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Bubble Extraction as an Improvement of Bubble Fractionation. Modeling of a Simple Apparatus

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ABSTRACT

A bubble extraction apparatus which utilizes a "hydrodynamic trap" effect is examined. The behavior of the trapping device, combined with various columns, can be described by means of a simple two-parameters model even when a concentration gradient is found to occur in the column. Experimental results on Sulphan Blue, Rhodamine B and picric acid are reported and checked against the model. The values of the parameters thus determined appear useful to investigate substances with respect to their surface activity and/or bubble conditioning effects.

INTRODUCTION

Bubble fractionation is perhaps the simplest of the various adsorptive bubble processes for separating surface-active materials. However, due to axial diffusion processes, redispersion of the solute from the top of the solution limits the degree of separation, especially when relatively large columns are used (1).

The redispersion of the solute can be reduced by making the process continuous, though the aqueous top part has to be removed at a relatively high rate, typically one-half of the input rate (2, 3), thus leading to a low enriching efficiency. In batch processes, on the other hand, collection in foams or in immiscible solvents is usually required in order to increase

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the extent of separation. However, it may be useful, or even necessary in some cases, to operate in the absence of foams or nonaqueous solvents. Various apparatuses have been proposed for this purpose (4, 5) to improve bubble fractionation by reducing the overall axial dispersion. They operate substantially by dividing the liquid solution into two portions, the lower part constituting the fractionation column and the upper one the enriched solution.

In the experimental set-up of Ref. 5, the separation is performed by inserting a suitable restriction at the top of the column, which fits into a collecting vessel. When the system is properly operating, a small foam column is formed where the cross section is reduced. This foam column acts as a "hydrodynamic trap" by reducing the backdiffusion of the surface-active substances which, owing to gas bubbling, are progressively transferred from the column into the collecting vessel where the bubbles break. This leads to an increase in separation yield together with an easy collection of the enriched solution in both batchwise and in continuous flow operation. In bubble fractionation, on the other hand, effective separation of the enriched section is feasible only when operating in the continuous mode.

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Quantitative removal of surface-active materials present in natural waters at ppb levels has thus been obtained with an increase in concentration reaching a few hundredfold. The same "hydrodynamic trap" effect has been applied on a pilot scale (6) for drinking water treatment. By means of a similar apparatus, bubble extraction has been applied to both solutions and colloidal dispersions as a preconcentration step in trace analysis with preconcentration factors reaching up to about 1000 (7, 8).

Optimum conditions of hydrodynamic trap performance were rather empirically achieved in the above-mentioned applications. Modeling of such a device therefore appears worthwhile and will be dealt with in this paper.

EXPERIMENTAL

Materials

In order to obtain reliable measurements with respect to mass balance of the solute, it was necessary to choose substances that did not present significant adsorption effects on the walls of the collector, as is typical of various surfactants and coloring agents of a cationic nature (5). An anionic coloring agent with a limited surface activity, Sulphan Blue (Merck), subsequently indicated as SB, and a more surface-active amphoteric agent, Rhodamine B (Carlo Erba RS), subsequently indicated as RB, were found to be suitable for this purpose. Furthermore, picric acid (Carlo Erba RPE),

subsequently indicated as PA, was used as a nonsurface-active substance in order to follow exclusively the dispersion effects. The solutions were prepared with MilliQ reagent-grade water. RB and PA were used without any further purification. On the contrary, the SB solutions displayed a shift of the absorption peak from 635 to 638 nm following the enrichment process, and as a result the reagent was purified as follows.

An excess of a 0.1% solution of the coloring agent was treated with 10 mL of a solution of 10^{-3} M hexadecyltrimethyl ammonium bromide (Aldrich, purity 99%) and extracted three times with 10 mL portions of chloroform. The three portions were collected together, and the solvent was completely evaporated. The residue was recovered with 1 mL of ethanol, and subsequently water was added to make the volume up to 100 mL. The resulting solution was then passed through a cationic-exchange resin in the form of a sodium salt. The resin was then washed with water until complete discoloring of the solution was obtained ($A_{639} < 0.01$ per 10 mL collected), and the total volume collected was made up to 1 L in order to provide the mother solution for subsequent tests. The absorbance of this solution, with a nominal concentration of 1×10^{-5} M, presented a peak maximum at 639 nm ($\epsilon = 1.02 \times 10^5$ L·mol^{-1}) which remained stable following both dilution and enrichment of the dilute solution by bubble extraction. The working solutions were prepared by diluting the mother solution from 5 to 10 times (1–0.5 ppm approximately). For RB, even more dilute working solutions were required (0.5 ppm or lower) in order to avoid the formation of foam in the collector.

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Apparatus

The apparatus used, which was wholly made of Pyrex glass, was essentially composed of a fine porosity glass frit through which nitrogen was introduced, an extraction column of variable dimensions, a bell-shaped (to reduce turbulence) trapping device, a collector tube, a soap bubble flowmeter, and a water manometer. The various parts were assembled by means of screw junctions with Teflon washers, as shown in Fig. 1(a). The trapping devices, which had an exit diameter that varied from 8 to 12 mm, were combined with various types of columns.

All the experiments were done by semibatch operation. For each system investigated the gas rate ranges were chosen over which the hydrodynamic trap was properly operating as a result of the presence of a sufficient number of bubbles to form a small foam column but not so great as to favor excessive coalescence. Different starting conditions were used for RB and SB samples in comparison with PA samples. In the former case the system was charged under gas bubbling with the same solution up to

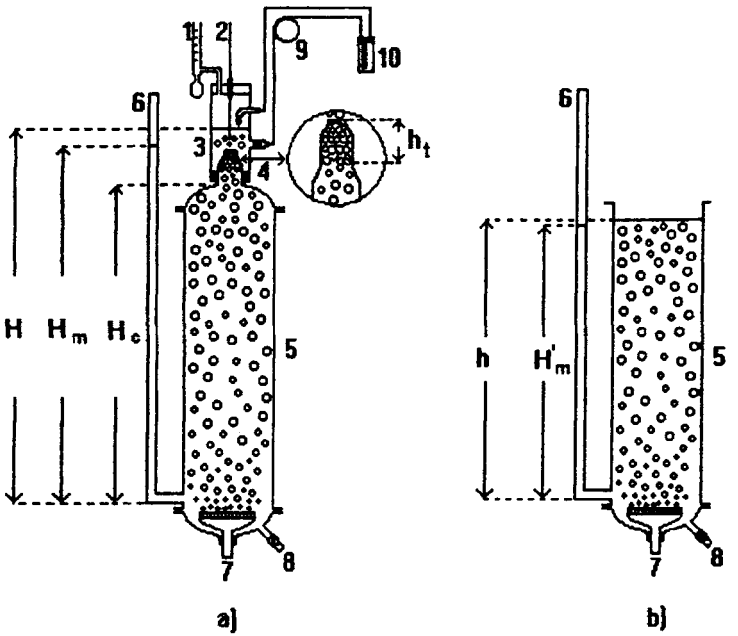

FIG. 1 Bubble extraction apparatus. Experimental setup: (1) soap bubble flowmeter, (2) stirrer, (3) collector, (4) trapping device, (5) column, (6) water manometer, (7) gas inlet, (8) column solution outlet, (9) peristaltic pump, (10) flow cell.

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a partial filling of the collector. The increase of absorbance of the solution in the collector was then recorded versus time to investigate both the adsorption and dispersion effects on the separation of the dye. In the second case PA was used merely as a tracer to investigate the dispersion effects only. Column and trap were therefore charged with water only (ethanol was added in some cases) under gas bubbling, the collector was then partially filled with the PA solution, and the decrease of absorbance of the solution in the collector was recorded.

Continuous measurement of the absorbance of the collected solution was carried out at selected wavelengths (639 nm for SB, 554 nm for RB, 355 nm for PA) through a circuit consisting of a peristaltic pump and a flow cell with relative tubing. The flow cell was placed in the sample cell holder of a Varian DMS 200 spectrophotometer. The sample solution was withdrawn from the lower access port of the collector and then returned through the upper one at a nominal flow rate of 10 mL/min. The solution in the collector was stirred by means of a mechanical stirrer placed on

top of the collector itself in order to ensure homogeneity. The total volume of the measuring circuit was about 5 mL, with a time constant of about 24 seconds when operating at a nominal rate of 10 mL/min. The value of the time constant was determined apart from the trace of the time-related absorbance response to a step change of the dye concentration in the liquid flowing at the selected rate.

When the absorbance of the enriched solution reached a practically stationary state, from 5 to 40 minutes afterward depending on the column used, the solution in the collector was removed from the lower port and its volume was measured (usually 20–50 mL); the flow of gas was stopped, and the residual solution in the column was discharged, and its volume was measured. The absorbance of both column and collector solutions was then measured, and the validity of the material balance of the solute was checked. Measurements were considered to be significant when this balance was respected within a 10% error. Higher discrepancies were nearly always related to negative mass balance due to carry off of the solute by the droplets of enriched solution which adhered to the walls of the collector. This event, although advantageous for extraction efficiency, substantially invalidated the assessment of the kinetic model. Determination of the extraction factor was possible, however, at the end of bubble extraction by measuring the absorbance of the collected solution, after it was used to wash the walls of the collector. A mass balance within 10% was again usually achieved. The gas holdup (voidage fraction) Φ in the trap was calculated with the equation

$$\Phi = (H - H_m - \Phi' H_c)/h_t$$

where H is the height of the total liquid + gas system (column + trap + collector), H_m is the height of the liquid in the manometer, H_c is the height of the column, h_t is the height of the foam in the trap, and Φ' is the gas holdup in the column as determined by the relation:

$$\Phi' = (h - H'_m)/h$$

where h is the height of the gas–liquid dispersion in the column and H'_m is the height of the liquid in the manometer when only the column is operating under the same conditions, as shown in Fig. 1(b).

KINETIC MODEL OF THE SYSTEM

In accordance with contemporary practice in the field of bubble and foam fractionation, it is assumed that the solute is transported from the column to the collector through the liquid–gas dispersion of the trap, both by adsorption on the surface of a bubble and by entrainment in the bound-

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ary layer of liquid surrounding the bubble. At the same time, some solute is carried downward in the liquid flow, which balances the upward flow of boundary layer liquid. This assumption appears to hold for the case where the boundary layer liquid is an appreciable fraction of total liquid in the foam and solute dispersion occurs as a consequence of liquid upflow and downflow (9). We assume that the surface concentration of solute is always in local equilibrium with the concentration of solute in the entrained liquid; moreover, we neglect solute transfer between countercurrent streams within the foam, owing the very short residence time of a bubble in the trap (5). A complete mixing in both the collector and the column solutions can also be assumed for columns where the axial dispersion is sufficiently large. If Q and D are the volumetric flow rates associated with solute transport by adsorption and by dispersion, respectively, a solute mass balance in the collector gives

$$V_2 dC_2/dt = QC_1 - D(C_2 - C_1) \tag{1}$$

where V_2 indicates the volume of solution in the collector, and C_2 and C_1 indicate the concentrations of the solute in the collector and in the column, respectively. Owing to the low solute concentrations, the equilibrium between the solute surface excess Γ and the solute in the entrained liquid can be expressed by a linear adsorption isotherm: $\Gamma = KC_1$. For spherical bubbles, Q is then defined by

$$Q = 6GK/d \tag{2}$$

where G is the gas flow rate and d is the diameter of the bubble: $6G/d$ gives the surface area throughput.

For batchwise operation, the material balance is

$$C_0(V_2 + V_1) = C_2V_2 + C_1V_1 \tag{3a}$$

where C_0 indicates the initial concentration of the solute in the whole column + collector system, and V_1 represents the volume of the column.

If the solute is added only to the collector, Eq. (3a) becomes

$$C_{02}V_2 = C_2V_2 + C_1V_1 \tag{3b}$$

Relationships (3) ignore the component adsorbed on the surface of the gaseous phase which, however, may be presumed to be very small.

The solution of Eq. (1) in combination with Eq. (3a) gives

$$(C_2 - C_0)/C_0 = (Q/kV_2)(1 - e^{-kt}) \tag{4a}$$

where

$$k = (Q + D)/V_1 + D/V_2$$

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An analogous expression can be obtained for C_1 by combining Eq. (4a) with Eq. (3a). From the combination of Eq. (1) with Eq. (3b), alternatively, we obtain

$$(C_{02} - C_2)/C_{02} = (D/kV_2)(1 - e^{-kt}) \tag{4b}$$

In stationary conditions the relationship which defines the extraction factor of the system, E, must be valid in all cases:

$$E = (C_2/C_1)_\infty = 1 + Q/D \tag{5}$$

which can be obtained directly from Eq. (1) when $dC_2/dt = 0$.

DISCUSSION OF RESULTS

Analysis of the experimental kinetic curves was carried out using the Sigma Plot 4.0 program for nonlinear fitting. In this way k and Q can be determined directly from Eq. (4a), as can k and D from Eq. (4b). The values of D in the first case and of Q in the second can be obtained indirectly through the expression of k. On account of different initial conditions, experimental data concerning RB and SB samples were treated according to Eq. (4a) whereas those concerning PA samples were treated according to Eq. (4b). Excellent agreement was observed between experimental and fitted curves (Fig. 2) whenever the material balance according to Relationships (3a) or (3b) was respected.

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Dependence of *Q* and *D* on the Gas Flow Rate

When the values of Q and D thus calculated were plotted against Φ, curves were obtained of the type shown in Fig. 3, which could easily be adapted to parabolic equations of the types

$$Q = \alpha\Phi(1 - \Phi) \tag{6}$$

and

$$D = \delta - \beta\Phi(1 - \Phi) \tag{7}$$

where α, β, and δ are characteristic parameters of the system considered, whose significance can be explained through the dynamics of the bubbles.

By defining u as the ratio G/A, where A is the exit section of the trap, u and Φ were found to be linearly correlated for all the samples examined, with correlation coefficients higher than 0.97, as long as no coalescence was observed in the trap. When coalescence began to occur, a curvature was observed in the plot corresponding to an increasingly slower variation of Φ with respect to u.

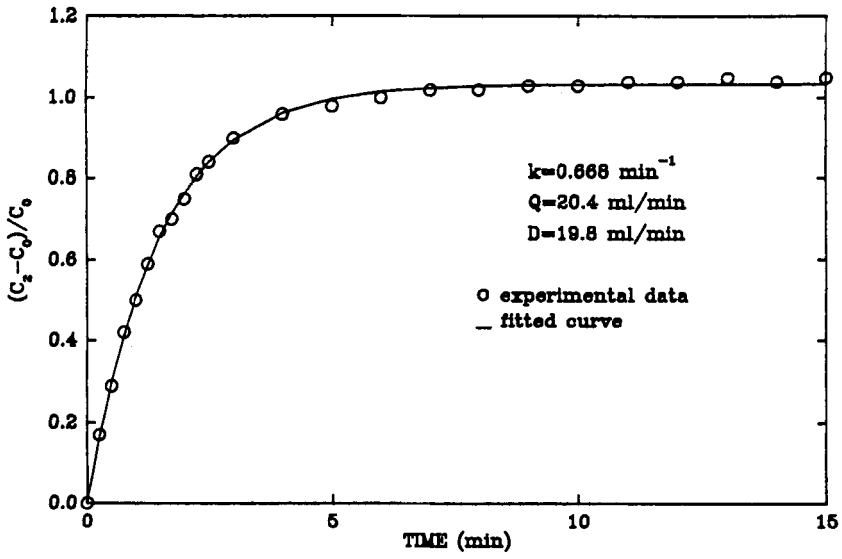

FIG. 2 Bubble extraction on 0.57 ppm SB solution. V_1 = 2460 mL; V_2 = 29 mL.

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The following analysis is limited to the range of linearity between u and Φ, so that we may write

$$u = u_0\Phi \tag{8}$$

Equation (8) is one of the various expressions for drift-flux as reported elsewhere (10), where u_0 is equal to the free rise velocity of single bubble. For batch systems, Eq. (8) was found to describe the measured data for air–water systems fairly well up to gas velocities of about 5 cm/s. The upper limit of linearity we have found is, however, quite higher, reaching up to 10 cm/s for solutions with ethanol. The values of u_0 as determined from the slopes of the corresponding straight lines were found to depend only on the solution examined, varying from 4.5 cm/s for solutions with 0.3% v/v ethanol to 25 cm/s for solutions without ethanol.

Combining Eq. (8) with Eqs. (2) and (6) yields an expression for the diameter of the bubble:

$$d = 6AKu_0(1 - \Phi)^{-1/\alpha}$$

According to Rice et al. (11), the bubble-free rise velocity is related the corresponding bubble diameter d_0 by the relationship

$$u_0 = \chi d_0$$

where $\chi = (2g/15\nu^{1/2})^{2/3}$ is approximately equal to 120 s^{-1} for dilute solutions at 20°C.

The expression for bubble diameter therefore becomes

$$d = 6AK\chi d_0(1 - \Phi)^{-1}/\alpha$$

Since d_0 represents the bubble diameter when $\Phi \rightarrow 0$, the following relationships must be valid:

$$d = d_0/\chi(1 - \Phi) \tag{9}$$

and

$$\alpha = 6AK\chi \tag{10}$$

According to Eq. (9) a gradual increase of bubble diameter was visually observed in the trap with increasing gas rate. Relationship (10) gives the physical interpretation of α and makes it possible to calculate the adsorption constant of a given surface-active solute. It also allows a partial check of the above derivation by comparing the values of K thus obtained with the corresponding values reported elsewhere. Average values of K obtained for RB and SB solutions were 2.3×10^{-3} cm and 3.7×10^{-2} cm, respectively. The latter value may be compared with the result obtained elsewhere (12) by means of surface-activity measurements (7.7×10^{-2} cm).

Equation (6) then becomes

$$Q/A = 6\chi K\Phi(1 - \Phi) \text{ cm/s} \tag{6a}$$

which expresses the effective gas-phase flux as regards the transfer of solute into the collector. The term $6\chi\Phi(1 - \Phi)$ represents the surface area flow per unit cross-section, as may be seen by comparison with Equation (2).

Equation (7) appears to be very similar to others derived in order to described the backflow of liquid through foam columns (13, 14). The parameter δ, then, presumably represents the backflow of liquid through the network of capillaries relative to the rising bubbles in the trap, while β is related to the upward motion of the bubbles themselves. An analysis of the available data was carried out in order to study the dependence of β and δ on system parameters, that is, the exit section of the trap and solution properties as related to u_0. Both parameters were found to depend in a linear manner on the exit section of the trap. Furthermore, δ was found to be directly proportional to u_0 while β was found to be independent it. The corresponding regression analysis yielded $\delta = 0.039Au_0$ cm^3/s and $\beta = 2.11A$ cm^3/s. Equation (7) therefore becomes

$$D/A = 0.039u_0 - 2.11\Phi(1 - \Phi) \tag{7a}$$

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A physical interpretation of the empirically found numerical coefficients may be given according to the following assumptions:

(a) The average velocity of the liquid in the capillary network is

$$L = g\lambda^2/96\nu$$

where λ is the capillary diameter (14)

(b) The capillary diameter is related to the bubble diameter through the equation

$$\lambda^2 = fd^2 (1 - \Phi)/\Phi$$

where f is a coefficient depending on the assumption used in the derivation (13, 14).

(c) The thickness of the hydrodynamic boundary layer of a bubble is given by the Levich (15) expression

$$\theta = (\nu d/2u_b)^{1/2}$$

where u_b, the rise velocity of a bubble, can be substituted by χd, to obtain

$$\theta = (\nu/2\chi)^{1/2}$$

(d) The volumetric fraction of liquid flowing downward, which is equal to that carried upward, is therefore

$$\epsilon = 6\theta\Phi/d$$

$6/d$ being the surface area per unit volume of gas phase

(e) The velocity of the bubble surfaces upward is given by $u\Phi$ (13, 14), which is equal to u_0 according to Eq. (9)

(f) The area available for liquid downflow per unit cross-section area is equal to the volume fraction of liquid flowing downward (14), corresponding therefore to ϵ

The downward velocity of the liquid in the capillaries, relative to the laboratory, is $v_L - u_0$, and the corresponding flux is therefore $(v_L - u_0)\epsilon$. According to Assumptions (a)–(e), we obtain the following expression for the liquid flux downward:

$$[fgd^2(1 - \Phi)/96\nu\phi - u_0]6\theta\Phi/d$$

which, on account of Eq. (9), becomes:

$$f(g\theta/16\nu\chi)u_0 - 6\theta\chi\Phi(1 - \Phi)$$

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Substituting numerical values for g, χ, and v yields:

$$D/A = 0.33fu_0 - 4.64\Phi(1 - \Phi) \text{ cm/s} \quad (7b)$$

Depending on f values found in the literature (13, 14), $0.33f$ becomes 0.112 or 0.040. The mean value, 0.076, may be taken as an indicative value. The agreement between Eqs. (7a) and (7b) can be considered rather satisfactory for the validation of the model proposed. Better agreement can be found, however, by rectifying Assumption (f). As regards the distribution of bubbles in a foam, it has indeed been observed (16) that the number of bubbles of a given diameter per unit area is not equal to the number of bubbles of the same diameter contained in a volume of foam equal to the unit area multiplied by the bubble diameter. The first number is indeed related to the second one by a coefficient always smaller than unity, varying, in general, between 0.4 and 0.7. This requires a reduction of the value of ϵ, therefore allowing a better agreement between Eqs. (7a) and (7b).

The condition $\Phi \cong 0.5$, whereby Q and D assume their maximum and minimum values, respectively, represents the optimal situation of the system in which the extraction factor expressed by Eq. (5) is at its maximum. This is the condition in which the system displays the maximum surface area flow, and this is also the optimal condition required in foam separation processes, where $\Phi \cong 0.5$ represents the voidage value above which a foam regime is observed, and below which the system behaves like a highly aerated liquid (17). In the system studied by us, the above condition is observed when the maximum foam height is reached in the trap, in combination with the minimum height in the manometer. It can thus be controlled visually, also bearing in mind that the shift from the optimal conditions is relatively nonsensitive to the gas flow rate, as can be seen from Fig. 3.

For any gas rate, however, D/A decreases with decreasing u_0. Correspondingly, addition of ethanol in the concentration range examined was not found to affect the Q values significantly for either the SB and RB solutions. As a consequence, higher values of E were obtained. On account of the relationship between u_0 and d, this confirms the importance of producing very small bubbles for enriching and/or separating purposes.

As has been observed in practice, Eqs. (6a) and (7a) express the independence of the Q/D ratio from the trap exit section. It may be observed, however, that larger sections make it possible to reach the stationary state in shorter times by working compatibly with the column utilized at higher gas flow rates.

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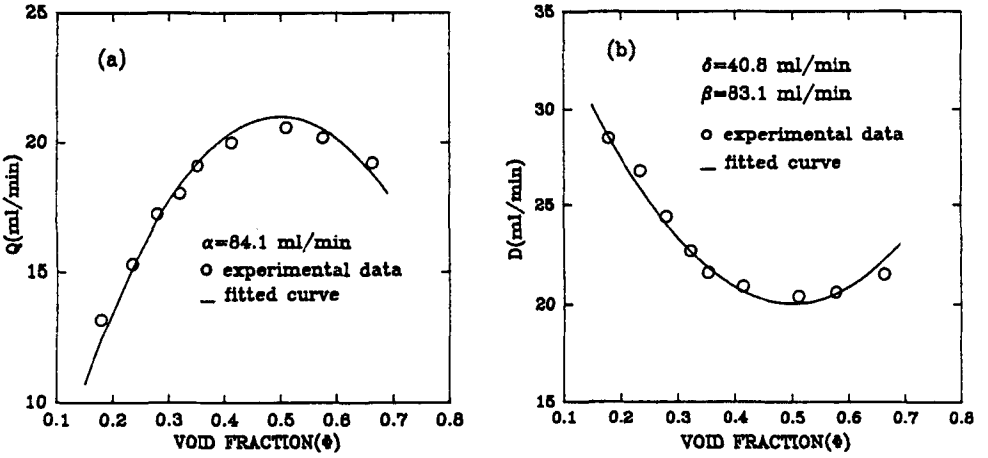

FIG. 3 Dependence of Q (a) and D (b) on gas voidage for 0.57 ppm SB solution.

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Verification of the Kinetic Model

Even if supported by a good fit to the experimental curves, the validity of the model proposed may be further verified by means of Eq. (5), comparing E (measured as the ratio of the respective absorbances once the system was in practically stationary conditions) with $1 + Q/D$, as determined from the fitting to the curve. Table 1 shows the good agreement between the two terms, calculated for different solutions of SB and RB in optimal gas flow conditions. The significantly similar values obtained when using two very different columns, yet such as to ensure the homogeneity of the solution inside them, indicate that the behavior of the trap is what conditions the whole system.

In the case of PA solution, E was always found to be very close to unity, as was to be expected. The determination of Q, carried out indirectly through Eq. (4b) appeared to be subject to large percentage errors, even if they oscillate around zero.

Combination of the Trap with Concentration Gradient Columns

The formation of a concentration gradient in the column was followed by recording the concentration variations at the top of the column over

TABLE 1
Comparison of Results for Complete Mixing Columns

	C (ppm)	$1 + Q/D$	E
SB	0.57[a]	2.10	2.16
	1.14[a]	2.05	2.06
	0.28[b]	2.03	1.98
	1.14[b]	2.14	2.08
RB	0.05[b]	7.26	7.80
	0.10[a]	7.60	7.52
	0.50[a]	7.64	7.85

[a] Column volume = 110 mL, inner diameter = 3 cm.
[b] Column volume = 2420 mL, inner diameter = 10 cm.

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time, in the same way as the measurements made in the collector. For all the columns used, a kinetic trend was observed that was analogous to the one found by combining the trap with complete mixing columns, that is:

$$C_h = C_m + m(1 - e^{-t/\tau})$$

where C_h represents the concentration at the top of the column, C_m is the mean column concentration, and τ is the system time constant. The values of m obtained by regression analysis of the curves were in good agreement with the corresponding ratios $(C_h/C_m)_\infty$ determined experimentally. The dependence of this ratio on the height of the column was studied using columns with an inner diameter of 3 cm and of a height varying from 20 to 100 cm, and it was found to depend on the height of the gas–liquid dispersion in the column, h, in accordance with the equation already deduced by Shah and Lemlich (1):

$$C_h/C_m = zh/[1 - \exp(-zh)]$$

where z is a typical parameter of the system. In our case, z was found to be equal to about 0.008 cm^{-1} for SB and 0.065 cm^{-1} for RB.

By combining the trap with a concentration gradient column, a multistage system is obtained. However, starting from an initially homogeneous solution, and following the concentration in the collector over time, we observed a trend for the substances examined which was perfectly analogous to the one observed in the case of complete mixing column. An analysis of the experimental data was therefore carried out by adapting them to Eq. (4a), as reported in Fig. 4. The procedure was often not possible for RB solutions because, owing to the high enrichment factors, there was a considerable deposition of substance on the walls of the collector, thus falsifying the measurements.

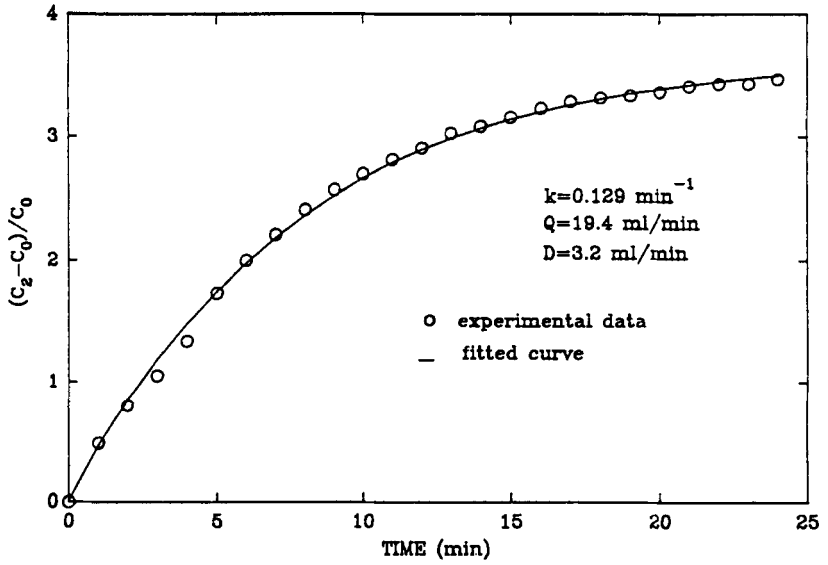

FIG. 4 Bubble extraction on 0.57 ppm SB solution with 0.1% v/v ethanol. Column height = 100 cm.

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The results obtained for SB solutions (without and with 0.1% v/v ethanol) in columns with a diameter of 3 cm in optimal flow conditions are shown in Table 2. As can be observed, the values of Q appear to be independent of both the presence of ethanol and of the column height, while the values of D diminish for both the presence of ethanol and for increasing column height, where the reduction factor appears to corre-

TABLE 2
Results on 0.57 ppm SB Solutions for Concentration Gradient Columns. *a*: Without Ethanol; *b*: with 0.1% v/v ethanol.

Q (mL/min)		D (mL/min)		E		$(C_h/C_m)_\infty$		h
a	*b*	*a*	*b*	*a*	*b*	*a*	*b*	(cm)
20.6	21.5	18.8	8.2	2.11	3.86	1.04	1.38	20
21.1	19.8	16.1	5.4	2.45	4.73	1.22	2.35	60
21.4	20.7	15.3	3.9	2.69	6.12	1.31	3.01	80
20.8	19.4	13.9	3.2	3.14	7.67	1.42	3.56	100

spond with a good approximation to the ratio $(C_h/C_m)_\infty$. Comparison of E values with the corresponding $(C_h/C_m)_\infty$ values shows the improvement achieved by means of the trap in comparison with only bubble fractionation. As can be seen, the efficiency is increased by a factor nearly equal to the separation obtained in a 100-cm tall column. The good agreement between the experimental values of E and the corresponding values of $1 + Q/D$ calculated from the analysis of the curve should also be noted.

CONCLUSIONS

The use of a hydrodynamic trap in combination with appropriate columns makes it possible to enrich and separate surface-active substances in the same aqueous starting solution without any further treatment, which is often necessary in the case of solvent sublation or foam fractionation.

The possibility of describing the behavior of such a system by means of a simple two-parameters model through the choice of different initial conditions suggests its use also to investigate components with respect to their surface activity and/or bubble conditioning effects.

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NOTATION

A	trap exit section (cm^2)
C_0	overall initial concentration (mol/cm^3)
C_{02}	initial collector concentration (mol/cm^3)
C_1	column concentration (mol/cm^3)
C_2	collector concentration (mol/cm^3)
C_h	concentration at top of column (mol/cm^3)
C_m	average concentration in the column (mol/cm^3)
d	bubble diameter (cm)
d_0	bubble diameter at zero gas voidage (cm)
D	liquid phase flow related to dispersion, upward and downward (cm^3/s)
f	geometrical factor (adimensional)
E	extraction factor (adimensional)
g	acceleration due to gravity (cm/s^2)
G	gas rate flow (cm^3/s)

h height of gas–liquid dispersion in the column (cm)
h_1 height of gas–liquid dispersion in the trap (cm)
H height of total gas–liquid dispersion (cm)
H_c column height (cm)
H_m liquid height in the manometer during bubble extraction (cm)
H'_m liquid height in the manometer during bubble fractionation (cm)
k rate constant (s^{-1})
K adsorption constant (cm)
m parameter (mol/cm^3)
Q gas phase flow related to adsorption (cm^3/s)
t time (s)
u superficial gas velocity (cm/s)
u_0 free rise velocity of single bubble
v_L average velocity of the liquid downwards in the capillary network (cm/s)

Greek Letters

α parameter (Eq. 6) (cm^3/s)
β parameter (Eq. 7) (cm^3/s)
Γ surface excess (mol/cm^2)
δ parameter (Eq. 7) (cm^3/s)
ϵ volume fraction of liquid carried upward and flowing downward (adimensional)
θ boundary layer thickness (cm)
λ capillary diameter (cm)
ν kinematic viscosity of liquid (cm^2/s)
τ parameter (s^{-1})
ϕ void fraction in the trap (adimensional)
ϕ' void fraction in the column (adimensional)
χ ratio between single bubble rise velocity and bubble diameter (s^{-1})

Subscript

∞ steady-state conditions

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