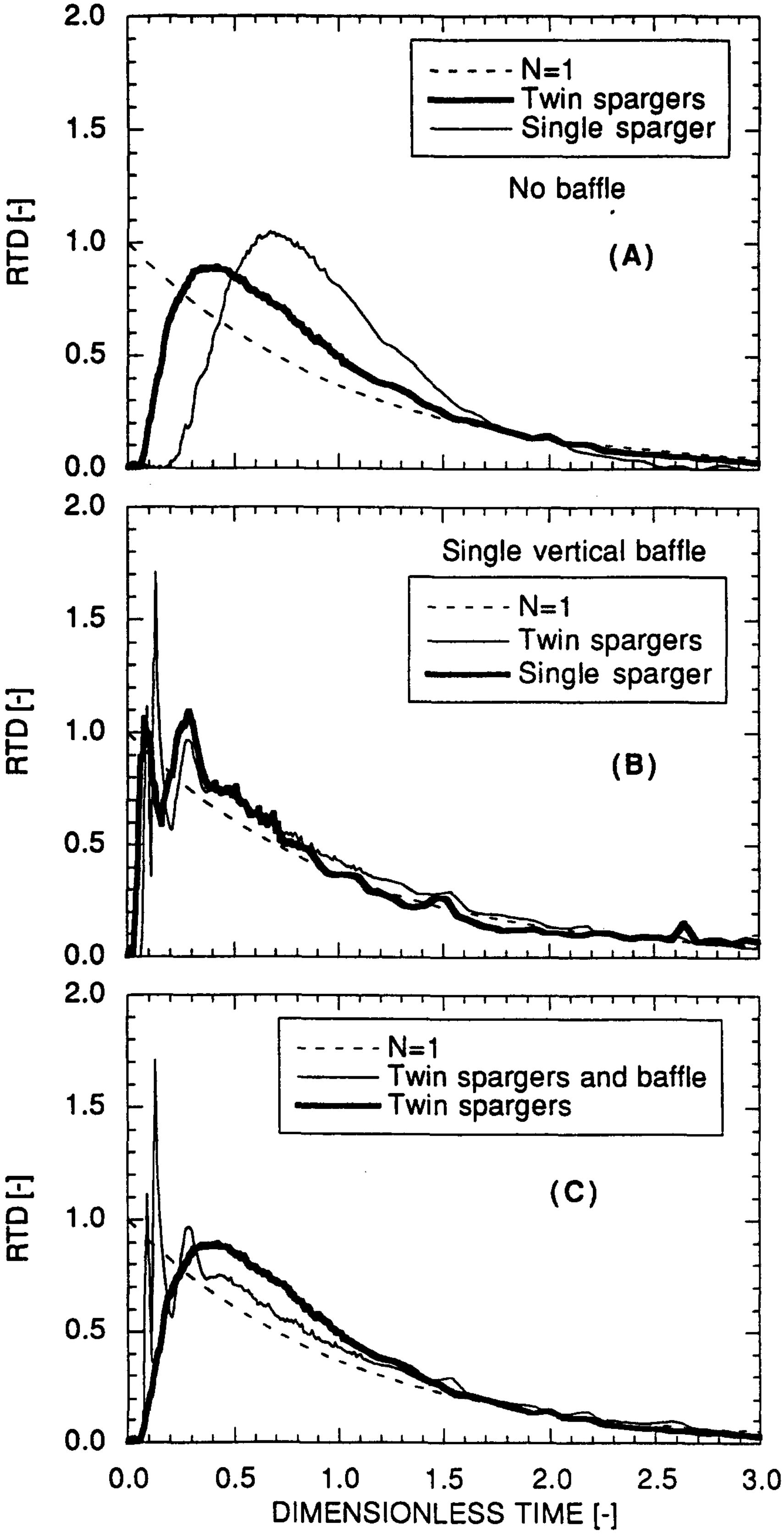
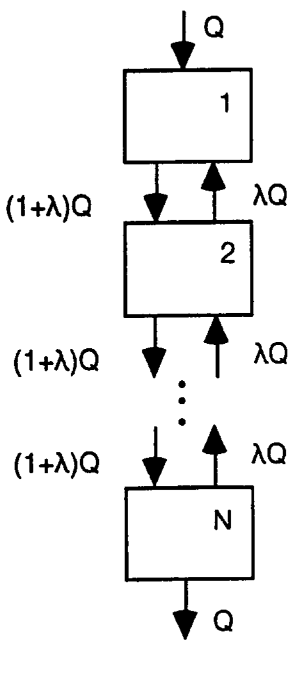
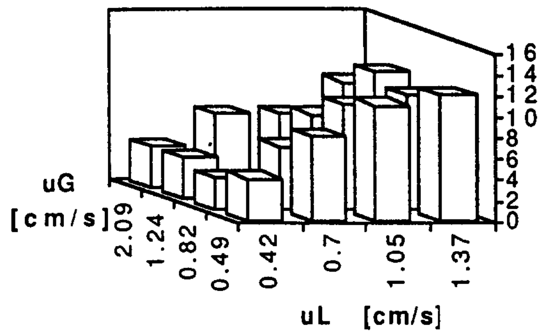
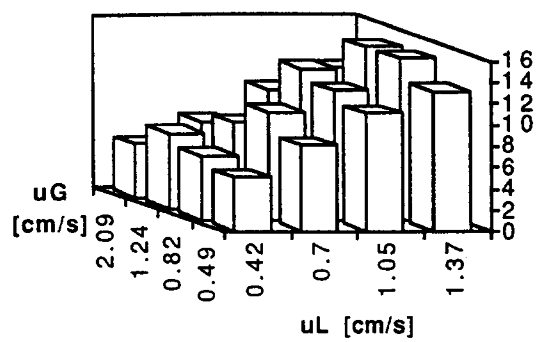


Fig.5 Comparison of effect of vertical baffling and/or single/twin sparger on column RTD; u_L = 1.05 cm/s, u_G = 1.24 cm/s.





(B) Twin-sparger column (λ = 3)



(A) (C) Single-sparger column (λ = 1)

Fig.6 (A) Model of mixed zones-in-series with backflow. Number of mixed zones-in-series for the twin-sparger column (B) compared to the single-sparger column (C) (the backflow parameter value indicated in each case was kept constant).

An average value of the backflow parameter $\lambda \cong 3$ could be used to describe the twin sparger system, as against $\lambda \cong 1$ for the single-sparger column (Table 1). An immediate conclusion from these results is that the internal recirculation between adjacent mixed zones is enhanced in the case of the twin-sparger column—in fact, it is three times the amount of backmixed flow for the single plate sparger—indicating an enhanced mixing process. Using these backflow parameter values, a new fitting of the RTD profiles was obtained, in order to determine the number of mixed zones corresponding to each experimental condition (Figures 6B and 6C). The results indicated that, in general, fewer mixed zones were necessary to represent the flow in the twin-sparger column than in the single-sparger one, again indicating a more mixed condition. The results also showed that the mixing process depended upon the liquid superficial velocity rather than on the superficial gas velocity.

It is also conceivable that any uneaveness in the gas flow through the two spargers could also contribute to the mixing process; however, the flow of the gas is unsteady even from a single sparger, as already noticed with a single porous sparger [15]. It was therefore concluded that the addition of a second sparger intensified the mixing process, and this was enhanced further when a vertical baffle was also present.

Packing material

Another possibility of modifying the flow and contact pattern in a flotation column is by introducing packing material, in order to increase the contact area and avoid the excessive turbulence [25,26]. The effect of packing on the column hydrodynamics has been studied mainly for bubble columns [27-30], but they have also been tested recently in actual flotation processes [31,32].

In this work, a plate with large holes was fixed 15.0 cm above the single porous plate gas sparger, and packing was added up to a height of 130.0 cm. The packing material was made of glass tubes with an inside diameter of 15 mm and a height of 16 mm.

TABLE 1 Backflow model parameter values (number of zones, N, and backflow parameter, λ for the twin-sparger (F4H) and the single-sparger (F4F) column.

	Twin spargers (F4H)				Single sparger (F4F)			
	N / λ				N / λ			
u_G \ u_L	0.42	0.7	1.05	1.37	0.42	0.7	1.05	1.37
0.49	4/3	8/3	11/3	8/2	5/1	3/0.001	4/0.1	5/0.1
0.82	5/5	8/5	7/2	4/1	6/1	10/1	12/1	14/1
1.24	6/5	---	8/3	4/1	7/1	8/1	13/1	14/1
2.09	4/3	7/3	11/5	10/3	5/1	7/1	4/0.1	12/1

	N (λ = 3)				N (λ = 1)			
u_G \ u_L	0.42	0.7	1.05	1.37	0.42	0.7	1.05	1.37
0.49	4	8	11	12	5	8	11	13
0.82	3	6	10	11	6	10	12	15
1.24	4	---	8	12	7	8	13	15
2.09	4	7	7	10	5	7	10	12

The RTD results obtained in the packed column (series "E") were compared to the results obtained in this column but without the packing (series "A"). A sharp reduction of mixing in the collection zone was observed (Figure 7), with the RTD profile exhibiting the sharp bell shape typical of systems with little mixing. The analysis of the results using the backflow model (Table 2) indicated that a larger number of mixed cells was necessary for the representation of the flow inside the column, than in the case of the unpacked one; the backflow parameter value was also generally lower than in the case of the unpacked column.

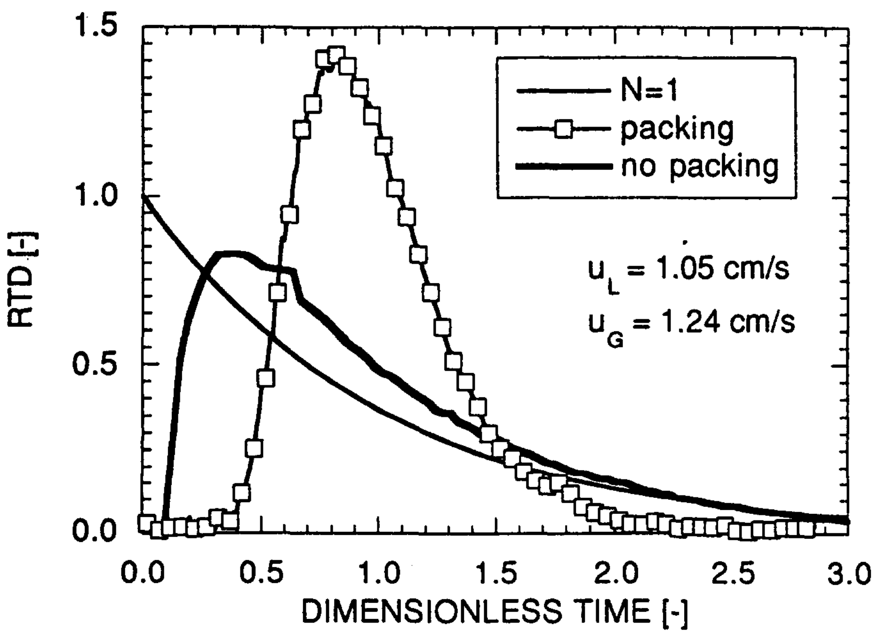


Fig.7 Effect of packing material on the collection zone RTD.

It is therefore concluded that the presence of packing would be potentially beneficial to the column flotation process, since it reduces considerably the mixing of the liquid phase, while at the same time providing the necessary interface for the contact of the bubbles with the particulate matter.

TABLE 2 Backflow model parameter values (number of zones, N, and backflow parameter, λ for the packed (F4E) and the unpacked (F4) column.

	Packed (F4E)				Unpacked (F4)			
	N / λ				N / λ			
u_G \ u_L	0.42	0.70	1.05	1.37	0.42	0.70	1.05	1.37
0.49	9/0.1	14/0.1	14/0.1	14/0.001	2/2	3/1	4/1	8/2
0.82	14/1	10/0.1	13/0.1	14/0.1	2/2	8/5	3/1	7/2
1.24	13/1	14/1	13/0.1	13/0.1	4/5	10/5	3/1	4/1
1.65	---	---	---	---	2/2	10/5	3/1	3/1
2.09	11/1	12/1	14/.01	12/0.1	2/2	9/5	11/5	3/1

DISCUSSION

These results indicate that the collection zone is—except for the case of the packed flotation column—fairly well mixed and that alterations like multiple gas spargers or vertical baffles effectively enhance the mixing of the liquid phase. The RTD profiles correspond in most cases to a number of perfectly-mixed cells with a considerable inter-cell flow, which is a multiple of the net incoming liquid/pulp volumetric flow rate. The number of cells is usually small, of the order of magnitude of the column aspect ratio. The circulation cell concept [16,33] seems to be thus validated, although its recent application by Millies and Mewes [34] to the backmixing in bubble columns resulted in small liquid velocities between adjacent cells, which seems to contradict the very fast tracer breakthrough and the recirculation peaks experimentally observed in this work.

The origin of the mixing process itself seems to be linked to gas flow instabilities, which generate in their turn velocity fluctuations, as postulated by Millies and Mewes [33]. Indeed, visual observation of the region of the gas sparger showed that its surface was neither fully nor steadily occupied by the emerging bubble swarm:

- at low gas flow rates, only the top part of the sparger was producing bubbles; moreso, they seemed to evolve from a region of the sparger, which changed with time, following a low-frequency rotary motion (this maldistribution was initially thought to be due to pore plugging, and the sparger was thoroughly cleaned with dilute HCl, but to no effect);

- as u_G increased, the surface of the sparger became increasingly covered by the bubbles (already noted by Finch and Dobby [13]); in the case of cylindrical gas diffuser spargers, the front of the "bubble-producing surface" progressively moved downwards, covering the side of the sparger;

- the bubble swirling and bubble swarm rotation was observed even at high gas flow rates.

It is thus likely that the mixing process is linked to the non-uniform spatial generation of bubbles. The flow pattern and the overall mixing process would then depend both upon the spatial and the temporal scale chosen for the flow analysis; the effect of the time scale on the overall flow pattern has already been illustrated by Lapin and Lübbert [35,36]. It would therefore be beneficial for the understanding of the mixing process to obtain detailed information about the flow micro-structure, using appropriate methods, like for example laser Doppler velocimetry; this technique is used extensively in liquid flow studies (see for example ref. [37]), and has started being applied to multiphase flows [38,39,40]. Detailed flow fields, covering all the height of the collection zone, would then reveal the correct cell structures and their dependence on the scale and geometry of the equipment, as well as the operating parameters.

CONCLUSIONS

The mixing process in the collection zone of a flotation column depends not only on the operating parameters, e.g., the gas and/or liquid volumetric flow rates, but on the internal geometry of the column. In this work, the effect of several alterations on the mixing, as determined by the residence time distribution of the liquid phase, has been investigated:

- the presence of vertical baffles inside the collection zone of a laboratory column, extending from the sparger almost to the pulp entry level, was found to enhance considerably the liquid circulation; this was contrary to expectations, since it was hoped that partitioning the column would lead to less mixing of the liquid phase and would therefore be beneficial to the flotation process.

- in contrast, the presence of packing material—in this case, small glass tubes—reduced considerably mixing, yielding plug-flow-like RTD profiles; further experiments are necessary, however, in order to determine how the type and depth of the packing affect the flotation process;

- finally, the presence of multiple gas spargers enhanced the liquid-phase mixing; this is probably due to the flow instabilities generated by the gas sparging.

Therefore, it is concluded that internal vertical baffling and/or multiple gas sparging result in a considerable enhancement of the mixing process, as characterised by the global RTD profiles.

Further work should concentrate on the study of the time- and space-dependent flow fields, in order to determine through their alteration possible means of reducing the liquid-phase mixing process.

LIST OF SYMBOLS

d_C	(internal) column diameter [m]
h_{L0}	initial (no gas) collection zone height [m]
k	conductivity cell constant [cm^{-1}]
N	number of perfectly mixed zones [−]
Q	liquid volumetric flow rate [$m^3\ s^{-1}$]
u_G	superficial gas velocity [cm/s]
u_L	superficial liquid velocity [cm/s]

Greek letters

θ	dimensionless time [−]
λ	backflow parameter [−]

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