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# Laws of Foam Formation and Foam Fractionation. I. The Effect of Different Operating Parameters on the Foam Fractionation of Albumin from a Solution Containing Organic and Inorganic Materials

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# Laws of Foam Formation and Foam Fractionation. I. The Effect of Different Operating Parameters on the Foam Fractionation of Albumin from a Solution Containing Organic and Inorganic Materials

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## Abstract

This study develops a continuous foam fractionation process for the separation of albumin from a dilute solution containing organic and inorganic materials. It also investigates various operating parameters such as pH, nitrogen flow rate, height of foam, height of solution, and feed position of an albumin solution. From the investigations the factors of a pH of 4.9, an $N_2$ rate of 10 l/hr, a feed rate of 1.8 l/hr, a solution height of 8 cm, a foam height of 3 cm, and a feed into the solution are found optimal. A comparison of the distillation and extraction processes with foam fractionation is made on the basis of the experimental results obtained.

## INTRODUCTION

Foam separation of protein from potato and sugar beet juice was first demonstrated by Ostwald et al. (*1*). Schnepf and Gaden (*2*) have since employed a foam separation technique in separating bovine serum albumin from dilute solution. The work carried out by these investigators takes into consideration only a two-component system which includes albumin and water. The work carried out to date has been limited to the batch

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process only. This process suffers from the inherent disadvantage that it is a nonsteady-state process. The continuous process overcomes this drawback. Recently, Grieves et al. (*3*, *4*) have used a continuous foam separation process for waste water treatment. However, no detailed study on the separation of proteins from dilute solutions has been taken up.

In the present study, the initial work determines various operative parameters of the continuous foam fractionation process as used by Grieves et al. (*3*, *4*). The pH, the nitrogen flow rate, the ratio between nitrogen and albumin flow rates, the height of foam, the height of solution, and the feed position of the albumin solution have been studied in order to observe their effect on the separation of albumin from a dilute solution.

## EXPERIMENTAL

*Materials.* The albumin (RBG 244 Kabi, Stockholm) used contained 97.7% protein. The pH was adjusted by means of small additions of solutions of sodium hydroxide and hydrochloric acid. All solutions were made using twice distilled water.

*Apparatus.* A schematic picture of a continuous foam fraction process

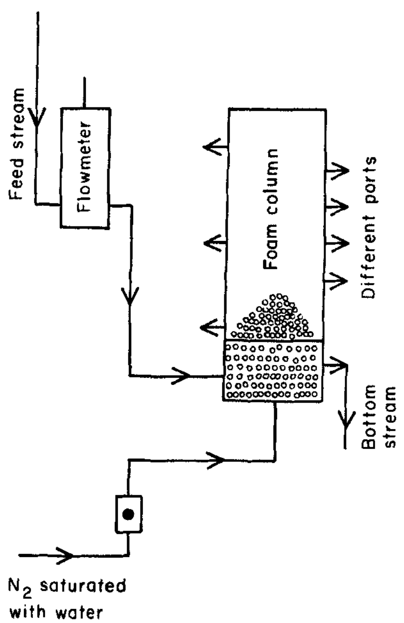


FIG. 1. Schematic diagram of continuous foam fractionation process.

is shown in Fig. 1. The foam column, 50 cm high, was made of Pyrex glass with an internal diameter of 4 cm. The bottom of the column was fitted with a sparger of 100 $\mu$ porosity. Several outlet ports were fitted in the column, spaced at 4 cm intervals. These ports were used to feed the protein solution and to remove the foam as well as the stripped solution. Flowmeters were incorporated in the apparatus to measure the rates of flow of the protein solution and nitrogen gas. A saturation chamber filled with distilled water was connected to the apparatus to prevent a subsequent depletion of either foam or bulk by evaporation of water by the dry nitrogen gas.

## Theory of Foam Separation

Grieves and co-workers (*3*, *4*) have given the theory for a continuous foam fractionation process. The equilibrium relation $Y = Y(x_b)$ (where $Y$ is the concentration of the albumin in the liquid volume $dV$, and $x$ is the concentration in the drain stream) is taken by considering the column height equivalent to an equilibrium stage. The foam column has a number of equilibrium stages, and the material balance throughout the column for the continuous process is given as

$$L = F + B$$

or

$$x_1 L = x_f F + x_b B$$

where $L$, $F$, and $B$ are the flow rate of feed, foam, and effluent, respectively, in ml/min; and $x_1$, $x_f$, and $x_b$ are the concentrations of solute in the feed, foam, and effluent streams, respectively, in ml/min.

*Procedure.* The albumin solution was established at a fixed liquid height (8 cm). The height of the solution was adjusted by fixing the needle valves of the feed and the drain. A further adjustment of the drain valve was necessary in order to maintain constant solution height when nitrogen gas was introduced in the column through the sparger. High purity nitrogen gas at 5 kg/cm$^2$ was passed through a saturation chamber before it was introduced into the foaming column. The nitrogen gas was passed into the foaming column for a fixed time, and the flow rates of foam and drain were calculated. The concentrations of the albumin in the foam and the drain were also determined. A random analysis of the foam was conducted in order to control the analytical balance.

*Analysis.* The albumin concentration was determined by using a DU spectrophotometer. Albumin exhibits selective light absorption in the region of 275 mμ. The albumin concentration was determined in the solutions containing an emulsifier, monoglyceride, sugar, etc. from the calibration curves obtained at 275 mμ at required pH values by modifying the method used by Lowry et al. (*5*).

In the samples, sugar and monocapryline were determined by the methods given by Glick (*6*) and Pole (*7*), respectively. The concentration of EMU 09 was determined from the calibration curve obtained at 275 mμ.

## RESULTS

### Experimental Design

*Effect of pH.* The effect of pH on the efficiency of the albumin separation process was investigated over the pH range from 4.0 to 8.0. The results revealed that a pH of 4.9 is the most effective one for separating the albumin from the solution (Table 1). The enrichment ratio ($x_f/x_b$) was found to be higher at pH 4.9 than at other pH values.

*Effect of Nitrogen Flow Rate.* Nitrogen flow rates between 5 and 30 l/hr were used, and separations of up to 60% were obtained. The two sets of experiments carried out employed 50 and 100 ppm of albumin, respectively. At 30 l/hr the 50 ppm feed solution became stripped, so that only 15 ppm remained in the drain. The drain concentration was 30 ppm for 100 ppm of albumin. From these results it appears that the percentage of removal of albumin from the solution remains constant.

Figure 2 shows the effect of the nitrogen flow rate on the enrichment of the foam ($x_f/x_b$) and the degree of stripping ($F/B$). The enrichment ratio is found to decrease with an increase in the nitrogen flow rate.

Figure 3 shows the effect of nitrogen on the removal of albumin from the solution. Two sets of experiments with the flow rate of the liquid into

TABLE 1

Effect of pH on the Separation of Albumin (150 ppm)

| pH | Feed (ml/min) | Air (ml/min) | $x_f$[a] (mg/ml) | $Y_f$[b] (ml/min) | $x_b$[a] (mg/ml) | $Y_b$[b] (ml/min) | $x_f/x_b$[c] |
|---|---|---|---|---|---|---|---|
| 4.0 | 30 | 333 | 0.210 | 45.520 | 0.150 | 85.40 | 1.40 |
| 4.9 | 30 | 333 | 0.170 | 80.180 | 0.100 | 19.13 | 1.70 |
| 6.0 | 30 | 333 | 0.150 | 51.330 | 0.125 | 19.20 | 1.20 |
| 8.0 | 30 | 333 | 0.160 | 16.481 | 0.130 | 147.00 | 1.23 |

[a] $x_f$ and $x_b$ are the concentrations of albumin in foam and effluent streams, respectively.
[b] $Y_f$ and $Y_b$ are the flow rate of foam and effluent, respectively.
[c] $x_f/x_b$ is the enrichment ratio.

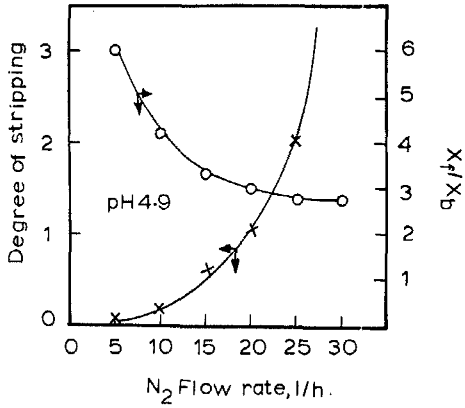


FIG. 2. Effect of nitrogen flow rate on degree of stripping ($F/B$) (×) and enrichment ratio $x_f/x_b$ (○) of albumin (100 ppm).

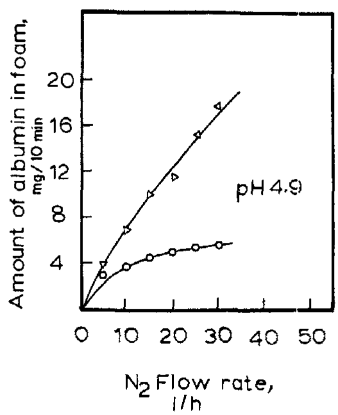


FIG. 3. Effect of liquid flow rate—9 ml/min (○) and 18 ml/min (△)—on total removal ($x_f F$) of albumin (50 ppm) at different nitrogen flow rates.

the column are taken as the parameters for different flow rates of gas. The flow rate of the feed is found to have an effect on the separation of albumin from the solution.

*Effect of G/L Ratio.* The efficiency parameter $x_f F/x_b B$ is shown in Fig. 4. This parameter is found to reach a maximum at a value of 16. Any further increase in the $G/L$ ratio has no influence on the separation efficiency. For an albumin concentration of 100 ppm, the efficiency achieved was 6 at $G/L = 16$ and pH 4.9.

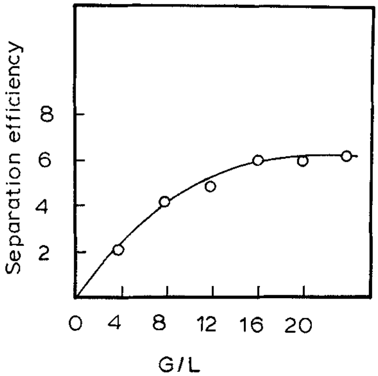


FIG. 4. Effect of gas–liquid ratio ($G/L$) on separation efficiency ($x_f F/x_b B$) of albumin (100 ppm) at pH 4.9.



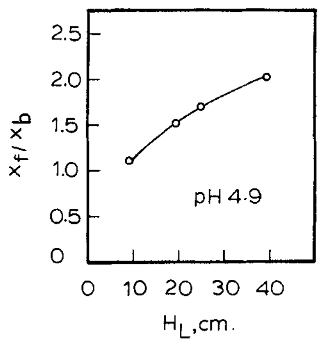


FIG. 5. Effect of height of liquid above sparger ($H_L$) on enrichment ratio ($x_f/x_b$) of albumin (100 ppm).

*Effect of Height of the Liquid above the Sparger.* With the experiments set at a constant foam height (3 cm), a constant nitrogen rate (20 l/hr), and a constant albumin feed rate (30 ml/min), the results obtained showed that there was an appreciable change in the enrichment ratio of albumin when the height of the liquid surface above the sparger was varied (Fig. 5). With the depth of liquid fixed and with varying solution feed rates in the experiments, it was found that the separation of albumin was a function of both the liquid feed rate and the liquid residence time (Fig. 6).

*Effect of Foam Height.* The effect of foam height on the separation of albumin was measured in a series of experiments using foam heights between 3 and 36 cm. The results showed that the foam height had a

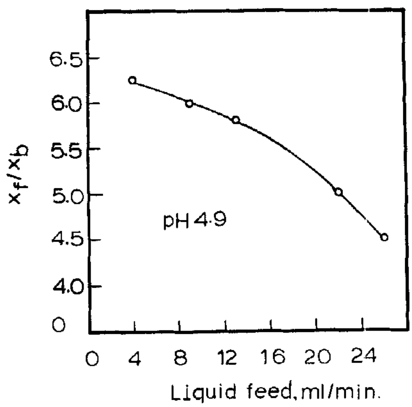


FIG. 6. Effect of liquid feed rate on enrichment ratio ($x_f/x_b$) of albumin (100 ppm).

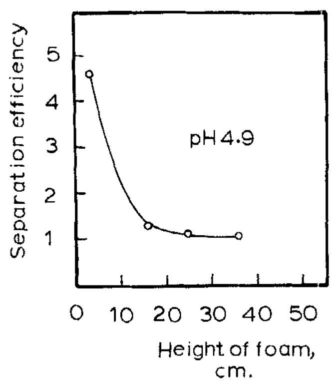


FIG. 7. Effect of foam height ($H_F$) on separation efficiency ($x_fF/x_bB$) of albumin (100 ppm).

significant effect on the separation, and the effect was very pronounced near the foam–liquid interface. A change in foam height from 3 to 17 cm produced a drastic change in the foam stream. At a foam height of 3 cm the volume of the solution carried away in the form of foam was 24 ml/min, while at 17 cm of foam height a volume of 10 ml/min was obtained. Further, it was observed that an increase in foam height produced a small decrease in the efficiency of the process (Fig. 7).

*Effect of Feeder Position.* The experiments were carried out with the introduction of feed either directly into, or from the top of, the solution with a constant feed rate (30 ml/min). The albumin concentration was 150 ppm, the solution height was held constant (8 cm), and various rates of $N_2$ flow were used (15 to 30 l/hr). From the results obtained it was found that there was a small change in the drain concentration with a change of the feed position into the solution. The introduction of the feed at the foam–liquid interface reduced the drain concentration slightly and increased the drain volume. On raising the feed position to higher levels within the foam, the drain concentration decreased continuously (Fig. 8), whereas the efficiency of the process increased threefold. At low $N_2$ flow rates the change in the concentration of the drain was steeper compared to higher rates.

Figure 9 shows the enrichment ratio $x_f/x_b$ as a function of the feed at different levels. The enrichment of the foam was found to reduce at $H_L/H_F = 0$ when the solution was fed at the liquid–foam interface. Further, an increase of the feed height in the foam enriched the foam.



## DISCUSSION

The effect of pH on the separation of albumin indicates that pH 4.9 is the most effective value for separating albumin. Albumin has its isoelectric point at pH 4.9. Proteins at their isoelectric point show minimum solubility in an aqueous phase. However, albumin accumulates in that region

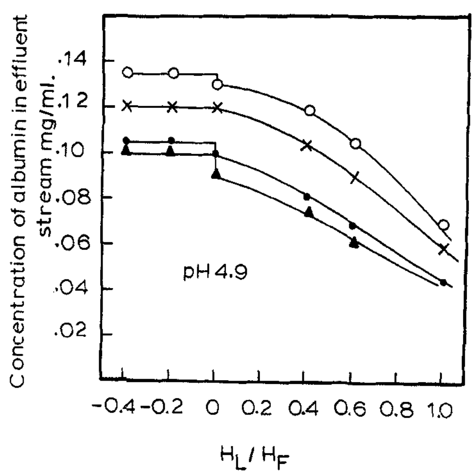


FIG. 8. Effect of feeder position on removal of albumin (150 ppm) from the solution at feed rates of 15 (○), 20 (×), 25 (●), and 30 l/hr (▲).

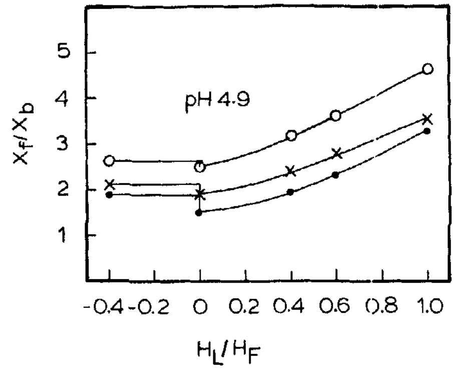


FIG. 9. Effect of feeder position on enrichment ratio ($x_f/x_b$) of albumin (150 ppm) at feed rates of 15 (○), 20 (×), and 25 l/hr (●).

of the solution where it is least surrounded by a solvent liquid; i.e., at the gas–liquid interface. Albumin strives to transfer from the bulk solution into the foam; however, maximum enrichment should occur. From the results given in Table 1, it is evident that the maximum enrichment is found at pH 4.9.

Schnepf and Gaden (*2*) showed with surface tension and concentration curves that the slope of the curve increases with a decrease of the concentration of albumin in a bulk liquid. However, according to Gibbs' equation (*8*), the enrichment ratio should be proportional to the rate of change of surface tension with concentration. At a constant pH the enrichment ratio should increase with decreasing concentration. In Fig. 10

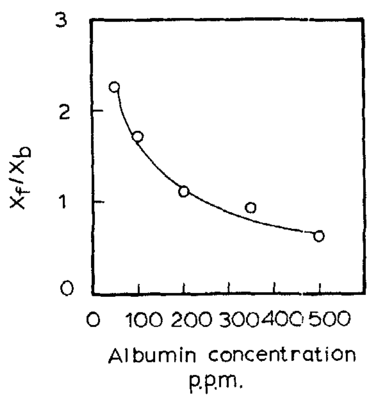


FIG. 10. Effect of albumin concentration on enrichment ratio ($x_f/x_b$) at pH 4.9.

the enrichment ratio ($x_f/x_b$) is plotted against the concentration of the feed. It is evident from the curve that the enrichment ratio continuously decreases with an increase of the concentration of albumin in the bulk. The behavior of albumin can be explained in terms of the amphiphilic nature of the albumin which has polar as well as nonpolar portions. At higher concentrations, albumin could start forming stable aggregates (micelles) in the bulk phase, which reduces the effective concentration of the molecules at the interface of the solution. However, for an effective separation of albumin from the solution, a concentration in the range of 50 to 200 ppm will be more suitable. From these results it may be concluded that the protein concentration in the foam is completely dependent on the concentration of the bulk and on the pH of the solution.

In the foam separation process the high stability of foam is necessary in order to achieve good separation. In the present study a higher stability of the foam occurs at the isoelectric point (pH 4.9) of the protein. Foam of less stability is obtained at higher (8.0) and lower (3.0) pH values. The rate of foam formation is also higher at the isoelectric pH with a maximum liquid content of 80 ml/min. The foam in the column is of the Kugelschaum type with thick lamellae. This high stability of foam could be due to an accumulation of albumin in an ordered structure on the water–air interface.

Figure 3 shows the total removal ($x_fF$) of albumin with an increasing rate of nitrogen gas in two sets of experiments. In one set the liquid feed rate is 9 ml/min and in the other it is 18 ml/min. The total removal is found to increase with an increasing flow rate of feed. Although $x_fF$ increases with the nitrogen rate, the effect of a high foam rate or high foam concentration may not be differentiated. It appears that a better removal may be obtained by increasing the gas rate, but in fact it is only due to an increase in the foam rate. The effect of the gas rate on the enrichment ratio will reveal the utility of the foam process. In Fig. 2 the results on the enrichment ratio are given for different gas rates. These results show that the enrichment ratio ($x_f/x_b$) decreases with the nitrogen rate (Fig. 2). Thus, for a fixed feed rate, an increasing nitrogen rate provides a decrease in concentration of the effluent but yields a proportionally larger increase in the foam rate ($F/B$) in addition to a less rich foam.

The enrichment ratio $x_f/x_b$ at a lower gas rate is larger because of an internal reflux in which foam bed drainage as well as breakage of the foam takes place. The liquid drains back downward through the rising foam. The resulting countercurrent contact enriches the rising foam as well as the interstitial liquid. At a lower flow rate, however, the draining time available to the foam will be greater. The entrainment of the liquid is also less at a lower gas rate. At a higher gas flow rate, better entrainment of the liquid takes place and less time is available to the drainage. However, a decrease occurs in the enrichment of the foam in operations where the colligend in question is found to be partly adsorbed at the bubble surfaces and partly in the interstitial liquid. A high flow rate of gas is necessary to avoid the coalescence of the bubbles. This rate keeps the liquid content of the foam quite high, thereby keeping the lamellae thick and the foam bubbles separated.

Wace and Banfield (*9*) studied the flow pattern of foam in a foam column with different air rates in order to design the multistage foam column. A pseudorigid foam with a countercurrent flow through it is found at low air rates. At a low rate of air, the foam is carried downward by the liquid. This kind of liquid behavior is found in a bubble-cap-type apparatus. At higher rates of air, foam bubbles are found separated and subjected to eddy forces in a regime identical to that obtainable in a liquid pool. This regime is found in foam columns as a mixer stage and preserves bubble identity as with bubble cap columns.

From the results given in Fig. 3 it appears that the separation of the albumin is also a function of the liquid feed rate. The total removal ($x_f F$) is higher with a high feed rate (18 ml/min) than with a low feed rate (9 ml/min). Experiments keeping the nitrogen rate constant and varying the feed rate have been conducted, and the results of the enrichment ratio ($x_f/x_b$) at different feed rates are plotted in Fig. 6. The enrichment ratio decreases with an increase in the feed rate.

These results clearly indicate the effect of the variation of liquid residence time. By changing the feed rate at a constant liquid solution height, the average residence time of the feed element at the liquid–foam interface is varied. The foam separation process is an equilibrium process that is primarily dependent on the diffusion of the solute at the interface. Gibbs' equation (*8*) is based on this assumption. Equilibrium is reached very slowly in dilute solutions compared with concentrated solutions. However, variation of the feed element at the foam–liquid interface will change the diffusion rate of albumin. An increase in feed rate (Fig. 6) decreases the time when the feed element is in contact with the liquid surface; therefore, the enrichment ratio decreases (Fig. 6).

From the results of these studies it is clear that there is a combined effect of gas and feed rate on the separation of albumin from solution. Thus, when separating albumin from solutions, the gas and feed ratio ($G/L$) must be fixed, since gas and feed have a definite effect on the enrichment and on the entrainment of the albumin solution. The efficiency parameter $x_fF/x_bB$ (the ratio of albumin in the foam and in the drain solution) could cause a combined effect which is due to the enrichment and entrainment of the liquid in the foam fractionation process. The parameter $x_fF/x_bB$ is plotted against the $G/L$ ratio in Fig. 4. These results indicate that at higher values of $G/L$ the separation efficiency of the process becomes almost constant. However, above $G/L = 16$ the equilibrium of the separation process is reached and no further effect takes place on the separation. From these results it is evident that above $G/L = 16$ the process is completely controlled by the transfer of albumin molecules which takes place through diffusion from the liquid–foam interface.

The attainment of equilibrium is primarily dependent on the diffusion and is more rapid in concentrated solutions than in dilute solutions. The time required for equilibrium is much larger for dilute solutions. Because of the slow diffusion rates of proteins in dilute solutions, the contact time between the rising bubbles and the feed element is important. Also significant are studies of different liquid column heights which change the contact time between the liquid and the rising bubbles before they reach the surface. This change will control the mass transfer of the solute to the rising gas bubbles. Thus different column heights (8 to 20 cm) have been studied. In Fig. 5 the results of the enrichment ratio ($x_f/x_b$) are plotted against liquid column height. The enrichment of the albumin in the foam is found to increase continuously with increasing liquid height. By extending the liquid column height, the contact time between the bubbles and the liquid can be increased, allowing more time for the albumin to diffuse onto the surface of the rising gas bubbles.

In previous results, when the liquid residence time was changed by continuously increasing the feed rate, the efficiency of the process was affected. The results of these experiments, in which liquid residence time was changed in two ways, suggest that the time period in which an element of feed remains in contact with the surface layer and rising bubbles is an operating parameter. By changing the feed rate at a constant liquid solution height, the average surface residence time of a feed element varies, while by changing the liquid column height, the residence time of an element of feed near the surface remains constant but the contact time varies with the rising gas bubbles.

In order to obtain a known degree of extraction of albumin from the solution, calculations of the height of the liquid column can be made by considering the mass transfer and velocity of the rising bubbles. Wace, Alder, and Banfield (*10*) have given a relation to determine the required height of the liquid.

The results of different foam heights show a significant effect on the separation process. An increase in the foam height brings about a drastic change in the mass transfer of the process: with a foam height increase from 3 to 17 cm, the foam rate decreases from 24 to 10 ml/min, but at the same time the enrichment of the foam increases from 150 to 220 ppm. A further increase in the foam height brings about a minor decrease in the foam rates but it improves the enrichments. The height of the foam is related to the gas content—$H_{sp} = 1/(1 - \psi)$—and the gas content is related to the interfacial transfer area—$f_{sp} = 6\psi/d$. Both these equations will produce the relation (*11*)

$$f_{sp} = \frac{6}{d}\left(1 - \frac{1}{H}\right)$$

where $\psi$ is the gas content, $d$ is the diameter of a foam bubble, and $H$ is the height of the foam.

An increase in foam height will bring an increase in the interfacial transfer area. Foam separation, of course, depends on the presence of a surface-active solute which is adsorbed on the extended gas–liquid interface caused by a swarm of gas bubbles. However, an increase of foam height will provide more surface to the albumin to be adsorbed, and more albumin-rich foam will be produced as the foam height increases. This is the result of the present study. The increase in the foam rate with decreasing foam height could be explained by taking into consideration the relation obtained by Maminov (*11*) in estimating the mass transfer coefficient in a foam layer:

$$k = 5.35 \times 10^3 H^{-0.7}\left(D\frac{w_{rel}}{R}\right)^{0.7} \frac{1}{(1 + \mu_\delta/\mu_c)^{\frac{1}{2}}}$$

where $k$ is the mass transfer coefficient, $H$ is the height of foam, $D$ is the diffusivity of gas, $w_{rel}$ is the relative phase velocity, $R$ is the radius of the foam bubble, and $\mu_\delta$ and $\mu_c$ are the viscosities of the dispersed and continuous phases, respectively.

In the present equation the mass transfer coefficient is inversely related to the height of the foam in the column. The mass transfer coefficient increases with a decrease in foam height, and the converse is true.

The rising foam in the column is subjected to drainage and coalescence. Foam drainage dictates the entrainment of the liquid in the outgoing foam and is governed by the exchange of thick films for thin, with its accompanying drainage of liquid into the Plateau borders. In very stable foams, coalescence does not take place to any great extent; only drainage of the liquid into the Plateau borders occurs. But generally, in the foam separation of a solute, breakage of the foam is necessary in order to enrich the foam.

There are two causes of coalescence in foam. The first arises from the small difference in pressure between adjacent bubbles of differing size. As a result of the surface tension, the smaller bubble has a higher pressure than the larger. The pressure difference causes a diffusion of gas from smaller bubbles to larger ones across the film. The smaller bubbles, however, reduce in size, causing the size of the large bubbles to increase. The overall process is very much dependent on the residence time of the foam in the column. The coalescence is quite significant in a standing foam. The second cause of coalescence is due to the rupture of the film between bubbles. The stability of a film is a measure of the so-called *Marangoni effect*, which is characteristic of the surfactant molecules diffusing instantaneously to any locally stretched area in the film surface.

Another somewhat similar mechanism of foam stability is the *Gibbs effect*, which involves the inability of molecules within the film liquid to recoat the stretched surface completely, regardless of the diffusion rate. In the case of ionic surfactants, the electrostatic repulsion between the charged parallel surfaces is also responsible for the stability of films. In a foam column with different heights, all these mechanisms are operative, and as the foam column height increases, these effects have a greater influence on coalescence. Whatever the cause of the coalescence within the rising foam, the coalescence furnishes the internal reflux. The reflux so created drains back through the rising foam, thus enriching it, and increases the concentration of the solute in the foam when foam fractionation is carried out. The extract must be concentrated, with as small a volume as possible. For this, a total external coalescence is required. It can be accomplished through some suitable mechanical or thermal device by breaking the foam at the top of the column. Wace, Alder, and Banfield (*10*) have given a relation for calculating the wetness in the foam in order to design the drainage section in which the extract is to be concentrated into a reasonably small volume:

$$\varepsilon = \frac{6k}{Ed(VR)}$$

where $k$ is surface/solution partition coefficient at equilibrium, $E$ is the slope of the equilibrium line, $d$ is the bubble diameter, and $VR$ is the volume reduction factor.

In the foam column (Fig. 1) the feed functions in the stripping mode when it is introduced in the middle of the foam. The stripping operation removes the solute from the feed. In the present study, when the feed was introduced into the liquid at any distance from the interface (where $H_L/H_F$ is zero), there was a small reduction in the enrichment (Fig. 9). This reduction confirms our earlier result that the residence time of the feed element is changed by changing the height of the liquid (Fig. 5). The feed has a definite effect when it is introduced in the vicinity of the foam–liquid interface (Fig. 9). A decrease in the drain concentration and an increase in the enrichment ratio are found when the liquid feed is introduced in the foam at any height (Figs. 8 and 9).

These facts can be compared to the processes in a distillation column which has a distinct number of theoretical plates. In the foam column the number of theoretical plates required for a given system can be calculated by constructing an equilibrium diagram with a surface excess and bulk concentration. The operating line may be represented by taking a mass balance for the process. The extraction factor is generally used for such a calculation. The only factor that differs in such calculations is the bubble diameter, which has to be taken into account. The slope of the operating line is the ratio of phase flow rates, i.e., liquid rate/surface rate (*10*).

If the operating line has a large slope, then the number of theoretical plates required will be small for an efficient separation process. Complete separation can be achieved only if no product is removed. The column then is said to operate under conditions of *total reflux*. If the operating line has a small slope, then the number of theoretical plates required will be great. If an infinite number of stages are needed under these conditions, the steps come very close together and no enrichment occurs between any two contiguous plates. This condition is known as *minimum reflux*.

The ratio of the amount of liquid returned to that removed is known as the *reflux ratio*. Any small increase in the reflux ratio will be effective although a large number of plates will be required. Thus foam fractionation is, in a sense, analogous to distillation with entrainment. The bubble surfaces correspond to the vapor; the rising interstitial liquid corresponds to the entrainment.

In the present study, feeding into the liquid column at different heights keeps the reflux ratio constant. However, no appreciable decrease on the drain concentration or enrichment of the foam takes place (Figs. 8 and 9).

A feed at different heights into the foam changes the reflux ratio as well as the number of theoretical plates. A feed at a maximum $H_L/H_F$ value will have a higher reflux ratio because of the increases in liquid drainage in the foam phase. The enrichment of the foam will be increased with a concentration pinch from the feed (Fig. 9), and drain concentration will be reduced (Fig. 8). The results of the present study indicate that with an increase in height of the feed position, the concentration of the drain is reduced (Fig. 7).

From the above investigations the following factors have been found optimal for use in further studies in order to see the effect of different additives: pH = 4.9, $N_2$ rate = 20 l/hr, feed rate = 1.8 l/hr, solution height = 8 cm, foam height = 3 cm, and feed into the solution.

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