Separation Processes, ChE 4M3, 2014

Assignment 5

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Objectives: We have been doing non-stop examples and problems in class. This assignment gives you a chance now to try some more problems related to liquid-liquid extraction, adsorption and drying; without my help and guidance.

All these questions are from prior exams and tests.

Question 1

The isotherm for benzene, at 25°C, on an activated carbon adsorbent is given as:

$$C_{A,S} = 32 C_A^{0.428}$$

where $C_{A,S}$ is in units of mg benzene per gram of carbon, and C_A is in units of mg benzene per litre of water-based solution.

You want to create your own adsorber packed bed from a piece of piping that has diameter of 24.5 cm.

The activated carbon supplier has given you the following specification sheet (and the isotherm information above):

- activated carbon mean diameter = 2 mm

- activated carbon size distribution range 0.4 mm to 3.8 mm

- activated carbon bulk density = 410 g/L

- activated carbon particle density = 520 g/L

- cost of activated carbon is $5.50 per kilogram.

You would like a breakthrough time of 4 hours when treating a feed stream containing 2.8 g of benzene per litre. You have to treat 30 L per minute of waste water.

1. What type of adsorption isotherm is this? **[1]**

2. How long should your packed bed be? Be clear with any simplifying assumptions you make. **[14]**

    Use the rule of thumb that if you cannot perform a lab experiment to calculate the MTZ, that your MTZ is 4ft, and assuming a symmetric wavefront, that the LUB = 2 × MTZ.

3. What will be the cost of the adsorbent you need to purchase? **[3]**

Question 1 - *thanks to Helen*

1. Based on the equation $C_{A,s} = 32C_A^{0.428}$, the following isotherm can be determined:
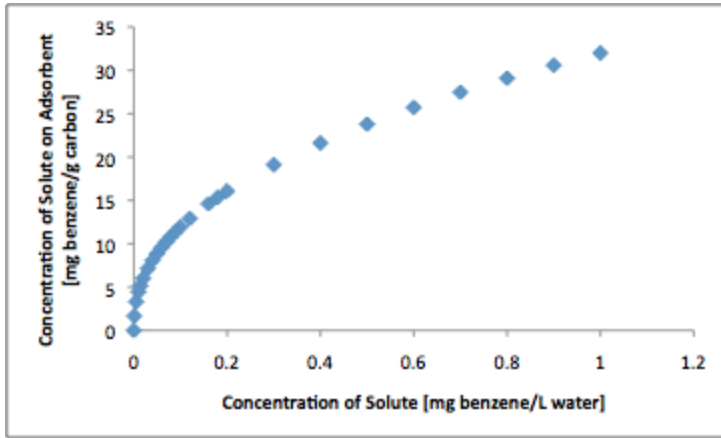
Since the curve tends to increase, but doesn't seem to reach or head towards a plateau, this isotherm would be Freundlich in nature.

2. T = 25 °C = 298 K   Solute = Benzene   Adsorbent = Activated Carbon
   $C_{A,s} = 32C_A^{0.428}$ $D_{pipe} = 0.245$ m $\theta_b = 4$ hours = 14,400 s
   $C_{A,F} = 2.8$ g benzene/L $Q_F = 30$ L/min = 0.5 L/s $\varrho_B = 410$ g C/L

Since no data is available, a mass transfer zone (MTZ) of 4 ft or 1.2192 m will be used.
Also assuming that the LUB = 2MTZ, the length of unused bed will be 2.4384 m.
L_{total} = LUB + LES
To determine the total length of the bed, the length of the bed that is used must first be found.

$$Q_F C_{A,F} \theta_b = C_{A,S}^e \rho_B A L_{LES}$$
$$C_{A,S}^e = 32C_{A,F}^{0.428} = 32(2800)^{0.428} = 956.1667 \; mg \; benzene/g \; carbon$$

*Note: At equilibrium, the concentration of solute is equal to the concentration of solute in the feed stream.

$$A = \pi R^2 = \pi\left(\frac{D_{pipe}}{2}\right)^2 = \pi\left(\frac{0.245}{2}\right)^2 = 0.047144 \; m^2$$

$$(0.5 \; L/s)\left(2800\tfrac{mg \; benzene}{L}\right)(14,400 \; s) = \left(956.1667\tfrac{mg \; benzene}{g \; carbon}\right)\left(410\tfrac{g \; carbon}{L}\right)(0.047144 \; m^2)(LES \; m)\left(\tfrac{1000 \; L}{1 \; m^3}\right)$$

$$LES = 1.09 \; m$$

L_{total} = LUB + LES = 2.44 + 1.09 = 3.53 m
Therefore, the adsorption bed will have a total length of about 3.53 m.

3. Cost = $5.50/kg C

$$V_C = A(LUB + LES) = 0.047144 \; m^2 (3.53 \; m)\left(\tfrac{1000 \; L}{1 \; m^3}\right) = 166.3 \; L$$
$$m_C = \rho_b V_c = \left(410\tfrac{g \; C}{L}\right)(166.3 \; L) = 68,183 \; g \; C$$
$$Cost = (\$5.50/kg \; C)m_C = (\$5.50/kg)(68,183 \; g \; C)\left(\tfrac{1 \; kg \; C}{1000 \; g \; C}\right) = \$375$$

Therefore, the activated carbon required to fill the entire length of the adsorption vessel will cost about $375.

Question 2

A filter cake from a plate-and-frame press is to be dried by circulating warm, dry air over the solids. See this photo for a visual idea of what the material looks like. Trays are loaded with the solid, which is 3 cm high and an area of 2.0 m^2 per tray. Each tray contains 80 kg of wet filter cake, and the filtration press step leaves the solids with approximately 30 wt% moisture on a dry basis.

Air at 1 atmosphere, 70°C, and a relative humidity of 10% is used, at an approximate velocity of 4.2m.s^{-1}, in a direction that flows parallel to the solids.

1. Estimate the mass of water that would be evaporated from the cake after 4 hours. Be clear on all assumptions you make as you proceed. **[12]**

2. What is the moisture content of the cake after 4 hours, expressed on a dry basis? **[2]**

3. Name one method we can implement to reduce the drying time. **[1]**

Solution

Your answer should be more complete than these few bullet-points of essential values.

- $v_H = 1.0165\,\text{m}^3.(\text{kg moist air})$

- $T_{\text{wb}} = 37.5C$

- $\Delta H_{\text{vap}} = 2410\,\text{kJ.kg}^{-1}$

- $G = 14875\,\text{kg.hr}^{-1}.\text{m}^{-2}$

- $h = 44.4\,\text{W.m}^{-2}.\text{K}^{-1}$

- Mass of water evaporated = 17.25 kg water

- Water in each tray at the start = 18.46 kg (the rest is solids)

- so the dry basis moisture is about $2\% = \dfrac{18.46 - 17.25}{61.53}$.

- We can increase the velocity or increase the surface area to reduce the drying time.

Question 3

$140\,\text{kg.hr}^{-1}$ of a 40% acetone-in-water mixture are to be separated using trichloroethane as solvent.

1. Draw a flow diagram that illustrates the cross-current streams, having only 2 cross-current stages.

2. Draw a general flow diagram that illustrates the counter-current system, with two stages on one end, and two stages on the other end, and a general "Nth" stage in the middle.

3. If $80\,\text{kg.hr}^{-1}$ of pure solvent is fed into the first cross-current stage and $60\,\text{kg.hr}^{-1}$ into the second cross-current stage, what will be the acetone purity leaving in the raffinate from stage 1 and stage 2? Show all constructions and calculations on the ternary diagram (next page). Make sure all lines are clearly visible. *Hint*: you should achieve an acetone concentration in the raffinate of about 11%. **[8]**

4. What is the overall acetone recovery from such a 2-stage cross-current system? **[3]**

5. Now use a clean copy of the drawing (i.e. your assignment submission should have two ternary diagrams). In this second diagram start the construction for the counter-current system. The objective

is to achieve the same (or better) raffinate concentration in terms of acetone as the cross-current system, but using $40\,\mathrm{kg.hr}^{-1}$ of pure solvent.

With a few basic lines on the drawing you should be able to find the values for these cross-current system:

(a) the expected raffinate flow rate;

(b) the expected extract flow rate;

(c) the expected extract composition.

6. Now locate the operating point, P, and use this to calculate the number of stages required. Submit your ternary diagram showing these calculations.

7. Assume that the last stage is at the point you selected in part 5 of this problem (i.e. that it was at that desired 11% level for acetone). Calculate the recovery of acetone for the counter-current system.

8. Now compare **and contrast** the following parameters for the two configurations:

- the extract concentration (for the cross-current system this is the blended concentrations of E_1 and E_2)

- the extract flow rate

- the recovery

- the solvent use compared

- *for extra credit*: the capital and operating costs compared between the two systems.

Acetone

Trichloroethane
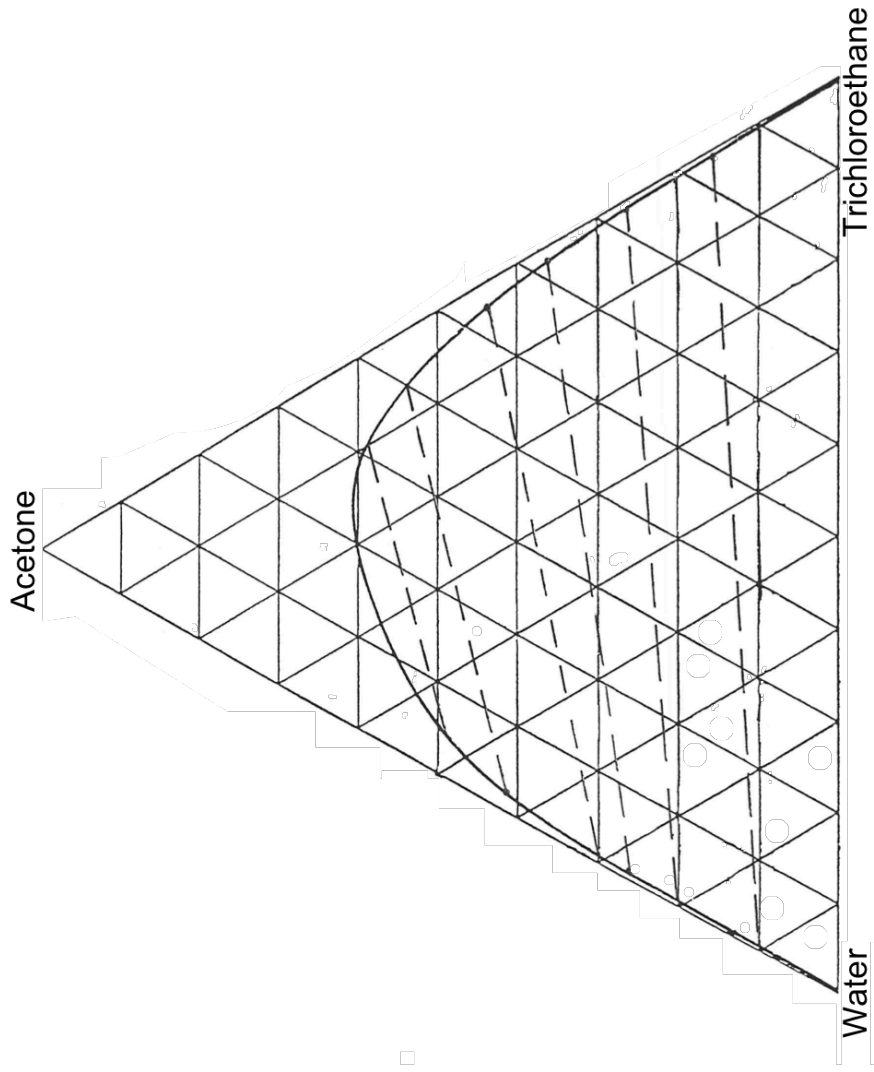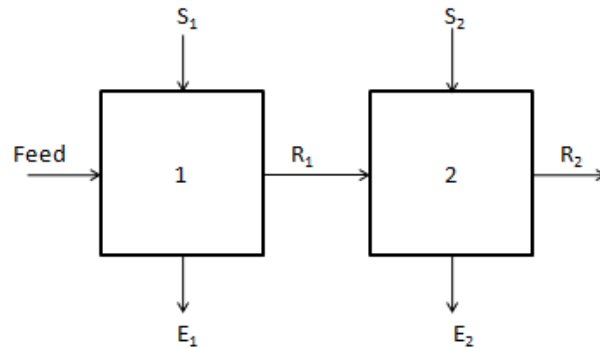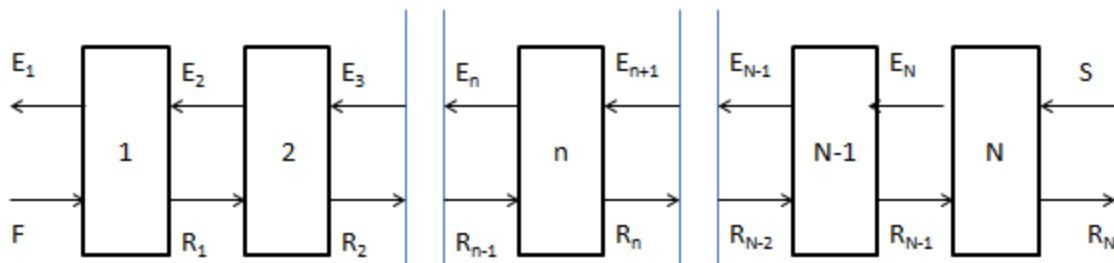
Water

Feel free to use this page for calculations as well

Question 3 - *thanks to Robin*

1. Cross-current system:

2. Countercurrent system:

3. solute = acetone; carrier = water; solvent = trichloroethane
   $F = 140$ kg/h, $x_{F,A} = 40\%$, $x_{F,C} = 60\%$
   $S_1 = 80$ kg/h, $S_2 = 60$ kg/h

For the first cross-current stage: (denoted in blue on the ternary diagram)
   overall balance: $F + S_1 = 140 + 80 = 220$ kg/h $= M$
   balance on acetone: $F x_{F,A} + S_1 x_{S,A} = x_{M,A}M$
   $\qquad\qquad (140)(0.4) + 0 = x_{M,A} (220) \rightarrow x_{M,A} = 0.255$
   balance on solvent: $F x_{F,S} + S_1 x_{S,S} = x_{M,S}M$
   $\qquad\qquad 0 + (80)(1) = x_{M,S} (220) \rightarrow x_{M,S} = 0.363$
   by composition balance: $x_{M,C} = 0.382$

   Reading off the ternary diagram,
   $\qquad$ **$x_{R1,A} = 0.23$** $\qquad\qquad$ **$x_{E1,A} = 0.27$**
   $\qquad$ $x_{R1,C} = 0.75$ $\qquad\qquad$ $x_{E1,C} = 0.01$
   $\qquad$ $x_{R1,S} = 0.02$ $\qquad\qquad$ $x_{E1,S} = 0.72$

   $x_{M,A}M = x_{R1,A}R1 + x_{E1,A}E1 \rightarrow (0.225)(220) = (0.23)R1 + (0.27)E1$
   $\qquad$ and R1 = 220 - E1
   solve to find, **E1 = 135 kg/h** and **R1 = 85 kg/h**
Therefore, the acetone purity in the raffinate from the first stage is 23%.

For the second cross-current stage: (denoted in red on the ternary diagram)

overall balance: $R1 + S2 = 85 + 60 = 145$ kg/h $= M2$

balance on acetone: $R1\, x_{R1,A} + S_2\, x_{S2,A} = x_{M2,A} M2$
$$(85)(0.23) + 0 = x_{M,A}\,(145) \rightarrow x_{M2,A} = 0.135$$

balance on solvent: $R1\, x_{R1,S} + S_2\, x_{S,S} = x_{M2,S}\, M2$
$$(85)(0.02) + (60)(1) = x_{M,S}\,(145) \rightarrow x_{M2,S} = 0.425$$

by composition balance: $x_{M,C} = 0.44$

Reading off the ternary diagram,

$x_{R2,A} = 0.11$ **$x_{E2,A} = 0.17$**
$x_{R2,C} = 0.88$ $x_{E2,C} = 0.82$
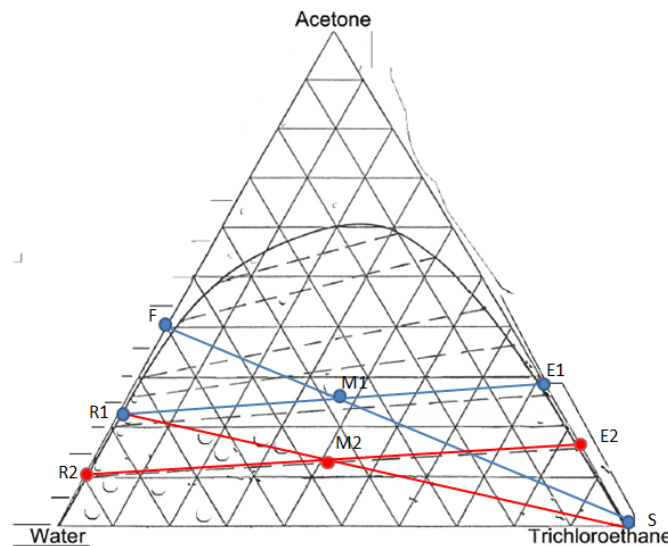$x_{R2,S} = 0.01$ $x_{E2,S} = 0.01$

$x_{M,A} M = x_{R1,A} R1 + x_{E1,A} E1 \rightarrow (0.225)(220) = (0.23)R1 + (0.27)E1$
and $R1 = 220 - E1$
solve to find, $E1 = 135$ kg/h and $R1 = 85$ kg/h

Therefore, the acetone purity in the raffinate from stage 2 is 11%

Acetone

E1

M1

R1

M2

E2

R2

S

Water   Trichloroethane

4. $Cross-current\ overall\ recovery = 1 - \frac{x_{RN}R_N}{x_F F} = 1 - \frac{0.11(82)}{0.4(140)} = 83.9\%$

5. $F = 140$ kg/h, $x_{F,A} = 40\%$, $x_{F,C} = 60\%$
$S = 40$ kg/h

overall balance: $F + S = M = R_N + E_1 =$
$140 + 40 = 180$ kg/h $= M$
acetone balance: $x_{M,A} M = x_{F,A} F + x_{S,A} S = (0.4)(140) + (0)(40) \rightarrow x_{M,A} = 0.311$
water balance: $x_{M,C} M = x_{F,C} F + x_{S,C} S = (0.6)(140) + (0)(40) \rightarrow x_{M,C} = 0.467$
and $x_{M,S} = 0.222$

achieving same/better raffinate concentration:
$x_{RN,A} = 0.11$, $x_{RN,C} = 0.88$, $x_{RN,S} = 0.01$

a. R_N = ?

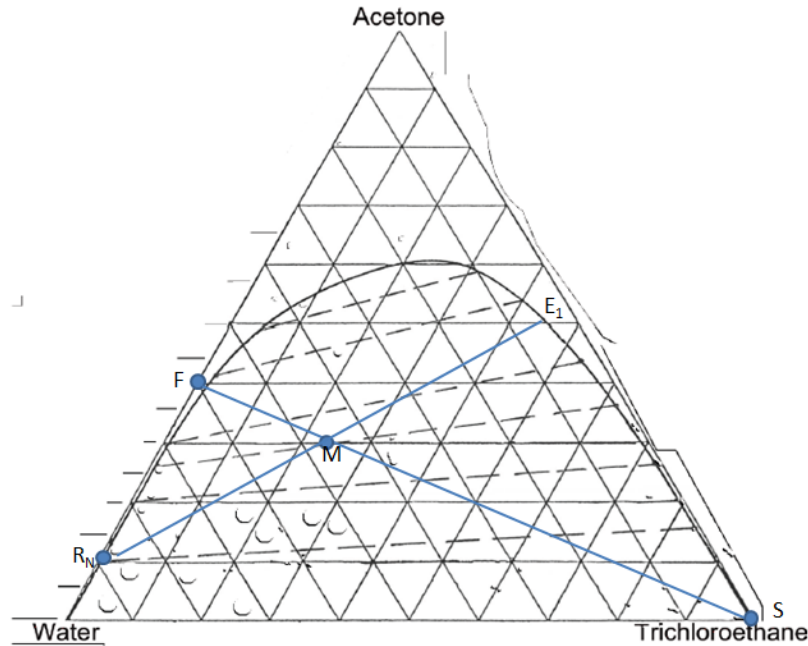lever rule: $\frac{mass\ R_N}{mass\ M} = \frac{length\ E_1 M}{length\ E_1 R_N}$
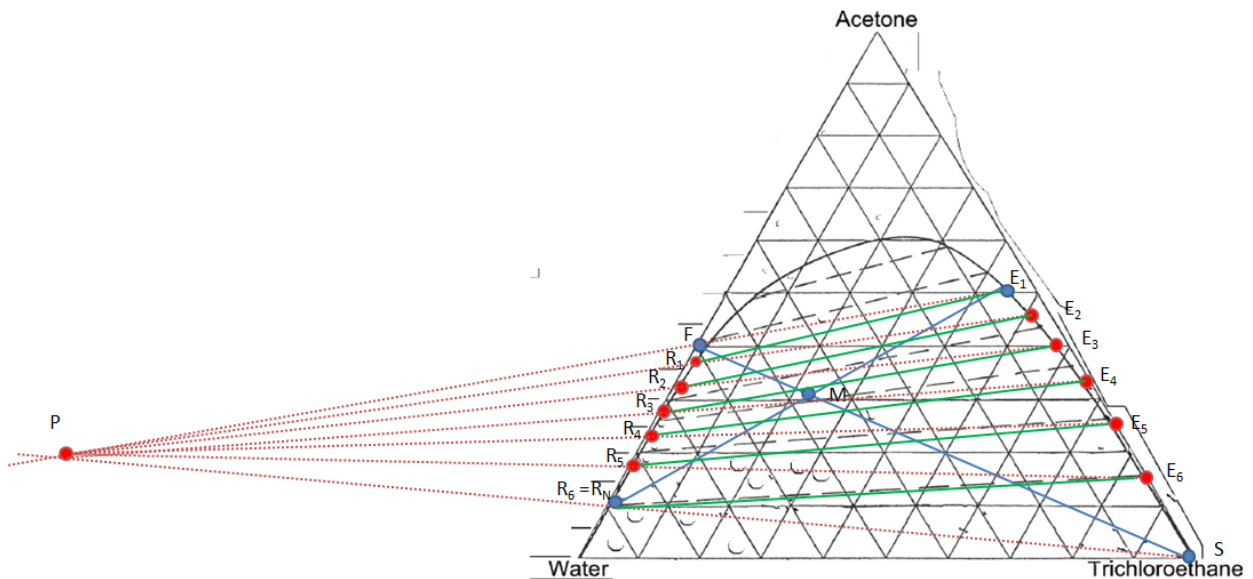
$mass\ R_N = 180\ kg/h\ (\frac{41\ mm}{84\ mm}) = 87.9\ kg/h$

b. $E_1 = M - R_N = 180 - 87.9$ kg/h = 92.1 kg/h

c. reading from the ternary diagram:
$x_{E1,A} = 0.51$, $x_{E1,C} = 0.05$, $x_{E1,S} = 0.44$

6. From the following ternary diagram, it is determined that 6 stages are required for the acetone composition in raffinate stream to be 11%

7. *Counter current recovery* $= 1 - \frac{x_{RN}R_N}{x_F F} = 1 - \frac{0.11(87.9)}{0.4(140)} = 82.7\%$

8. Comparing the two systems:

	Cross-current	Countercurrent
Extract concentration	$\frac{135(0.27)+63(0.17)}{135+63}$ = 23.8%	51%
Extract flow rate	135+63 = 198 kg/h	92.1 kg/h
Recovery	83.9%	82.7%
Solvent Use	80+60 = 140 kg/h	40 kg/h

The recovery for the two systems are similar, however the countercurrent system requires considerable less solvent use than the cross-current system. In addition, the countercurrent system has a higher extract concentration, which may be favourable for downstream applications.

Question 4 [0]

For practice.

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.

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