S	extraction solvent flow rate (= extract flow rate when solvents are immiscible and solute concentrations are low) (liter h^{-1})
SPM	rate of reciprocation of plates (strokes min^{-1})
t	time (h)
x	concentration of solute in raffinate phase or heavy phase (M, or g $liter^{-1}$)
y	concentration of solute in extract phase or light phase (M, or g $liter^{-1}$)
z_p	net surface charge of protein

Greek Letters

λ	lumped parameter in equation for partition coefficient K [Equation (6.2.2)]
ϕ	electrical potential (mV)

PROBLEMS

6.1 Two-Stage Countercurrent Extraction In a two-stage countercurrent extraction of a pharmaceutical product, what is the relationship between the feed concentration and the final raffinate concentration in terms of the extraction factor E if both stages are at equilibrium? For a partition coefficient K of 5.0 and a solvent-to-feed ratio (S/F) of 0.5, what will be the ratio of the raffinate concentration to the feed concentration?

6.2 Purification Factor for Extraction of an Enzyme You are preparing an industrial enzyme, alcohol dehydrogenase, from yeast using two-phase aqueous extraction. The crude, clarified extract contains only proteins and has a specific activity of 200 units/g protein. After a single stage of affinity extraction using a Cibacron dye–PEG complex, the extract contains 400,000 units of enzyme activity and 20 g of protein. What is the purification factor for this step?

6.3 Extraction Conditions for Various Bioproducts For the following bioproducts, outline how extraction can be used in the purification process using information obtained from work reported in the literature:

(a) Magnamycin, a macrolide antibiotic from *Streptomyces halstedii*

(b) Glumamycin, a peptide antibiotic from *Streptomyces zaomyceticus*

(c) β-Galactosidase, an enzyme from *Escherichia coli*

(d) Pullulanase, an enzyme from *Klebsiella pneumoniae*

Give as much information as possible about what the process conditions should be (solvents, pH, concentration, etc.).

6.4 Required Solvent-to-Feed Ratio in Countercurrent Extraction In a countercurrent, equilibrium staged extractor with four equilibrium stages, determine the necessary ratio of extract to feed (S/F) to purify bioproduct A to 90% purity from contaminant B. The feed contains two components, 60% A and 40% B, and the partition coefficients are $K_A = 3.0$ and $K_B = 1.0$.

6.5 Purification of an Antibiotic by Countercurrent Extraction A countercurrent extraction unit with three equilibrium stages is used for the separation of a desired antibiotic (partition coefficient = 6.0) from a major contaminant (partition coefficient = 1.0) in an aqueous feed stream. The feed (or raffinate) and extract phase flow rates are equal. What fraction of each is discarded from the raffinate? Assuming that the feed contains only these two components at an antibiotic-to-contaminant ratio of 3:1, what is the purity of the antibiotic in the exit extract from stage 3? What do you conclude about the effectiveness of this extraction as a means of purification of the antibiotic?

6.6 Mixer–Settler Extraction System You are assigned the task of extracting zithramycin with a yield of at least 90% from a clarified fungal fermentation broth, using a four-stage mixer–settler extraction unit in the pilot plant. (One mixer–settler constitutes one equilibrium stage in the countercurrent extraction cascade shown in Figure 6.7.) The n-butanol extraction solvent flows at 20 liters/h, while the clarified broth flows at 30 liters/h. The partition coefficient of zithramycin is adjustable by changing the pH. What minimum value of the partition coefficient should you use for the successful completion of your assigned task?

6.7 Graphical Equilibrium Stage Calculations for Extraction of a Peptide The equilibrium partitioning of a peptide between an aqueous feed phase and an organic solvent extract phase has been found to be nonlinear and can be represented by the following equation:

$$y = 1.47 \ln x + 3.96$$

where y and x are concentrations of the peptide in the extract and aqueous feed (or raffinate) phases, respectively, in grams per liter. It is desired to extract 95% of the peptide from a feed stream having a peptide concentration of 4.0 g/liter. For a feed stream at a flow rate of 5.0 liters/min and an extract stream at a flow rate of 3.3 liters/min, graphically estimate how many equilibrium stages will be required for countercurrent flow of the phases. What is the concentration of the peptide in the exit extract stream? As the concentration of the peptide in the raffinate decreases, does the partitioning of the peptide into the extract become more or less favorable?

6.8 **Scaleup of a Podbielniak Centrifugal Extractor** Pilot plant tests with a Podbielniak centrifugal extractor indicated that excellent recovery (>95%) of a desired bioproduct could be obtained from filtered fermentation broth by extraction with an immiscible organic solvent. The flow rates were the following:

Filtered broth (aqueous) flow rate = 500 ml/min (continuous phase)

Organic solvent flow rate = 125 ml/min (dispersed phase)

The pilot plant extractor delivers a centrifugal force of $11{,}400 \times g$, and the rotating cylinder inside the extractor has a diameter of 20 cm and is 2.5 cm wide.

You have been asked to scale up this extraction by using a larger Podbielniak extractor, which delivers $2300 \times g$ and has a rotating cylinder with a diameter of 91 cm and a width of 91 cm. What flow rates should be used in the larger extractor to achieve the same recovery of bioproduct?

TABLE P6.9

Run number	Flow rates (ml/min)		Antibiotic concentration in raffinate (mg/liter)
	Broth	Chloroform	
1	45	135	2
2	67.5	135	3
3	125	135	30
4	80	120	5
5	100	150	7
6	120	180	9
7	150	225	25

6.9 **Scaleup of Pilot Plant Tests of a Reciprocating-Plate Extraction Column** The pilot plant data in Table P6.9 are for the extraction of an antibiotic from whole fermentation broth using the solvent chloroform in a reciprocating-plate extraction column. The concentration of the antibiotic was 1.4 g/liter in the broth. The column had a diameter of 2.54 cm, and the height of the plates was 3.05 m. The partition coefficient K for the antibiotic is known to be 2.68.

For each pilot run, determine the diameter and height of the plates for the plant column that would be required for processing 50,000 liters of broth in 12 h to give an exit raffinate concentration of antibiotic of 10 mg/liter, assuming a concentration of antibiotic in the feed broth of 1.0 g/liter (a spreadsheet is convenient for these calculations). Without doing a complete economic analysis, in your judgment which scaled-up pilot run appears to be optimum? (Data from A. E. Karr, W. Gebert, and M. Wang, *Can. J. Chem. Eng.*, vol. 58, p. 249, 1980.)

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