## PROCESS ENGINEERING AND DESIGN

1. Outline processes for manufacturing (a) HCl, (b) hydrogen, (c) acetic acid, (d) ammonia (e) sulfuric acid, (f) nitric acid, (g) HF, (h) NaOH, (i) chlorine, (j) methanol, (k) phosphoric acid, (l) EO, (m) PE, (n) HCN, (o) sulfur (p) formaldehyde, (q) ethanol, (r) acetone, (s) benzene, (t) phenol, (u) vinyl chloride (v) styrene, (w) urea.

2. Why is distillation done at high pressure?

3. If you have an HCl gas stream and an $N_2$ stream how do you dispose of them?

4. Which has larger diameter, the suction or discharge on a pump?

5. Sketch typical temperature and composition profiles in a distillation column.

6. How would you remove 1% phenol from water?

7. How would you control a distillation column?

8. How is syn gas made from coal?

9. How would you go about estimating the cost of a distillation column, pump or heat exchanger?

10. Suggest several methods for obtaining fresh water from sea water. Which would you use?

11. What is bleach? How is it made?

12. Outline a method for separating two organic compounds with similar boiling and melting points.

13. How would you obtain pure oxygen from air?

14. Living in Phoenix, Arizona where the temperature is 100F, how would you cool a room using 120F water?

15. Consider an exothermic, zeroth order reaction in a CSTR. What happens if there is a step change increase in the feed temperature?

16. Sketch and describe a multi-effect evaporator. How does the pressure vary through the system?

17. How would you separate ethanol and water?

18. How does an ice skate work?

19. Increasing the heat to the boiler of a steamboat caused the boat to slow down. Why?

20. Consider two pressurized vessels connected in series with recycle. If the recycle is cut off, how will the pressure in each vessel vary with time?

21. How would you remove water vapor from Ar gas to a level of 1ppb (volume%) if

the water is initially present at a level of 200ppb? desiccant, $H_2O$ absorber

22. What is the lowest temperature water can be cooled to in a cooling tower? Dew pt.

23. Several years ago there was a report of a boiler explosion in a church. When interviewed the janitor explained that he lit the gas flame in the boiler. After a time he noticed the pressure gauge readings were too high. He immediately extinguished the burners. Five minutes later the boiler blew up. Why?

24. Given the pressure drop, L and D for a pipe, how would you find the velocity?

25. What is the reflux ratio and a pinch point?

26. Diagram an HCl or $SO_2$ absorber. p-448 Hen

27. How do you make pure $N_2$ from air without cryogenic techniques? Hen

28. Know how to establish a scheme to separate a multicomponent system of liquids. — boiling point

29. Consider two pressurized vessels connected in series. If the downstream vessel suddenly develops a large leak what happens to the flowrate in the pipe connecting the two vessels? Sketch a flow vs. time curve.
— large $\Delta P$ = flowrate increase

30. How does a heat pump work in winter? How is it different in the summer?

31. What temperature and pressure are used in the synthesis of ammonia? Is the reaction reversible? exothermic? (why?). To carry it out economically what must you know about the reaction? How do you get $K_{eq}$ without experimental data? How does $K_{eq}$ depend on T?

32. Give expressions for:
a. reversible heat in an electrochemical cell
b. irreversible heat in an electrochemical cell
b. net work in an electrochemical cell

33. You have a continuous distillation set-up. What can you do to save energy (i.e. reduce heat duty at the reboiler).

34. You want to extract mechanical energy from geothermal steam which contains 1 % incondensible gases $CO_2$, $H_2S$, $NH_3$. What exit T, P would you choose? Would you get rid of the incondensibles? How?

35. Derive the Fenske equation. Distillation

36. What is the procedure for designing a multicomponent distillation column?

37. Outline the principles underlying pressure swing absorption. When would you use it?

38. Give a method for manufacturing acetylene, starting from inorganic compounds only. 430-431 Hen

39. How would you separate a single temperature sensitive component (e.g. a protein) from a stream containing a multicomponent mixture of similar sized molecules?

40. Where does bromine come from, e.g. that used in bromo-seltzer? 467-68

41. Why is there so much concern about high and low frequency outage to the electrical power of compressors feeding gas into tanks?

41
422
6.3

# PROCESS DESIGN

② Why is distillation done at high P?

Advantages ~ Why?

1. Decrease diameter of column because vapor volume ↓
2. ↑ P so that refrigeration might not have to be used for distillate whose condensing temp. is lower than cooling water (~ 90°F)

Disadvantages

1. High column cost since high P materials.
2. " condenser and reboiler costs also because high P materials.
3. Lowers relative volatility ⇒ harder to separate components.

Main reason why high P is used is for compounds whose condensing temp. is too low to use cooling water. Since refrigeration (w/ liq. $NH_3$ usually) is very expensive, ↑ P will let distillate condense at higher temp.

Aside: vacuum distillation.

Opposite reason as above. If evaporation temp. is too high for bottoms so that high P steam is expensive, maybe more economical to ↓ P. This will allow bottoms to evaporate at lower T.

Generally don't use vacuum because:

1. ↓ P will ↑ diameter of column
2. Special material to build column
3. Harder to condense overhead

③ How do you dispose of an HCl gas and $N_2$ gas stream?

Maybe we can absorb HCl(g) into $H_2O$ and sell as HCl(aq)

Simply vent $N_2$ to atmosphere. Or can react it with $H_2$(g) in Haber process:

$$N_2 + 3H_2 \longrightarrow 2NH_3$$

④ Which has a larger diameter, the suction or discharge of pump?

First of all, pumps generally do two things: increase velocity or pressure.

Continuity: $-[\nabla \cdot \rho \underline{v}] = \frac{\partial \rho}{\partial t}$ $\qquad \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0$

$A_1 \langle v_1 \rangle \cancel{\rho_1} = A_2 \langle v_2 \rangle \cancel{\rho_2}$ $\qquad \rho = \text{const.}$

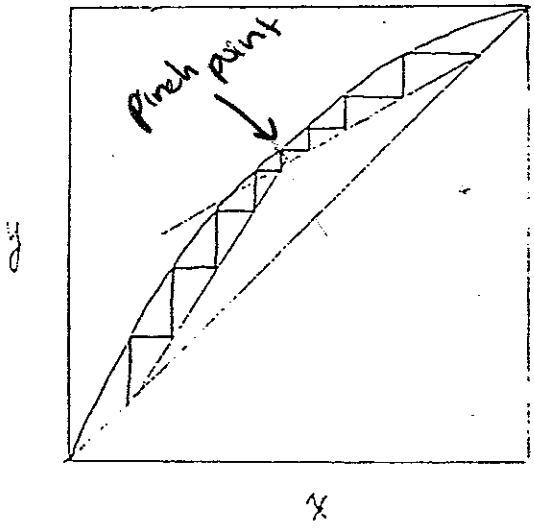
If $\langle v_2 \rangle > \langle v_1 \rangle$:

Then $A_1 > A_2 \Rightarrow$ suction larger

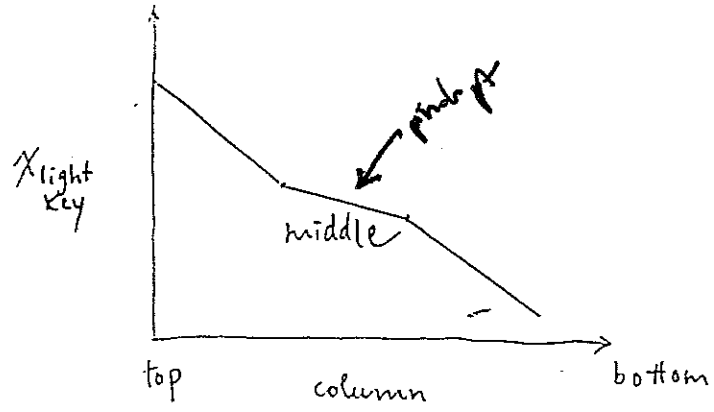
If $P_2 > P_1$, but $\langle v_1 \rangle = \langle v_2 \rangle$ :

Then, suction D = discharge D

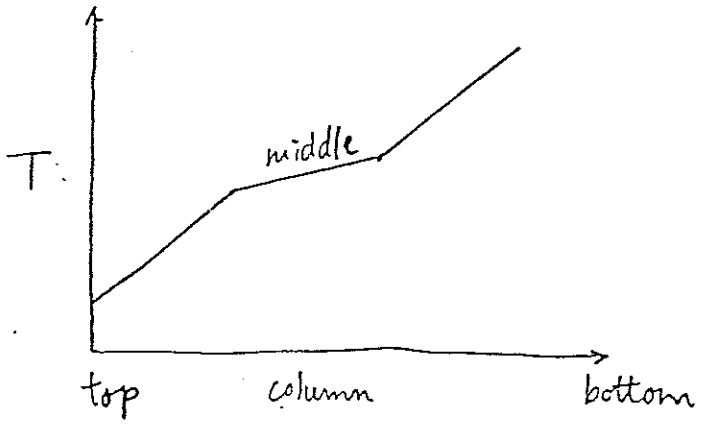
⑤ Sketch typical temp. and composition profiles in distillation columns.



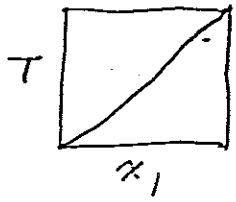

Note also = pinch pts. can also be approached if we want very pure products. The pinch pt. approached in the middle is due to $R \rightarrow R_{min}$. (probably to save $ in column cost and energy)




Composition changes fastest at top and bottom of column because steps there cover more ground. This is due to larger driving forces.




T also changes fastest near top and bottom of column because T is a function of comp. and vice versa:




⑥ How would you remove 1% phenol from water?

- don't use distillation because conc. too low to be profitable
- liquid-liquid extraction with something like ethanol
- ~~maybe add surfactant~~
- membrane separation

Why ethanol?

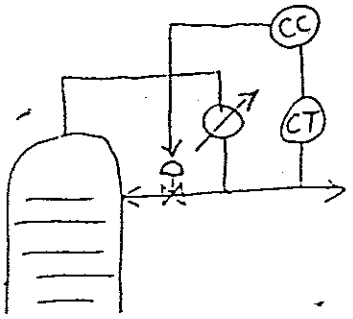
⑦ How would you control distillation column?

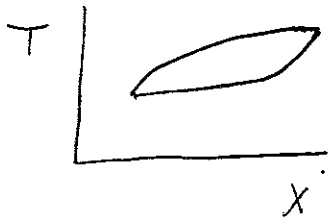
Disturbances : $x_{feed}$, $F_{feed}$

Output : $x_D$, $x_B$

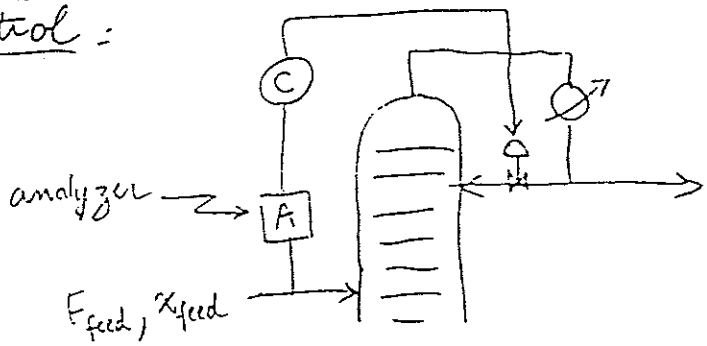
Manipulated variable : $R = \frac{L}{D}$

Feedback control :

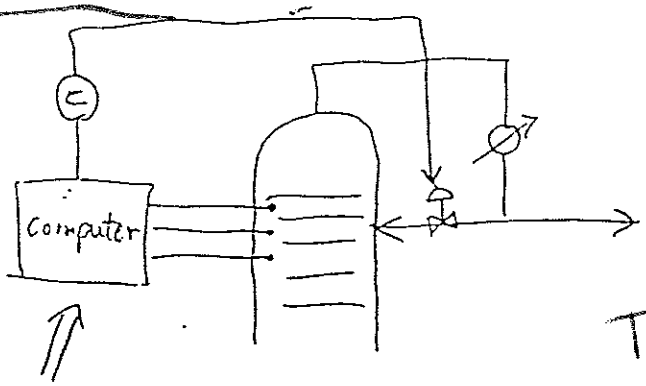



Feed forward control :



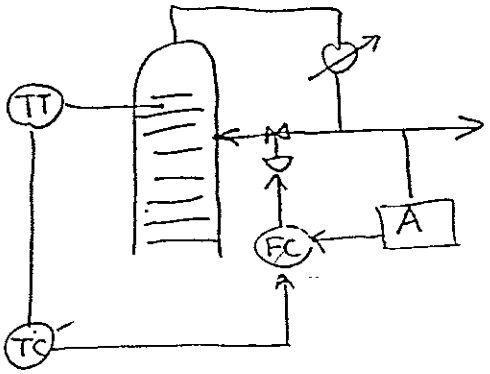

More complex control :




T vs. X data

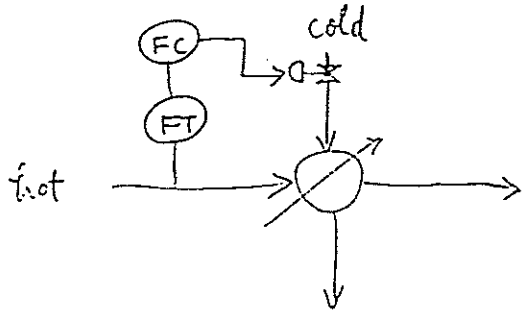
temp. used with T vs. composition data to calculate composition

## Cascade control :

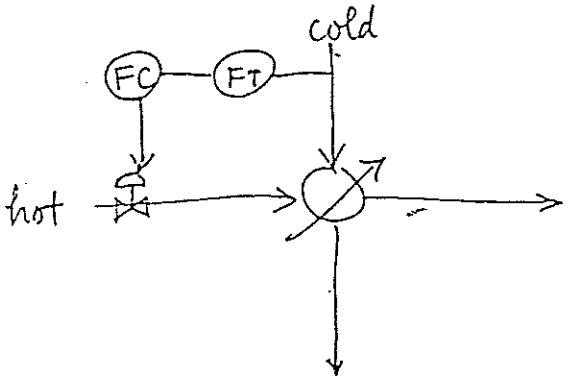



temp control
+
composition
control

## Control heat exchangers (condenser & reboiler) :




Condenser



HX

$\dot{Q}$, A

U given material

⑨ How would you go about estimating the cost of a distillation column, pump or heat exchanger?

## Distillation column

minimize entrainment
- bubble cap
- sieve

### Preliminary calcs:

- Find diam., height, # of trays, types of trays. To do this, need to know amount of vapor and liquid flowrate.
- Find pressure of column.
- Find heat load and condenser cooling load.

### Pricing

- Price column under pressure vessels according to diameter & length. Also material of column.
- Price trays according to type (bubble cap, sieve) and number. Also material of trays.
- Price condenser and reboiler according to surface area (from heat & cooling load). Material too.
- Utility from heating steam and cooling water.

## Pumps

Pricing according to $\Delta P$ and $Q$. Also types of pumps.

?

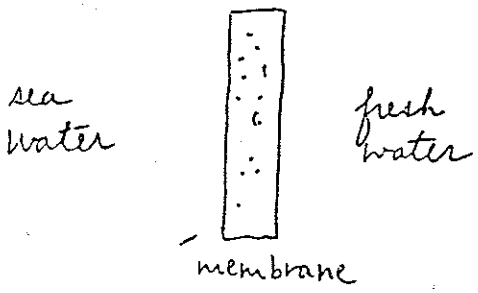
(Q = flow rate)

$$\text{Power} = \frac{\Delta P Q}{\eta}$$

$\eta$ = efficiency

(10) Suggest several methods for obtaining fresh water from sea water. Which would you use?

(a) Reverse osmosis

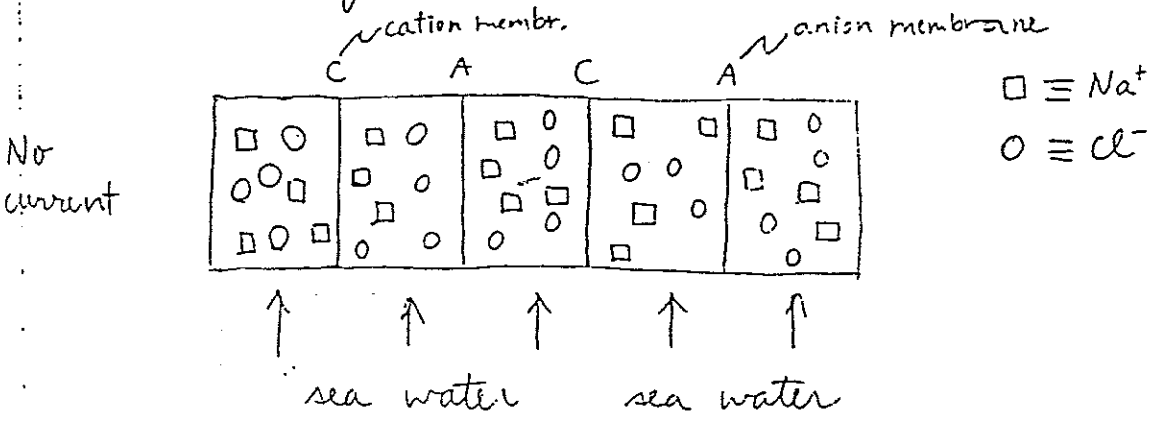



Apply $\Delta P$ so that it is larger than osmotic pressure to drive $H_2O$ to the right. Salt cannot pass the membrane. High initial costs.

(b) Evaporation / flash

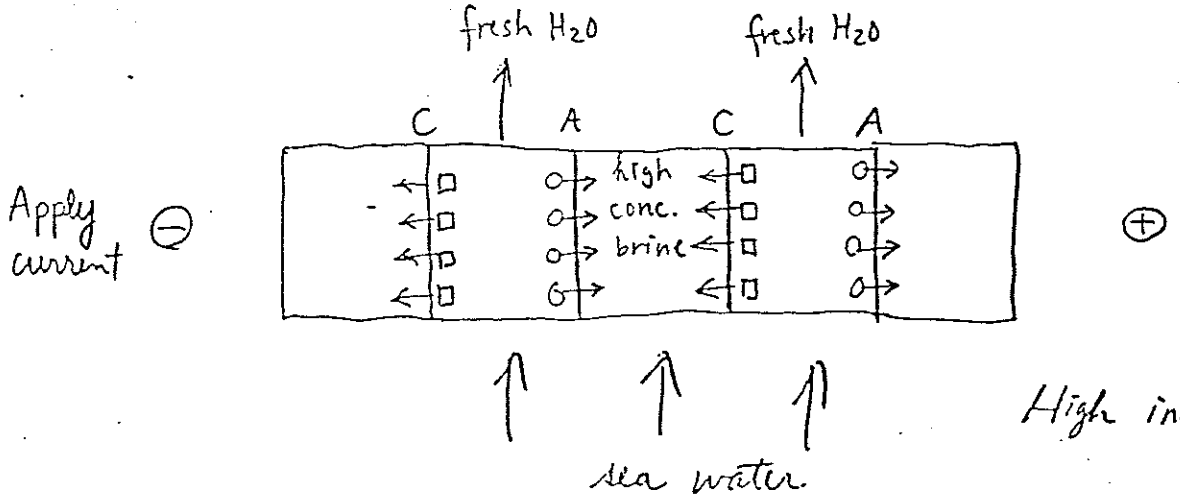
Take advantage of volatility differences. Too costly because of energy demands

(c) Electrodialysis : use cation & anion membranes




cation membr : lets only cations through

anion " : " " anions "




High initial costs.

Not sure which to use; probably reverse osmosis since it seems easiest.

Cl2
O2

(11) What is bleach? How is it made?

Active ingredient is sodium hypochlorite NaClO; In household bleach, it's ~ 5% NaClO.

$$2\,NaOH(aq) + Cl_2(g) \longrightarrow NaClO + H_2O + NaCl$$

(12) Outline a method for separating two organic compounds with similar boiling and melting points.

Since bp and mp are similar, simple distillation and crystallization are no good.

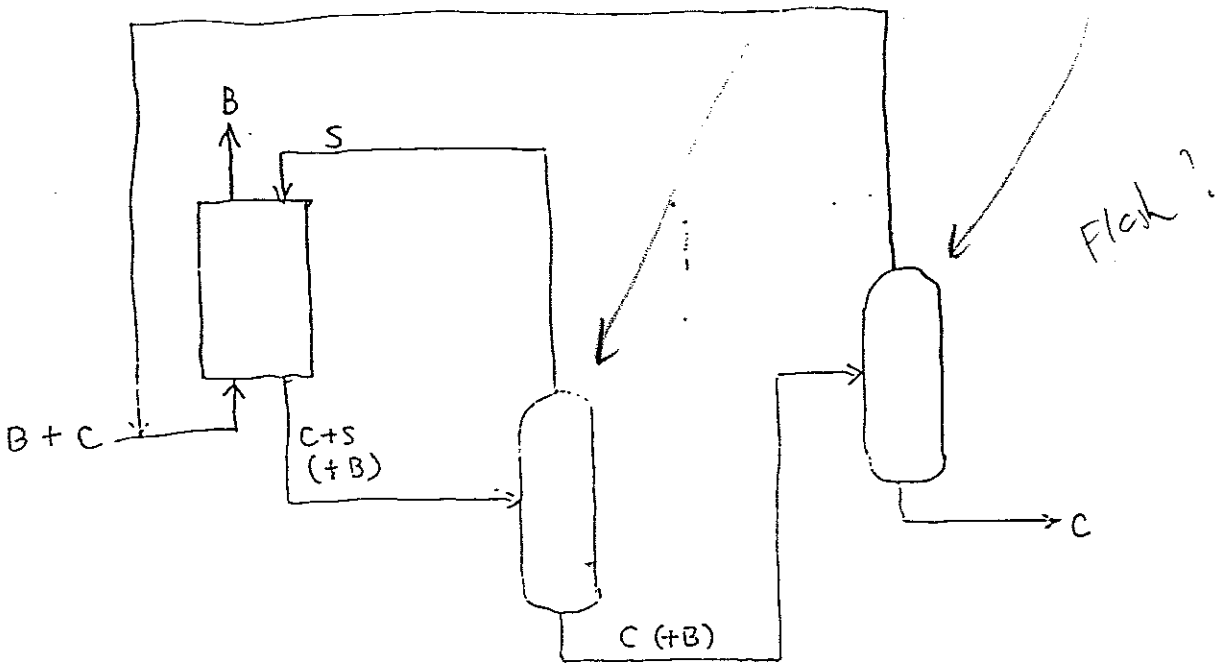
(a) Liquid/liquid extraction: This requires a solvent that is selective towards one of the solvents, preferably the one of lesser conc. Some distillation still required, but doesn't have to separate as much.

(b) Extractive distillation: Add a heavy solvent that changes VLE for the two organics so that one of the organics comes out nearly-pure from distillate.

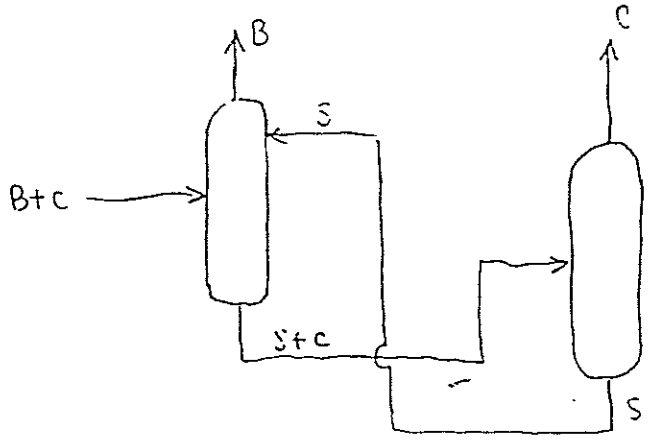
(c) Reactive distillation: Add a third compound that reacts with one component in the mixture.

Operation:

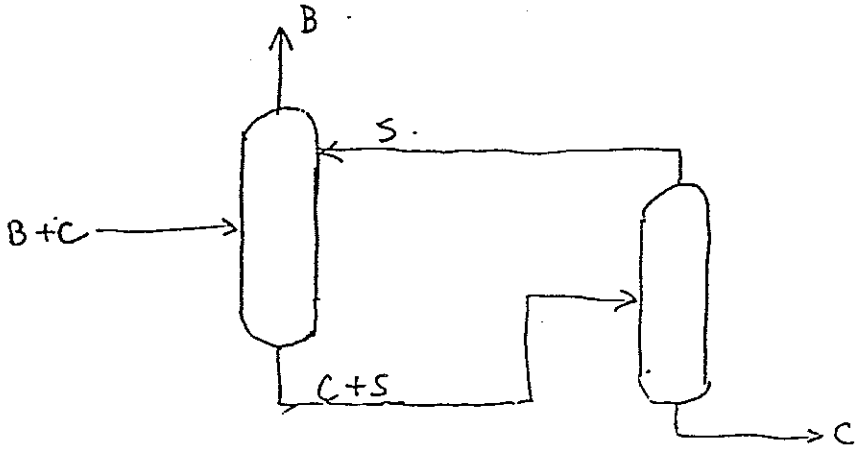
## Liquid/liquid extraction:




## Extractive distillation:

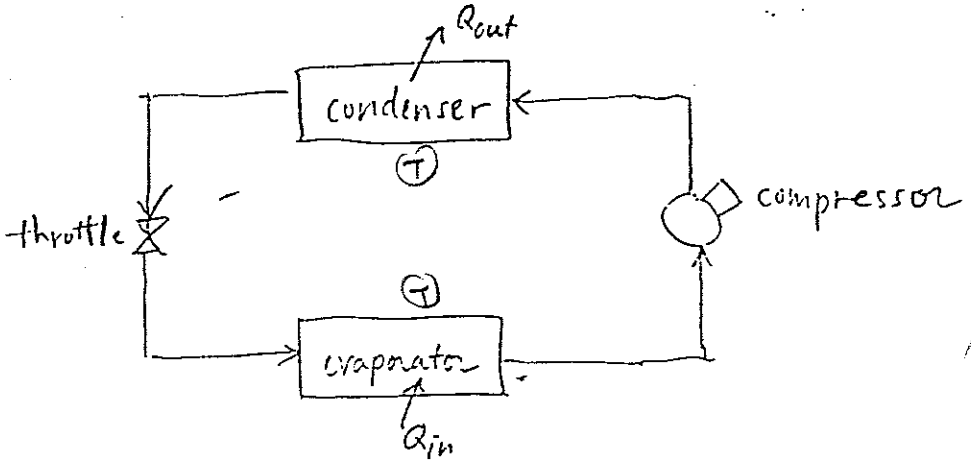


? Reactive distillation :

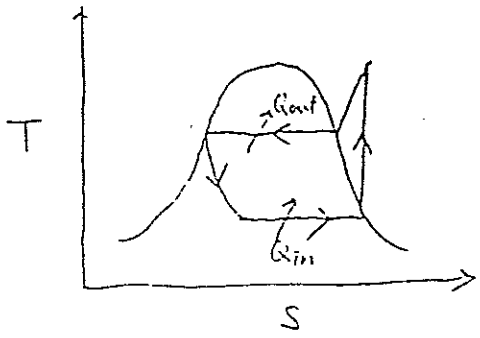


(14) Living in Phoenix, AZ where the T is 110 °F, how would you cool a room using 120 °F water?

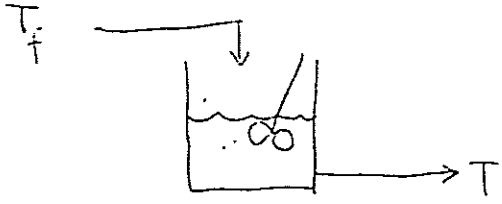
Use water as cold reservoir for refrigerant to reject heat in a refrigeration cycle.




Spray water. Evaporate Latent heat




(15) Consider an exothermic, zeroth order reaction in a C-STR. What happens if there is a step change in the feed T?




$$A \xrightarrow{k} B$$

$$r_A = k = A \exp\left(\frac{-E}{RT}\right)$$

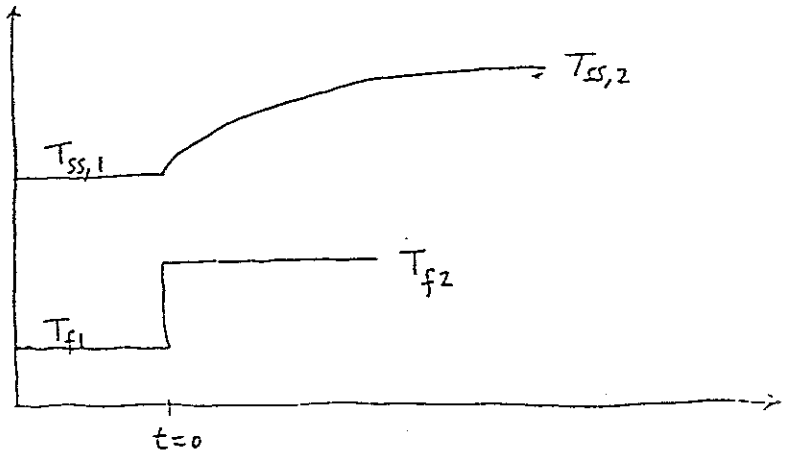
$$V C_p \rho \frac{dT}{dt} = F \rho C_p (T_{f2} - T) + A \exp\left(-\frac{E}{RT}\right) V \Delta h^{rxn}$$

This DE eqn can be solved with IC : at $t=0$, $T = T_{ss}$

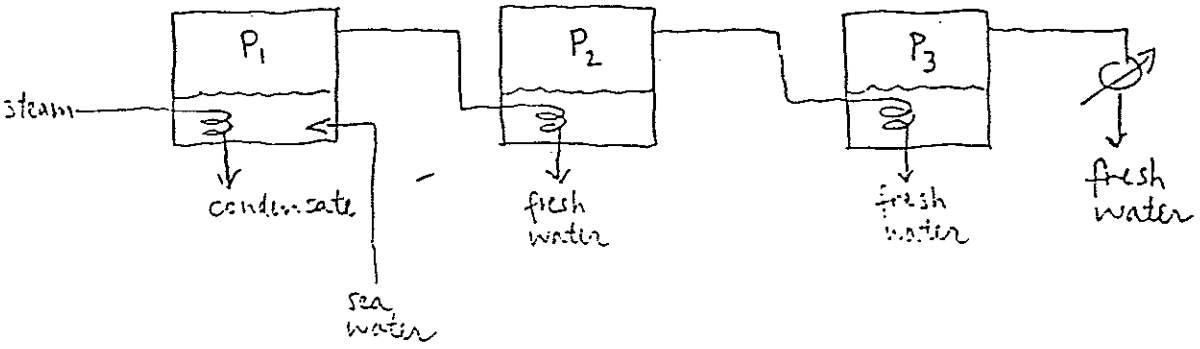
To find $T_{ss}$ : where $T = T_{ss,1}$ for $t < 0$

$$0 = F \rho C_p (T_{f1} - T_{ss1}) + A \exp\left(-\frac{E}{R T_{ss}}\right) V \Delta h^{rxn}$$

Can solve for $T_{ss}$.



(16) Sketch and describe a multi-effect evaporator. How does P vary through system?



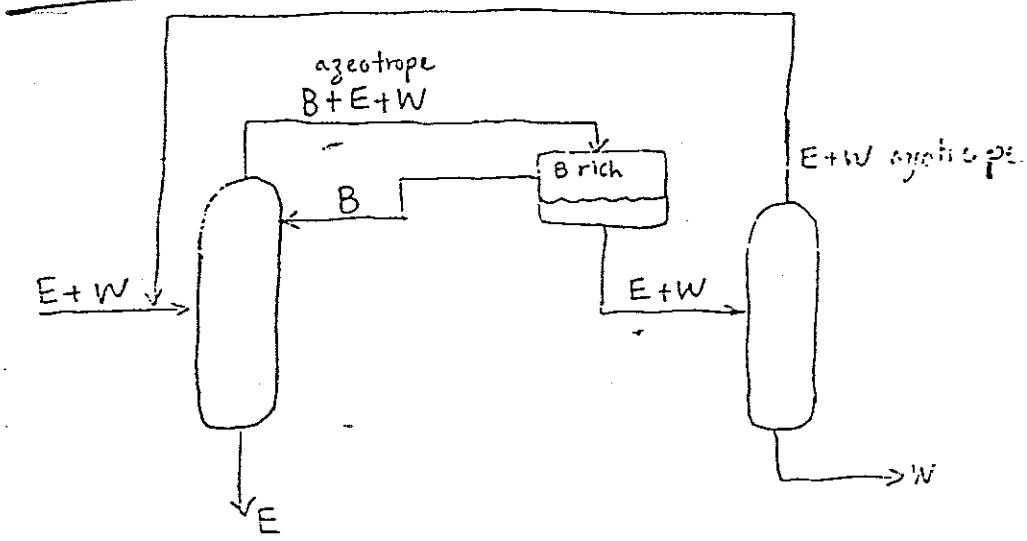

It's like heat integration. The pressures must decrease: $P_1 > P_2 > P_3$.

What?

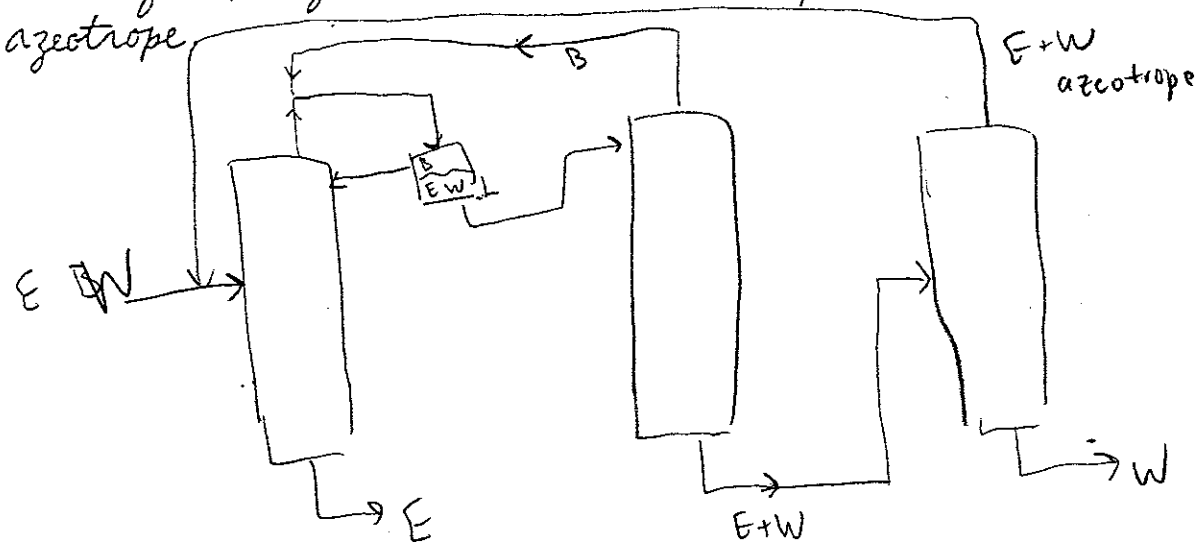
Why?

⑰ How would you separate ethanol from water?

Since they form a azeotrope, need to break it. Most commonly, a third compound added that forms ternary azeotrope with both water & ethanol. Benzene is often used.

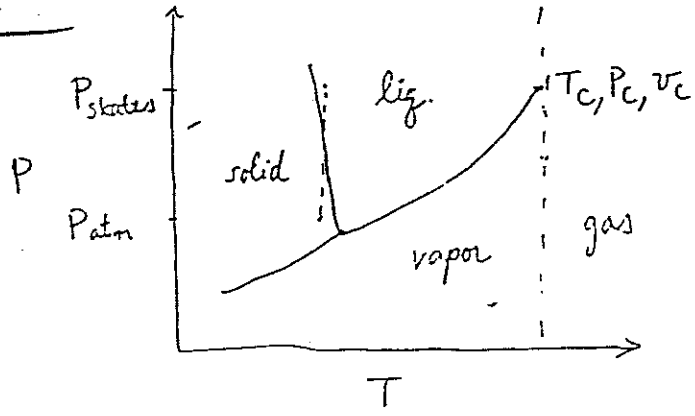



Sometimes, the third compound added (entrainer) forms an azeotrope with just one of the feed compounds. Could use liquid/liquid extraction to separate this new azeotrope



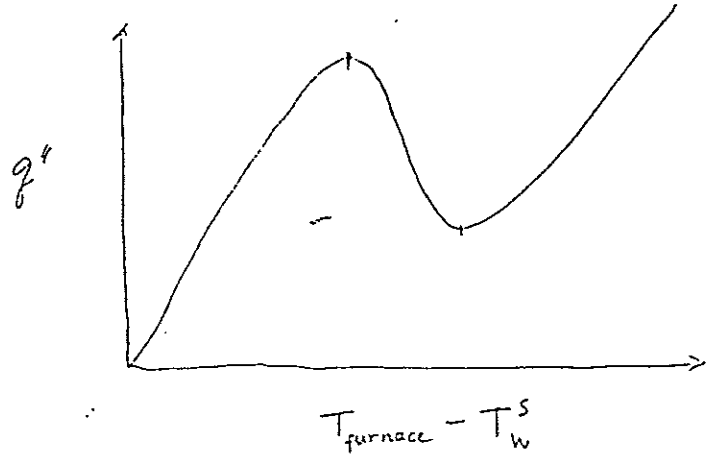
(18) How does an ice skate work?

The blade of the skate actually glides on a thin layer of water instead of on ice. This is because the blade is thin and so a large P is applied over the ice which melts it. This is due to water's special solid/liq. equil. line.



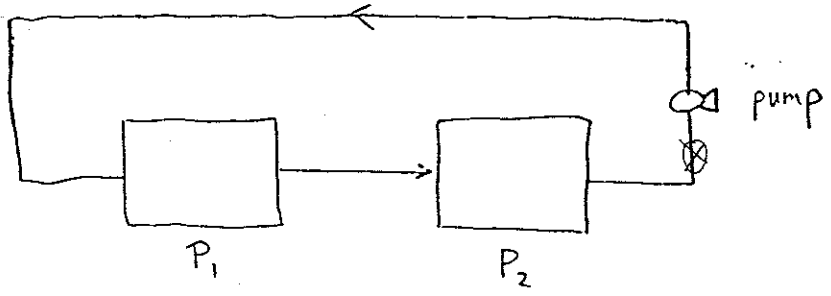

(19) Increasing the heat to the boiler of a steamboat caused the boat to slow down. Why?

Because of boiling curve.

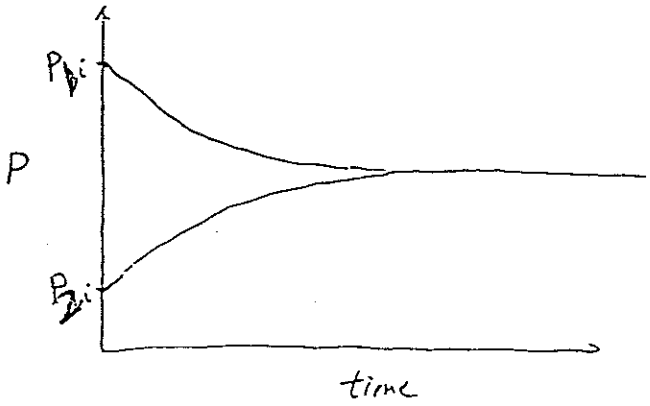



Boiler must have been in nucleate boiling region. By adding heat ($\uparrow T_{furnace}$), $q'' \downarrow$.

(2D) Consider two pressurized vessels connected in series with recycle. If recycle is cut off, how will the P in each vessel vary with time?




Initially $P_{1,i} > P_{2,i}$. Then, at SS (after cut off pump), $P_1 = P_2$.



"Keasling is the only one who asks about Control." – Yoshie

01/5/2001
11:08 pm

(24) Given the pressure drop, L and D for a pipe, how would you find the velocity?

$$F_k = AKf$$

force balance on fluid of length L and diameter D: assume horizontal

$$P_1 \pi R^2 - P_2 \pi R^2 = F_k$$

$$F_k = \pi R^2 (P_1 - P_2) = \pi R^2 \Delta P$$

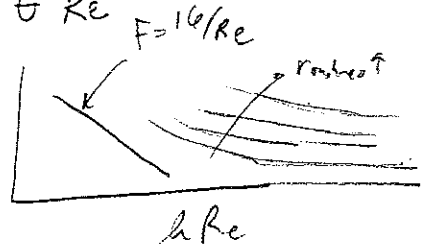
$$A = 2\pi RL \qquad K = \tfrac{1}{2}\rho \langle v \rangle^2$$

$$f = \frac{\pi R^2 \Delta P}{2\pi RL \, \frac{1}{2}\rho \langle v \rangle^2} = \frac{R \Delta P}{L \rho \langle v \rangle^2}$$

$$Re = \frac{\rho \langle v \rangle D}{\mu} \Rightarrow \langle v \rangle = \frac{Re\, \mu}{\rho D}$$

$$\therefore f = \frac{R \Delta P}{L} \frac{\rho^2 D^2}{Re^2 \mu^2} = \frac{R \rho D^2 \Delta P}{L \mu^2} \frac{1}{Re^2} = \theta \, Re^{-2}$$

$\theta$

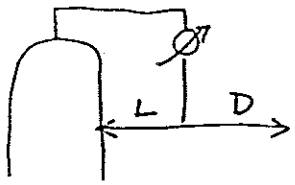



$$\boxed{\ln f = \ln \theta - 2 \ln Re}$$

Plot above eqn. on Moody chart ($\ln f$ vs. $\ln Re$) and it will give a line. Where the two lines intersect, get $Re = \frac{\rho \langle v \rangle D}{\mu}$. Can then get $\langle v \rangle$!!

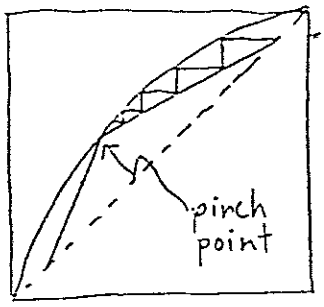
(25) What is the reflux ratio and pinch point?

Reflux ratio: $R = \frac{L}{D}$




- total reflux is when $R = \infty$
- minimum reflux is when we'll need an $\infty$ number of trays to effect the separation.

Pinch point:




at a pinch point, an $\infty$ number of trays is required to get to the pinch point. We get a pinch pt. like this at minimum reflux ratio.

(28) Know how to establish a scheme to separate a multicomponent system of liquids.

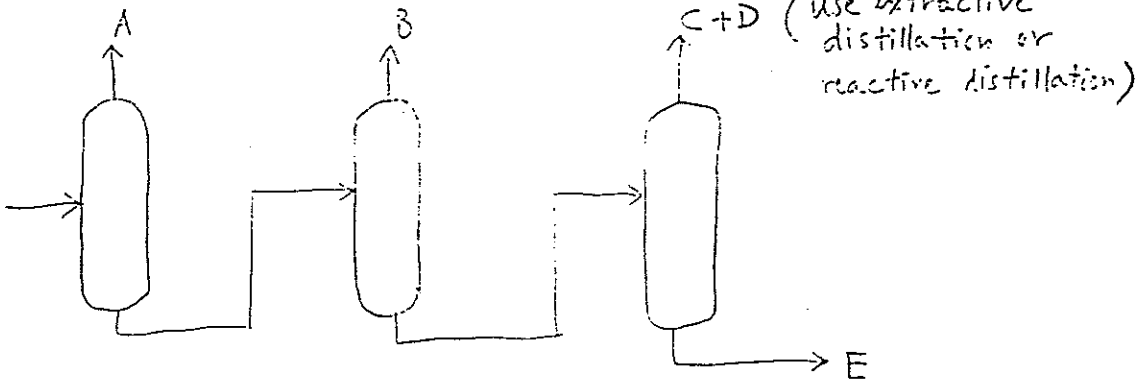
General heuristics:

(a) Separate corrosives and reactives first
(b) Usually want valuable products and recycles as distillates. This is because bottoms has tendency to accumulate more contaminants (solids, crud).
(c) Lightest component first
(d) Most abundant component first
(e) Most difficult separation last

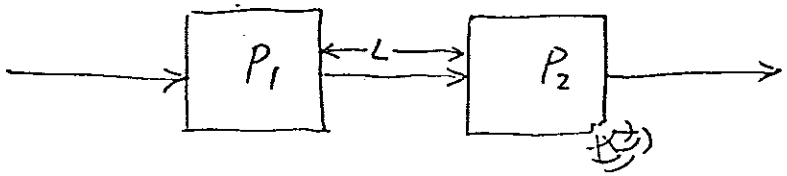
Make a list of boiling points (or relative volatilities):

| $\alpha_i$ | |
|---|---|
| 4.5 | A |
| 3.2 | B |
| 1.1 | C |
| 1.0 | D |
| 0.3 | E |

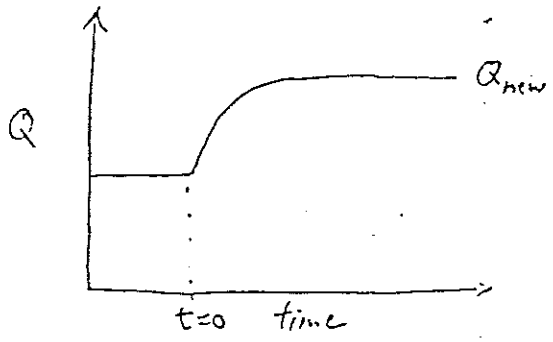
difficult separation



(29) Consider two pressurized vessels connected in series. If the downstream vessel suddenly develops a large leak, what happens to the flowrate in the pipe connecting the two vessels? Sketch flow vs. time curve.




If large leak develops, $P_2$ decreases. This will increase $P_1 - P_2 \Rightarrow$ increase in flow rate.




For turbulent flow, $f$ almost independent of $Re$.

$$f = \text{const.}$$

$$\frac{\Delta P \cancel{\pi} R^{\cancel{4}}}{\cancel{\frac{1}{2}} \rho \langle v \rangle^2 \cancel{\pi} R^{\cancel{2}} L} = \text{const.}$$

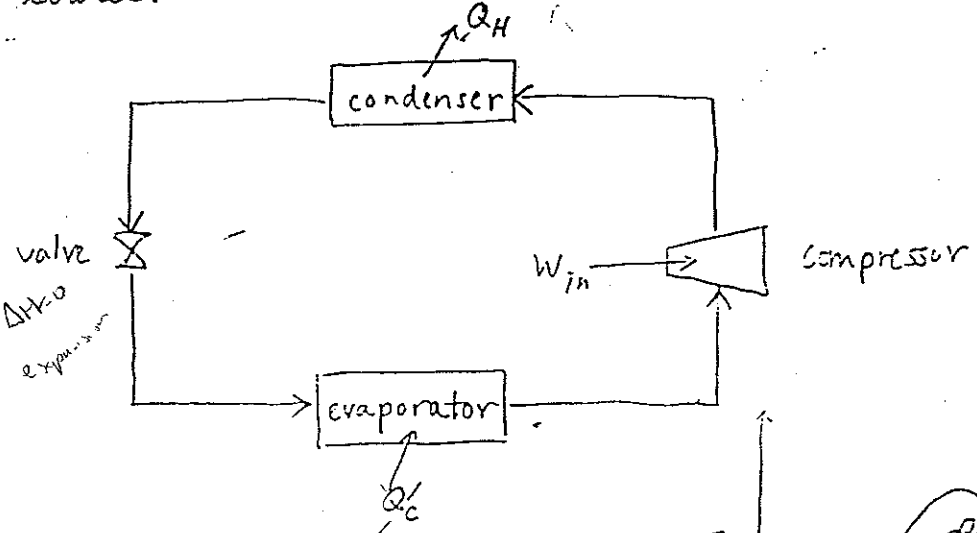
$$Q = \langle v \rangle \pi R^2 \quad \Rightarrow \quad \langle v \rangle = \frac{Q}{\pi R^2}$$

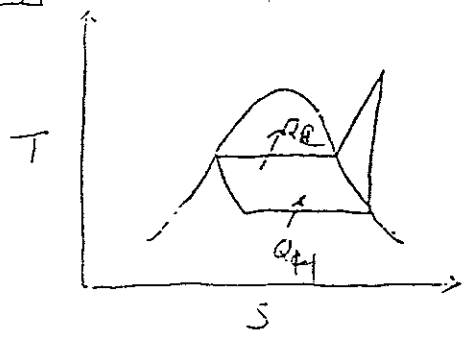
$$\frac{\Delta P R}{\rho L} \frac{\pi^2 R^4}{Q^2} = \text{const.}$$

$$Q^2 = \underbrace{\left(\frac{R^5 \pi^2}{\rho \cdot L}\right)}_{C} \Delta P \quad \Rightarrow \quad Q = C\sqrt{\Delta P}$$

(30) How does a heat pump work in winter? In summer?

A heat pump is like a refrigerator in principle. It takes heat from a cold source and rejects heat to hot source.




$$\Delta U = Q_c - Q_H - W_{in} = 0$$

$$W_{in} = Q_c - Q_H$$

negative

In the winter, $Q_c$ comes from the air outside the house. In the summer, $Q_c$ comes from the air inside the house. So, simply switch the ends of the heat pump. Also note that the source from which $Q_c$ comes from is colder in the winter than in summer.

$$COP \equiv \text{coeff. of performance} = \frac{-Q_H}{W_{net}} = \boxed{\frac{|Q_H|}{|Q_c - Q_H|}} \quad \text{Winter}$$

$$COP = \frac{Q_c}{W_{net}} = \boxed{\frac{|Q_c|}{|Q_c - Q_H|}} \quad \text{Summer}$$

(31) What temperature and pressure are used in the synthesis of ammonia? Is the rxn reversible? Exothermic? Why? To carry it out economically, what must you know about the reaction? How do you get $K_{eq}$ without experimental data? How does $K_{eq}$ depend on T?

$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g) \quad \text{Reversible}$$

$$:N\equiv N: + 3\,H-H \rightleftharpoons 2\,H-\underset{\displaystyle H}{\overset{\displaystyle H}{\underset{|}{\overset{|}{N}}}}-H$$

↑ breaking this triple bond releases lots of energy. Thus it's exothermic.

Whether a rxn is reversible or not depends on how large or small $K_{eq}$ is.

$$K_{eq} = \frac{a_{NH_3}^2}{a_{N_2}\, a_{H_2}^3} = \frac{y_{NH_3}^2 \varphi_{NH_3}^2 P^2}{y_{N_2}\varphi_{N_2} y_{H_2}^3 \varphi_{H_2}^3 P^3} \frac{P^\circ (P^\circ)^3}{(P^\circ)^2} \quad \text{where } P^\circ = 1 \text{ bar}$$

$$K_{eq} = \frac{y_{NH_3}^2}{y_{N_2}\, y_{H_2}^3} \frac{1}{P^2} \quad \text{assuming ideal gas}$$

We must know how conversion varies with P and T and how fast reaction occurs (need to know $E_a$) to carry rxn out economically.

$$\Delta g^\circ = -RT \ln K_{eq}$$

↑ get this from tables

$$\frac{\partial(\Delta g^\circ/T)}{\partial T} = \frac{-\Delta h^\circ}{T^2}$$

G - H

$A = U - TS$

$H = U + PV$

$G = H - TS$

$S = H - TS$

$\frac{\Delta G}{RT} = \frac{\Delta H}{RT} - \frac{\Delta S}{R}$

$\frac{\partial\left(\frac{\Delta G^\circ}{RT}\right)}{\partial T} = \frac{-\Delta h^\circ}{RT^2}$

$\frac{\partial(\ln K_{eq})}{\partial T} = \frac{\Delta h^\circ}{RT^2}$

$$g = h - Ts$$

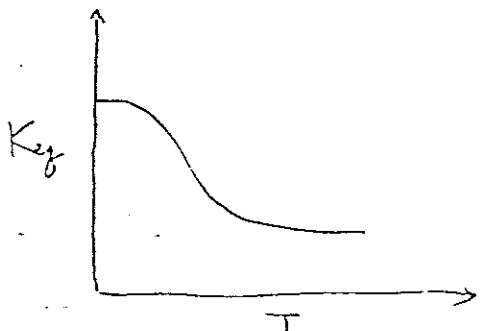
$$\frac{g}{T} = \frac{h}{T} - s$$

$$\left[\frac{\partial(g/T)}{\partial T}\right]_P = \frac{T\left(\frac{\partial h}{\partial T}\right)_P - h}{T^2} - \left(\frac{\partial s}{\partial T}\right)_P$$

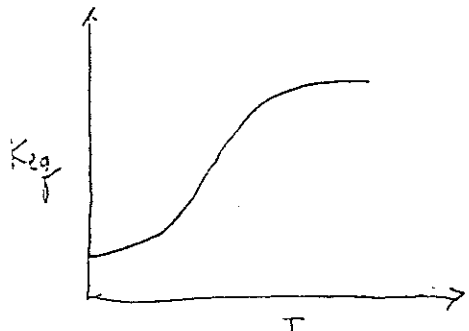
$$\left[\frac{\partial(g/T)}{\partial T}\right]_P = \frac{C_P}{T} - \frac{h}{T^2} - \frac{C_P}{T} = -\frac{h}{T^2}$$

$$\frac{\partial}{\partial T}\left[\frac{-RT \ln K_{eq}}{T}\right] = \frac{-\Delta h^\circ}{T^2}$$

$$\boxed{\frac{\partial}{\partial T}[\ln K_{eq}] = \frac{\Delta h^\circ}{T^2}}$$ Van't Hoff




exothermic




endothermic

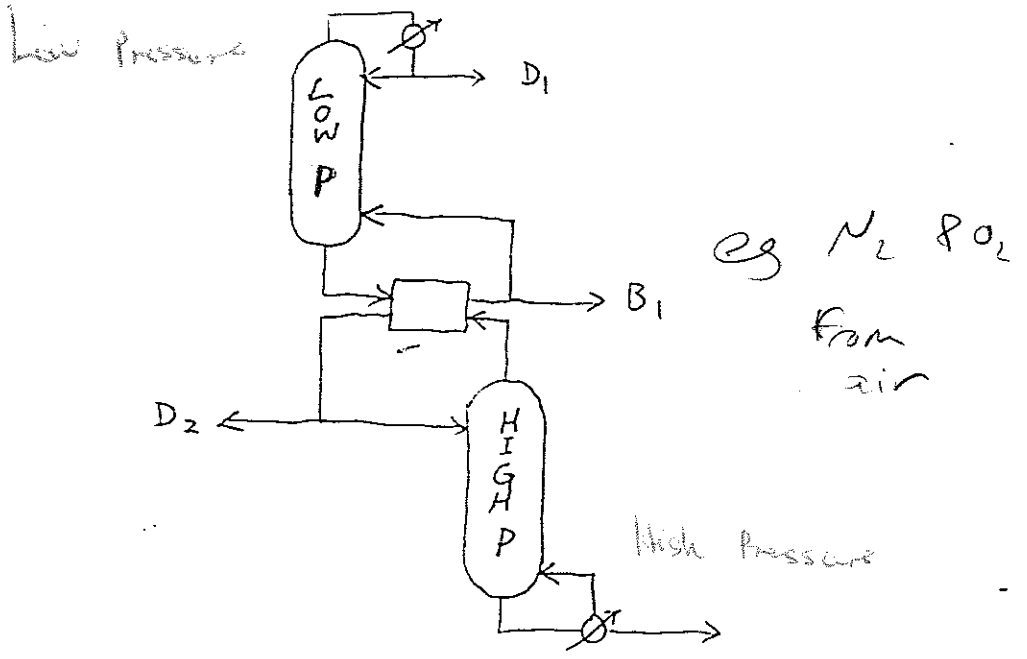
Therefore, we want high P (why?) and low T.

Typical values are: $400^\circ C < T < 500^\circ C$

$120 \text{ atm} < P < 900 \text{ atm}$

(33) You have a continuous distillation set-up. What can you do to save energy?

- Operate the column at a lower pressure. This will make vaporization easier ⇒ reduces reboiler load.
  not necessarily - increases condenser load.
- ~~Increase feed temp. ⇒ reduces reboiler load.~~
  ↖ need energy to do this!
- Insulate the column.
- Decrease reflux ratio. $= \frac{L}{D}$
- Use heat exchanger networks
- Divide the column into 2 columns. The vapor coming out the top of the higher pressure column can be used as the heating stream of the reboiler of the lower pressure column. Called Linde columns.



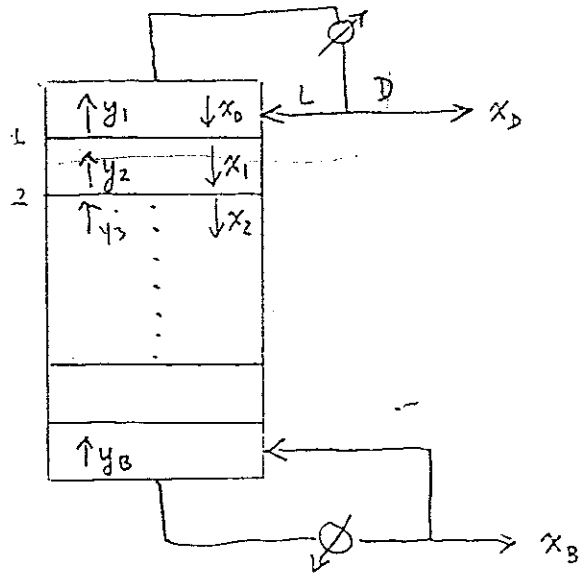

eg $N_2$ & $O_2$ from air

(34) You want to extract mechanical energy from geothermal steam which contains 1% incondensible gases $CO_2$, $H_2S$ and $NH_3$. What exit T, P would you choose? Would you get rid of the incondensibles? How?

Since most geothermal steam are not at very high P, exit P should be low to allow a good driving force. The T should be high enough so that no condensation occurs at the specified P.

$CO_2$ is harmless, but $H_2S$ and $NH_3$ are corrosive to steel. Get rid of them by adsorbing them onto activated carbon or some other solids.

(35) Derive Fenske eqn. (for multi-component distill.)




For: - total reflux
- total condenser

Define LK and HK:

LK = light key = usually heaviest component in distillate

HK = heavy key = " lightest " " bottoms

Consider LK:

$y_1 = k_1 x_1$

Since $y_1 = x_D$ (because total reflux and total condenser), $x_D = k_1 x_1$

$y_2 = k_2 x_2$

Total mole bal: $G_2 = L_1 + D^{\circ}$ MB around 1st stage and condenser

LK mole bal: $y_2 G_2 = x_1 L_1 \Rightarrow y_2 = x_1$ (none out of distillate)

$\therefore \quad x_1 = k_2 x_2$

$\therefore \quad x_D = k_1 k_2 x_2$

Repeat until $x_W$: $x_D = k_1 k_2 \ldots k_W x_W$

Repeat above calc for HK: $x_D' = k_1' k_2' \ldots k_W' x_W'$

$$\alpha_1 = \frac{y_1/x_1}{y_1'/x_1'} = \frac{k_1}{k_1'}$$

— Prime means HK

$$\frac{x_D}{x_D'} = \frac{k_1}{k_1'}\frac{k_2}{k_2'} \cdots \frac{k_W}{k_W'}\frac{x_W}{x_W'} = \alpha_1 \alpha_2 \ldots \alpha_W \frac{x_W}{x_W'}$$

Assume $\alpha$'s don't vary much $\Rightarrow \alpha_{avg}$ ~ ?

$\therefore$ $$\boxed{\frac{x_D}{x_D'} = (\alpha_{avg})^{N_m}\frac{x_W}{x_W'}}$$ original Fenske eqn.

(35) Give a method for manufacturing acetylene, starting from inorganic compounds only.

New methods: Starting with organics

Pyrolysis or cracking of natural gas or liquid hydrocarbons.

Key processes include:

a) partial oxidation using $O_2$

b) thermal cracking

c) an electric arc to supply both high T and energy.

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

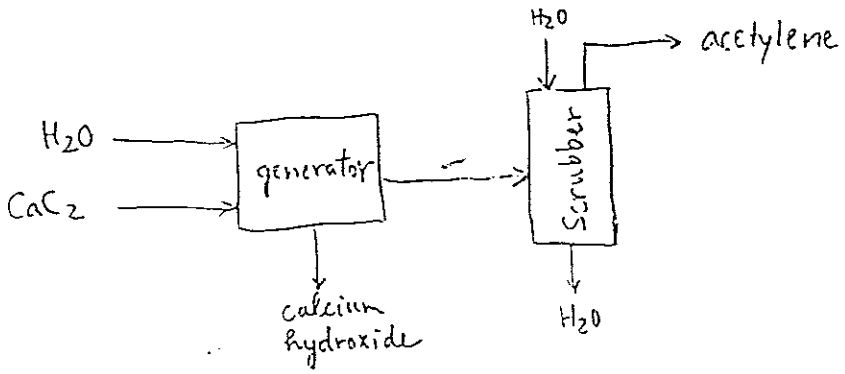
$$2CH_4 \longrightarrow C_2H_2 + 3H_2$$

} competing reactions

Using only inorganics:

$$CaC_2 + 2H_2O \longrightarrow C_2H_2 + Ca(OH)_2$$

Calcium carbide



(39) How would you separate a single temperature sensitive component (e.g. a protein) from a stream containing a multicomponent mixture of similar sized molecules?

Two separation techniques come to mind:

- affinity separations
- membrane separations
- ion exchange

Affinity

Ligands on a solid, immobile phase selectively bind the protein reversibly. After all the other components are washed out, the protein can be washed out with another solvent that will make the protein detach from ligands.

Membrane

A carrier that passes through membrane easily can selectively complex reversibly with protein of interest. Then the protein is carried to the other side of membrane, where some of it is released.

Ion exchange

If the protein of interest is of an opposite charge from other compounds, it can be separated by a charged immobile phase.

(40) Where does bromine come from, e.g. that used in bromo-seltzer?

$Br_2$ comes from two major sources:

- seawater
- natural brine deposits

From sea water:

$$2NaBr + Cl_2 \longrightarrow 2NaCl + Br_2(g)\uparrow$$

From brine:

"Steaming out" of brine.