

Distillation

① Introduction:-

Distillation is the technique of separation of the more volatile component from the less volatile ones in a feed solution by partial vaporization of the feed followed by condensation.

The vapor produced is richer in the more volatile component. The distribution of the components in the phases is governed by the vapor-liquid equilibrium relationship.

The more volatile components move from the liquid to the vapor phase, and the less volatile move from the vapor to the liquid phase.

The function of distillation may be:-

- Separation of products from a mixture, separation of aniline and nitrobenzene.
- Recovery of products, recovery of ethanol from its solution in water.
- Increasing the purity of a product, drying of benzene to remove any trace of water.

Because of its importance and wide use in separation of mixtures, distillation is called "The work horse" of chemical engineering or chemical industries.

- The main difference between distillation and evaporation is that in evaporation a solution containing a volatile solvent and a non volatile solute or a solute having a very low volatility (sugar (non volatile solute), water (volatile solvent)).

Schematic of a typical distillation column is shown in Figure below :-

There are two main types of mixtures:

- 1- Binary mixture, consist of two components only.
- 2- Multi-component mixture, for more than two components

- Bubble point :- temp. cause first bubble on the liquid surface to appear. It is a characteristic for mixture and compounds.

- Boiling point :- temp. at which vap. press. equal to atm. press. It is a characteristic for pure substance like P, μ, \dots

Separation of a mixture by distillation is based on equilibrium distribution of the components between the liquid and vapor phases. Therefore vap.-liq. equilibria is essential in distillation.

Distillation always used when there is difference in boiling points and volatility.

$$\text{Volatility } (\alpha_A) = \frac{P_A}{x_A} = \frac{y_A \cdot P_T}{x_A}$$

For two components (A, B) to be separated
 $\alpha_A \neq \alpha_B$

$$\text{Relative Volatility } (\alpha_{AB}) = \alpha = \frac{\alpha_A}{\alpha_B} = \frac{y_A \cdot x_B}{y_B \cdot x_A}$$

(3)

For high (α_{AB}), distillation become easier.

When $\alpha_A = \alpha_B$, Special treatment is used, that is called "extractive-distillation".

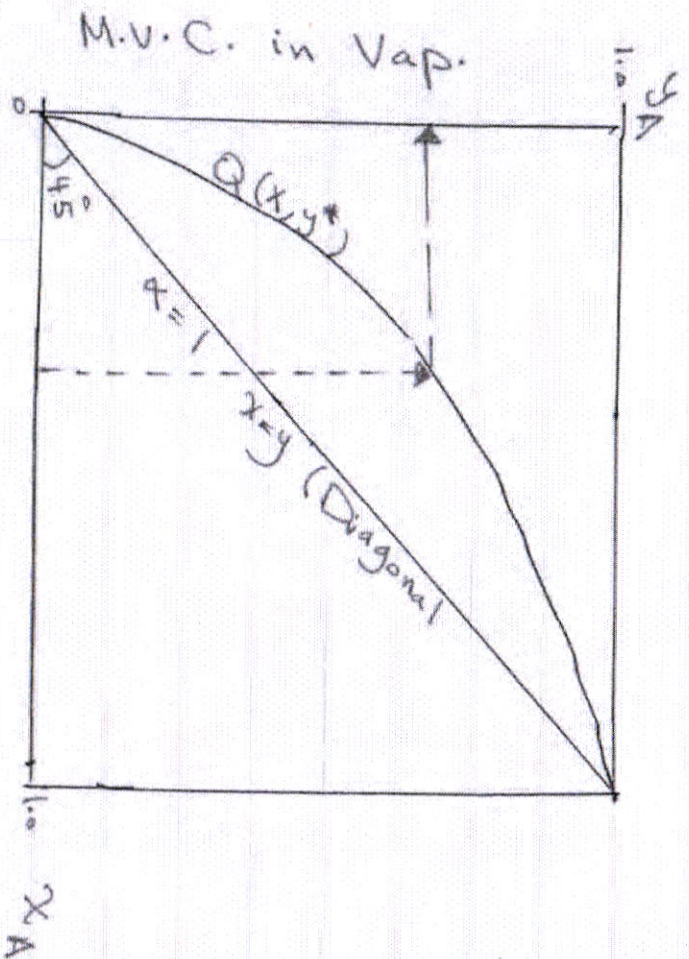
* if $\alpha_{AB} > 1$. = then (A) is the M.V.C

if $\alpha_{AB} < 1$. = then (A) is the L.V.C

② Vapour - liquid Equilibrium (VLE) :-

هذه حالة تعطينا تركيز البخار الذي هو في حالة توازن مع كل تركيز من تركيز السائل، يتكون من المادتين (A, B).
 دائماً نؤخذ عند ضغط ثابت. وهي التي ندرس عليها لتغير
 الذي سيتم استنتاجها بالاعتماد على عامل (K_{AB}).
 الرسم البياني أدناه هو (Vap. Liq. Equil^m) (Boiling point diagram)
 رسم بياني تائي يصف

M.V.C : more volatile Comp. (Less boiling point)
 L.V.C : Less volatile comp. (higher boiling point)



M.V.C in liquid
 (5)

③ Boiling Point Diagram

① عند ثبوته لضغط :-

المختبر اسفل يوضع لنا درجات الغليان لتراكيز مختلفة من
السائل. زي انقلوب في لتراكيز سيغير درجة غليان.

(T_A) درجة غليان لمادة (A) لثقيت .

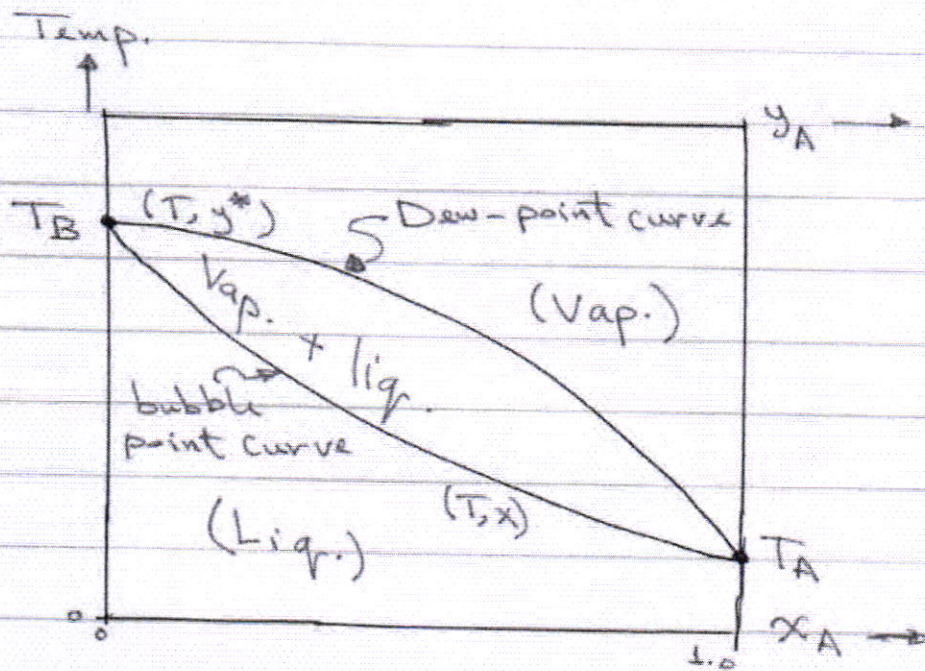
(T_B) درجة غليان لمادة (B) لثقيت .

المختبر العلوي يعطيه درجة الحرارة التي يبدأ بها الغاز بالتكثف.
كل هذا المختبرات لثقيات في (T_A) / (T_B) لثقيت للمادة لثقيات
لدرجة غليان تساوي درجة التكثف.

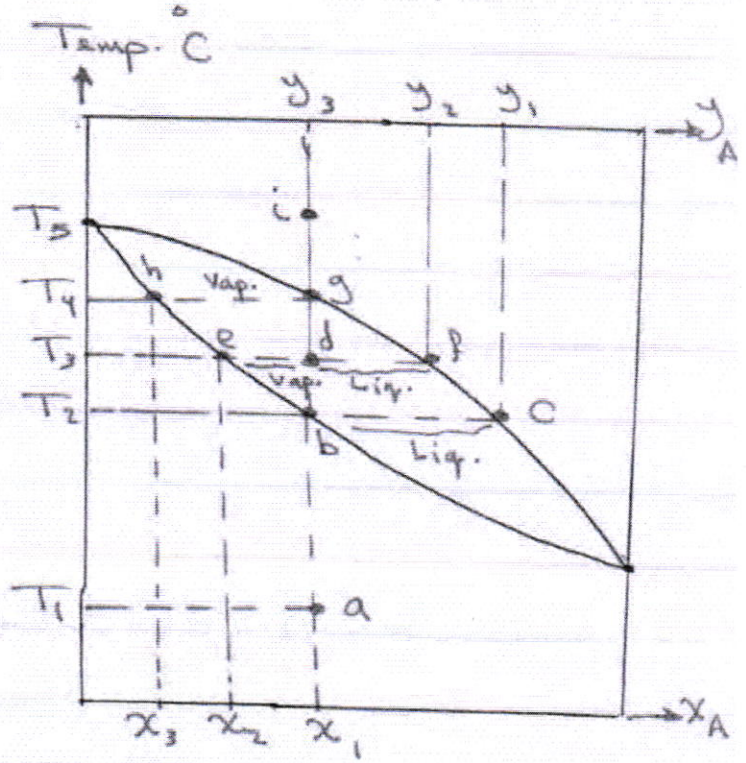
كل نقطة اسفل المختبر اسفل تكون في محور سائل.

كل نقطة زيها المختبر الاعلى تكون في محور بخار.

بينه المختبرين هناك مزيج من هذا البخار والسائل.



لو عندنا سائل معين بدرجته حرارة معينه وتبدأ بتغيير درجته الحرارة تدريجياً.



- الان لو فرضت عندنا سائل بدرجته حراره (T_1) وتركيزه (x_1) النقطة (a).

- الان لو رفعتا درجته الحرارة من (T_1) الي (T_2) فهو يبقى في الحالة السائله حتى نصلك الي نقطه (b). هيه تظهر اوله فقاعة بالظهور على سطح السائل وتركيزها في الغور البخاري (y_1) . النقطة (c) تركيز او قاعه من البخار.

- الان ترفع الحرارة حتى نقطه (d) بدرجته حراره (T_3) هيه تزداد كمية البخار ويصعب لدينا عزيم من السائل والبخار تركيز السائل نحدد في نقطه (e) وتركيز البخار بالنقطه (f) ويكون (y_2) . اوله فقاعة ظهرت في (b, c) وتمت كما ارتفاعك الاعداد.

$$\frac{liq.}{vap.} = \frac{dF}{de}$$

where $F = \text{vapor (sat.)}$, $e = \text{liq. (sat.)}$

- The line (ef) is called "Tie-line" (Enthalpy of liq. & vap. at equilibrium)

- section length / section length ed or

$\frac{dF}{de}$ is called "Lever-arm rule" (Flash vaporization)

- رفع درجة الحرارة إلى النقطة (g) ، هنا السائل يتبخر كله ويحدث
عندنا تبخر تام ، والنقطة (h) تمثل تركيز البخار عند نقطة
السائل يتبخر .

- رفع درجة الحرارة حتى لو هو السائل ، النقطة (i) يصبح لدينا حالة
(Super - heated - vapour) مع ما يفوقه انه تركيز البخار يتساوى
تركيزه في (g) .

* الان لو عندنا بخار ونريد ان نكثفه تدريجياً :-

- عندنا بخار في (T_a) وتركيزه (x_1) . لو قللنا الحرارة إلى (T_b)
عند نقطة (g) حيث تمثل اوله قطره تكثف إلى سائل تركيزها
عند (h) .

- نقلك الحرارة إلى (T_c) عند النقطة (d) ، يتغير البخار بالتكثف
ونظير لدينا مزيج من البخار والسائل لانه يتبريد غير كافيه لتكثفه
كله البخار .

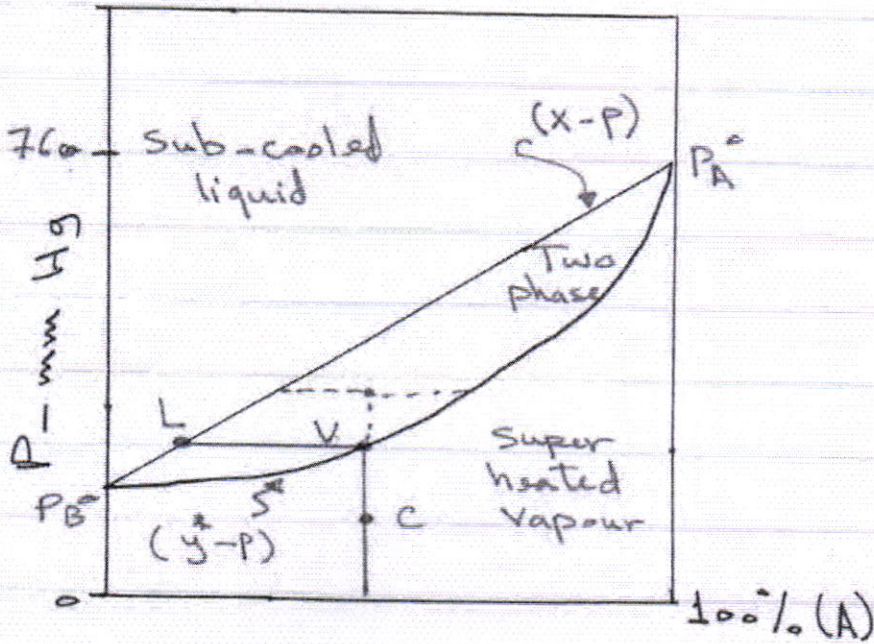
- عند (b) يتحول كله البخار إلى سائل ويحدث عندنا قطره سائل :-
(Total condensation)

- الان لو استمرينا لفاتح (T_1) نصل على تركيز ثابت والعمليه هي
(sub-cooled liq.)

- عند الحملات المذكورين سابقين هناك خمس حالات لل Feed
ظهرت عند استخدامها :-

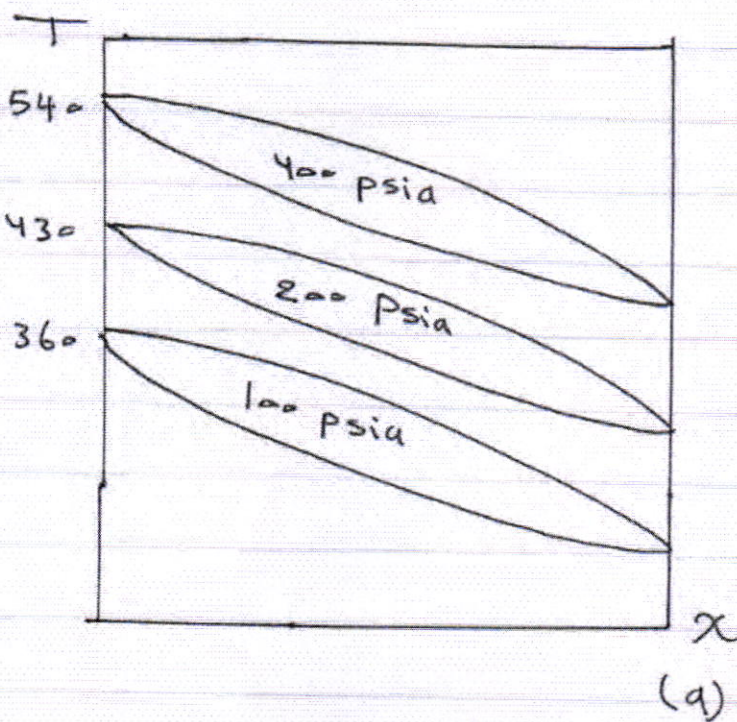
- 1- sub-cooled , 2- at bubble point
- 3- partial vaporized , 4- dew point ,
- 5- super heated .

③ عند ثبوت درجة الحرارة :-



L: First drop of liquid appear after compression

Effect of pressure on boiling point diagram.



Increasing the pressure will cause the two lines to become closer and closer

How to Find (Vap. - Liq. Equilb^m. data) analytically.

① Raoult's Law (for liq. mixture)

- for component (A):-

$$P_A = P_A^\circ \cdot x_A$$

- for component (B):-

$$P_B = P_B^\circ \cdot x_B$$

- For a binary mixture:-

where:- P_A° : vap. press

P_A = parti. press

x_A = mole fraction
in liq. phase

$$x_A = \frac{P_T - P_B^\circ}{P_A^\circ - P_B^\circ} \quad \text{--- (1)}$$

H.W :- Try to find the above relation.

② Dalton's Law (ideal gas)

$$P_T = \sum P_i$$

for binary mixture:-

$$P_T = P_A + P_B$$

$$\therefore P_A = y_A \cdot P_T$$

$$P_A = P_A^\circ \cdot x_A$$

$$\therefore y_A = \frac{P_A^\circ \cdot x_A}{P_T} \quad \text{--- (2)}$$

(10)

③ Using relative volatility (α_{AB}) or (α)

$$\alpha_{AB} = \frac{y_A \cdot x_B}{y_B \cdot x_A} = \frac{y_A (1 - x_A)}{(1 - y_A) \cdot x_A}$$

$$y_A = \frac{\alpha \cdot x_A}{1 + x_A (\alpha - 1)} \quad \text{--- (3)}$$

$$x_A = \frac{y_A}{\alpha - (\alpha - 1) y_A} \quad \text{--- (4)}$$

④ Using equilibrium constant (k_i) (Henry's Law) or (equilibrium vaporization ratio) or (distillation coefficient)

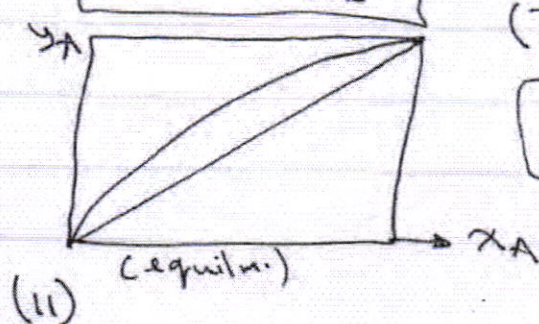
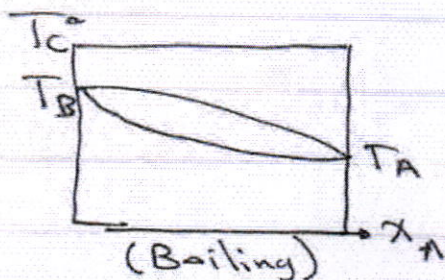
$$P_A = H x_A \Rightarrow y_A = \frac{H}{P_T} x_A \quad (\text{for hydrocarbon mixture})$$

$$y_A = k_A \cdot x_A \quad \text{where then} \quad k_A = \frac{y_A}{x_A} \quad (\text{for multi-component mixture})$$

k = called (k) value, it is function of (T) and (P).

For ideal system

$$\alpha_{AB} = \frac{k_A}{k_B}$$



(Typical system)

$$x_A = \frac{1 - k_B}{k_A - k_B}$$

$$y_A = \frac{k_A - k_A k_B}{k_A - k_B}$$

Notes For multicomponent system =

① if $\sum P_i < P_T$ liq. is sub cooled, below B.Pt
if $\sum P_i > P_T$ s s super heated, above B.Pt

② $y_i = k_i x_i$

③ if $\sum y_i = 1.0$ liq. at bubble Pt.

④ if $\sum y_i < 1.0$ liq. is sub cooled.

⑤ if $\sum y_i > 1.0$ liq. is super heated

⑥ if $\sum y_i / k_i = 1.0$ at dew-point-vap.

⑦ if $\sum y_i / k_i < 1.0$ vap. is super heated

⑧ if $\sum y_i / k_i > 1.0$ sub cooled

⑨ Some times, it is required to calculate (P_i°) if it is not given.

$$\ln P_A^\circ = A - \frac{B}{C+T} \quad \text{Antoine-equation}$$

where :- P_A° in mmHg.

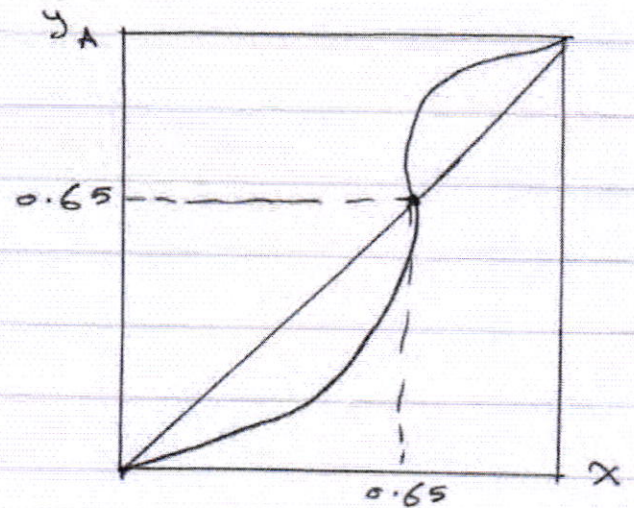
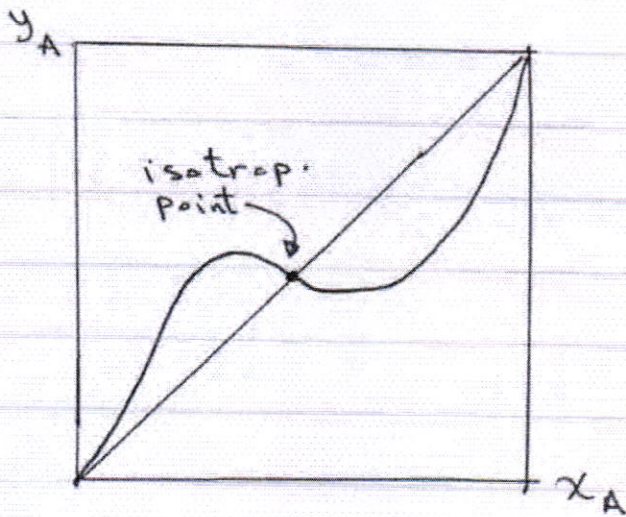
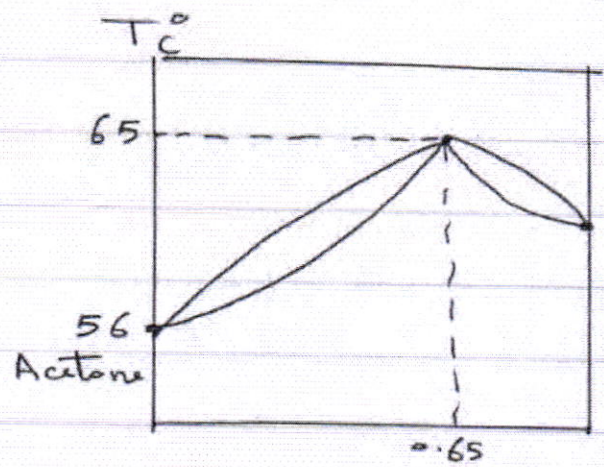
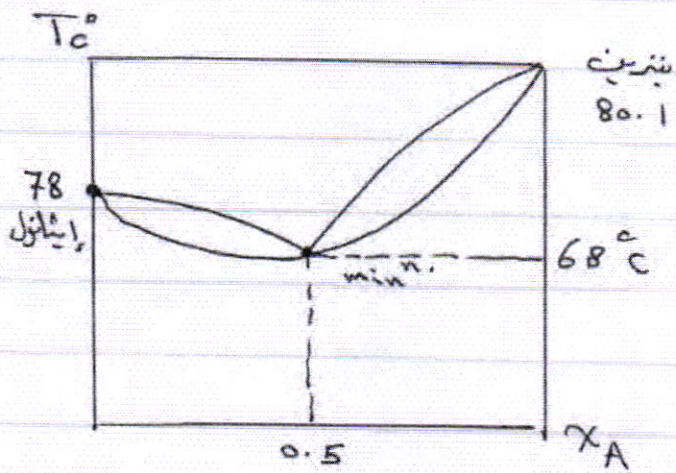
T in $^\circ\text{C}$.

(A, B, c) are constants.

Deviation from ideality and formation of Azeotropes

Deviation from ideality may be of two types :-

- Positive - deviation, causing min^m. boiling azeotropes
- Negative - deviation, causing max^m.



Case ① :
Benzene - Ethanol
system

Case ② :
Acetone - chloroform
system

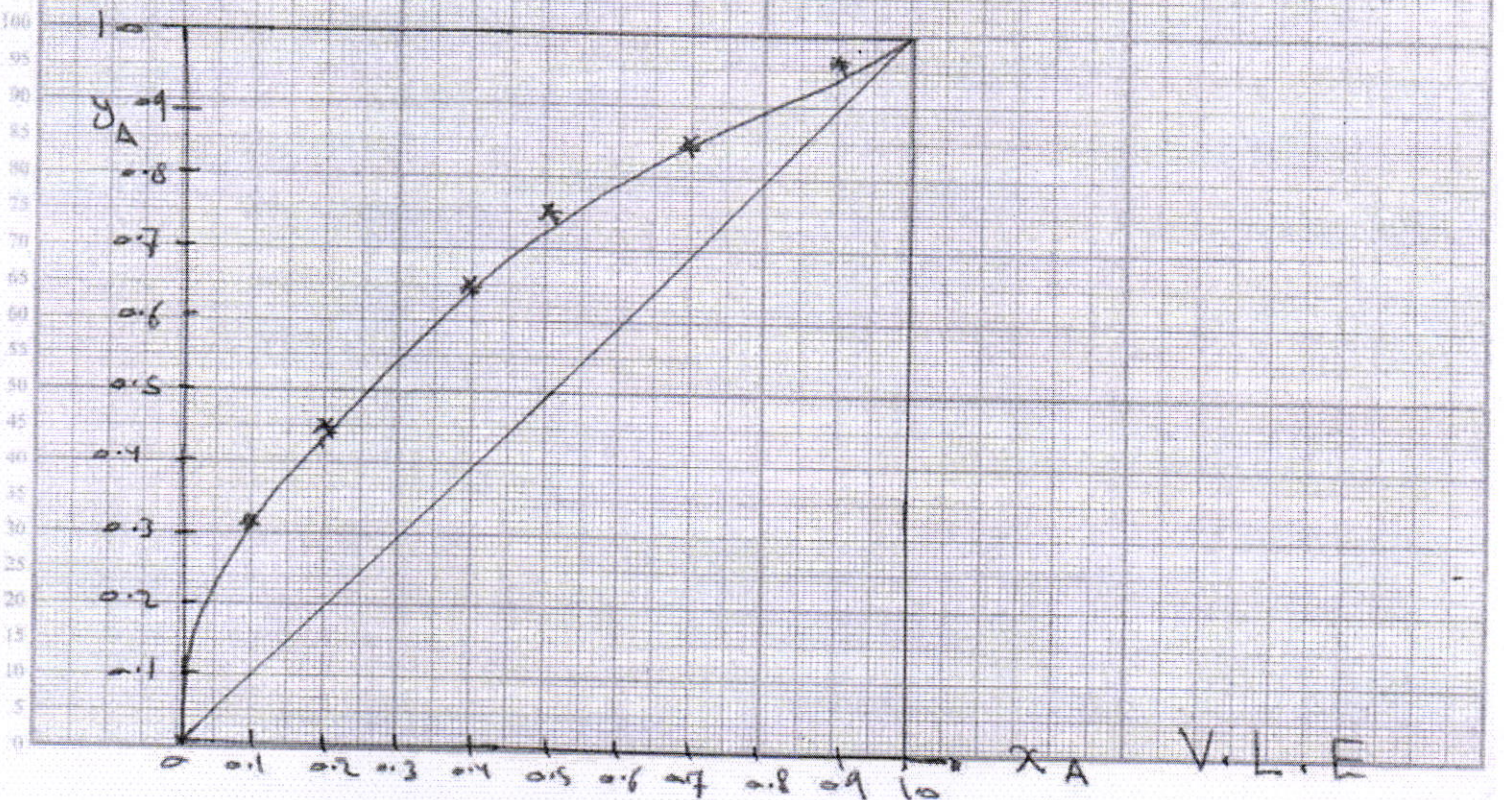
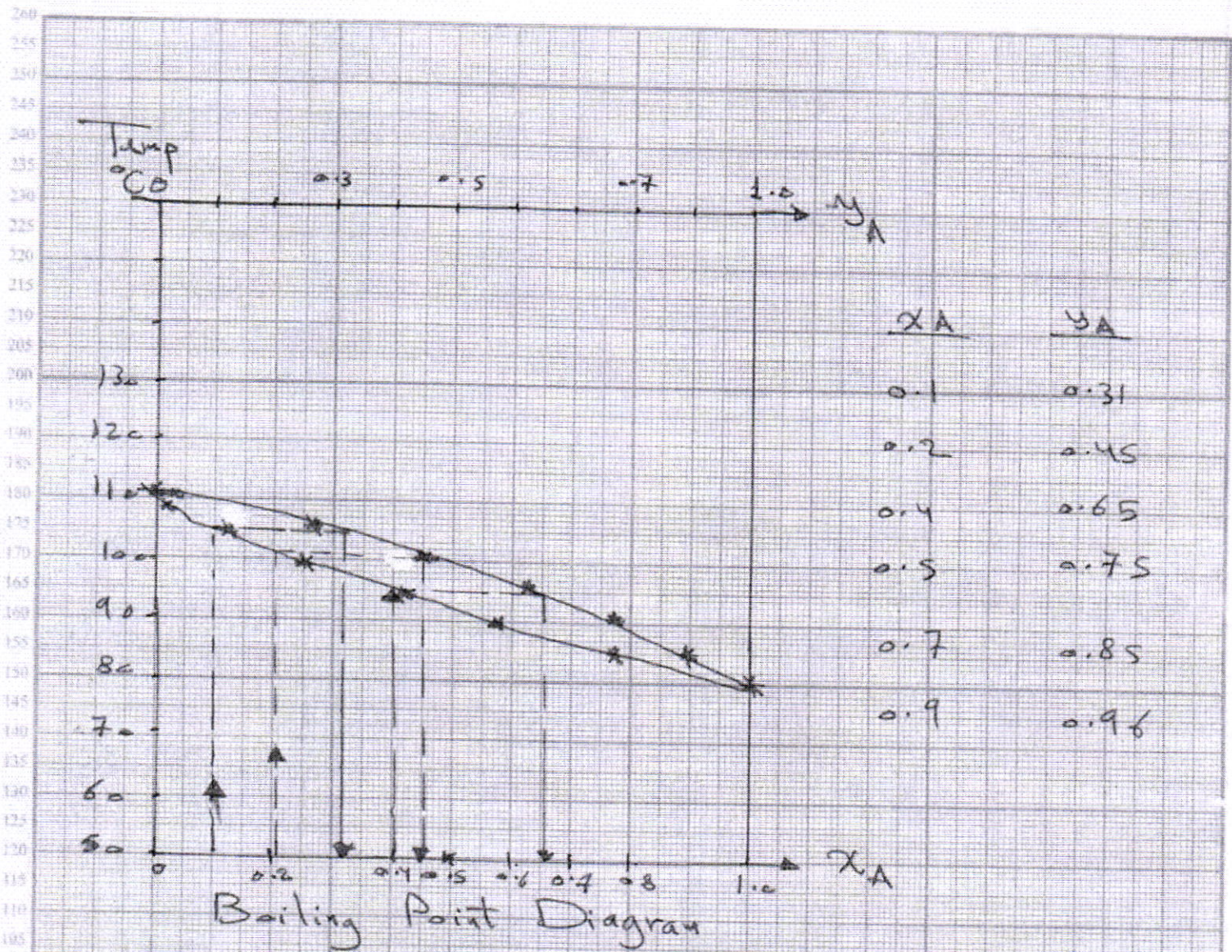
Ex. 2 - Calculate and plot the boiling point and equilibrium diagrams of the system of benzene-toluene at total press. of 1 atm. Assuming all mixtures are ideal mixtures. The vap. press. data of the system as a

| <u>Temp. °C</u> | <u>P_A° (Benzene)</u> | <u>P_B° (Toluene)</u> |
|-----------------|---|---|
| 80.1 | 760 | 300 |
| 85.0 | 877 | 354 |
| 90.0 | 1016 | 405 |
| 95.0 | 1168 | 475 |
| 100.0 | 1344 | 557 |
| 105.0 | 1532 | 645 |
| 110.0 | 1748 | 743 |
| 110.6 | 1800 | 760 |

Sol. - $P_T = 1 \text{ atm} = 760 \text{ mm Hg.}$

$$x_A = \frac{P_T - P_B^\circ}{P_A^\circ - P_B^\circ} \quad , \quad y_A = \frac{P_A^\circ \cdot x_A}{P_T}$$

| <u>Temp.</u> | <u>x_A</u> | <u>y_A</u> | <u>Temp.</u> | <u>x_A</u> | <u>y_A</u> |
|--------------|-------------------------|-------------------------|--------------|-------------------------|-------------------------|
| 80.1 | 1 | 1 | 105.0 | 0.12 | 0.24 |
| 85.0 | 0.782 | 0.90 | 110.0 | 0.016 | 0.038 |
| 90.0 | 0.581 | 0.77 | 110.6 | 0.0 | 0.0 |
| 95.0 | 0.411 | 0.63 | | | |
| 100.0 | 0.25 | 0.45 | | | |



Distillation Processes

Distillation processes can be classified according to:

A. Type of separation method

1. Differential distillation.
2. Flash or equilibrium distillation.
3. Rectification distillation.

B. Number and type of component.

1. Binary distillation
2. Multicomponent distillation.
3. Complex distillation.
4. Azeotropic and extractive distillation.

C. Operating design and conditions.

1. Batch distillation.
2. Continuous distillation.
3. Vacuum distillation.
4. Steam distillation.

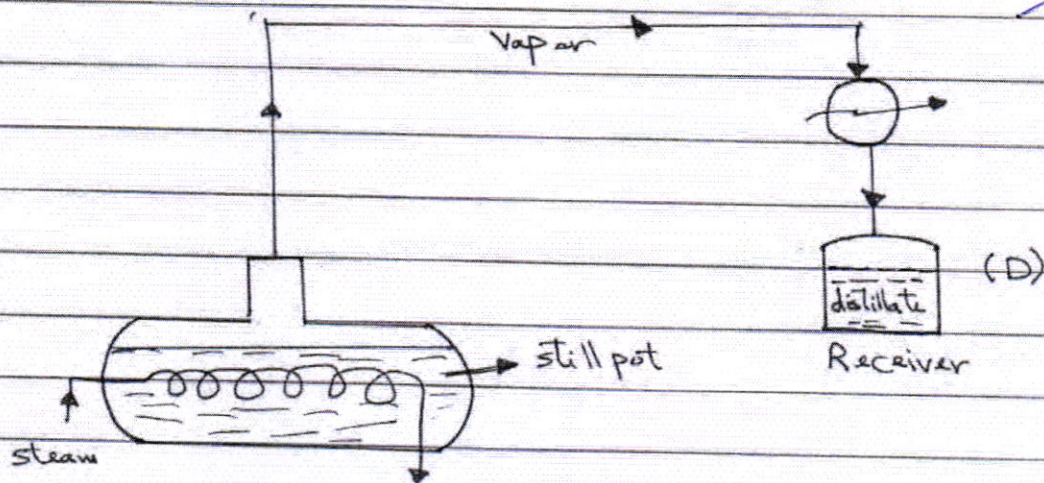
1- Differential Distillation (Batch)

Feed is charged to the still pot to which heat is supplied continuously through a steam jacket or a steam coil. As the mixture boils, it generates a vapor richer in the M.V.C. But as boiling continues, concentrations of M.V.C in the liquid decrease. It is generally assumed that equilibrium vaporization occurs in the still. The vapor is led to a condenser and the condensate or top product is collected in a receiver.

At the beginning, the condensate will be rich in the M.V., but the concentrations of the M.V. in it will decrease as the condensate is usually withdrawn intermittently having products or cuts of different concentrations.

Batch distillation is used when the feed rate is not large enough to justify installation of a continuous distillation unit.

The schematic of a batch distillation setup is shown below



Batch or Differential or Rayleigh distillⁿ

Overall M.B. :-

$$F = D + W \quad \text{--- (1)}$$

No. of moles present in the still = No. of moles in vapor + No. of moles in residue

$$F \cdot x = dF \cdot y + (F - dF)(x - dx) \quad \text{--- (2)}$$

where :- F = No. of moles of a mixture in the still.

x = mole fraction in liq. phase.

y = s s s Vapor phase.

dF = amount of liquid vaporize at any time.

$(F - dF)$ = amount of residue.

$(x - dx)$ = mole fraction of residue.

$$F/x = y dF + xF - x dF - F dx + dx dF \rightarrow \text{small}$$

$$F dx = (y - x) dF$$

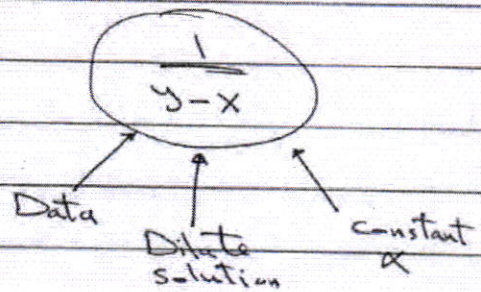
$$\frac{dF}{F} = \frac{dx}{y-x} \Rightarrow \int_F^W \frac{dF}{F} = \int_{x_f}^{x_w} \frac{dx}{y-x}$$

$$\ln \frac{W}{F} = \int_{x_f}^{x_w} \frac{dx}{y-x} \quad \text{--- (3) (Rayleigh Eq.)}$$

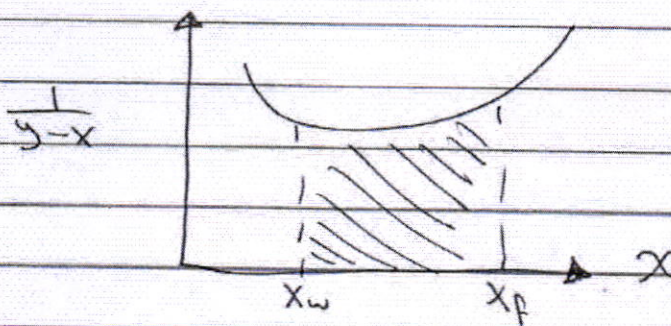
For the R.H.S term:-

The relation between (y) and (x) is an equilibrium relation, So:-

- * $y = m \cdot x$
- * $y = k \cdot x$
- * data (x, y)



① if the equilibrium data are known, then by plotting $\frac{1}{y-x}$ vs. (x) and getting area under curve.



(19)

(20)

(s)

For constant (K)

$$\ln \left(\frac{F}{W} \right) = \frac{1}{\alpha - 1} \ln \left(\frac{x_f(1-x_w)}{x_w(1-x_f)} \right) + \ln \left(\frac{1-x_w}{1-x_f} \right)$$

Solve by Partial Fractions

$$= \int \frac{dx}{x(x-1)(1-x)} + \int \frac{\ln \frac{1-x}{1-x}}{x(x-1)(1-x)} dx$$

$$= \int \frac{1 + (\alpha - 1)x}{x(x-1)(x-x^2)} dx$$

$$y = \frac{\alpha \cdot x}{1 + (\alpha - 1)x}$$

$$\int \frac{y - x}{dx} = \int \frac{\alpha \cdot x}{1 + (\alpha - 1)x} dx$$

(3) For mixture of constant (K)

$$\left(\frac{F}{W} \right)^{m-1} = \frac{x_f}{x_w}$$

$$y = mx$$

(2) For dilute solution where

Ex. (1) - 1000 kg of mixture containing 60% wt of ethanol and 40% wt of water, is subjected to batch distillation to produce a residue concentration of 5% wt. ethanol. Calculate

- 1 - Amount of distilled and residue (D, W).
 - 2 - Composition of total distilled obtained (X_D, y_D)
- V.L.E. for (ethanol-H₂O) system at 1 atm is :-

| | | | | | | | | | |
|-----|-------|------|-------|-------|------|------|------|------|------|
| x̄: | 0.025 | 0.05 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 |
| ȳ: | 0.225 | 0.36 | 0.516 | 0.655 | 0.71 | 0.74 | 0.76 | 0.78 | 0.81 |

Sol. :- F = 1000 kg, x_F = 0.6, x_w = 0.05

$$\ln \frac{F}{W} = \int_{x_w}^{x_f} \frac{dx}{y-x}$$

From eq. equilibrium data: (1/y-x) was calculated

| | | | | | | | | | |
|----------|-----|------|-----|-----|-----|-----|-----|-----|-----|
| (1/y-x): | 5.0 | 3.22 | 2.4 | 2.2 | 2.4 | 2.9 | 3.7 | 5.8 | 9.1 |
|----------|-----|------|-----|-----|-----|-----|-----|-----|-----|

To plot, we will use simple rule :-

Let n=6, h = (x_F - x_w) / n ⇒ h = 0.6 - 0.05 = 0.09

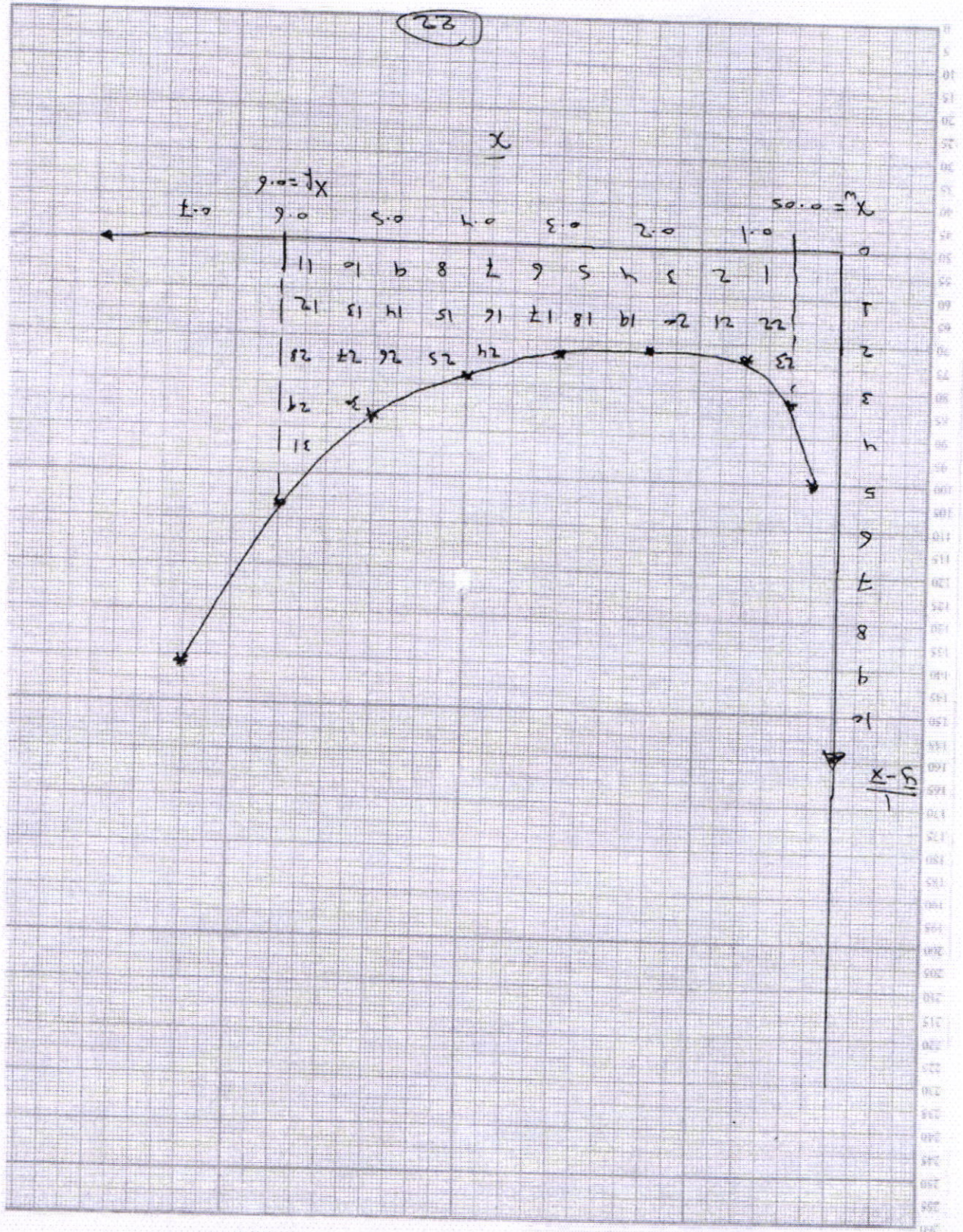
Area under-curve from (0.6) to (0.05)

$$\text{Area} = (h/3) \times \sum y$$

$$A = \frac{3}{0.09} \times 31 \Rightarrow A = 0.93 = \int \frac{dx}{y-x}$$

$$\ln \frac{F}{W} = 0.93 \Rightarrow \frac{1000}{W} = 0.394$$

22



$$W = 394 \text{ kg}$$

$$\text{Distillate (D)} = 1000 - 394 = 606 \text{ kg}$$

2- To find distillate composition

$$1000 \times 0.6 = 606 \times X_D + 394 \times 0.05$$

$$600 = 606 \times X_D + 19.7$$

$$606 X_D = 580.3$$

$$X_D = 0.957$$

Ex. (2) - A charge of 50 kmol of a mixture of benzene and chlorobenzene, having 55% of the L.V. is to be batch distilled.

- If 25 moles of the solution is vaporized and condensed as the distillate, Calculate the concⁿ of accumulated distillate.

- If the concentration of the accumulated product is found to be 72 mol% benzene, calculate its amount.

$$\text{Take } (X_{\text{Benzene}}) = 4.15$$

Sol. 2- $F = 50 \text{ kmol}$

$$X_f = 1 - 0.55 \Rightarrow X_f = 0.45$$

(a) 25 Mole to be vaporized $\therefore D = 25 \text{ kmol}$

$$F = D + W \Rightarrow W = 25 \text{ kmol}$$

(23)

(24)

From M.B.:-
 $F \cdot X_D = D \cdot X_D + W \cdot X_W$
 $50 \cdot 0.45 = D \cdot 0.72 + W \cdot X_W$
 sub. for (D) $22.5 = 0.72(50 - W) + W \cdot X_W$

$$F = D + W \Rightarrow 50 = D + W \Rightarrow \boxed{D = 50 - W}$$

(B) if $y_{av.} = X_D = 0.72$, find D

From M.B., X_D can be found.
 $F \cdot X_D = D \cdot X_D + W \cdot X_W$
 $50 \cdot 0.45 = 25 \cdot X_D + 25 \cdot 0.218$
 $\therefore X_D = Y_{av.} = 0.682$

$$\boxed{0.218 = X_W}$$

$$-0.7 = 0.32 \ln \left(\frac{0.55 X_D}{0.45(1-X_D)} \right) + \ln \left(\frac{1-X_D}{0.55} \right)$$

$$\ln \left(\frac{50}{25} \right) = \frac{1}{1-0.15} \ln \left(\frac{X_D(1-0.45)}{0.45(1-X_D)} \right) + \ln \left(\frac{1-X_D}{1-0.45} \right)$$

$$\ln \left(\frac{F}{W} \right) = \frac{r-1}{1} \ln \left(\frac{X_D(1-X_D)}{X_W(1-X_D)} \right) + \ln \left(\frac{1-X_D}{1-X_D} \right)$$

To find X_D ($y_{av.}$)
 using eq. (5) to find X_W

$$\therefore W = \frac{13.5}{0.72 - x_w}$$

sub. for (W) in eq. (5) :-

$$\ln \left(\frac{13.5 / (0.72 - x_w)}{50} \right) = \frac{1}{4.15 - 1} \ln \left(\frac{x_w (1 - 0.45)}{0.45 (1 - x_w)} \right) + \ln \left(\frac{1 - 0.45}{1 - x_w} \right)$$

$$\therefore x_w = 0.309$$

$$\therefore W = 32.85 \text{ kmol}$$

$$\therefore D = F - W$$

$$= 50 - 32.85$$

$$D = 17.15 \text{ kmol}$$

Ex. (3) - A mixture of 100 mole containing 50% mole of n-pentane and rest is n-heptane, is distilled under differential conditions at 1 atm, until (40 mole) is distilled. What are the compositions of liquid left and total vapour distilled?

| | | | | | | | | |
|----|-----|-------|-------|-------|------|-------|------|-----|
| X: | 1.0 | 0.867 | 0.594 | 0.398 | 0.25 | 0.145 | 0.05 | 0.0 |
| y: | 1.0 | 0.987 | 0.925 | 0.836 | 0.7 | 0.521 | 0.27 | 0.0 |

Sol. - Overall M.B

$$F = D + W \Rightarrow 100 = 40 + W$$

$$W = 60 \text{ mole.}$$

$$\ln \frac{F}{W} = \int_{x_w}^{x_f} \frac{dx}{y^* - x} \Rightarrow \ln \frac{100}{60} = \int_{x_w}^{0.5} \frac{dx}{y^* - x}$$

$$0.51 = \int_{x_w}^{0.5} \frac{dx}{y^* - x}$$

assume $x_w = 0.3$, y^* from the Fig.

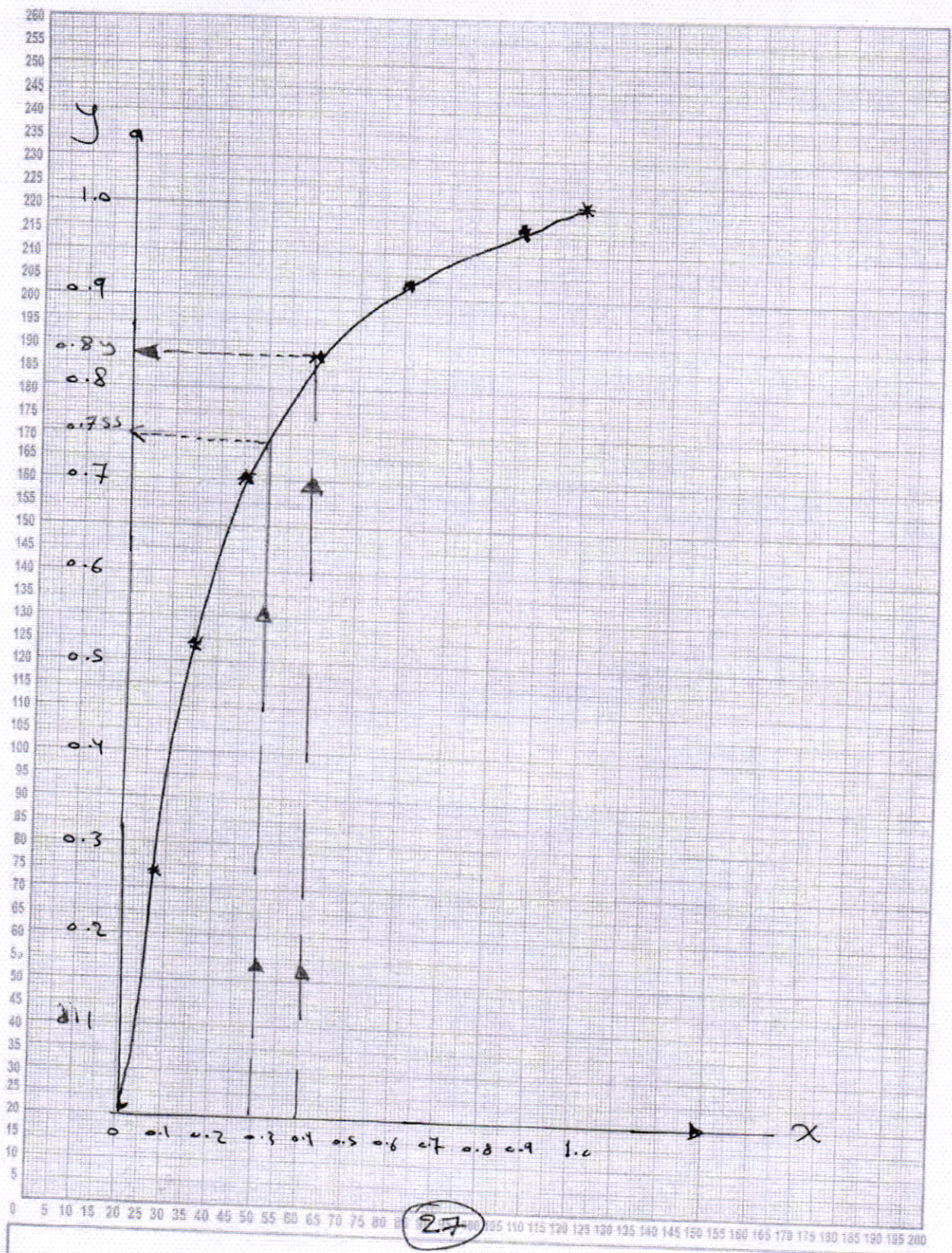
assume

| | | | | | |
|----|-----|------|-----|------|-----|
| X: | 0.3 | 0.35 | 0.4 | 0.45 | 0.5 |
|----|-----|------|-----|------|-----|

| | | | | | |
|--------------|-------|-----|------|------|------|
| From Fig. y: | 0.755 | 0.8 | 0.84 | 0.86 | 0.89 |
|--------------|-------|-----|------|------|------|

| | | | | | |
|-------------|-------|------|------|------|------|
| $y^* - x$: | 0.455 | 0.45 | 0.44 | 0.41 | 0.39 |
|-------------|-------|------|------|------|------|

| | | | | | |
|-----------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| $\frac{1}{y^* - x}$: | 2.197 | 2.22 | 2.27 | 2.44 | 2.56 |
| | (F ₀) | (F ₁) | (F ₂) | (F ₃) | (F _n) |



المادة: الموضوع: 27 / / 201

$$A = \frac{h}{3} [F_0 + 4 \sum_{\text{odd}} + 2 \sum_{\text{even}} + F_n]$$

$$A = \frac{0.05}{3} [2.197 + 4 \times (2.22 + 2.44) + 2 \times 2.27 + 2.56]$$

$$A = 0.47 \neq 0.51$$

Assume another $x_w = 0.277$

| | | | | | |
|-----------|-------|-------|-------|-------|-------|
| X: | 0.277 | 0.373 | 0.389 | 0.444 | 0.5 |
| y^* : | 0.73 | 0.78 | 0.815 | 0.855 | 0.889 |
| $y - x$: | 0.453 | 0.407 | 0.426 | 0.411 | 0.389 |

$$\frac{1}{y-x} : 2.207 \quad 2.23 \quad 2.3474 \quad 2.433 \quad 2.57$$

$$h = \frac{0.5 - 0.277}{5} = 0.045$$

$$A = \frac{0.045}{3} [2.207 + 4 \times (2.23 + 2.433) + 2 \times 2.347 + 2.57]$$

$$A = 0.42 \neq 0.51$$

$\Rightarrow x_w = 0.3$ we take this value

$$F \times x_p = W \times x_w + D \times y_D$$

$$100 \times 0.5 = 60 \times 0.3 + y_D \times 40$$

$$y_D = 0.8$$

11.201

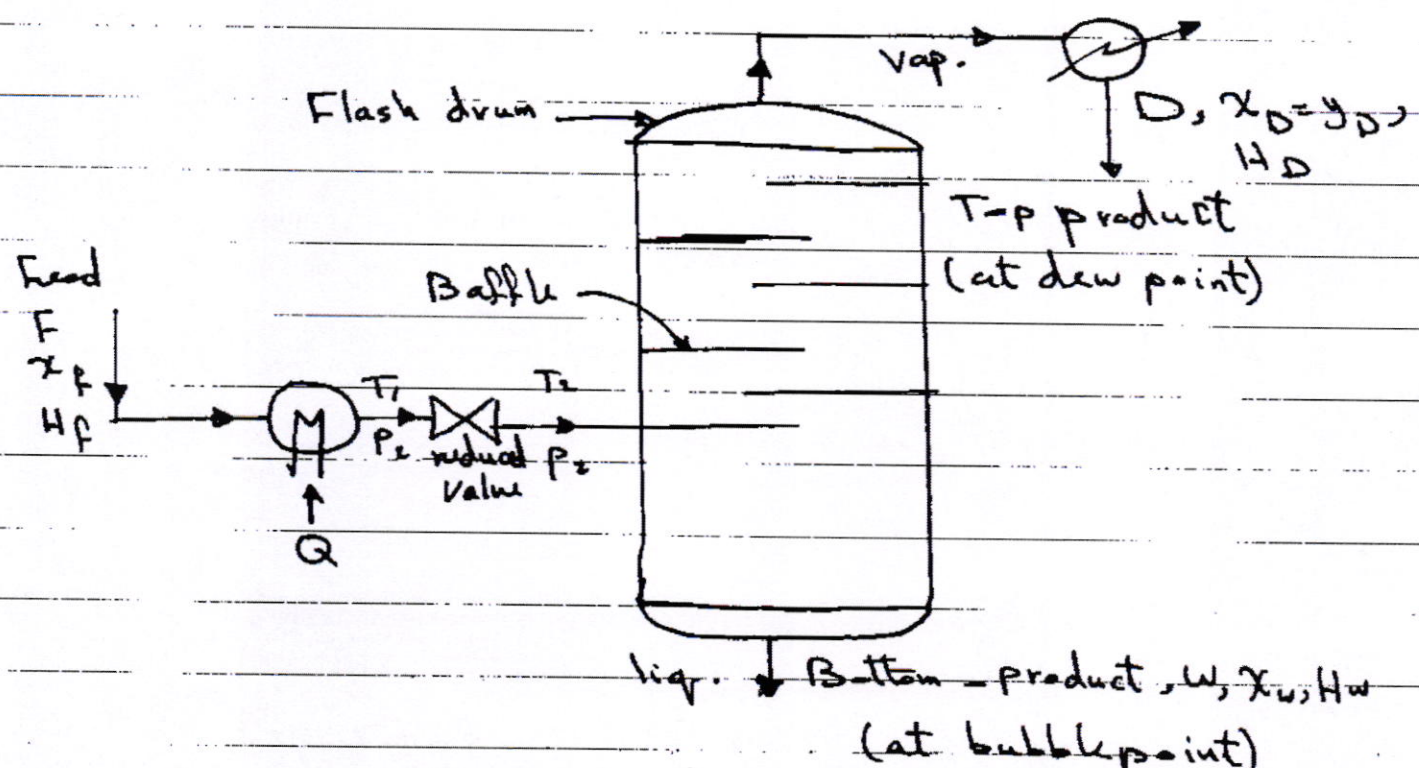
2- Flash (equilibrium) or Integral Distillation

If a sufficiently hot liquid mixture is throttled into a vessel, a part of it will vaporize. The vapour produced will be richer in the M.V.C., and thus partial separation of the desired components will be achieved. This is called "Flash vaporization or equilbⁿ vaporization". The feed is first heated in a heat exchanger under pressure and then led to a flash drum by throttling where partial vaporization of the feed occurs under reduced pressure. The vapour leaves the drum at the top and is condensed to get the top product. The fraction having a higher concentration of the L.V. leaves the drum as a liquid bottom product. It is often assumed that the liquid and vapour streams leaving the flash drum are in equilibrium, therefore the process is also called "equilibrium-vaporization".

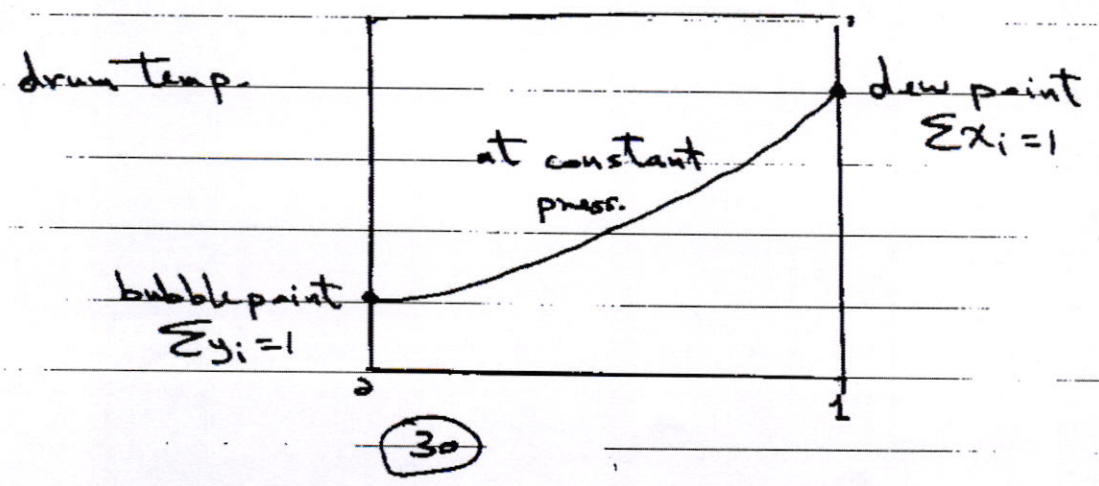
Assumption:

- 1- large contact surface between liq. and vapor, and vapor after forming should contact liquid till equilibrium occurs

- 2- Temp. and press. of vapour out = Temp. and press. of liquid out (at equilibrium).
- 3- All components exist in liquid should be exist in vapour, for vapour $\sum y_i = 1$ and liquid $\sum x_i = 1$.



" Schematic of Flash distillation Unit "



Overall M.B =

$$F = D + W$$

$$F \cdot x_F = D \cdot y_D + W \cdot x_W$$

$$F \cdot x_F = D \cdot y_D + (F - D) x_W$$

$$x_F = \frac{D}{F} y_D + \frac{(F - D)}{F} x_W$$

$$x_F = P_V \cdot y_D + (1 - P_V) x_W$$

$$y_D = \frac{x_F}{P_V} - \frac{1 - P_V}{P_V} x_W$$
 operating line equation for binary system.

$$\text{Slope} = -\frac{1 - P_V}{P_V}, \text{ intercept with (y) axis} = \frac{x_F}{P_V}$$

(*) For multicomponent system, equilibⁿ relation will be:-

$$y_i = k_i x_i \Rightarrow x_i = y_i / k_i \Rightarrow (\text{sub. for } x_W) :-$$

$$y_i = \frac{x_{Fi}}{P_V} - \frac{1 - P_V}{P_V} \frac{y_i}{k_i}$$

$$y_i = \frac{k_i x_{Fi}}{P_V (k_i - 1) + 1}$$
 for multi component.

Assume a value for $P_V < 1.0$, and calculate (y_i) for each component.

if $\sum y_i = 1$ then value assumed for (P_v) is correct.

* For ideal solutions where:

$$P_A = P_A^\circ \cdot x_A \quad \text{and} \quad k_A = \frac{y_A}{x_A}$$

then:

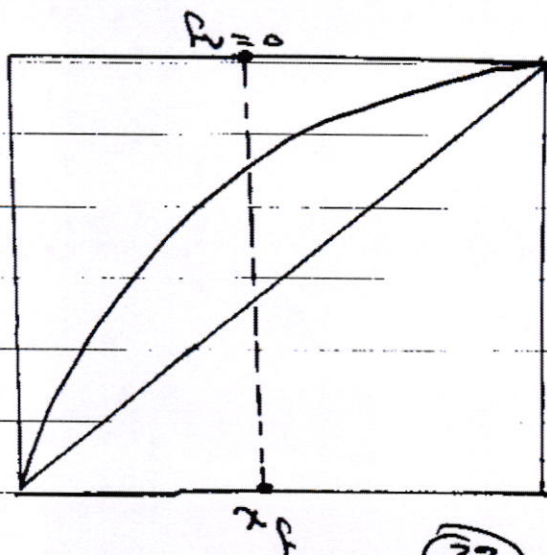
$$y_i = \frac{x_i P_i^\circ}{P_v + \frac{P_T}{P_i^\circ} (1 - P_v)}$$

For ideal solutions

* if there is no vaporization, then $D = 0$

$$P_v = \frac{D}{F} = 0, \quad \text{then slope} = \infty$$

\therefore Vertical line

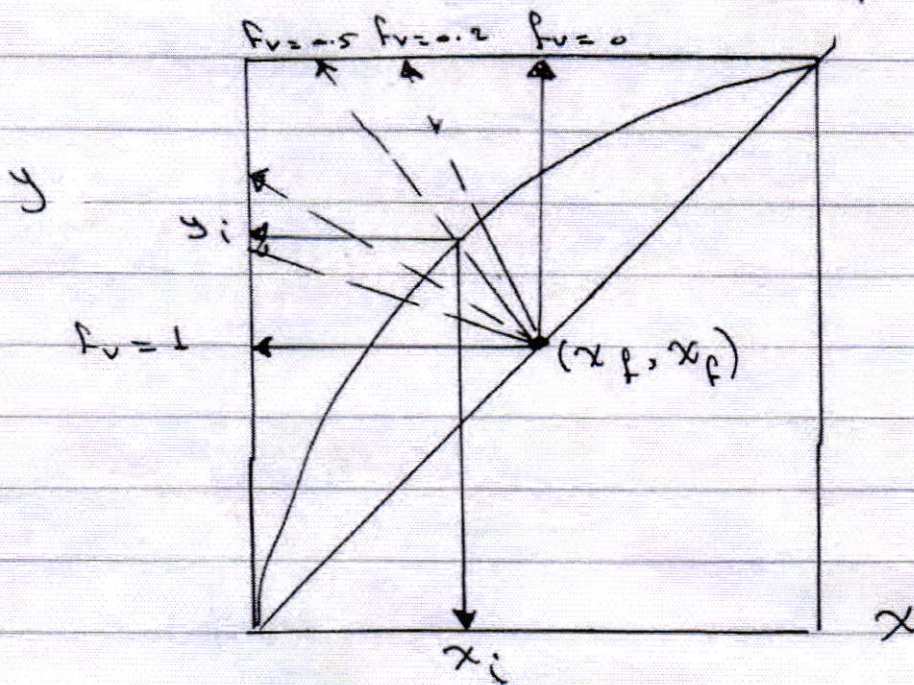
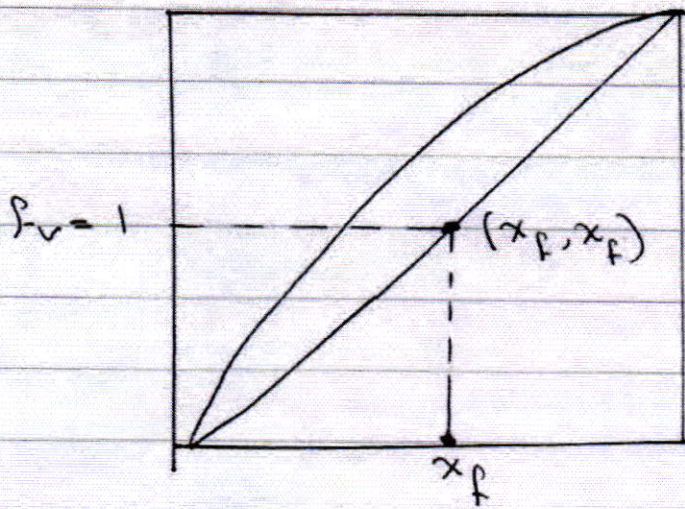


\therefore composition of product = composition of feed.

* If there is total vaporization $D \leq F$

$$\therefore \frac{D}{F} = 1, \text{ then slope} = 0$$

= horizontal line



Ex. (1) = What fraction of a liquid mixture containing 10% mole propane, 65% mole n-butane, 25% mole n-pentane, would be vaporized in a flash vaporizⁿ. process at 40°F and press. of 600 mm Hg. Assume liquid solution an ideal and vapour as an ideal.

Vapour pressure at 40°F is:-

$$P_{\text{propane}}^{\circ} = 3800 \text{ mm Hg}, \quad P_{\text{n-but.}}^{\circ} = 820 \text{ mm Hg}$$

$$P_{\text{n-pent.}}^{\circ} = 140 \text{ mm Hg}$$

Sol. = For ideal solution $\Rightarrow y_i = \frac{x_i P_i}{P_v + \frac{P_i}{P_i^{\circ}} (1 - P_v)}$

Let $P_v = 0.3$

$$y_1 = \frac{0.1}{0.3 + \frac{600}{3800} (1 - 0.3)} = 0.244$$

$$y_2 = \frac{0.65}{0.3 + \frac{600}{820} (1 - 0.3)} = 0.8$$

$$y_3 = \frac{0.25}{0.3 + \frac{600}{140} (1 - 0.3)} = 0.076$$

$$\therefore \sum y_i = 1.119$$

Assume $P_v = 0.49$

$$y_1 = 0.17, \quad y_2 = 0.75, \quad y_3 = 0.08$$

$$\therefore \sum y_i = \underline{\underline{1.0}}$$

Ex. (2) :- It is desired to separate a binary mixture by distillation, the composition of the mixture 0.5 mol%. Calculate the fraction vaporized (f_v) required to obtain a top product composition 0.75 mol. fraction when using flash distillation. Equilibrium curve $y = 1.2x + 0.3$ with the range of liquid composition (0.3 to 0.8)

Sol. :- $y = 1.2x + 0.3$

∴ vapour in contact with liquid then :-

$$y_D = 1.2x_w + 0.3$$

For $y_D = 0.75$

$$\therefore 0.75 = 1.2x_w + 0.3 \Rightarrow x_w = 0.375$$

∴ We have now two points (0.75, 0.375) and (0.5, 0.5)

∴ slope of (f_v) line can be found.

$$\text{slope} = \frac{\Delta y}{\Delta x} = \frac{0.75 - 0.5}{0.375 - 0.5} = -2$$

$$\therefore \text{slope} = -\left[\frac{1 - f_v}{f_v}\right] = -2$$

$$\therefore \underline{\underline{f_v = 0.33}}$$

Ex. (3) :- It is required to vaporize 50% of the following liquid mixture :-

60% Benzene, 30% Toluene, 10% Xylene.

What would be the composition of vapour if this mixture is subjected to flash distillation process at 1 atm, assuming an ideal liquid solution and gas.

Vapour - pressure data as follows :-

| <u>Temp. °C</u> | <u>P[°]_{Benz.}</u> | <u>P[°]_{Tol.}</u> | <u>P[°]_{Xyl.}</u> |
|-----------------|--------------------------------------|-------------------------------------|-------------------------------------|
| 60 | | 139 | 51 |
| 70 | 540 | 206 | 78 |
| 80 | 756 | 287 | 116 |
| 90 | 1008 | 404 | 168 |
| 100 | 1338 | 557 | 238 |
| 110 | 1740 | 741 | 330 |
| 120 | 2215 | 990 | 449 |

Sol. ; Hints :-

1- Take any temp. given, then multiply mole fraction (X_i) by each (P_i°) for each component and find (P_i) to each.

2- make summation (Σ) for (P_i) to find total press.

3- If this total press. = total press. given = 760 mmHg or (1 atm), then (T) chosen is correct.

- 4- From this (T) found, $(P_A^\circ, P_B^\circ, P_C^\circ)$ are known.
 5- Now, assume many values for (P_V) and find y_i , according to :-

$$y_i = \frac{x_i}{P_V + \frac{P_T}{P_i^\circ} (1 - P_V)}$$

- 6- Plot (y_i) vs (P_V) , and find (P_V) at $(y_i=1)$

if we take (assume) $T = 90$

- 1- find $P_1^\circ, P_2^\circ, P_3^\circ$ from Fig.

- 2- then calculate P_i from

$$P_1 = P_1^\circ \cdot x_1 \quad \leftarrow 0.6$$

$$P_2 = P_2^\circ \cdot x_2 \quad \leftarrow 0.3$$

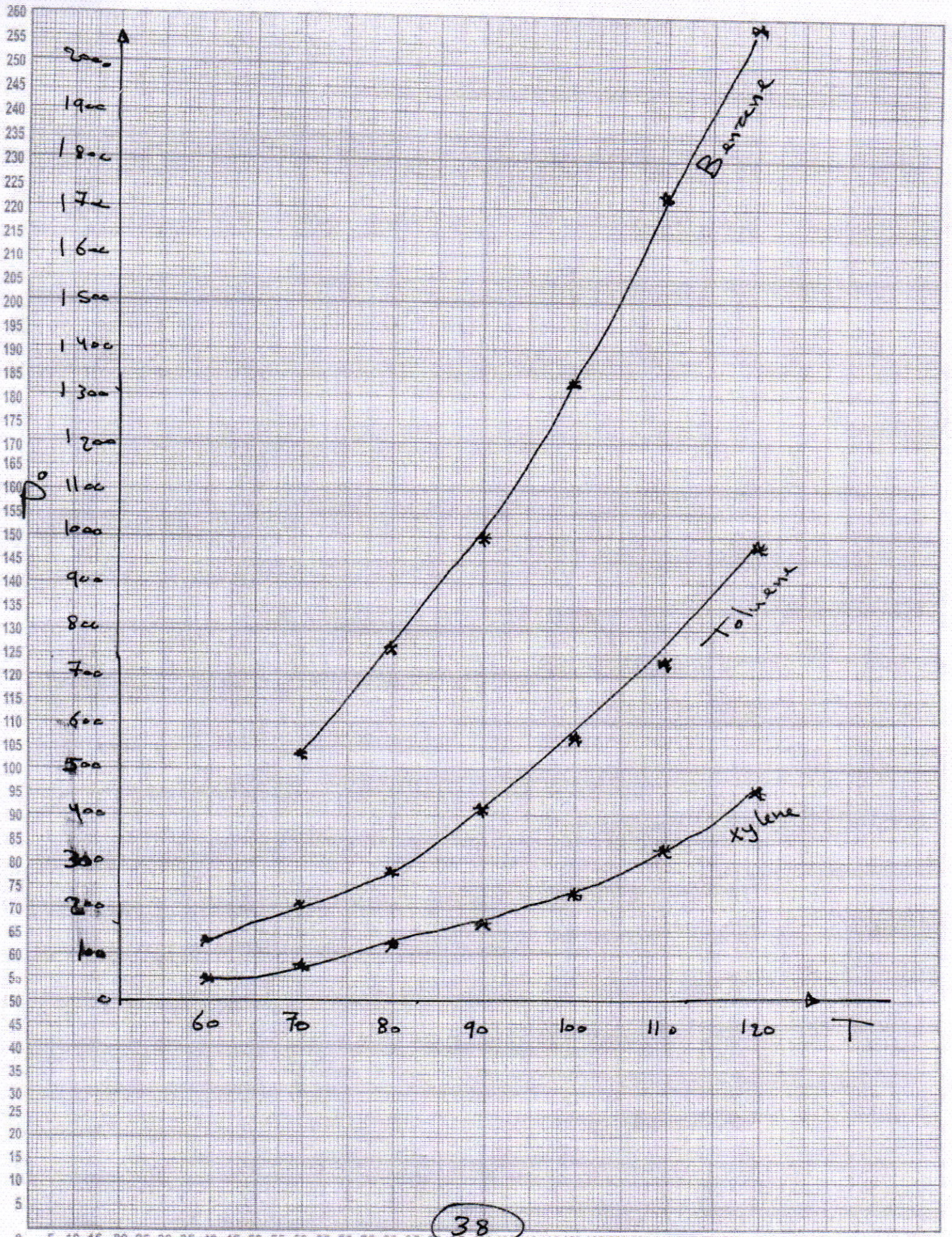
$$P_3 = P_3^\circ \cdot x_3 \quad \leftarrow 0.1$$

- 3- then if $\sum P_i \approx 1$ atm, then $\therefore T_{\text{ass.}} = \text{correct}$

- 4- then take, $P_1^\circ, P_2^\circ, P_3^\circ$, \Rightarrow Assume $P_V = 0.4$

- 5- find y_1, y_2, y_3 from $y_i = \frac{x_i}{P_V + \frac{P_T}{P_i^\circ} (1 - P_V)}$

- 6- if $\sum y_i = 1$ $\Rightarrow \Rightarrow P_{V, \text{ass.}} = \text{correct}$



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UNIT OPERATIONS

1/15

SHEET (1)

Q1: A liquid mixture containing 50% n-heptane and 50% octane were subjected to differential distillation at atmospheric pressure with 60% of liquid distilled. Compute the composition of distilled and residue, take:

- 1) Relative volatility is 2.16
- 2) The equilibrium data:

| | | | | | | |
|---|-------|-------|-------|-------|-------|-------|
| X | 0.5 | 0.46 | 0.42 | 0.38 | 0.34 | 0.32 |
| y | 0.689 | 0.648 | 0.608 | 0.567 | 0.523 | 0.497 |

Q2: A mixture of A and B is contains 50mol% of A fed to a simple distillation. Calculate the quantity of product obtained. The relative volatility is 1.6 *→ and the product contains 5 mol% of A is required*

Q3: A liquid mixture containing 40mol% n-heptane and 60mol% n-octane is fed to flash distillation at atmospheric pressure to vaporized 70% of feed, what will be the composition of vapor and liquid. The relative volatility is 2.16.

Q4: 100 moles of benzene and toluene mixture containing 50mol% benzene is subjected to differential distillation at atmospheric pressure the composition of benzene residue is 33mol%. Calculate the total moles of mixture distilled. The relative volatility is 2.16.

Q5: A liquid feed containing 1200moles of mixture A and B containing 30mol% A is differentially distilled at 100mmHg pressure and final distillate contains 55mol% of the feed solution. Calculate the composition of A in the residue. The data is:

| | | | | | | | |
|----|------|------|------|------|------|------|----|
| X% | 8.4 | 11.6 | 28.0 | 50.6 | 68.7 | 80.6 | 88 |
| Y% | 22.3 | 41.1 | 62.9 | 74.8 | 80.2 | 84.4 | 88 |



UNIT OPERATIONS

SHEET (2)

Q1: a fractionating column is required to distill a mixture of benzene and toluene containing 28.2mol% benzene, so as to give a top product of benzene 91.3% at top and 5.8% at bottom. If the reflux ratio is 3.5 is to be used and the feed enter at its boiling point. If the plates used are 100% efficient, calculate:

- 1) The composition of liquid and vapor on the third plate by Lewis-Sorel method.
- 2) Estimate the number of theoretical plates required by McCabe and thiels method.

Take the equilibrium data:

| | | | | | | | | | |
|---|-----|------|------|------|------|------|------|------|------|
| X | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
| y | 0.2 | 0.38 | 0.51 | 0.63 | 0.71 | 0.78 | 0.85 | 0.91 | 0.96 |

Q2: A liquid mixture containing 45% heptane and 55% octane is to be continuously rectified at 1 atm. to provide 95% heptane at the top and 1mol% at bottom, the feed partially vaporized with 30% liquid and 70% vapor. Find the number of plates required if the reflux ratio used equal to 4 and relative volatility 2.16.

Q3: a continuous fractionating column operating at 1 atm pressure is to design to separate a mixture containing 95.3mol% CS₂ and waste of 94.7mol% CCl₄. Assume the plate efficiency of 70% and reflux of 3.16. Using the data bellow to determine the number of plates required. Take: T_F= 290k, B.P.T.= 336k, CP= 225.4 KJ/Kmol.K, latent heat =25900KJ/Kmol

| | | | | | | | | |
|---|------|-------|-------|-------|-------|-------|-------|-------|
| X | 2.96 | 6.15 | 11.06 | 14.35 | 25.85 | 53.18 | 75.75 | 86.04 |
| y | 8.23 | 15.55 | 26.6 | 33.2 | 49.5 | 74.7 | 87.8 | 93.2 |



UNIT OPERATIONS

SHEET (2)

Q4: A mixture of 40 mole percent benzene with toluene is distilled in a column to give a product of 95% benzene and waste of 5 mole percent benzene using a reflux ratio of 4

- a) Calculate by Sorel's method the composition of the vapor on the second plate from top.
- b) Using the McCabe method to determine the number of plate required if the feed supplied to column as liquid at its boiling point.
- c) Find the minimum reflux ratio possible.
- d) Find the minimum number of plate.

