Problem 1

In a heat exchanger which is to used to produce liquid propane by condensation of propane vapor, there is a concern about the role of non-condensible vapors (e.g. N₂ and Ar). In particular, there is concern that non-condensibles will concentrate at the vapor – liquid interface and thereby diminish the partial pressure of the propane. The general situation is depicted in the figure. It is agreed that this issue will be examined in a section of the exchanger where the condensing flux is expected to be 150 lbₘ / ft² hr. It is assumed that the propane contains only a little nitrogen and that, for the C₃H₈/N₂ system, the Prandtl number and the Schmidt number are equal. The density of the vapor is 0.20 lbₘ / ft³. Furthermore, the heat transfer coefficient from the bulk vapor to the vapor – liquid interface is estimated to be 60 Btu/hr ft² °F. The N₂ concentration in the bulk vapor will be denoted as C₀ and that at the liquid – vapor interface by Cₛ.

a) Estimate the mass transfer coefficient (in ft/hr) for exchange between the bulk vapor and the liquid – vapor interface.

b) Estimate the value of Cₛ/C₀
Problem 2

A wetted wall column is to be used to study the absorption of CO₂ into water. The column is supplied with solute-free water at the top and air containing 5 mole percent CO₂ is supplied at the bottom. The air flow rate is such that the change in gas composition may be neglected. The gas phase resistance to mass transfer is negligible. The situation is as depicted in Sketch A.

The velocity profile in the draining film is given by:

\[ u = \frac{1}{2} \frac{\rho g d^2}{\mu} \left[ 1 - \frac{y^2}{d^2} \right] \]

(See Sketch B)

It has been proposed that the absorption be analyzed by using “penetration” theory and setting

\[ u = \frac{1}{2} \frac{\rho g d^2}{\mu} \text{ for all values of } y \text{ which lie within the penetration depth.} \]

The anticipated range of d is 0.1 mm to 0.3 mm.

A. Is the penetration theory valid for this range of d? Justify.

B. It is permissible to neglect axial diffusion in this problem. Please justify this conclusion.

C. Assuming the penetration theory concept and the above approximation for the velocity profile to be valid, develop an expression for the mass transfer coefficient, as a function of x and other appropriate parameters.

D. What is the CO₂ flux (gm/cm² sec) at x = 10 cm if d = 0.3 mm?

See Sketches A & B next page.
Sketch A

Sketch B

\[ u = \frac{1}{2} \rho \frac{d^2}{\mu} \left[ \frac{y^2}{d} \right] \]

Properties, etc.

\[ \rho_{H_2O} = 1 \text{ gm/cm}^3 \]

\[ v_{H_2O} = 0.01 \text{ cm}^2/\text{sec} \]

\[ g = 980 \text{ cm/sec}^2 \]

\[ D_{CO_2-H_2O} = 2 \times 10^{-4} \text{ cm}^2/\text{sec} \]

\[ 0.1 \text{ mm} < d < 0.3 \text{ mm} \]

CO\text{\textsubscript{2}} solubility = 0.15 gm CO\text{\textsubscript{2}}/100 gm H\text{\textsubscript{2}}O at a CO\text{\textsubscript{2}} partial pressure of 1 atm.
Problem 3

A liquid/liquid extractor is being studied to determine the values of the "film coefficients" which characterize its performance. In the extractor, an aqueous solution forms the continuous phase and toluene drops which are dispersed by agitation constitute the organic phase. The volume ratio of the aqueous and organic phases is 2:1 ($V_{aq}/V_{org} = 2$). It is also known that the interfacial area for transport, $a$, is 20 cm$^2$/cm$^3$ of toluene. Furthermore, a "lumped" analysis may be employed in order to describe the device, i.e., it may be assumed that concentrations are uniform within each phase and all of the resistance to transport is associated with the interface.

Two separate experiments using quite different solutes, X and Y, have been performed in which the solute is dissolved in the aqueous phase and then extracted into the organic phase. In each case, the initial concentration in the aqueous phase was 0.01M.

The results are as follows:

<table>
<thead>
<tr>
<th>Time (seconds)</th>
<th>Concentration of X in organic phase (mol/l)</th>
<th>Concentration of Y in organic phase (mol/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>$3.2 \times 10^{-4}$</td>
<td>$7.9 \times 10^{-5}$</td>
</tr>
<tr>
<td>50</td>
<td>$1.5 \times 10^{-3}$</td>
<td>$3.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>200</td>
<td>$5.3 \times 10^{-3}$</td>
<td>$1.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>1000</td>
<td>$1.4 \times 10^{-2}$</td>
<td>$3.5 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

It is believed that solutes X and Y have identical diffusivities in water. The diffusivities in toluene are different than in water, but still the same for X and Y. However, the partition coefficient for X and Y is quite different. It is defined here as:

$$S_{o/Aq} = \frac{\text{equilibrium concentration in toluene}}{\text{equilibrium concentration in water}}$$

and it is known that $S_{o/Aq} = 8$ for X and $S_{o/Aq} = 0.5$ for Y.

a) What is the overall transport coefficient for solute X based on an overall organic phase driving force? Based on an overall aqueous phase driving force?

b) What is the overall transport coefficient for solute Y based on an overall organic phase driving force? Based on an overall aqueous phase driving force?

c) What are the values of the individual coefficients for the two phases?

d) Does one or the other phase pose a dominant resistance for the transport of solute X? If so, which phase? Repeat for solute Y.

Notes:
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In the above, the individual coefficients are defined by:

\[ N' = h_{m,aq}(C_{aq} - C_{aq,i}) = h_{m,o}(C_{o,i} - C_o) \]

Where "i" refers to the interface
and "o" refers to the organic phase
and "aq" refers to the aqueous phase

Overall coefficients are defined by:

\[ N' = U_{m,o} \left( S_{o/Aq} C_{aq,i} - C_o \right) = U_{m,aq} \left( C_{aq} - \frac{C_o}{S_{o/Aq}} \right) \]

**Problem 4**

A perfume is to be manufactured by using an organic solvent to extract the perfume oil from a filtered aqueous solution of ground-up Chilean roses. The oil is much more soluble in the organic solvent than in the aqueous phase, so this process concentrates the oil in the solvent. It has been proposed that a hollow fiber exchanger be used for this operation. The aqueous solution to be extracted will be pumped through the inside of the hollow fibers, and the solvent will be pumped through the shell side of the exchanger in true countercurrent flow, as shown in the figure. The walls of the hollow fibers are very porous and filled with the solvent; the fiber walls thus essentially behave as a stationary solvent phase. As the water passes through the interior of the fibers, the oil diffuses across the fiber wall and is convected away in the shell side.

The intention is to produce 500 liters/hr of an 8 gm/L solution of oil in the solvent. The initial concentration of the oil in the aqueous phase is 1.0 gm/L, and at least 80% of the perfume oil must be extracted from the water if the process is to be economically feasible. The following exchanger design is under consideration:

- Number of tubes: 900
- Tube length: 500 cm
- Tube ID: 0.2 cm
- Wall thickness: 0.005 cm
- Surface area: \(3.456 \times 10^5\) cm²

\[ \text{aqueous (tube side)} \quad C_{a1} = 1.0 \text{ gm/L} \]
\[ \text{organic (shell-side)} \quad C_{o1} = 8 \text{ gm/L} \]
\[ 500 \text{ L/hr} \]

\[ C_{a2} < 0.2 \text{ gm/L} \]
\[ C_{o2} = 0 \text{ gm/L} \]
a) What must the flow rate of the aqueous phase be to get the minimum desirable separation?

b) What is the value of the overall mass transfer coefficient? Use an organic phase driving force.

c) Does the exchanger have sufficient area for this purpose?

**Data**

\[ S = \frac{c_{\text{organic}}}{c_{\text{a aqueous}}} = 70 \]

\[ h_{m,i} = \text{shell-side mass transfer coefficient (organic phase driving force)} = 0.01 \text{ cm/s.} \]

\[ h_{m,i} = \text{tube-side mass transfer coefficient} = 4 \times 10^{-4} \text{ cm/s.} \]

**Problem 5**

Consider a single spherical ice crystal growing in a stagnant sea of subcooled salt water. The fluid is water at -4°C containing 0.04 gm NaCl/cm³; and all NaCl is excluded from the interior of the growing ice particle.

(a) If the diffusivity of sodium chloride in water were (for the moment) assumed to be infinite, how long would it take for the ice crystal to grow from infinitesimal size to a radius of 0.1 cm? You may assume the temperature field around the ice particle to be quasi-steady.

(b) Demonstrate whether the assumption of quasi-steady behavior is satisfactory.

(c) In truth, the diffusivity of sodium chloride in water is about 1.2 x 10⁻⁵ cm²/sec. Please develop a better estimate of the time for a crystal to grow to a radius of 0.1 cm. You may assume that both the temperature and the concentration fields are quasi-steady. Since salt is totally excluded from the growing crystal, note that the flux of salt at the surface of the crystal is simply \( C_i \frac{dR}{dt} \) where \( C_i \) is the salt concentration at the surface of the crystal and \( R \) is the radius of the sphere. This flux due to rejection must equal the quasi-steady rate at which salt diffuses away.

**Data**

- The freezing point depression is given by: \( \Delta T_{\text{FPD}} = 60 \ C_{\text{NaCl}} \)
  where \( \Delta T_{\text{FPD}} \) is in degrees Kelvin and \( C_{\text{NaCl}} \) is in gms/cm³.

- The heat of fusion for water is about 250J/gm

- The density of water and ice may be assumed equal at the value of 1 gm/cm³.
• Other physical properties of liquid water include the following:

  thermal conductivity  = 5.7 x 10^{-3} \text{ W/cm K}
  kinematic viscosity  = 0.018 \text{ cm}^2/\text{sec}
  thermal diffusivity  = 1.3 x 10^{-3} \text{ cm}^2/\text{sec}
  specific heat  = 4.2 \text{ J/gm K}