The specifications satisfy the degrees of freedom as follows.

Stage pressures	N
Adiabatic stages	N
T and P of stream S_R	2
T and P of stream $(V_N - S_R)$	2
Heat leak and P of divider and solvent mixer	4
S (feed rate not given)	$C+1$
F	$C+2$
Feed stage location	1
Solvent/feed ratio S_B/F	1
Recovery of each component in the special separator	C
Concentration of A in product and bottoms	2
	$3C+2N+15$

The points F, L_R, D, B' (solvent-free), and B (solvent-saturated) are located in Fig. 10.23. The points P′ and P″, which lie on the verticals through D and B, are found by solving for D (or B) by material balances. An overall material balance for A is

$$0.95D + 0.05B = (1000)(0.55)$$

A total overall balance is

$$D + B = 1000$$

Thus $D = 556$, $B = 444$, and, since $S_B = 4{,}000$ kg, $S_B/B = 9.0$. Now the point P″ can be located and then P′, by constructing $\overline{P'FP''}$.

Next, step off stages starting with V_N. Slightly less than six are required with the feed introduced as indicated in Fig. 10.23.

The reflux ratio L_R/D on the top stage is $\overline{P'V_N}/\overline{V_ND} = 2.95$.

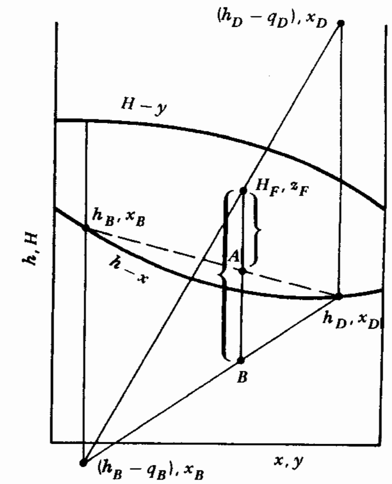
□

References

1. Ponchon, M., *Tech. Moderne*, **13**, 20, 55 (1921).
2. Savarit, R., *Arts et Mètiers*, pp. 65, 142, 178, 241, 266, 307 (1922).
3. Smith, B. D., *Design of Equilibrium Stage Processes*, McGraw–Hill Book Co., New York, 1962, 193.

Problems

10.1 An equimolal mixture of n-hexane in n-octane having an enthalpy of 4000 cal/gmole is (1) pumped from 1 to 5 atm, (2) passed through a heat exchanger, and (3) flashed to atmospheric pressure. Sixty mole percent of the feed is converted to vapor in the process. Using Fig. 10.8, determine the composition of liquid and vapor leaving the flash drum and the total heat added in the heat exchanger.



10.2 In the H-y-x diagram above, what is the significance of the lines $H_F - A$ and $H_F - B$?

10.3 An equimolal mixture of carbon tetrachloride and toluene is to be fractionated so as to produce an overhead containing 4 mole% toluene and a bottoms containing 4 mole% carbon tetrachloride. Calculate by the Ponchon method the theoretical minimum reflux ratio, the theoretical minimum number of stages, and the number of theoretical stages when $L/D = 2.5$. The thermal condition of the feed is saturated liquid, which is sent to the optimum stage.

The assumption may be made that the enthalpies of the liquid and the vapor are linear functions of composition.

	Normal Boiling Point, °C	Average Liquid Specific Heat	Latent Heat of Vaporization
CCl_4	76.4	0.225 cal/gm °C	46.42 cal/gm at 76.4°C
Toluene	110.4	0.500 cal/gm °C	86.8 cal/gm at 110.4°C

Equilibrium data (mole fractions CCl_4)

y	0.37	0.62	0.79	0.92
x	0.2	0.4	0.6	0.8

10.4 A mixture of 45 mole% isobutane in n-pentane, at conditions such that 40 mole% is vapor, is to be rectified into a distillate containing only 2 mole% n-pentane. The pressure on the system will be 308 kPa (3.04 atm absolute). The reflux is saturated liquid.

Using the data below, construct an enthalpy-concentration diagram based on an enthalpy datum of liquid at 68°F and determine the minimum number of stages required to make the separation. Also, calculate the condenser duty.

Equilibrium constants for isobutane and n-pentane.

$P = 308$ kPa (3.04 atm abs)

T, °F	K_{nC_5}	K_{iC_4}
100	0.36	1.7
140	0.70	2.6
160	0.90	3.1
150	0.80	2.9
120	0.50	2.1
80	0.25	1.3
70	0.10	1.1

Boiling point at 308 kPa (3.04 atm abs): isobutane = 20°C (68°F), n-pentane = 73.9°C (165°F).
Heat of mixing = negligible.
Heat capacity of liquid isobutane $= 0.526 + 0.725 \times 10^{-3}T$ Btu/lb · °F (T = °R)
Heat capacity of liquid n-pentane $= 0.500 + 0.643 \times 10^{-3}T$ Btu/lb · °F (T = °R)
Latent heat of vaporization at boiling point (308 kPa): isobutane = 141 Btu/lb (3.28×10^5 J/kg); n-pentane = 131 Btu/lb (3.4×10^5 J/kg).
Average heat capacity of isobutane vapor at 308 kPa (3.04 atm) = 27.6 Btu/lbmole · °F (1.15×10^5 J/kgmole · °K).
Average heat capacity of the n-pentane vapor at 308 kPa (3.04 atm) = 31 Btu/lbmole · °F (1.297×10^{-5} J/kgmole · °K)

10.5 A saturated liquid feed containing 40 mole% n-hexane and 60 mole% n-octane is fed to a distillation column at a rate of 100 gmole/hr.

A reflux ratio $L/D = 1.5\,(L/D)_{min}$ is maintained at the top of the column. The overhead product is 95 mole% hexane, and the bottoms product is 10 mole% hexane. If each theoretical plate section loses 80,000 cal/hr (3.35×10^5 J/hr), step off the theoretical plates on the Ponchon diagram, taking into account the column heat losses.

See Fig. 10.8 for H-x-y data.

10.6 A mixture of 80 mole% isopropanol in isopropyl ether is to be fractionated to produce an overhead product containing 77 mole% of the ether and a bottoms product containing 5 mole% of the ether. If the tower is to be designed to operate at 1 atm and a reflux ratio L/D of $1.3\,(L/D)_{min}$, how many theoretical plates will be required?

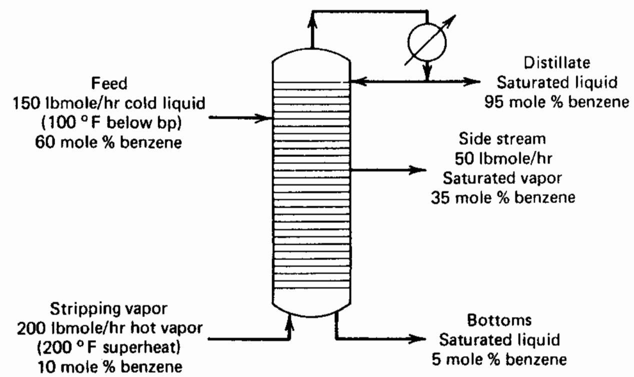
Determine the number of plates by means of an enthalpy concentration diagram. Assume that the enthalpies of the saturated liquid and the saturated vapor are linear functions of composition. The feed is introduced at its bubble point.

	Normal Boiling Point, °F	H_L, Btu/lbmole	H_V, Btu/lbmole
Isopropyl ether	155	6,580	18,580
Isopropyl alcohol	180	6,100	23,350

Equilibrium data at 1 atm with mole fractions of ether

y	0.315	0.465	0.560	0.615	0.660	0.205	0.750	0.79
x	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8

10.7 A refluxed stripper is to operate as shown below. The system is benzene–toluene at 1 atm. The stripping vapor is introduced directly below the bottom plate, and the liquid from this plate is taken as bottoms product. Using the Ponchon method, determine:
(a) The reflux ratio (L/D) at the top of the tower and the condenser heat duty.
(b) Rates of production of distillate and bottoms product.
(c) Total number of theoretical stages required.
(d) Optimum locations for introducing the feed stream and withdrawing the side stream.
Equilibrium data are given in Problem 10.16.



10.8 An equimolal mixture of carbon tetrachloride and toluene is to be fractionated so as to produce an overhead containing 6 mole% toluene and a bottoms containing 4 mole% carbon tetrachloride and a side stream from the third theoretical plate from the top containing 20 mole% toluene. The thermal conditions of the feed and side stream are saturated liquid.

The rate of withdrawal of the side stream is 25% of the column feed rate. External reflux ratio is $L/D = 2.5$. Using the Ponchon method, determine the number of theoretical plates required. However, if the specifications are excessive, make revisions before obtaining a solution.

The assumption may be made that the enthalpies of the liquid and vapor are linear functions of composition. Equilibrium data are given in Problem 10.3.

Methanol–water vapor-liquid equilibrium and enthalpy data for 1 atm (MeOH = Methyl alcohol)

Mole%	Enthalpy above 0°C Btu/lbmole solution				Vapor-Liquid Equilibrium Data J. G. Dunlop, M.S. thesis, Brooklyn Polytechn. Inst., 1948)		
MeOH	Saturated Vapor		Saturated Liquid		Mole% MeOH in		
y or x	t°C	H_V	t°C	H_L	Liquid, x	Vapor, y	Boiling Point, °C
0	100	20,720	100	3240	0	0	100
5	98.9	20,520	92.8	3070	2.0	13.4	96.4
10	97.7	20,340	87.7	2950	4.0	23.0	93.5
15	96.2	20,160	84.4	2850	6.0	30.4	91.2
20	94.8	20,000	81.7	2760	8.0	36.5	89.3
30	91.6	19,640	78.0	2620	10.0	41.8	87.7
40	88.2	19,310	75.3	2540	15.0	51.7	84.4
50	84.9	18,970	73.1	2470	20.0	57.9	81.7
60	80.9	18,650	71.2	2410	30.0	66.5	78.0
70	76.6	18,310	69.3	2370	40.0	72.9	75.3
80	72.2	17,980	67.6	2330	50.0	77.9	73.1
90	68.1	17,680	66.0	2290	60.0	82.5	71.2
100	64.5	17,390	64.5	2250	70.0	87.0	69.3
					80.0	91.5	67.6
					90.0	95.8	66.0
					95.0	97.9	65.0
					100.0	100.0	64.5

10.9 Using the above equilibrium data and the enthalpy data at the top of page 405, solve Problem 8.26 by the Ponchon method.

10.10 One hundred pound-moles per hour of a mixture of 60 mole% methanol in water at 30°C and 1 atm is to be separated by distillation at the same pressure into a distillate containing 98 mole% methanol and a bottoms product containing 96 mole% water. The overhead condenser will produce a subcooled reflux at 40°C. Determine by the Ponchon method:
(a) The minimum cold external reflux in moles per mole distillate.
(b) The number of theoretical stages required for total reflux.
(c) The number of theoretical stages required for a cold external reflux of 1.3 times the minimum.
(d) The internal reflux ratio leaving the top stage, the stage above the feed stage, the stage below the feed stage, and the bottom stage leading to the reboiler.
(e) The duties in British thermal units per hour of the condenser and reboiler.
(f) The temperatures of the top stage and the feed stage.
(g) All the items in Parts (c) to (f) if an interreboiler is inserted on the second stage from the bottom with a duty equal to half that determined for the reboiler in Part (e).

Enthalpy of the liquid, btu/lb mole of solution

Mole % MeOH	Temperature, °C 0	10	20	30	40	50	60	70	80	90	100
0	0	324	648	972	1296	1620	1944	2268	2592	2916	3240
5	−180	167	533	887	1235	1592	1933	2291	2646	2997	
10	−297	50	432	810	1181	1564	1922	2300	2673		
15	−373	−18	364	751	1145	1548	1915	2304	2686		
20	−410	−58	328	718	1129	1541	1908	2304	2693		
25	−428	−76	310	706	1123	1527	1901	2304			
30	−427	−79	308	704	1120	1537	1901	2304			
40	−410	−65	320	713	1123	1543	1910	2304			
50	−380	−36	340	731	1138	1557	1930	2318			
60	−335	7	380	765	1174	1577	1953	2345			
70	−279	63	434	812	1220	1600	1985				
80	−209	130	495	869	1260	1638	2016				
90	−121	211	562	940	1310	1678	2048				
100	0	333	675	1022	1375	1733	2092				

(h) All the items in Parts (c) to (f) if a boilup ratio of 1.3 times the minimum value is used and an intercondenser is inserted on the third stage from the top with a duty equal to half that for the condenser in Part (e).
Equilibrium and enthalpy data are given in Problem 10.9.

10.11 An equimolal bubble-point mixture of propylene and 1-butene is to be distilled at 200 psia (1.379 MPa) into 95 mole% pure products with a column equipped with a partial condenser and a partial reboiler.
(a) Construct y-x and H-y-x diagrams using the method of Section 4.7.
(b) Determine by both the McCabe–Thiele and Ponchon methods the number of theoretical stages required at an external reflux ratio equal to 1.3 times the minimum value.

10.12 A mixture of ethane and propane is to be separated by distillation at 475 psia. Explain in detail how a series of isothermal flash calculations using the Soave–Redlich–Kwong equation of state can be used to establish y-x and H-y-x diagrams so that the Ponchon–Savarit method can be applied to determine the stage and reflux requirements.

10.13 One hundred kilogram-moles per hour of a 30 mole% bubble-point mixture of acetone (1) in water (2) is to be distilled at 1 atm to obtain 90 mole% acetone and 95 mole% water using a column with a partial reboiler and a total condenser. The van Laar constants at this pressure are (E. Hale et al., *Vapour-Liquid Equilibrium Data at Normal Pressures*, Pergammon Press, Oxford, 1968) $A_{12} = 2.095$ and $A_{21} = 1.419$.
(a) Construct y-x and H-y-x diagrams at 1 atm.

(b) Use the Ponchon–Savarit method to determine the equilibrium stages required for an external reflux ratio of 1.5 times the minimum value.

10.14 A feed at 21.1°C, 101 kPa (70°F, 1 atm) containing 50.0 mass% ethanol in water is to be stripped in a reboiled stripper to produce a bottoms product containing 1.0 mass% ethanol. Overhead vapors are withdrawn as a top product.
(a) What is the minimum heat required in the reboiler per pound of bottoms product to effect this separation?
(b) What is the composition of the distillate vapor for Part (a)?
(c) If V/B at the reboiler is 1.5 times the minimum and the Murphree plate efficiency (based on vapor compositions) is 70%, how many plates are required for the separation?
Equilibrium data for this system at 1 atm are as follows.

Saturation Temp., °F	Ethanol Concentration: Mass fraction in liquid	Ethanol Concentration: Mass fraction in vapor	Enthalpy of Mixture Btu/lb: Liquid	Enthalpy of Mixture Btu/lb: Vapor
212	0	0	180.1	1150
208.5	0.020	0.192		
204.8	0.040	0.325		
203.4	0.050	0.377	169.3	1115
197.2	0.100	0.527	159.8	1072
189.2	0.200	0.656	144.3	1012.5
184.5	0.300	0.713	135.0	943
179.6	0.500	0.771	122.9	804
177.8	0.600	0.794	117.5	734
176.2	0.700	0.822	111.1	664
174.3	0.800	0.858	103.8	596
174.0	0.820	0.868		
173.4	0.860	0.888		
173.0	0.900	0.912	96.6	526
173.0	1.000	0.978	89.0	457.5

Note: Reference states for enthalpy = pure liquids, 32°F.

10.15 An equimolal mixture of acetic acid and water is to be separated into a distillate containing 90 mole% water and a bottoms containing 20 mole% water with a plate column having a partial reboiler and a partial condenser. Determine the minimum reflux, and, using a reflux L/D 1.5 times the minimum, calculate the theoretical plates. Assume linear H-x-y, feed on the optimum plate, and operation at 1 atm.
If the Murphree efficiency is 85%, how many stages are required?

Equilibrium data (mole fraction water)

y	0.17	0.3	0.42	0.53	0.63	0.72	0.79	0.86	0.93
x	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9

Notes: Acetic Acid: Liquid C_p = 31.4 Btu/lbmole · °F(1.31 × 10^{-5} J/kgmole · °K).
At normal bp, heat of vap. = 10,430 Btu/lbmole (2.42 × 10^7 J/kgmole).
Water: Liquid C_p = 18.0 Btu/lbmole · °F (7.53 × 10^4 J/kgmole · °K).
At normal bp, heat of vap. = 17,500 Btu/lbmole (4.07 × 10^7 J/kgmole).

10.16 An equimolal mixture of benzene and toluene is to be distilled in a plate column at atmospheric pressure. The feed, saturated vapor, is to be fed to the optimum plate. The distillate is to contain 98 mole% benzene, while the bottoms is to contain 2 mole% benzene. Using the Ponchon method and data below [*Ind. Eng. Chem.*, **39**, 752 (1947)], calculate:
(a) Minimum reflux ratio (L/D).
(b) The number of theoretical plates needed and the duties of the reboiler and condenser, using a reflux ratio (L/V) of 0.80.
(c) To which actual plate the feed should be sent, assuming an overall plate efficiency of 65%.

Enthalpy data (1 Atm, 101 kPa)

Composition, mole fraction benzene: x	y	Enthalpy, Btu/lbmole: Saturated Liquid	Saturated Vapor
0	0.00	8,075	21,885
0.1	0.21	7,620	21,465
0.2	0.38	7,180	21,095
0.3	0.51	6,785	20,725
0.4	0.62	6,460	20,355
0.5	0.72	6,165	19,980
0.6	0.79	5,890	19,610
0.7	0.85	5,630	19,240
0.8	0.91	5,380	18,865
0.9	0.96	5,135	18,500
1.0	1.00	4,900	18,130

10.17 A feed stream containing 35 wt% acetone in water is to be extracted at 25°C in a countercurrent column with extract and raffinate reflux to give a raffinate containing 12% acetone and an extract containing 55% acetone. Pure 1,1,2,-trichloroethane, which is to be the solvent, is removed in the solvent separator, leaving solvent-free product. Raffinate reflux is saturated. Determine
(a) The minimum number of stages.
(b) Minimum reflux ratios.
(c) The number of stages for an extract solvent rate twice that at minimum reflux.
Repeat using a feed containing 50 wt% acetone. Was reflux useful in this case? Feed is to the optimum stage.

System acetone-water-1, 1, 2-trichloroethane, 25°C, composition on phase boundary [*Ind. Eng. Chem.*, 38, 817 (1946)]

	Acetone, weight fraction	Water, weight fraction	Trichloroethane, weight fraction
	0.60	0.13	0.27
	0.50	0.04	0.46
	0.40	0.03	0.57
Extract	0.30	0.02	0.68
	0.20	0.015	0.785
	0.10	0.01	0.89
	0.55	0.35	0.10
	0.50	0.43	0.07
	0.40	0.57	0.03
Raffinate	0.30	0.68	0.02
	0.20	0.79	0.01
	0.10	0.895	0.005

Tie-line data

Raffinate, weight fraction acetone	Extract, weight fraction acetone
0.44	0.56
0.29	0.40
0.12	0.18

Note: This problem is more easily solved using the techniques of Chapter 11.

10.18 A feed mixture containing 50 wt% *n*-heptane and 50 wt% methyl cyclohexane (MCH) is to be separated by liquid–liquid extraction into one product containing 92.5 wt% methylcyclohexane and another containing 7.5 wt% methylcyclohexane. Aniline will be used as the solvent.

(a) What is the minimum number of theoretical stages necessary to effect this separation?

(b) What is the minimum extract reflux ratio?

(c) If the reflux ratio is 7.0, how many theoretical contacts will be required?

Liquid–liquid equilibrium data for the system *n*-heptane–methyl cyclohexane–aniline at 25°C and at 1 atm (101 kPa)

Hydrocarbon Layer		Solvent Layer	
Weight percent MCH, solvent-free basis	Pounds aniline/ pound solvent-free mixture	Weight percent MCH, solvent-free basis	Pounds aniline/ pound solvent-free mixture
0.0	0.0799	0.0	15.12
9.9	0.0836	11.8	13.72
20.2	0.087	33.8	11.5
23.9	0.0894	37.0	11.34
36.9	0.094	50.6	9.98
44.5	0.0952	60.0	9.0
50.5	0.0989	67.3	8.09
66.0	0.1062	76.7	6.83
74.6	0.1111	84.3	6.45
79.7	0.1135	88.8	6.0
82.1	0.116	90.4	5.9
93.9	0.1272	96.2	5.17
100.0	0.135	100.0	4.92