Separation Processes, ChE 4M3, 2013

Assignment 5

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Objectives: Understanding liquid-liquid extraction systems, adsorption, and drying.

Question 1 [20]

A stream of acetic acid and water (also called diluent) is being fed in a counter current manner at 1000 kg/hour, in order to extract the acetic acid. The feed composition is 30 wt% acetic acid, and 70 wt% water.

The solvent is 99% pure IPE (isopropyl ether), and contains 1% acetic acid, at an inlet flow of 2500 kg/hour.

We desire the exiting raffinate stream to contain 5 wt% acetic acid.

1. Find the number of equilibrium stages to achieve this separation (show all calculations).
2. Calculate the exiting raffinate flow, and the exiting extract flow rate.

Unfortunately, we don't have the equilibrium data, however, various samples of the 3 species were made, mixed, and when they came to equilibrium they were found to have the following compositions (each row gives the aqueous and organic phase compositions):

Aqueous phase (weight %)			Organic phase (weight %)		
IPE	**Water**	**Acetic acid**	**IPE**	**Water**	**Acetic acid**
1.2	98.1	0.7	99.5	0.5	0
1.5	97.1	1.4	99.0	0.7	0.3
1.6	95.5	2.9	98.5	0.8	0.7
2.0	91.7	6.3	97	1	2
2.5	84.5	13	93	2	5
3	71	26	84	4	12
4	59	37	72	7	21
10	45	45	58	11	31
16	37	47	49	15	36

Feel free to download and use this empty ternary diagram. Electronic submissions that are based on photos are not acceptable, unless the photo is perpendicular to the page, and every detail is clear. If in doubt, submit your assignment in paper form.

Solution

See http://www.youtube.com/watch?v=N7MIH0_ELO0 for the full solution.

Question 2 [11 = 2 + 2 + 2 + 2 + 3]

1. What is the dew point temperature of an air stream containing 15% humidity at 70°C?
2. What is the amount of water carried in 5 kg of this stream?
3. This stream is cooled adiabatically; what is the adiabatic saturation temperature?

4. What is the amount of moisture held now, after this adiabatic cooling?
5. What is the wet-bulb temperature, dew point temperature, and percentage humidity of an air stream at 90°C and containing 100 grams of water per kilogram of dry air?

Solution

Please see assignment 5, from 2012

Question 3 [10 = 6 + 4]

From the final exam, 2012.

An undesirable solute is to be removed from $20\,\text{m}^3$ of liquid by contacting it with a batch of adsorbent. The adsorption of the solute on the adsorbent follows a Langmuir type adsorption isotherm:

$$C_{\text{A,S}} = \frac{1.5C_{\text{A}}}{0.5 + C_{\text{A}}}$$

where C_{A} is measured in kg.m^{-3} and $C_{\text{A,S}}$ is in kg.kg^{-1}. The concentration of the solute in the feed liquid is $0.1\,\text{kg.m}^{-3}$ when it is first charged to the batch reactor.

1. How much adsorbent will be needed to reduce the solute concentration in the liquid to $0.01\,\text{kg.m}^{-3}$? And what mass of solute is loaded onto the adsorbent?
2. Describe an experimental procedure (use bullet points) that will provide the data necessary to fit the two coefficients in the Langmuir isotherm. Note, do not provide details how to numerically calculate the coefficients, only describe the exact procedure to obtain a data table of C_{A} and $C_{\text{A,S}}$ values.

Solution

1. The aim is to calculate S, the mass of adsorbent required, and then mass of solute adsorbed.

   From the explore step we'd come to the conclusion that we are dealing with a batch system, and assuming we are at equilibrium a mass balance over the system will be used, together with the isotherm.

   Solute added = (solute adsorbed onto adsorbent) + (solute remaining in solution)

   - solute remaining in solution = $C_A V = 0.01\,\text{kg.m}^{-3} \times 20\,\text{m}^3 = 0.2$ kg in solution
   - solute added = $0.1\,\text{kg.m}^{-3} \times 20\,\text{m}^3 = 2.0$ kg charged
   - so solute adsorbed/removed = 2.0 - 0.2 = 1.8 kg

   Using the isotherm, the mass of solute adsorbed = 1.8 kg = $SC_{A,S}$, neither of which we know. However, $C_{A,S}$ can be found from the isotherm, and is $C_{A,S} = 0.0294\,\text{kg.kg}^{-1}$.

   From which we calculate $S = 61.2$ kg of adsorbent is required.

2.
   - Fill small beakers with solute/solvent mixture at a fixed volume
   - Each beaker then contains the same amount (grams) of starting solute
   - Add increasing amounts of adsorbent to each beaker (increase amount of grams)
   - Mix and allow beakers to reach equilibrium
   - Measure the remaining solute in solution (e.g. UV-VIS, or some other analytical method)

- Calculate, by difference, the amount of solute adsorbed
- $C_{A,S}$ = (mass solute adsorbed) / (mass adsorbent), both quantities which are known now
- C_A = solute concentration remaining in solution

Question 4 [24 = 2 + 2 + 4 + 10 + 4 + 2]

From the final exam, 2012.

A cylindrically-shaped food product (e.g. snack food, or pet food) that is 0.5cm in diameter and 2cm in length according to the product requirements, is extruded with a moisture content of 35% on a dry basis. These extruded pellets are to be dried to 8% dry basis to obtain the correct level of consistency for flowability and long-term storage, another product requirement. Drying air is available from an facility at your site, and is rated at 30% humidity and 70°C; this is provided at a velocity of $3\,\text{m.s}^{-1}$ in the batch drier. The mass of moist material is 150 kg, and corresponds to about 50,000 pellets per tray.

Heat transfer coefficients for drying are estimated from correlations. For a packed bed, a correlation by Gamson, Thodos and Hougen in *AIChE Journal*, **39**, p $1 - 35$, 1943 where:

- h is the heat transfer coefficient, in $[\text{W.m}^{-2}.\text{K}^{-1}]$
- G is the mass flux of air, in $[\text{kg.hr}^{-1}.\text{m}^{-2}]$
- d_p is the particle size diameter [m], for spherical particles, are then used in the following equation:

$$h = 0.151\frac{G^{0.59}}{d_p^{0.41}}$$

1. Explain why food products often require a specific level of dryness.
2. Since these particles are not spherical, *justify* a suitable equivalent-particle diameter to use as d_p in the above heat transfer correlation.
3. Now *calculate* this equivalent-particle diameter.
4. Calculate the drying time required *in minutes*. State any assumptions made.

   Note: for packed beds, it is common practice to use only 50% of the external air stream velocity as the effective velocity within the packed bed.
5. This correlation requires the packed bed Reynolds number, $N_{\text{Re}} = \dfrac{d_p G}{\mu} > 350$, where the air's viscosity is approximately $2 \times 10^{-5}\,\text{kg.m}^{-1}.\text{s}^{-1}$. Is this condition met? Note that G must be expressed in SI units for calculating the Reynolds number.
6. Describe a parameter you could adjust on the drier to decrease the drying time, and why your change would work. You can consider minor capital expenditure to implement this change.

Solution

Not a full solution: see the notes for important assumptions and details.

1. To maintain a specific level of moisture for desired organoleptic properties; prevents bacterial formation; reduces shipping costs; dry solids can be processed more readily; *etc*

2. A suitable equivalent particle diameter is one that is relevant to the problem. Here it is heat transfer to the surface and mass flux away from it. Everything is occurring at the particle's surface. So the equivalent sphere of the same area as the particle is required.

3. - Area of a sphere = $4\pi r_p^2 = \pi d_p^2$
   - Area of particle = front + back + length = $\pi r^2 + \pi r^2 + 2\pi r h = \pi(0.0025)^2 + \pi(0.0025)^2 + 2\pi(0.0025)(0.02) = 0.000353\,\text{m}^2$
   - Equate these, and solve for $d_p = \sqrt{\dfrac{0.000353}{\pi}} = 0.0106\,\text{m}$, or approximately equivalent to a sphere with diameter of 1.06 cm, which seems reasonable.

4. Some important assumptions are made (see the notes) and calculations to get to a point where:
   - $G = 4879\,\text{kg.hr}^{-1}.\text{m}^{-2}$
   - $h = 146.1\,\text{W.m}^{-2}.\text{K}^{-1}$
   - $A = 50000 \times 000353 = 17.65\,\text{m}^2$

   $$\frac{(\Delta M_W)(\Delta H_{\text{vap}})}{(h)(A)(T_{\text{db}} - T_{\text{wb}})} = \frac{(30)(2376 \times 1000)}{(146.1)(17.65)(18)} = 1535\,\text{seconds}$$

   or 25.6 minutes.

5. Here $G = 4879\,\text{kg.hr}^{-1}.\text{m}^{-2} = 1.355\,\text{kg.s}^{-1}.\text{m}^{-2}$, so then $N_{\text{Re}} = \dfrac{0.106 \times 1.355}{2 \times 10^{-5}} = 7181 > 350$.

6. Increase the velocity of the incoming air (i.e. increase G), which increases h, which decreases drying time.

   Cannot increase the area A.

   You likely cannot increase the dry bulb to wet-bulb temperature difference, because it is utility stream (you just accept the drying air you are given), but if you could change it, it will also decrease drying time.

END