

A FLUIDIZED BED ADSORPTION LABORATORY EXPERIMENT

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There are a variety of pedagogical and motivational advantages in exposing students to real process equipment in a laboratory course.^[1] There is also a need, however, to use simple laboratory experiments in order to help students better understand basic principles learned in their coursework. Therefore, it is often advantageous to start students off with simple experiments where the connection to basic principles is obvious and then move on to more challenging and complex systems that resemble real-world situations.

A fluidized bed adsorption process provides a somewhat unique opportunity for students to carry out a series of experiments (on one piece of apparatus) that steadily approaches the real process equipment. The series starts with a study of bed expansion in a fluidized bed, goes on to residence time distribution measurements, and ends with a study of a bioseparation in a fluidized bed. This allows students to build upon ideas they have already learned in fluid mechanics, mass transfer, separations, and reaction engineering. The experiment was developed in the Department of Chemical and Biochemical Engineering at Rutgers University and forms part of the Process Engineering Laboratory course for seniors.

PROCESS OVERVIEW

Advances in biotechnology have resulted in the production of a multitude of therapeutic proteins by mammalian, bacterial, and yeast fermentations. The global market for therapeutic proteins used in the treatment of cancer and AIDS, as well as growth factors and monoclonal antibodies for diagnostic applications is rising. Current work on genomics and proteomics is likely to make it easier to discover new therapeutic proteins, which will in turn lead to an increase in the production of proteins.

At the same time, primary recovery and purification of the protein from the fermentation broth continues to be a significant limiting factor in the overall economics of therapeutic protein production. Therefore, bioseparations is a critical step both from a processing and research point of view. In fact, as

much as 80% of the production costs for many proteins can be incurred during product isolation and purification.^[2] For example, therapeutic proteins such as interferons and interleukins are considered high-value proteins with a price of \$1,000,000 per gram or more.^[3] Product concentrations in a typical feed stream are low, between 10^{-2} and 10^{-6} mg/L, and much of the high manufacturing costs can be attributed to recovery time and product losses across each step of the purification process.^[4] In addition, the final purified product must often be greater than 99.9% pure, with less than 10 pg per dose of nucleic acids and endotoxins.^[5]

In the biotechnology and pharmaceutical industries, ion exchange chromatography (IEC) is the most widely used operation for purification of proteins. The operation typically involves a packed bed of resin particles or adsorbent beads that selectively adsorb the target protein. After the resin par-



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ticles become filled with protein, the feed to the column is stopped and an eluent buffer is passed through the column in an elution step. This leads to the product being released into the eluent buffer, and the end result is that the product is typically concentrated 10X to 40X.

Generally, the fermentation broths contain suspended solids, *e.g.*, cells or cell debris that would clog a packed bed. To prevent this, feedstocks are usually clarified by filtration or centrifugation before the chromatographic separation in order to remove the cell debris. Fluidized or expanded bed adsorption has increasingly become an alternative method of interest for adsorption of proteins from feedstocks containing cells.^[6,7] In this process, a bed of adsorbent beads is expanded or fluidized by the upflow of liquid, leading to large voids between the adsorbent beads and allowing cells and cellular debris to pass through the bed without becoming trapped. As a result, fluidized bed adsorption eliminates the need for the expensive operations of filtration and centrifugation.

Another advantage that fluidized bed adsorption has over a packed bed is enhanced mass transfer, which can lead to increased process yields.^[8] This means that for a given pressure drop across the bed, the fluidized bed can in principle achieve a higher rate of protein removal. For these reasons, this technology is increasingly being applied as a downstream separation technique in the pharmaceutical and biotechnology industries. At the present time, the technique has been used for the recovery of recombinant proteins from mammalian cell culture and *E. coli* fermentation broths.^[9-11]

Karau, *et al.*,^[12] defined expanded bed adsorption as a subset of fluidized bed adsorption that specifically addresses situations with low superficial velocities close to the minimum fluidization velocity. For most resins, the expression “expanded bed adsorption” is applicable only to bed expansions of less than two times the settled bed height. In this article, adsorption is investigated at bed expansions of two to four-

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and-one-half times the settled bed height. Thus, the expression “fluidized bed adsorption” is used to emphasize that we are investigating protein adsorption for a large range of bed expansions, including high expansions.

The basic process of fluidized bed adsorption includes the application of feed through the bottom of a column filled with resin, as illustrated in Figure 1. Initially, the resin is settled, but the upward feed flow results in suspension or fluidization of the resin bed. Product in the feedstock adsorbs to the resin while nonproduct solid material (*e.g.*, cell debris) washes out with the spent feed. Subsequent washing with a buffer further removes nonproduct solid material that may remain associated with the resin. Product is then recovered by introducing an eluent buffer (salt solution) through the top of the column. To minimize process volumes, elution is usually conducted in the packed-bed mode where the product is concentrated 10X to 40X. After elution, the resin can be cleaned and regenerated for repeated use.

To determine the bed expansion characteristics, study the effects of liquid velocity and bed expansion on the flow hydrodynamics, and identify the dominant mechanistic features in a fluidized bed adsorption column, the laboratory course is divided into three parts: bed expansion characterization, tracer studies, and adsorption of protein. Each of the three experiments involved in this project requires approximately four hours of work and is carried out in a single afternoon. Experiments are finished in three weeks, and the project write-up is due in the fourth week. Before the first day of each lab, students are required to read the introduction section from the laboratory manual for that week’s experiments as well as related materials in the library.

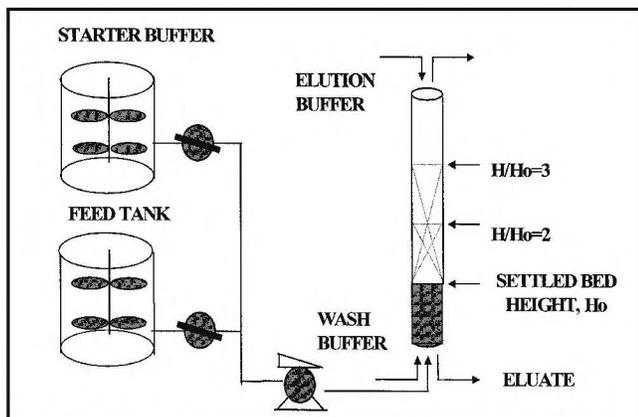


Figure 1. Schematic of normal operating mode of fluidized bed adsorption process.

EXPERIMENTAL EQUIPMENT AND MATERIALS

The laboratory equipment consists of a Streamline 50 expanded bed adsorption column (Pharmacia Biotech, Piscataway, NJ), a peristaltic pump, an in-line UV sensor, and a UV analyzer. A schematic of the experimental setup is shown in Figure 2 (next page), with the principal components listed in the caption. The column is constructed of a borosilicate glass tube, 5 cm in diameter and 100 cm long. The normal operating pressure is less than 0.5 bar, but the column can withstand pressures up to 1 bar. The column should not be operated above 1 bar pressure or without liquid.

The column is supported by a stainless steel mounting for

protection and contains an adsorbing resin. The minimum resin loading is 200 mL or 10 cm settled height; the maximum loading is 600 mL or 30 cm settled height. The resin is retained by a stainless steel 60-mesh screen at the base of the column. A peristaltic pump is used to pump fluid into the base of the column through a stainless steel distributor plate with 12 equally spaced 1-mm holes. The distributor plate is mounted in the base of the column below the screen and it and the screen are held in place with rubber gaskets. The column is equipped with a moveable rod piston fitted with a 60-mesh screen to retain the resin at high flow rates or high expansions. During operation, the piston is moved just above the expanded bed height to minimize head space. Spent charge is pumped out through the piston and fed to an in-line UV sensor (Wedgewood Technology, San Carlos, CA).

The signal from the sensor is analyzed by an UV analyzer at 280 nm. The resin used in the experiment is Streamline SP (Pharmacia Biotech, Piscataway, NJ), which is a cation exchange resin with a particle radius range from 45 to 178 μm . A Malvern Mastersizer X was used to determine that the average particle radius is 89 μm , with a particle-size distribution that is approximately Gaussian with a skewness of 0.878. Streamline SP has been used previously in several fluidized bed adsorption applications, and its hydrodynamic and expansion properties are well characterized.^[10,13,14] The average particle density is 1.18 g/mL. Each particle is composed of a crystalline quartz core, covered by 6% cross-linked agarose. The dynamic binding capacity reported by the manufacturer is 70–85 mg/mL for most proteins. Bound proteins inside the particle remain attached at one adsorption site until they are eluted.

The protein lysozyme (EC 3.2.1.17, Sigma Chemical Company, St. Louis, MO) was selected as an adsorbing species since it is relatively inexpensive, well-characterized, and easily assayed by spectrophotometric methods. Most importantly, it adsorbs and desorbs readily from Streamline SP resin.

Lysozyme is a globular protein with hydrolytic enzyme properties. It is nearly spherical, with dimensions of 4.5 x 3 x 3 nm.^[15] The molecular weight is 14,600 and the isoelectric pH is 10.7 to 11.3.^[16] This high isoelectric pH allows adsorption by cation exchange resins at a wide range of pH values. A point worth mentioning is that the use of protein is not, in principle, necessary for this experiment. One could do a much less expensive experiment by changing the protein adsorption into an ion exchange experiment—for example, exchanging Na^+ from a NaCl solution. We believe, however, that stu-

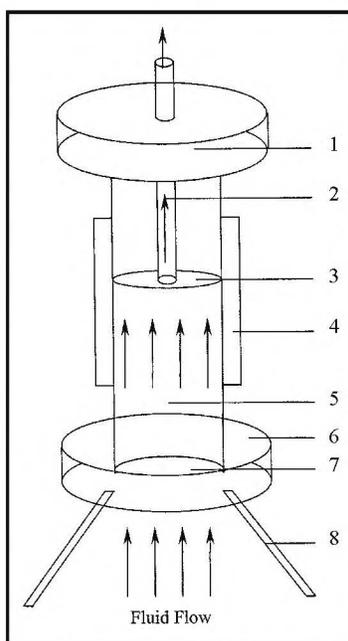


Figure 2. Fluidized bed adsorption column.

1. Top flange
2. Adapter rod piston
3. Adapter distributor and net
4. Stainless steel mount
5. Glass column
6. Bottom flange
7. Column distributor and net
8. Stand

dents benefit from being exposed to a bioseparation and working with a real protein and a commercial resin.

EXPERIMENTAL PROCEDURE

Column Setup • Before experiments, students are required to familiarize themselves with the standard operating procedure for operating the Streamline 50 expanded bed adsorption column. The procedure is

■ The first step is to remove the adapter from the column. The purpose of the adapter is to minimize the head space above the resin particles during fluidization. To push out the adapter from the column, use the hydraulic pump to pump water into the base of the column at a pump setting of 2 (150 mL/min). The adapter rises. Stop pumping when the adapter sits in the upper flange at the top of the column. Then remove the domed nuts and washers on the lid, raise the lid, and remove the piston and adapter plate. Once the piston and adapter have been removed, reverse the pump to decrease the level of water in the column to approximately 30 cm.

■ Prepare an adsorbent-water slurry with deionized water. To maintain the dynamic

binding capacity, the adsorbent should always remain wet—by no means should it ever be isolated via filtration. Quickly pour the slurry into the column. Resuspend any adsorbent remaining in the container with deionized water and pour this into the column. If aggregates of air-adsorbent remain floating on the liquid surface, they need to be removed or pushed down into the liquid. Allow the resin to settle and add more resin if necessary to obtain desired settled bed height. Fill the column to the rim of the glass tube with deionized water.

■ When the column is secure in the steel mounting assembly, carefully tilt the adapter and insert it into the column so that one side of the gasket on the adapter net is in the water-filled column. Without trapping air under the net, carefully put the adapter into a vertical position. Slowly push the adapter down until the gasket can be seen under the upper flange. When the adapter is firmly seated in the column, push down the lid and replace the washers and domed nuts. Fill the space above the adapter with deionized water.

■ To lower or raise the adapter, pump deionized water into the column side connector (above the adapter) or into the base of the column at a pump setting of 2 (150

mL/min). Stop the pump when the adapter is at the desired height in the column. Once the resin is in the column and the adapter height has been set, the column is ready for operation.

Bed Expansion Characterization • The first step prior to starting adsorption is to characterize the bed expansion as a function of linear velocity and viscosity in a nonadsorbing system with 200 mL of resin in the column. Viscous and non-viscous fluids are pumped into the base of the column at four different linear velocities. The expanded bed height is measured at each velocity to obtain expansion plots and Richardson-Zaki plots.^[17] This information is used to compare fluidization conditions with published results and also to identify desirable conditions for adsorption studies.

In this experiment, students are divided into three groups and each group carries out experiments with a fluid of different viscosity. The groups share their data at the end of the experiment in order to increase the amount of data each group has to analyze. Group A performs experiments using a 0.05 mol/L sodium acetate buffer solution with 0% glycerol and a sodium acetate buffer solution with 5% glycerol. Group B performs experiments with a 0.05 mol/L sodium acetate buffer solution with 0% glycerol and a sodium acetate buffer solution with 15% glycerol. Group C uses a 0.05 mol/L sodium acetate buffer solution with 0% glycerol and a sodium acetate buffer solution with 30% glycerol. The fluid viscosity is measured by a viscometer. The experimental procedure is

■ Record the pump setting and allow ten minutes for the bed to stabilize. The flow rate is determined by the volume collected per unit time (mL/min). Once the flow rate is known, the linear superficial velocity is just the flow rate divided by the cross-sectional area.

■ After ten minutes has passed, read off the stabilized expanded bed height. The McCabe equation below determines the fluidized bed porosity:^[18]

$$\frac{H}{H_0} = \frac{(1 - \epsilon_0)}{(1 - \epsilon)} \quad (1)$$

where ϵ_0 is the voidage of the particles in settled bed mode, H_0 is the settled bed height, H is the expanded bed height, and ϵ is the expanded bed porosity. A value of $\epsilon_0 = 0.4$ was measured for the particles in settled bed mode.

■ After the experiment, students can plot the logarithm of the linear superficial velocity versus the logarithm of the expanded bed porosity. The slope of this line is the Richardson-Zaki coefficient.^[17]

Tracer Studies • To characterize the internal flow hydrodynamics and axial mixing of Streamline SP resin, tracer studies are performed using a 0.25% acetone pulse to determine the dispersion and residence time distribution (RTD) characteristics of the system as a function of bed expansion. The

[This] experiment also provides an opportunity for students to carry out a series of experiments that increases in complexity and approaches the real process equipment.

acetone is added into the sodium acetate buffer as well as the various percentage glycerol buffer solutions. The acetone at the column outlet is monitored by the UV analyzer at 280 nm for a given degree of bed expansion, which is determined by the liquid velocity corresponding to each fluidized bed height. Students can obtain this information from the *Bed Expansion Characterization*. A positive step signal is used to obtain residence time distributions by the F-curve method.^[19] Measurements associated with the positive step signal lead to an F-curve. The data in the F-curve is then differentiated to obtain the C-curve. Values for the variance (σ_B^2) of the C curve are used to calculate the mean residence time in the expanded bed, axial dispersion coefficient (D_{ax}), and the number of theoretical plates (N). In the interest of saving time, only one run per a given flow rate is carried out. The experimental procedure is

■ After recording such information as pH, temperature, flow rate, and the characteristics of the solution, students should move the adapter approximately 1 cm above the desired expansion height. A large gap (or large head space) above the resin may lead to a region of pure fluid above the resin, and this will affect the residence time distribution measurements. Start the recorder/UV-monitor and allow it to warm up for 20 minutes or more. Prior to expansion, two 20-L carboys need to be set up. One should be filled with sodium acetate buffer solution and the other should be filled with tracer (0.25% acetone in sodium acetate buffer solution). Air bubbles should be evacuated from the lines before expansion. Once the adapter is in position, bed expansion can be started by introducing the buffer solution. When the bed is fully expanded at the test flow rate, note the expanded bed height from the calibrated column and continue pumping buffer. At this time, zero the UV sensor. After this is done, unclamp and bleed the tracer line and clamp the buffer line.

■ At the instant tracer is introduced, begin to record the time and UV readings from the sensor. UV recordings should be taken every 30 seconds in the beginning, until an increase in activity is noticed, at which point readings should be taken every 15 seconds. Continue to take readings approximately 5-10 minutes after the UV readings have leveled off.

■ Then clamp the tracer line and re-open the buffer line. Record this time and continue to record UV readings in 15-30-second intervals until the readings go

down to approximately zero.

■ Every group should do three expansions that include 2X, 3.3X, and 4.5X the settled height.

Adsorption of Protein • After examining particle fluidization and axial dispersion characteristics of the resin, dynamic adsorption capacities are measured for the resin to assess mass-transfer effects under different hydrodynamic conditions. To identify the dominant mechanistic features of the fluidized bed adsorption system, the fluidization studies should be designed to isolate mass-transfer effects from hydrodynamic effects. This can be accomplished by frontal analysis of breakthrough curves to determine dynamic adsorption capacity of the resin under varying conditions of linear velocity, viscosity, and axial dispersion. The experimental procedure is

■ Prior to experimentation, several initial steps should be performed. The resin should be washed with 10 L of a 1-mol/L NaCl solution at a pump setting of 1.5 (100 mL/min). This expands the bed and allows for proper cleaning of the resin. Following the salt solution wash, 20 L of deionized water should be introduced into the column with a pump setting of 1.5 (100 mL/min). This removes the salt as well as other impurities that are introduced while the resin is sitting immobile in the column. The conductivity of the outlet should be checked to ensure all the salt has been removed by obtaining a conductivity reading of less than 5 mS. If the conductivity is too high, continue washing the resin with another 10 L of deionized water. Equilibrate the resin with 20 L of a 0.05-mol/L sodium acetate buffer solution at a pH of 5. If the resin is not equilibrated to the buffer, inaccurate data will be obtained for the adsorption. Prior to experimentation, additional buffer solution (20 L) as well as protein solution (10 L) should be prepared, and the UV sensor should be allowed to warm up for 20 minutes to obtain accurate readings for concentration. Then zero the UV sensor using 0.05-mol/L sodium acetate buffer.

■ Before starting the experiments, a sample of the protein solution should be introduced into the UV sensor to obtain an initial concentration reading. This is the C_0 value. The desired breakthrough concentration (usually 10 to 30% of initial concentration) is the breakthrough percentage multiplied by the initial concentration.

■ For operation of the column, the following procedure should be followed. From the *Bed Expansion Characterization*, students have a direct correlation between pump setting, linear velocity, and expanded bed height. Due to the expense of the protein, only one adsorption is carried out for each group. Group A uses a 2X expansion, Group B uses a 3.3X expansion, and Group C uses a 4.5X expansion. The lines to the column

should be bled prior to introducing any fluid into the column, and the lines from each solution must be void of air bubbles. The buffer solution should be introduced first in order to obtain a stable bed height.

■ Once this is achieved, the protein solution can be introduced. Record UV readings at 1-minute intervals until increased activity in the UV output is noticed. Then take UV readings at 30-second intervals until C/C_0 of 0.15 has been reached. This point is defined as column breakthrough, which is the point of reduced binding capacity. In most commercial applications, the adsorption is discontinued at a point where the exit concentration is 10% to 15% of the inlet feed concentration, to prevent unacceptable product losses. In this study, 15% has been used. Once breakthrough is achieved, the time should be recorded as well as the buffer volume.

■ After the above procedure has been finished, unclamp the buffer solution line and clamp the protein solution line. At this point, 10 L of a 1-mol/L NaCl solution at pH 5 should be introduced into the column at a pump setting of 1.5 (100 mL/min) to recover the protein. After that, 20 L of deionized water should be introduced into the column at a pump setting of 1.5

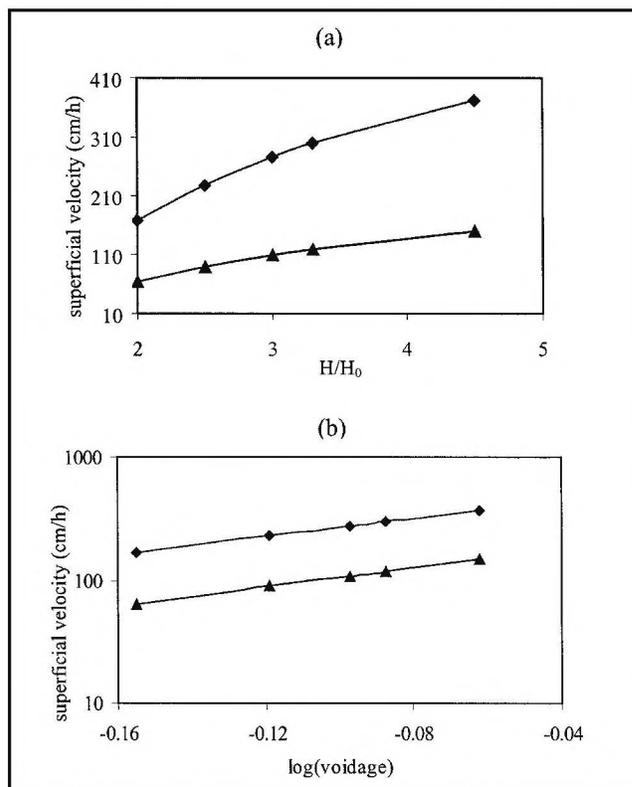


Figure 3. The characteristics of the bed expansion. (a) Plot of H/H_0 versus linear velocity in the buffer solution without glycerol (◆), and with 30% glycerol (▲). (b) Richardson-Zaki parameter plots in the buffer solution without glycerol (◆) and with 30% glycerol (▲).

(100 mL/min) to rinse the column and resin.

RESULTS AND DISCUSSION

Bed Expansion Characterization • The effects of fluid velocity and viscosity on the bed expansion can be seen in Figure 3. As would be expected, an increase in viscosity leads to a larger expansion for a given superficial velocity (see Figure 3a). Richardson and Zaki^[17] observed that if the log of the voidage was plotted versus the log of superficial fluidization velocity, a linear relationship is obtained. A correlation was developed and is generally called the “Richardson-Zaki equation,” written as

$$\frac{u_s}{u_t} = \varepsilon^{(n+1)} \quad (2)$$

where n is the Richardson-Zaki number, u_s is the superficial velocity, and u_t is the particle terminal velocity, which is a function of particle density, fluid density, particle diameter, and fluid viscosity. In the fluidized bed system, u_t can be seen as a constant. In order to compute the Richardson-Zaki number, n , one can plot the logarithm of linear velocity versus the

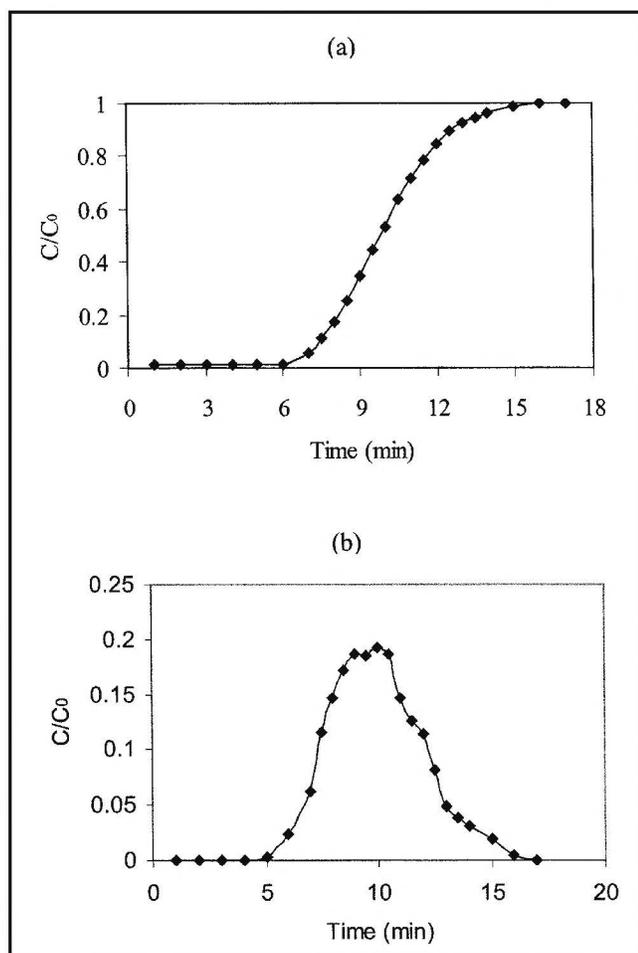


Figure 4. Acetone tracer curves for Streamline SP at an expansion of $H/H_0 = 2$ in 50 mol/L NAOAC buffer solution. (a) F-curve; (b) C-curve

logarithm of fluidized bed porosity. One should get a straight line with slope $n+1$. The Richardson-Zaki number is a function of the ratio of particle diameter to column diameter. Since the resin and the column are not changed during experiments, the Richardson-Zaki number should be the same for the different buffer solutions, as can be seen in Figure 3(b). Although the fluid viscosity does not change the Richardson-Zaki number, it does affect the bed expansion, as shown in Figure 3(a).

Tracer Studies • To characterize the internal flow hydrodynamics and axial mixing of Streamline SP, tracer studies are performed at different bed expansions. Good reproducibility is generally obtained from three trials at each condition and the standard deviation is generally less than 5% for each parameter. Figure 4 shows typical acetone tracer curves for Streamline SP at an expansion of $H/H_0 = 2$ in 0.05 mol/L NAOAC buffer. Axial dispersion coefficients are obtained from the variance, σ_θ^2 , in the C-curve as follows:^[12]

$$D_{ax} = (u_s H \sigma_\theta^2 / 2) \quad (3)$$

where H is the height of the fluidized bed and u_s is the superficial linear velocity. σ_θ^2 can be calculated in the following way:^[19]

$$t_{mean} = \left[\left(\int_0^\infty t C dt \right) / \left(\int_0^\infty C dt \right) \right] \quad (4)$$

$$\sigma^2 = \left[\left(\int_0^\infty (t - t_{mean})^2 C dt \right) / \left(\int_0^\infty C dt \right) \right] \quad (5)$$

$$\sigma_\theta^2 = (\sigma^2 / t_{mean}^2) \quad (6)$$

where C is the concentration of the tracer at time t . These quantities can be evaluated by making use of the following numerical integration formulas:

$$t_{mean} = \left[\left(\sum C_i t_i \Delta t_i \right) / \left(\sum C_i \Delta t_i \right) \right] \quad (7)$$

$$\sigma^2 = \left[\left(\sum (t_i - t_{mean})^2 * C_i \Delta t_i \right) / \left(\sum C_i \Delta t_i \right) \right] \quad (8)$$

where the data is divided into time intervals of Δt_i and C_i is the concentration of tracer at time t_i .

Once the value of σ_θ^2 and D_{ax} has been calculated, the Peclet number and the number of theoretical plates can be determined from

$$Pe = (u_s H / \varepsilon D_{ax}) \quad (9)$$

$$N = 1 / \sigma_\theta^2 \quad (10)$$

The axial dispersion coefficients for Streamline SP in buffer without glycerol at the expansion of 2X and 3.3X are computed to be $1.8 \times 10^{-6} \text{ m}^2/\text{s}$ and $7.27 \times 10^{-6} \text{ m}^2/\text{s}$, respectively. When 30% glycerol is added, axial dispersion is relatively unchanged at $H/H_0 = 2$, but lower linear velocities are required to obtain this same degree of expansion. For the fluid-

ized bed system, the Peclet number, which is the ratio of the convective transport to the dispersive transport in the expansion, can be used to quantify the extent of deviation from plug flow in the column.^[18] In true plug flow, the Peclet number approaches infinity. For completely mixed flow, the Peclet number approaches 0. In this study, the Peclet number ranges from 40 to 80, indicating a small deviation from plug flow.

Adsorption of Protein • For these experiments, the frontal analysis of breakthrough curves has been used to determine the effect of axial dispersion on adsorption in an expanded bed. The breakthrough curves are shown in Figure 5. To facilitate direct comparison of breakthrough, the adsorbed concentration, q , is normalized with respect to the equilibrium capacity q_0 and plotted as q/q_0 versus C/C_0 . As discussed earlier, breakthrough is defined as $C/C_0 = 0.15$ or at 15% of the feed concentration, C_0 . Results from RTD and frontal analysis are shown in Table 1 together with the q/q_0 values at breakthrough (*i.e.*, the q/q_0 value corresponding to $C/C_0 = 0.15$). Here the average residence time for each condition is defined as

$$\tau = \varepsilon H / u_s \quad (11)$$

When the expanded bed height is 2 times the settled bed height, the bed porosity, ε , is approximately 0.7. Under these conditions, the linear velocity is 168 cm/h, and q/q_0 is 0.97 at breakthrough. The addition of 30% glycerol resulted in an increased bulk phase viscosity and a linear velocity of only 64 cm/h is required to expand the bed to twice the settled height. Under this condition, breakthrough occurs at $q/q_0 = 0.86$ even though the residence time is significantly higher than for the buffer-only case. When Streamline SP is expanded to 3.3 times the settled height in buffer at 300 cm/h, q/q_0 decreases to 0.68 at breakthrough. The residence time does not change, but the axial dispersion increases compared to the case where $H/H_0 = 2$. Therefore, since the residence time is relatively constant, early breakthrough is likely due to increased axial dispersion.

When 30% glycerol is added, the expanded bed height increases to 4.5 times of the settled height at a reduced linear velocity of 150 cm/h, and a longer residence time than that for the $H/H_0 = 2$ expansion in glycerol is obtained. Here, breakthrough occurs even earlier at a q/q_0 value of 0.54 due to a 6-fold increase in axial dispersion. The shape of the breakthrough curves for Streamline SP resin under the conditions presented here is of interest as well. The breakthrough curves are all relatively sharp except for the condition of $H/H_0 = 4.5$ with 30% glycerol. In this case, a gradual breakthrough curve is obtained, indicating that a low level of lysozyme is bled through the column before breakthrough is established. In an actual application, this would amount to product loss.

These results suggest that a macroporous resin such as Streamline SP is best used for low viscosity feedstocks applied at intermediate linear velocities since dynamic capacities are severely reduced with higher viscosity feedstocks. It

should be mentioned that the particles used for this study were not elutriated, and so a wide particle size distribution was used for all cases (as supplied by the resin manufacturer). The effect of particle size distribution on breakthrough in fluidized bed adsorptions was investigated recently by Karau, *et al.*^[12] In their study, they found that particles with a wide size distribution would reduce axial dispersion compared to a narrow particle size distribution. The work described here could be extended by sieving the resin into narrow fractions and carrying out experiments to confirm the results of Karau, *et al.*

The results of this work also suggest that to maximize throughput with minimal product losses, the operation could be divided into two steps. Initially, one could operate at very high expansions until the onset of breakthrough due to high axial dispersion. At this point the particles are not saturated. Thus, the linear velocity can be reduced to decrease the bed height to a regime where only intraparticle or film mass transfer effects dominate. Adsorption could continue at this smaller expansion with a corresponding longer residence time and reduced axial dispersion until the point of breakthrough. Further experiments could be carried out to confirm this hypothesis.

CONCLUSIONS

This paper describes an experiment that exposes students

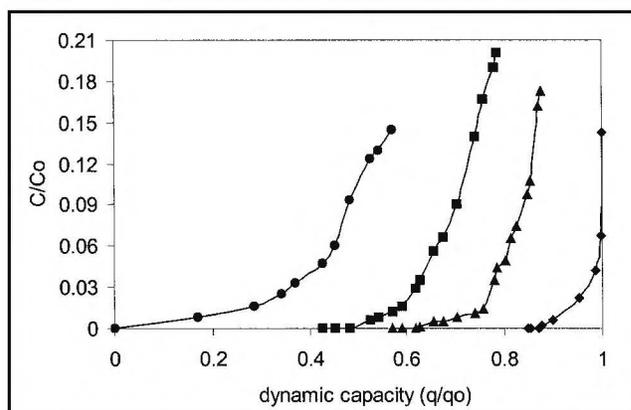


Figure 5. Breakthrough curves for Streamline SP.

- ◆ $H/H_0 = 2$, 0% glycerol and $u_s = 168$ cm/h
- $H/H_0 = 3.3$, 0% glycerol and $u_s = 300$ cm/h
- ▲ $H/H_0 = 2$, 30% glycerol and $u_s = 64$ cm/h
- $H/H_0 = 4.5$, 30% glycerol and $u_s = 150$ cm/h

TABLE 1
Results of Frontal Analysis with Streamline SP

Buffer (% glyc)	H/H_0	u_s (cm/h)	D_{ax} (m^2/s)	q/q_0	ε	τ (min)
0%	2.0	168	1.80×10^{-6}	1.00	0.70	5.0
0%	3.3	300	7.27×10^{-6}	0.75	0.82	5.4
30%	2.0	64	1.08×10^{-6}	0.86	0.70	13.1
30%	4.5	150	6.27×10^{-6}	0.57	0.87	15.7

to the basic principles of fluidized-bed operation and protein adsorption. Feedback from students who have worked on the laboratory experiment has been very positive. They have particularly enjoyed working with a real protein and a commercial resin (that needs to be handled with care).

In the experiment, students study the relation of the linear velocity and the buffer viscosity to the expanded bed height by simple bed operation, the flow hydrodynamics of the bed expansion system by tracer studies, and the protein adsorption characteristics by frontal analysis of breakthrough curves. In this way they are forced to put together concepts they have learned in separate courses in fluid mechanics, mass transfer, separations, and reaction engineering. The fluidized bed laboratory experiment also provides an opportunity for students to carry out a series of experiments that increases in complexity and approaches the real process equipment.

NOMENCLATURE

H	fluidized bed height (cm)
ϵ	fluidized bed porosity
n	Richardson-Zaki number
u_s	superficial velocity (cm/h)
u_t	particle terminal velocity (cm/h)
N	theoretical plate number
D_{ax}	axial dispersion coefficient (m ² /s)
t	time (s)
τ	average residence time
Pe	Peclet number
C	concentration (mol/L)
q	adsorbed concentration (mol/L)

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