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Verification of a Model for Foam Flotation Column Operation

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Abstract

We report experimental data testing the validity of a mathematical model for the time-dependent operation of a continuous-flow foam floating column. Sodium lauryl sulfate (NLS) was the surfactant being removed. The responses of the column in steady-state operation and under the influence of rectangular pulses in NLS concentration and in hydraulic loading rate were investigated and compared with the results of computer simulation. Effluent surfactant concentrations were well simulated under all conditions. It was found that the fraction of liquid in the Plateau borders varies somewhat with the hydraulic loading rate, which causes some discrepancy between calculated and observed collapsed foamate flow rates.

INTRODUCTION

We previously presented a model for a continuous flow foam flotation column which predicts foamate and effluent flow rates and concentrations as functions of time as the influent flow rate and conenctration vary (*1*). The model assumes that the foam consists of dodecahedral bubbles of uniform size. Only experimentally measurable parameters (column dimensions, air flow rate, bubble size, and adsorption parameters) and one nonmeasurable parameter, the fraction of liquid in the Plateau boarders, β, are needed to apply this model to a realistic situation.

We have used a 29.2 cm (i.d.) column to test this model using sodium lauryl sulfate (NLS) as the solute. The model accurately predicts the effluent concentration, which is fairly independent of β. This parameter appears to be dependent on the influent flow rate, and may be dependent on other variables

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as well. Therefore, less accurate predictions of flow rates and foamate concentration were found. Overall, the model should be quite useful in industrial wastewater treatment applications since the effluent concentration, being of primary importance, is not significantly dependent on β.

APPARATUS DESCRIPTION AND EXPERIMENTAL PROCEDURES

Apparatus Description

The continuous flow foam flotation system used in this work was built by Miller (*2*) and modified by Slapik (*3*). A detailed description of it appears in earlier papers (*2–4*). The column is illustrated in Fig. 1. The simulated wastewater is pumped from a 275 gal (1040 L) storage tank. The wastewater passes through the main pump, then NLS is injected into the waste stream. The NLS is fed by an adjustable, variable-flow, Masterflex chemical feed pump. After the wastewater passes through a flowmeter, it enters through the top of the column to the dispersion head located 2.5 ft (76.2 cm) below the top of the column. The dispersion head has eight radial arms, each arm containing nine holes which have a diameter of 3/32 in. (0.24 cm). The column itself consists of two 4-ft (1.22 m) sections of 11.5 in. i.d. (29.2 cm), 12.0 in. o.d. (30.5 cm), Lucite pipe flanged together and O-ring sealed. The column has an arrangement of 18 baffles, the top eight baffles spaces 2.75 in. (7 cm) apart and the 10 lower baffles spaced 3.75 in. (9.5 cm) apart. Air is supplied through a 5-in. (12.7 cm) diameter, fine porosity fritted glass disk at a maximum pressure of 10 psi. The disk is located below the bottom baffle and approximately 8 in. (20.3 cm) above the bottom of the column. The effluent leaves through the bottom of the column through a PVC pipe which is connected to a flexible line, the height of which can be adjusted to control the height of the liquid pool in the column. The foam leaves through the top of the column to a rotating disk foam breaker. The foam is collapsed by a 10-in. (25.4 cm) spinning disk rotating at 2000 rpm. The collapsed foamate is collected in a 13-gal (49.2 L) plastic clarifier mounted under the foam breaker.

Experimental Procedures

In this work the feed to the foam flotation system consisted of tap water with a hardness of around 100 mg/L as $CaCO_3$. To prevent any precipitation of calcium lauryl sulfate and the corresponding problems this precipitate

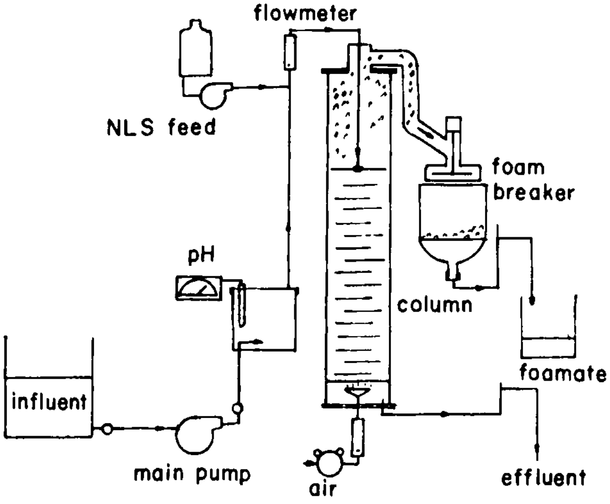

FIG. 1. The continuous foam folation column.

would produce in flotation performance, Na_2–EDTA·$2H_2O$ was added to water in a sufficient amount to complex all the calcium. The pH was adjusted to 9 by the addition of NaOH. Adjustment of pH as well as Na_2–EDTA·$2H_2O$ addition occurred in the storage tank prior to the injection of NLS into the system. No additional monitoring of the pH was done.

Three different runs were made. The purpose of the first was to determine the effects of a variation in the hydraulic loading of the column. In this first run the concentration of Na_2–EDTA·$2H_2O$ in the feed system was 0.4 g/L. The column was run at an initial influent flow rate of 2 gal/min (126 mL/s) and an influent NLS concentration of 35.7 mg/L during 10 min. Two samples of foamate and effluent were taken 2 min apart at the end of this time period. The hydraulic loading was then increased to 3 gal/min (189 mL/s), maintaining the NLS concentration close to the initial (39 mg/L). Foamate and effluent samples were collected for 20 s, all the liquid and foam exiting from the clarifier being collected during this time period. Effluent samples collected were approximately 100 mL in volume. After the collection of these samples, the column was run for an additional 17 min to ensure that steady-state had been reached at this flow rate. The hydraulic loading was then decreased again to 2 gal/min, the NLS concentration being 35.7 mg/L. Samples were taken, as described above, once every minute for 10 min. Operation continued for an additional 5 min at these conditions. The hydraulic loading was again increased to 3 gal/min with an NLS concentration of 39 mg/L. Samples were taken every 2 min for 7 min. Foamate samples were allowed to collapse overnight, and then their volumes were measured. Representative samples of foamate and effluent were analyzed for their NLS concentration.

The objective of the second run was to determine the effect of a variation in the influent NLS concentration. The influent flow rate was maintained constant at 2 gal/min (126 mL/s) and an initial NLS concentration of 19 mg/L was used. The Na_2–EDTA·$2H_2O$ concentration was 0.5 g/L. Twenty-three minutes after foam began exiting from the top of the column, three effluent and foamate samples were collected over a period of 10 s; effluent samples were approximately 100 mL in volume. The influent NLS concentration was then increased to 54 mg/L. Effluent and foamate samples were collected every 2 min for 20 min and then every 5 min for 10 min. The NLS influent concentration was then decreased to 19 mg/L. Samples were taken every 2 min for 20 min; a final sample was taken 5 min later. Before analysis, foamate samples were allowed to collapse overnight. Representative samples of foamate and effluent were analyzed for their NLS concentration.

A final run was made to determine the steady-state foamate flow rates for three different hydraulic loadings. Again the Na_2–EDTA·$2H_2O$ concentration was 0.5 g/L. The system was run at an influent flow rate of 2 gal/min and an influent NLS concentration of 17 mg/L for 30 min. The clarifier below the foam breaker was removed and replaced with a preweighed receiver. All the foam and liquid exiting from the foam breaker for a period of 10 min was collected and the receiver again weighed. The clarifier was replaced, the influent flow rate increased to 3 gal/min (189 mL/s), the NLS concentration to 24 mg/L, and operation continued for 30 min. A 10-min foamate sample was collected as before and weighed. The influent flow rate was increased to 4 gal/min (252 mL/s) and the influent NLS concentration was decreased to 20.5 mg/L. After 30 min of operation at these conditions, a 10-min foamate sample was collected and weighed. The foamate flow rates were calculated assuming a density of 1 g/mL.

The procedure used for the NLS analyses is a standard procedure for the analysis of anionic surfactants (5). The method consists of forming a methylene blue–surfactant complex in a buffered aqueous solution in the presence of excess methylene blue. The complex is extracted quantitatively with chloroform. The extract is diluted with chloroform to a final volume of 100 mL and analyzed colorimetrically, reading the absorbance at 652 mμ. A Bausch and Lomb Spectronic 20 spectrophotometer was used in this work. Standard solutions were analyzed and the calibration curve from these data was found to be linear and easily reproducible (*6*). No interference by the presence of Na_2–EDTA·$2H_2O$ was found.

RESULTS AND DISCUSSION

The experimental results obtained as described above have been compared to results of simulations of column operation based on the model described previously (*1*), with slight alterations in order to allow it to describe more exactly the column which was used to obtain the experimental results. Each region between two baffles is considered to be one slab of uniform composition. Therefore below the feed point there are nine slabs with a thickness of 9.5 cm each and eight slabs with a thickness of 7 cm each. The feed is assumed to enter the top baffled section. The region above the feed point has been partitioned into three slabs, each with a thickness of 25.4 cm. (Previously all slabs were considered to be of the same thickness.) The model neglects any mixing of foam which may occur after the foam exits the column and any nonuniformities which may occur in the drainage of the foam to the foam breaker in the foam breaking process. The foamate flow rate and concentration which are calculated using this model refer to the flow rate and concentration of the liquid resulting from a complete collapse of foam just as it exits from the top of the column. Upon column start-up, 2–3 min elapsed after foam reached the top of the column before any liquid exited from below the foam breaker. This time lag may increase once foam completely fills the pipe leading from the top of the column to the foam breaker. The model also neglects the liquid pool at the bottom of the column—that is, it assumes a plug flow mode of liquid flow as the liquid drains from the column to the point at which effluent samples are taken.

The parameters listed in Table 1 were used for the first simulations. The adsorption isotherm parameters are from Padday (7). The initial column composition was assumed to be 6.6×10^{-8} mol/mL (19 mg/L) NLS and a liquid volume fraction of 0.10. The fraction of liquid in the Plateau borders was assumed to be 0.75. The input conditions assumed were an influent flow rate of 126 mL/s and an influent NLS concentration of 6.6×10^{-8} mol/mL. These parameters were used to simulate 30 min of column operation. The resulting simulated column composition was assumed to be the steady-state composition for a column operating at these conditions. A second simulation was done beginning with this steady-state column composition and a constant influent flow rate of 126 mL/s; the influent NLS concentration was 6.6×10^{-8} mol/mL for 5 min, 1.87×10^{-7} mol/mL (54 mg/L) for the next 30 min, and 6.6×10^{-8} mol/mL for the final 30 min of simulated column operation. These conditions correspond to the experimental conditions for the second run described above.

The effluent concentration as a function of time for this simulation and the experimental values of the effluent concentration are illustrated in Fig. 2. If the liquid flows through the liquid pool and effluent line to the sampling point in a plug flow mode, one would expect a time lag of 1–2 min since the liquid

TABLE 1

Parameters Used in the Simulation of Column Operation

Column cross-section area	670 cm^2
Total number of slabs into which the column is partitioned	20
Thickness of slabs 1–9	9.5 cm
Thickness of slabs 10–17	7.0 cm
Thickness of slabs 18–20	25.4 cm
Index of feed slab	17
Air flow rate	260 mL/s
Bubble diameter	0.15 cm
Liquid density	1.0 g/mL
Liquid viscosity	0.009 P
Time increment	0.1 s
Maximum surface concentration	5.6×10^{-10} mol/cm^2
Liquid condentration when the surface concentration is 1/2 the maximum	5×10^{-7} mol/mL

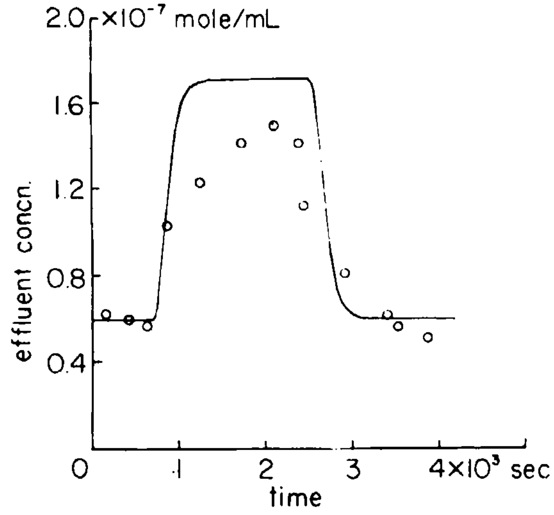

FIG. 2. Theoretical and Experimental values of the effluent concentration for a run with a variation in the influent concentration. Parameters given in text.

pool contains 2–4 gal of liquid and the flow rate is ~2 gal/min. Figure 2 indicates that the effluent concentration actually increases in less than a minute after an increase in the influent concentration. Therefore little or no time lag is present, which indicates that rapid mixing is occurring in the liquid pool in the column below the air disperser. This mixing would account for the somewhat less rapid increase of the effluent concentration upon an increase of the influent concentration, and the less rapid decrease of the effluent concentration upon a decrease of the influent concentration than is predicted by the model.

There is a larger discrepancy between the predicted values and experimental values of the foamate flow rate, as shown in Fig. 3. A poor selection of β and an inadequate method of sampling the foamate may be the cause of this error.

Additional simulations were done using the parameters given in Table 1, and an initial composition of foam in the column of 6.6×10^{-8} mol/mL NLS and 10% liquid, and an influent stream containing 6.6×10^{-8} mol/mL NLS to predict the steady-state foamate flow rate at influent flow rates of 2, 3, and 4 gal/min. The simulations were done for each flow with values of β of 0.75, 0.80, and 0.90. The results of these simulations and the experimental steady-state flow rates are given in Table 2.

The experimental result for an influent flow rate of 2 gal/min is in good agreement with the theoretical result for $\beta = 0.90$; the experimental results for the higher influent flow rates are in good agreement with the theoretical results for $\beta = 0.80$. This indicates that β is dependent on the total liquid volume fraction or some other variable which changes with the liquid flow rate.

The simulation shown in Fig. 2 was repeated with $\beta = 0.80$ and $\beta = 0.90$. The differences in the predicted effluent concentration as β is increased are quite minimal, as shown in Fig. 4; larger differences in the foamate concentration for simulation with various values of β are found, as illustrated in Fig. 5.

TABLE 2

Theoretical and Experimental Foamate Flow Rates for Steady-State Column Operation

Influent flow rate (mL/s)	Experimental	Foamate flow rate (mL/s), theoretical		
		$\beta = 0.75$	$\beta = 0.80$	$\beta = 0.90$
2	3.2	10.6	7.0	3.0
3	7.2	10.8	7.6	3.0
4	8.7	11.0	7.7	3.0

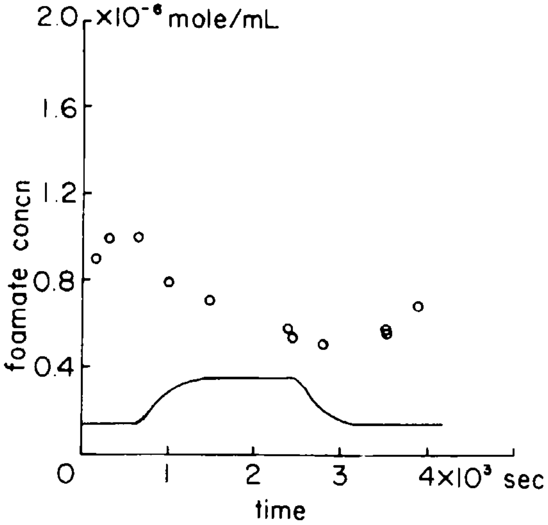

FIG. 3. Theoretical and experimental values of the foamate concentration for a run with a variation in the influent concentration. Parameters given in text.

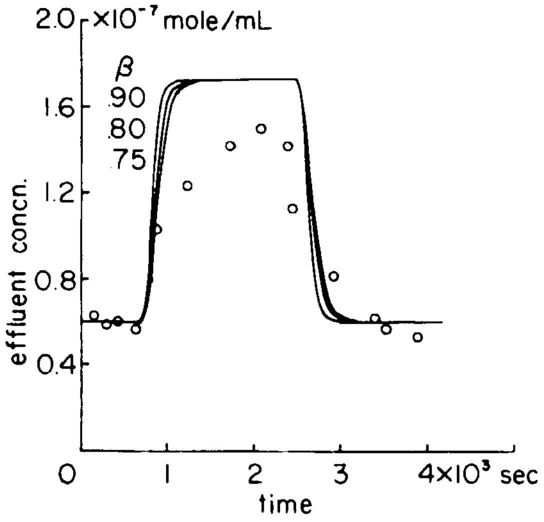

FIG. 4. Effect of β on effluent concentration. Parameters are given in the text.

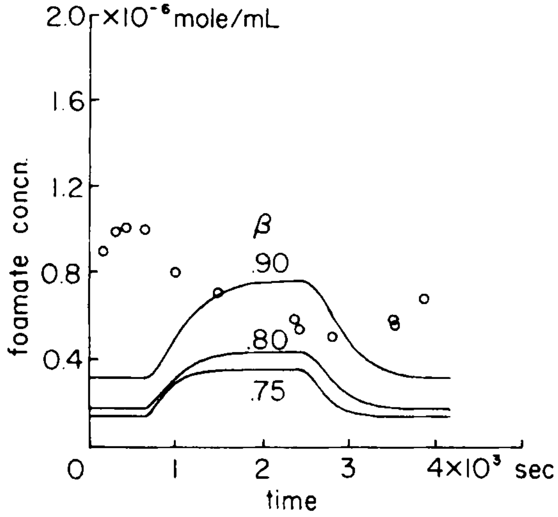

FIG. 5. Effect of β on foamate concentration. Parameters are given in the text.

The experiment with a variation in the hydraulic loading, described above, was simulated with $\beta = 0.90$.

The simulation began by assuming an influent flow rate of 126 mL/s, an influent NLS concentration of 1.24×10^{-7} mol/mL (35.7 mg/L), and an initial column composition of 1.24×10^{-7} mol/mL and 10% liquid. All other parameters used are those given in Table 1. The resulting column composition after 30 min of simulation was used as the initial column composition for the next simulation. In this case an influent flow rate of 126 mL/s and an influent NLS concentration of 1.24×10^{-7} mol/mL were assumed for 5 min of simulation; an influent flow rate of 189 mL/s and an influent concentration of 1.35×10^{-7} mol/mL (39 mg/mL) were assumed for the next 32 min of simulation; the original influent conditions of 126 mL/s and 1.24×10^{-7} mol/mL NLS were then assumed for 15 min of simulation; the final 6 min of simulation assume an influent flow rate of 189 mL/s and an influent concentration of 1.35×10^{-7} mol/mL NLS. The predicted effluent concentration as a function of time and the experimental values are shown in Fig. 6.

CONCLUSIONS

The model presented previously (*1*) predicts quite accurately the effluent concentration for the flotation of a dissolved surfactant. The foamate flow rate and concentration can be predicted with reasonable accuracy if the

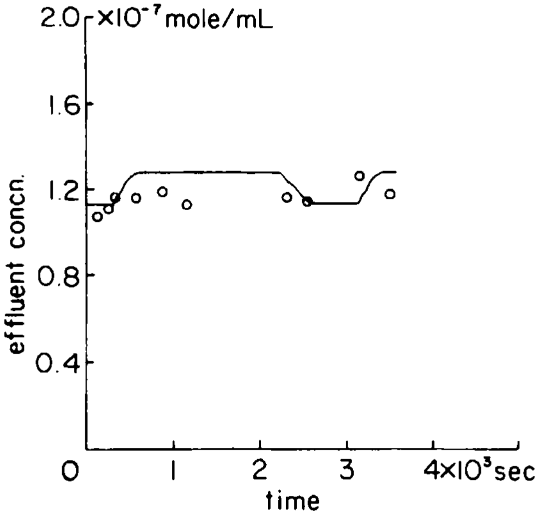

Fig. 6. Effect of moderate variations in dydraulic loading rate on effluent concentration. Parameters are given in the text.

correct value of β is chosen, but a method has not been developed to select this parameter correctly without some experimental work. It appears to be dependent on the influent flow rate and may also be dependent on other parameters. For the column described here, at an influent flow rate of 2 gal/min the model is most accurate with $\beta = 0.90$; for flow rates of 3 and 4 gal/min the model is more accurate with $\beta = 0.80$. The value of β probably is different for a system which contains surface-active particulates instead of a dissolved solute. For example, using the column described above and a flow rate of 2 gal/min with ferric hydroxide and NLS present, Rodriguez et al. (*8*) found the foamate flow rate to be ∿7% of the influent flow rate, or approximately 9 mL/s. This value implies that β is in the range of 0.75–0.80 rather than ∿0.90. The amount of foam drainage may also be dependent on the concentration of these particulates in the column, whereas this model does not predict any changes in foamate flow rate or column wetness with a change only in solute concentration. Therefore, for a model which describes the column operation exactly, one must develop an expression for β which depends on factors such as the total liquid fraction and the particulate concentration, but since effluent concentration is almost independent of this parameter, this expression is not necessary to make the model useful as presented above.

Another addition which could be made to improve the model would be to account for the mixing in the liquid pool below the air disperser. This procedure would be relatively simple if one assumes complete mixing in this region, and it would not add a significant amount of computation time. Such a change should allow one to predict more accurately the effluent concentration as a function of time as the influent conditions are abruptly changed.

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