

Chapter 7:

Batch Distillation

In the previous chapters, we have learned the distillation operation in the *continuous* mode, meaning that

- the feed(s) is(are) fed *continuously* into the distillation column
- the distillation products [*e.g.*, distillate, bottom, side stream(s)] are *continuously* withdrawn from the column

In the continuous operation, after the column has been operated for a certain period of time, the system reaches a **steady state**

At *steady state*, the **properties** of the **system**, such as

- the feed flow rate
- the flow rates of, *e.g.*, the distillate and the bottom
- the feed composition
- the compositions of the distillate and the bottom
- reflux ratio (L_o / D)
- system's pressure

are **constant**

With these characteristics, a ***continuous distillation*** is the *thermodynamically* and *economically* **efficient** method for producing ***large*** amounts of material of ***constant*** composition

However, when *small* amounts of products of *varying* compositions are required, a *batch distillation* provides several *advantages* over the *continuous* distillation (the details of the *batch* distillation will be discussed later in this chapter)

Batch distillation is *versatile* and commonly employed for producing *biochemical*, *biomedical*, and/or *pharmaceutical* products, in which the production *amounts* are *small* but a very high *purity* and/or an *ultra clean* product is *needed*

The equipment for batch distillation can be arranged in a wide variety of configurations

In a *simple* batch distillation (Figure 7.1), *vapour* (*i.e.* the *product*) is *withdrawn* from the *top* of the re-boiler (which is also called the “**still pot**”) *continuously*, and by doing so, the *liquid level* in the still pot is *decreasing continuously*

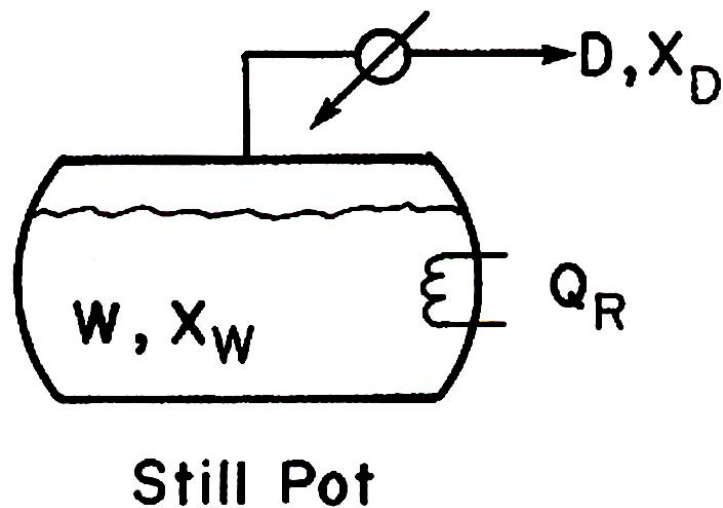


Figure 7.1: A simple batch distillation

(from “Separation Process Engineering” by Wankat, 2007)

Note that the *distillation system* shown in **Figure 7.1** is *similar* to the *flash distillation*

However, there are a number of *differences* between the *batch* distillation (*e.g.*, Figure 7.1) and the *flash* distillation: *i.e.*

- in the *flash* distillation, feed is *continuously* fed into the column, whereas there is ***no continuous feed*** input into the **still pot** for the *batch* distillation
- in the *flash* distillation, the products (*i.e.* vapour and liquid products) are withdrawn continuously from the system, whereas, for the *batch* distillation, the **remaining liquid** in the **still pot** is ***drained out*** of the pot (or the re-boiler) ***only*** at the ***end of the distillation***

Another configuration of batch distillation is a ***constant-level batch distillation***, which is similar to the simple batch distillation, as illustrated in Figure 7.1; however, in this configuration, the **liquid** (*i.e.* the feed) is ***continuously fed*** into the still pot (or the re-boiler) to **keep** the ***liquid level*** in the pot ***constant***

The ***more complex*** batch distillation (than the *simple* and the *constant-level* batch distillation) is the ***multi-stage batch distillation***

In this distillation system, a staged or packed distillation column is placed on top of the re-boiler (or the still pot), as shown in Figure 7.2

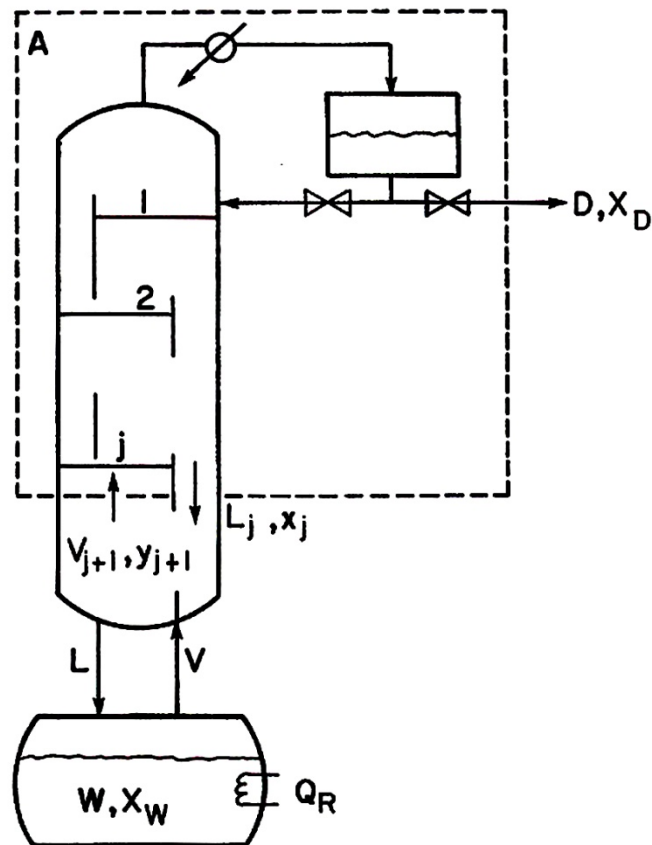


Figure 7.2: A multi-stage batch distillation

(from “Separation Process Engineering” by Wankat, 2007)

In the *usual* operation of the *multi-stage* distillation system, the **distillate** is **withdrawn continuously** from the system, until the distillation is ended

Another way of operating the multi-stage batch distillation is that the system is operated such that there is ***no distillate withdrawn*** from the column (or system), thus **resulting in a *continuous change*** in the ***concentration*** or ***composition*** of ***liquid*** in the ***pot*** (or the ***re-boiler***)

Additionally, when a ***pure bottom product*** is ***required***, an ***inverted batch distillation*** is employed

In this technique (*i.e.* the inverted batch distillation), the **bottom product** or the ***liquid*** in the **re-boiler** is **withdrawn *continuously*** while the ***distillate*** is **withdrawn only at the *end*** of the distillation

7.1 Binary-mixture Batch Distillation: Rayleigh Equation

The material balances for the *batch* distillation are *different* from those for *continuous* distillation

In the *batch* distillation, the *main focus* is at the **total amounts** of **input(s)** [*i.e.* feed(s)] and **outputs** (*e.g.*, distillate or bottom) collected at the end of the distillation, *rather than* the **rates** of such inputs and outputs

The material balances around the *batch distillation* system for the *entire operating time* are as follows

Overall:

$$F = W_{\text{final}} + D_{\text{total}} \quad (7.1)$$

where

F = the *total* amount of *feed* fed into the distillation column for the *entire* operating period

W_{final} = the final amount of liquid in the re-boiler (the notation W is used because the remaining liquid in the still pot is normally a *waste*)

D_{total} = the total amount of the distillate withdrawn from the distillation column (in some textbooks, the notation D_{final} may be used)

Species balance (for a more volatile component: MVC):

$$x_F F = x_{w, \text{final}} W_{\text{final}} + x_{D, \text{avg}} D_{\text{total}} \quad (7.2)$$

where

x_F = mole fraction of a more volatile species in the feed

$x_{w, \text{final}}$ = the mole fraction of an MVC of the remaining liquid in the re-boiler

$x_{D, \text{avg}}$ = an *average* concentration of an MVC in the distillate
(in some textbooks the notation $x_{D, \text{final}}$ may be used)

Normally, F and x_F are specified (or given in the problem statement), and the value of either $x_{w,\text{final}}$ or $x_{D,\text{avg}}$ is also specified (or given)

Thus, there are **3 unknowns** for the *binary-mixture batch* distillation system:

- W_{final}
- D_{total}
- either $x_{D,\text{avg}}$ or $x_{w,\text{final}}$

Problematically, however, by just performing material balances, we have only 2 equations (*i.e.* Eqs. 7.1 and 7.2)

Hence, another or additional equation is required

The *additional* equation for solving *batch distillation* problems is commonly known as the *Rayleigh* equation

To derive this equation, Lord Rayleigh (1902) employed the facts that (see Figure 7.1), at any instant of time,

- 1) the rate of the distillate flowing out of the batch distillation system, dD , is equal to the decreasing rate of the liquid in the still pot, $-dW$
- 2) the rate of species i in the distillate flowing out of the batch distillation system, $x_D dD$, is equal to the decreasing rate of species i the liquid in the still pot $-d(Wx_w)$

Thus, the following equations can be formulated:

$$dD = -dW \quad (7.3)$$

$$x_D dD = -d(Wx_w) \quad (7.4)$$

Note that it is assumed that, at any instant of time, the *concentration* or the *composition* of the *distillate* (x_D) is *constant*

Combining Eq. 7.3 with Eq. 7.4 and re-arranging gives

$$-x_D dW = -d(Wx_w)$$

$$-x_D dW = -W dx_w - x_w dW \quad (7.5)$$

Re-arranging Eq. 7.5 and integrating the resulting equation yields

$$W dx_w = x_D dW - x_w dW$$

$$W dx_w = (x_D - x_w) dW$$

$$\frac{dx_w}{(x_D - x_w)} = \frac{dW}{W}$$

$$\int_{W=F}^{W=W_{\text{final}}} \frac{dW}{W} = \int_{x_w=x_F}^{x_w=x_{w,\text{final}}} \frac{dx_w}{x_D - x_w}$$

which results in

$$\ln\left(\frac{W_{\text{final}}}{F}\right) = \int_{x_F}^{x_{w,\text{final}}} \frac{dx_w}{x_D - x_w} \quad (7.6a)$$

or

$$\ln\left(\frac{W_{\text{final}}}{F}\right) = - \int_{x_{w,\text{final}}}^{x_F} \frac{dx_w}{x_D - x_w} \quad (7.6b)$$

In order to perform an integration of the right hand side (RHS) of Eq. 7.6 (a & b), x_D must be a function of x_w :

$$x_D = y = f(x_w)$$

For a simple batch distillation shown in Figure 7.1, it is reasonable to assume that the *vapour* that comes out of the top of the still pot (or the re-boiler) [note that the amount of the vapour is equal to that of the distillate] is *in equilibrium* with the *liquid* (W) in the re-boiler

Thus, if the *total condenser* is used,

$$y = x_D$$

and x_D and x_w can be related to each other using an *equilibrium curve* or *equilibrium equation*

Accordingly, Eq. 7.6b can be re-written as follows

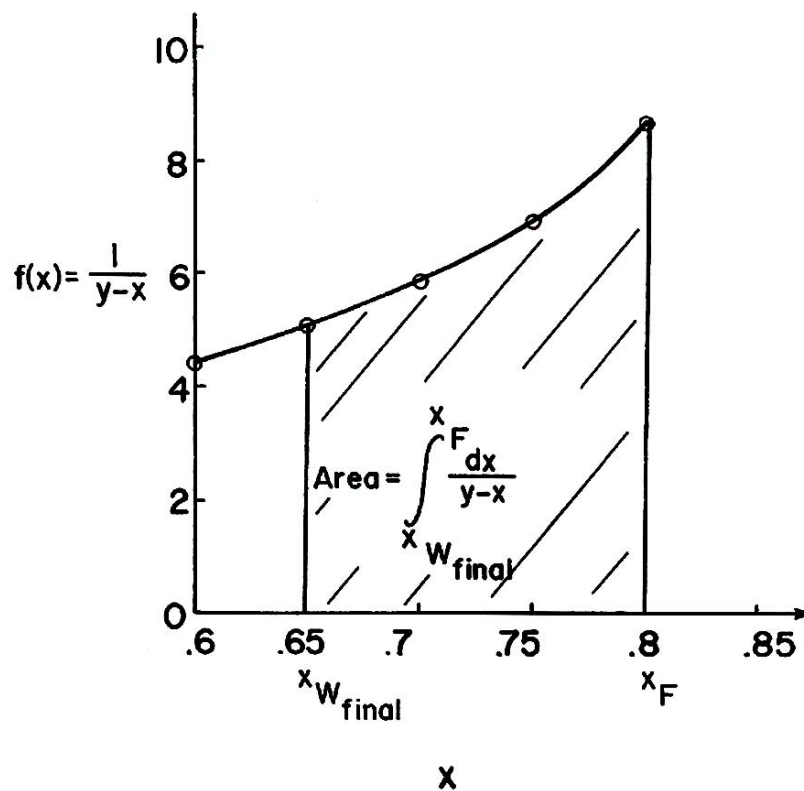
$$\ln\left(\frac{W_{\text{final}}}{F}\right) = - \int_{x_{w,\text{final}}}^{x_F} \frac{dx}{y-x} = - \int_{x_{w,\text{final}}}^{x_F} \frac{dx}{f(x)-x} \quad (7.7)$$

Note that $y = f(x) = x_D$ and $x = x_w$

The integration of the RHS of Eq. 7.7 can be done sequentially (ตามขั้นตอน) as follows

- 1) Plot an *equilibrium curve*
- 2) At each value of x (from x_F to $x_{w,\text{final}}$),
determine the value of y (or x_D) from the
equilibrium curve/equation

- 3) Plot $\frac{1}{y-x}$ (Y-axis) against x (X-axis) or fit it to an equation
- 4) Graphically determine the area under the curve from x_F to $x_{w, \text{final}}$ or perform the integration analytically or numerically from x_F to $x_{w, \text{final}}$; the graphical integration is as illustrated below



(from “Separation Process Engineering” by Wankat, 2007)

After the *numerical value* of the *integration* is obtained, the value of W_{final} (*i.e.* the amount of liquid remained in the still pot) can be obtained from manipulating Eq. 7.7 as follows

$$W_{\text{final}} = F \exp \left(- \int_{x_{w,\text{final}}}^{x_F} \frac{dx}{y - x} \right) \quad (7.8a)$$

or

$$W_{\text{final}} = F \exp \left(-\text{area under the curve} \right) \quad (7.8b)$$

Finally, the value of the *average* distillate concentration, $x_{D,\text{avg}}$, and the total amount of the distillate, D_{total} , can be obtained by solving Eqs. 7.1 and 7.2:

$$F = W_{\text{final}} + D_{\text{total}} \quad (7.1)$$

$$x_F F = x_{w, \text{final}} W_{\text{final}} + x_{D, \text{avg}} D_{\text{total}} \quad (7.2)$$

simultaneously, which results in

$$x_{D, \text{avg}} = \frac{x_F F - x_{w, \text{final}} W_{\text{final}}}{F - W_{\text{final}}} \quad (7.9)$$

and

$$D_{\text{total}} = F - W_{\text{final}} \quad (7.10)$$

In the case that the equilibrium relationship between $y(x_D)$ and $x(x_w)$ is given as

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

the RHS of Eq. 7.7 can be integrated *analytically* as follows

$$\begin{aligned}
\ln\left(\frac{W_{\text{final}}}{F}\right) &= - \int_{x_{w,\text{final}}}^{x_F} \frac{dx}{y-x} \\
&= \frac{1}{(\alpha-1)} \ln \left[\frac{x_{w,\text{final}}(1-x_F)}{x_F(1-x_{w,\text{final}})} \right] \\
&\quad + \ln \left[\frac{(1-x_F)}{(1-x_{w,\text{final}})} \right]
\end{aligned}
\tag{7.11}$$

For the problem that the value of x_D is specified, and the value of $x_{w,\text{final}}$ is to be determined, a *trial & error* technique must be employed as follows

- 1) Make a first (1st) guess for the value of $x_{w,\text{final}}$ and calculate the value of the integration of Eq. 7.8a or determine the area

under the curve for Eq. 7.8b, according to the *guessed* value of $x_{w, \text{final}}$

- 2) Then, the value of W_{final} can be calculated from Eq. 7.8 (either a or b)
- 3) Use the value of W_{final} obtained from 2 and the guessed value of $x_{w, \text{final}}$ made in 1, combined with the given values of F and x_F , to compute the values of D_{calc} and $x_{D, \text{calc}}$ using the following equations:

$$D_{\text{calc}} = F - W_{\text{final}} \quad (7.12)$$

and

$$x_{D, \text{calc}} = \frac{x_F F - x_{w, \text{final}} W_{\text{final}}}{D_{\text{calc}}} \quad (7.13)$$

4) Compare the value of $x_{D,\text{calc}}$ obtained from 3 with the given value of x_D : if $x_{D,\text{calc}} = x_D$, the trial & error procedure is finished; however, if $x_{D,\text{calc}} \neq x_D$, the **new trial & error** has to be repeated, until we obtain the guessed value of $x_{w,\text{final}}$ that makes $x_{D,\text{calc}} = x_D$

The following Example illustrates the employment of the *trial & error* technique to solve the *batch distillation* problem

Example Use the given equilibrium data of methanol (MeOH) and water for solving the simple *batch distillation* problem with the following description:

A *single-equilibrium-stage* (or a *simple*) batch still pot is used to separate MeOH from water

The feed with the total amount of 50 moles of an 80 mol% MeOH is charged into the still pot operated at 1 atm

The desired distillate concentration (x_D) is 89.2 mol% MeOH

Determine:

a) the total amount of the distillate collected

$$\left(D_{\text{total}} \right)$$

b) the amount of material (liquid or waste)

remained in the pot after the distillation

has ended $\left(W_{\text{final}} \right)$ and its corresponding

concentration $\left(x_{w, \text{final}} \right)$

It is given that

- $F = 50$ moles
- $x_F = 0.80$
- $x_{D, \text{avg}} = 0.892$

The equilibrium $(y - x)$ data of MeOH is as summarised in the following Table

Methanol liquid (x_{MeOH})	Methanol vapour (y_{MeOH})
(mol%)	(mol%)
0	0
2.0	13.4
4.0	23.0
6.0	30.4
8.0	36.5
10.0	41.8
15.0	51.7
20.0	57.9
30.0	66.5
40.0	72.9
50.0	77.9
60.0	82.5
70.0	87.0
80.0	91.5
90.0	95.8
95.0	97.9
100.0	100.0

In this Example, the unknowns are

- D_{total}
- W_{final}
- $x_{w,\text{final}}$

Since $x_{w,\text{final}}$, one of the integral boundaries, is NOT known, a *trial & error* technique must be

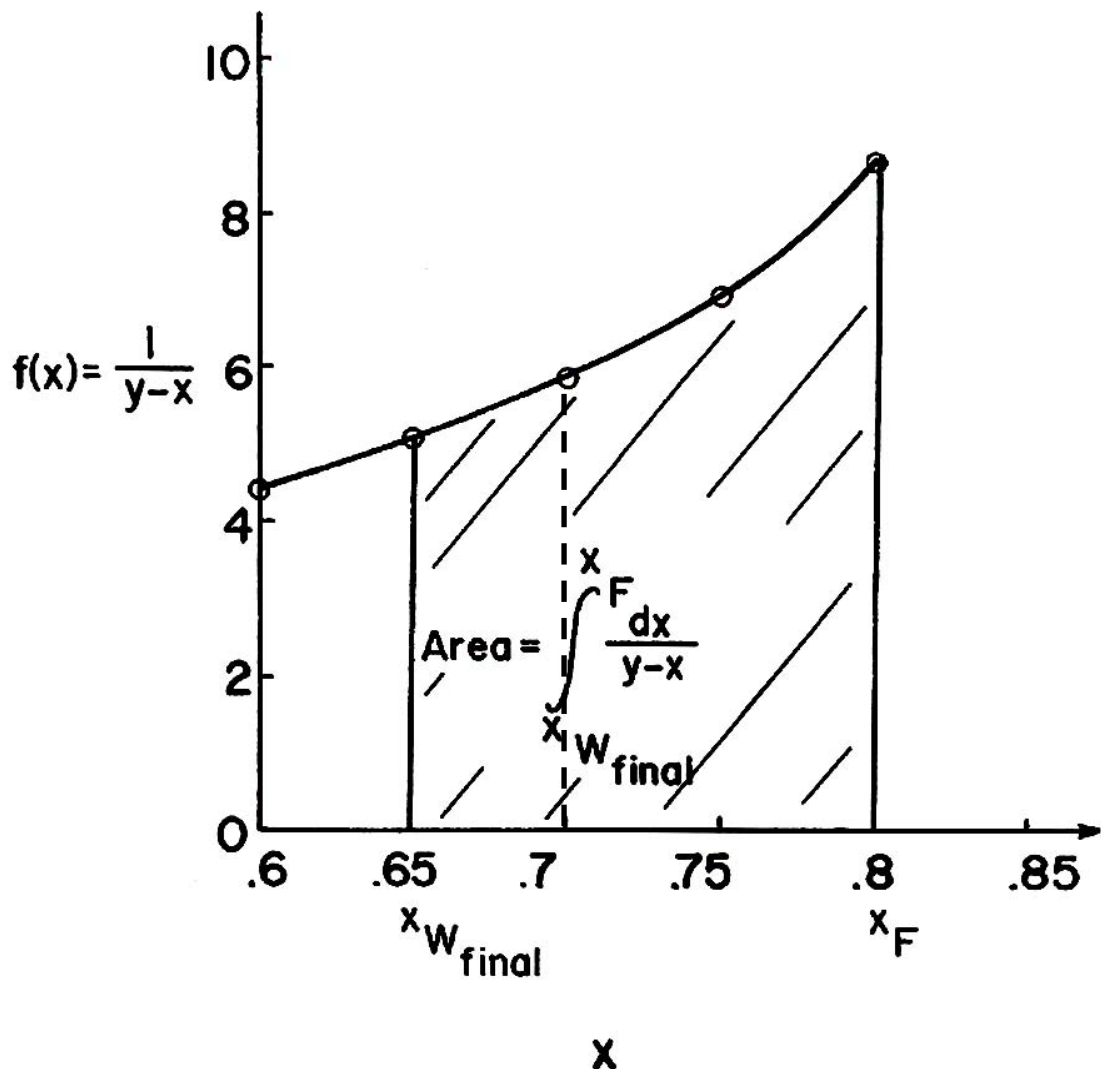
employed to compute the integral $\int_{x_{w,\text{final}}}^{x_F} \frac{dx}{y-x}$

To start the calculations, the 1st guess with $x_{w,\text{final}}$ of 0.70 is used

From the given *equilibrium data*, the value of $\frac{1}{y-x}$ for each value of x can be summarised in the following Table (note that interpolations are needed to obtain the values of y and $\frac{1}{y-x}$ when the values of x are, *e.g.*, 0.75, 0.65):

x	y	$y-x$	$\frac{1}{y-x}$
0.80	0.915	0.115	8.69
0.75	0.895	0.145	6.89
0.70	0.871	0.171	5.85
0.65	0.845	0.195	5.13
0.60	0.825	0.225	4.44
0.50	0.780	0.280	3.57

Plotting a graph between x (X-axis) and $\frac{1}{y-x}$ (Y-axis) using the data in the Table on the previous Page, from $x_{w, \text{final}} = 0.70$ (the dashed lines) to $x_F = 0.80$, yields the following graph



(from "Separation Process Engineering" by Wankat, 2007)

From the resulting graph, $\int_{0.70}^{0.80} \frac{dx}{y-x}$ is, in fact, the **area under the curve** from $x = 0.70$ to $x = 0.80$

For this Example, the **area under the curve** is found to be **0.7044**

The value of W_{final} (*i.e.* the liquid remained in the still pot) can then be calculated, using Eq. 7.8b, as follows

$$\begin{aligned} W_{\text{final}} &= F \exp(-\text{area under the curve}) \\ &= (50) \exp(-0.7044) \end{aligned}$$

$$W_{\text{final}} = 24.72 \text{ mol}$$

Thus, the *total* amount of the distillate can be computed using from Eq. 7.12 as follows

$$\begin{aligned}D_{\text{calc}} &= F - W_{\text{final}} \\ &= 50 - 24.72\end{aligned}$$

$$D_{\text{calc}} = 25.28$$

The value of $x_{D,\text{calc}}$ can be calculated using Eq. 7.13 as follows

$$\begin{aligned}x_{D,\text{calc}} &= \frac{x_F F - x_{w,\text{final}} W_{\text{final}}}{D_{\text{calc}}} \\ &= \frac{[(0.80)(50)] - [(0.70)(24.72)]}{(25.28)}\end{aligned}$$

$$x_{D,\text{calc}} = 0.898$$

However, the *desired* value of x_D or $x_{D,\text{avg}}$ is 0.892 – the **calculated x_D value is too high!**

Thus, a new guess of $x_{w, \text{final}}$ is needed

With the new guess of $x_{w, \text{final}}$ of 0.60, we obtain the following (by performing similar calculations as above):

- area under the curve from $x_{w, \text{final}} = 0.60$ to $x_F = 0.80$ is 1.2084
- $W_{\text{final}} = 50 \exp(-1.2084) = 14.93$
- $D_{\text{calc}} = F - W_{\text{final}} = 50 - 14.93 = 35.07$
- $x_{D, \text{calc}} = 0.885$ (**too low!**)

Hence, we need to make a new (the 3rd) guess for $x_{w, \text{final}}$

With the 3rd guess of $x_{w,\text{final}}$ of 0.65, we obtain the following (try doing the detailed calculations yourself):

- area under the curve (from $x = 0.65$ to $x = 0.80$) = 0.9710
- $W_{\text{final}} = 18.94$
- $D_{\text{calc}} = 31.06$
- $x_{D,\text{calc}} = 0.891$ (O.K. – **close enough!**)

7.2 Constant-level Batch Distillation

The recent Example is the *simple batch* distillation problem in which the amount of liquid in the still pot is decreasing as the distillation proceeds (while the distillate is being collected)

In a *constant-level* batch distillation, which is another configuration of a batch distillation, a **solvent** (or the feed) is **added** to the re-boiler (or the still pot) to **keep** the **level** of the liquid in the pot **constant**

Note that, during the addition of the solvent, the **total number of moles of all species** in the still pot is kept **constant**

The total mole balance is

$$[\text{In}] - [\text{Out}] = \left[\begin{array}{l} \text{Accumulation} \\ \text{in the still pot} \end{array} \right] \quad (7.14)$$

Since, in this kind of batch distillation, the **total number of moles is constant**, Eq. 7.14 becomes

$$[\text{In}] - [\text{Out}] = 0 \quad (7.15)$$

Also, since this is a **constant-level** batch distillation, the **amount of solvent evaporated** ($-dV$) must be **equal** to the amount of **solvent added** to the still pot ($+dS$) — note that the solvent added into the still pot is called “the *second solvent*”

$$-dV = dS \quad (7.16)$$

$$\text{(or } dV = -dS\text{)}$$

Performing a **species** (or **component**) **balance** on the *evaporated* solvent (called “the *original solvent*”) gives

$$\begin{aligned}
 -y dV &= -d(Wx_w) \\
 y dV &= d(Wx_w)
 \end{aligned}$$

[note that, at any instant of time, the concentration of the vapour evaporated from the liquid (y) is constant; thus, it is drawn from the differentiation)

$$y dV = W dx_w + x_w dW \quad (7.17)$$

but W is kept *constant*

Thus, Eq. 7.17 becomes

$$y dV = W dx_w \quad (7.18)$$

Substituting Eq. 7.16 into Eq. 7.18 yields

$$-y dS = W dx_w \quad (7.19)$$

Re-arranging Eq. 7.19 and integrating the resulting equation gives

$$\begin{aligned} -y dS &= W dx_w \\ \frac{dS}{W} &= -\frac{dx_w}{y} \\ \int \frac{dS}{W} &= -\int_{x_{w,\text{initial}}}^{x_{w,\text{final}}} \frac{dx_w}{y} \\ \frac{S}{W} &= \int_{x_{w,\text{final}}}^{x_{w,\text{initial}}} \frac{dx_w}{y} \end{aligned} \quad (7.20)$$

In this kind of batch distillation, **the vapour** phase and **the liquid** phase in the system (*i.e.* the still pot) are assumed to be **in equilibrium** with each other

Hence, the value of y (the concentration of the vapour phase) can be related to the value of x_w (the concentration of the liquid phase in the still pot) using either equilibrium curve or equation

If the relationship between y and x_w can be expressed in the following form:

$$y = \frac{\alpha x_w}{1 + (\alpha - 1)x_w} \quad (7.21)$$

the integral of the RHS of Eq. 7.20 is

$$\frac{S}{W} = \frac{1}{\alpha} \ln \left[\frac{x_{w, \text{initial}}}{x_{w, \text{final}}} \right] + \frac{\alpha - 1}{\alpha} (x_{w, \text{initial}} - x_{w, \text{final}}) \quad (7.22)$$

Alternatively, the graphical solution (for the value of $\frac{S}{W}$) to this kind of problem can be obtained as follows

For each value of x_w , the value of y can be read from the equilibrium curve, and the graph between x_w (X-axis) and $\frac{1}{y}$ (Y-axis) is plotted

The area under the curve from $x_{w, \text{ final}}$ to $x_{w, \text{ initial}}$ is, in fact, $\frac{S}{W}$

Generally, the value of W is given; thus, Eq. 7.20 (or 7.22) is normally used to compute the value of S (*i.e.* the *amount of solvent* required to keep the *liquid level* in the still pot *constant*)

7.3 Batch Steam Distillation

In the *batch steam* distillation, steam is purged directly into the still pot, as shown in Figure 7.3

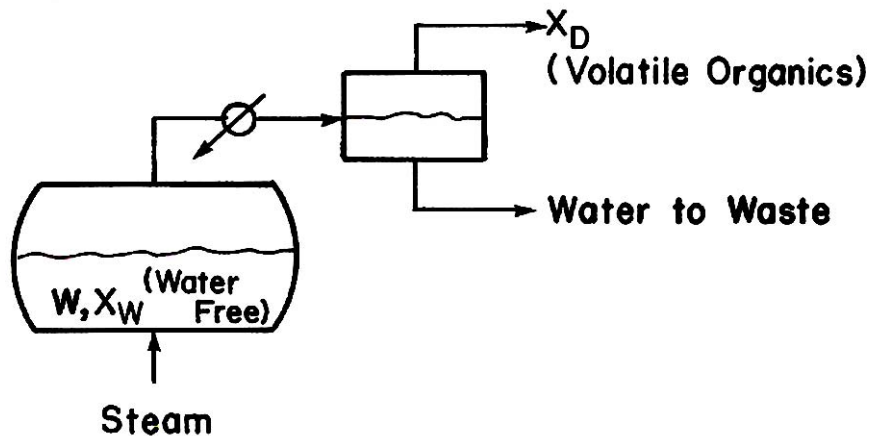


Figure 7.3: A batch steam distillation

(from "Separation Process Engineering" by Wankat, 2007)

Normally, the *direct addition* of *steam* into the still pot is done for the system that is NOT *miscible* (ละลาย) with water

Like the *steam* distillation in the continuous operation, the ***principal purpose*** of adding steam directly into the still pot is **to keep the temperature of the system *below* the boiling point of water**, while eliminating the need of a heat transfer device (as steam can provide heat/energy to the system)

By solving Eqs 7.1:

$$F = W_{\text{final}} + D_{\text{total}} \quad (7.1)$$

and 7.2:

$$x_F F = x_{w,\text{final}} W_{\text{final}} + x_{D,\text{avg}} D_{\text{total}} \quad (7.2)$$

simultaneously, we obtain the following equation:

$$W_{\text{final}} = F \left(\frac{x_D - x_F}{x_D - x_{w, \text{final}}} \right) \quad (7.23)$$

Since the more volatile component (*e.g.*, the volatile organic components: VOCs) is ***much more volatile than water, its concentration*** (*i.e.* x_D) in the ***vapour phase*** can be considered ***pure*** (*i.e.* the distillate contains only the VOCs, or x_D for the VOCs is 1.0)

Thus, Eq. 7.23 becomes

$$W_{\text{final}} = F \left(\frac{1 - x_F}{1 - x_{w, \text{final}}} \right) \quad (7.24)$$

The amount of the distillate, D , can, thus, be calculated using the following equation:

$$D = F - W_{\text{final}} \quad (7.25)$$

The amount of *water* in the *separating tank* (n_w) (see Figure 7.3), which is, in fact, the amount of *steam condensed* at the *condenser*, can be computed using the following equation:

$$n_w = \int_0^D \frac{P_{\text{total}} - x_{\text{VOC in the remaining liquid}} P_{\text{VOC}}^*}{x_{\text{VOC in the remaining liquid}} P_{\text{VOC}}^*} dn_{\text{org}} \quad (7.26)$$

The *total amount* of *steam* required is n_w *plus* with the amount of *steam* that is *condensed* and *remained* in the *still pot* (note that this steam is used to heat up the feed and vaporise the VOCs)

$$\left(n_{\text{steam}}\right)_{\text{total}} = n_w + \left(n_{\text{steam}}\right)_{\text{used to heat up the feed}} \quad (7.27)$$

7.4 Multi-stage Batch Distillation

If *very high purity* of a *product* (either distillate or bottom) is needed, a *multi-stage* column is added to the batch distillation system, as illustrated in Figure 7.2 (Page 7)

The complexity with the *multi-stage* equilibrium is attributed to the fact that x_D and x_w are *no longer in equilibrium* with each other as *per* the case of the *simple batch* distillation

In other words, the relationship between x_D and x_w can **no longer** be expressed using the equilibrium curve or equation

Accordingly, the Rayleigh equation (*i.e.* Eq. 7.6a or 7.6b), cannot be integrated until the relationship between x_D and x_w is established

Generally, this relationship between x_D and x_w for the *multi-stage* distillation can be obtained by performing *stage-by-stage* calculations

The following is how to formulate the relationship between x_D and x_w for the *multi-stage* distillation system

Performing material and energy balances for Figure 7.2 from stage j to the top of the column, with the assumption that the *accumulation* at *any* where *except* the *re-boiler* is *negligible*, yields

$$V_{j+1} = L_j + D \quad (7.28)$$

$$y_{j+1}V_{j+1} = x_jL_j + x_D D \quad (7.29)$$

$$Q_C + V_{j+1}H_{j+1} = L_j h_j + Dh_D \quad (7.30)$$

In order to simplify the calculations, CMO is assumed, and the *operating equation* of the *multi-stage* batch distillation can be written, by rearranging Eq. 7.29, as follows

$$y_{j+1} = \frac{L}{V} x_j + \left(1 - \frac{L}{V}\right) x_D \quad (7.31)$$

However, the *difficulty* of using Eq. 7.31 in the *batch* distillation is that either x_D or $\frac{L}{V}$ is *varying* during the operation, thus resulting in the fact that the *operating line* will *continuously* be *changing* (or it is *not constant*) throughout the operation

Normally, the *batch* distillation operation can be divided into **2 modes**:

- Constant *reflux ratio* $\left(\frac{L}{D}\right)$
- Constant *distillate concentration* (x_D)

The following is the details of each mode

7.4.1 Constant reflux ratio

One of the most common *multi-stage* batch distillation modes is the operation in which the **reflux ratio** $\left(\frac{L}{D}\right)$ is kept **constant** throughout the distillation

In this kind of operation, the *concentration* of the *distillate* (x_D) is *varied* (*changed*), while the values of L and V are kept constant (by *fixing* the *reflux ratio*)

Accordingly, we obtain the *operating lines* with the *same slope* (*i.e.* the same $\frac{L}{V}$) but various Y-intercepts; note that the points where $y = x = x_D$ are also varied

In other words, in this kind of distillation operation (*i.e.* *batch* distillation), there are *several operating lines*, which is in contrast to the case of *continuous* distillation, in which there is *only one* operating line

After an *appropriate* number of operating lines are plotted for each value of x_D , we step off stages (for a given number of equilibrium stages) to find the value of x_w for each x_D

Once x_w value for each value of x_D is obtained, we can perform the integration for the Rayleigh equation (Eq. 7.6), and the values of

- W_{final}
- D_{total}
- $x_{D,\text{avg}}$

will subsequently be obtained

Note, once again, that if the value of $x_{D,\text{avg}}$ is specified, the *trial & error* technique is to be employed to calculate the value of $x_{w,\text{final}}$

Let's examine the following Example, which illustrates how to solve the *constant reflux ratio* distillation problem

Example The 50-mol feed comprising 32% EtOH and 68% water is to be distilled in the *multi-stage* batch distillation with the additional 2 equilibrium stages on top of the re-boiler (still pot)

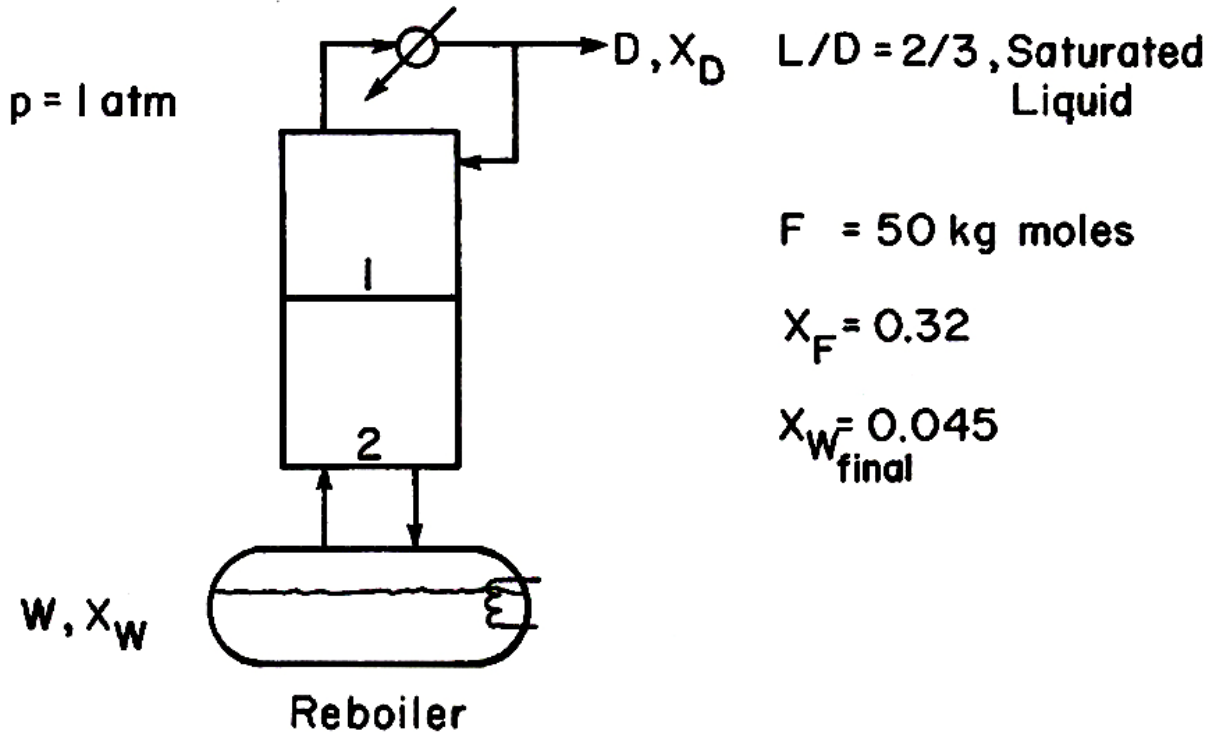
Reflux is returned to the column as a saturated liquid with the *constant* reflux ratio $\left(\frac{L}{D}\right)$ of $2/3$

It is desired that the solvent remained in the still pot has the concentration of EtOH of 4.5 mol%

Determine the average distillate composition $\left(x_{D,\text{avg}}\right)$, the final amount (in moles) of liquid in the still pot $\left(W_{\text{final}}\right)$, and the total amount of the distillate collected $\left(D_{\text{total}}\right)$

The operation is at 1 atm

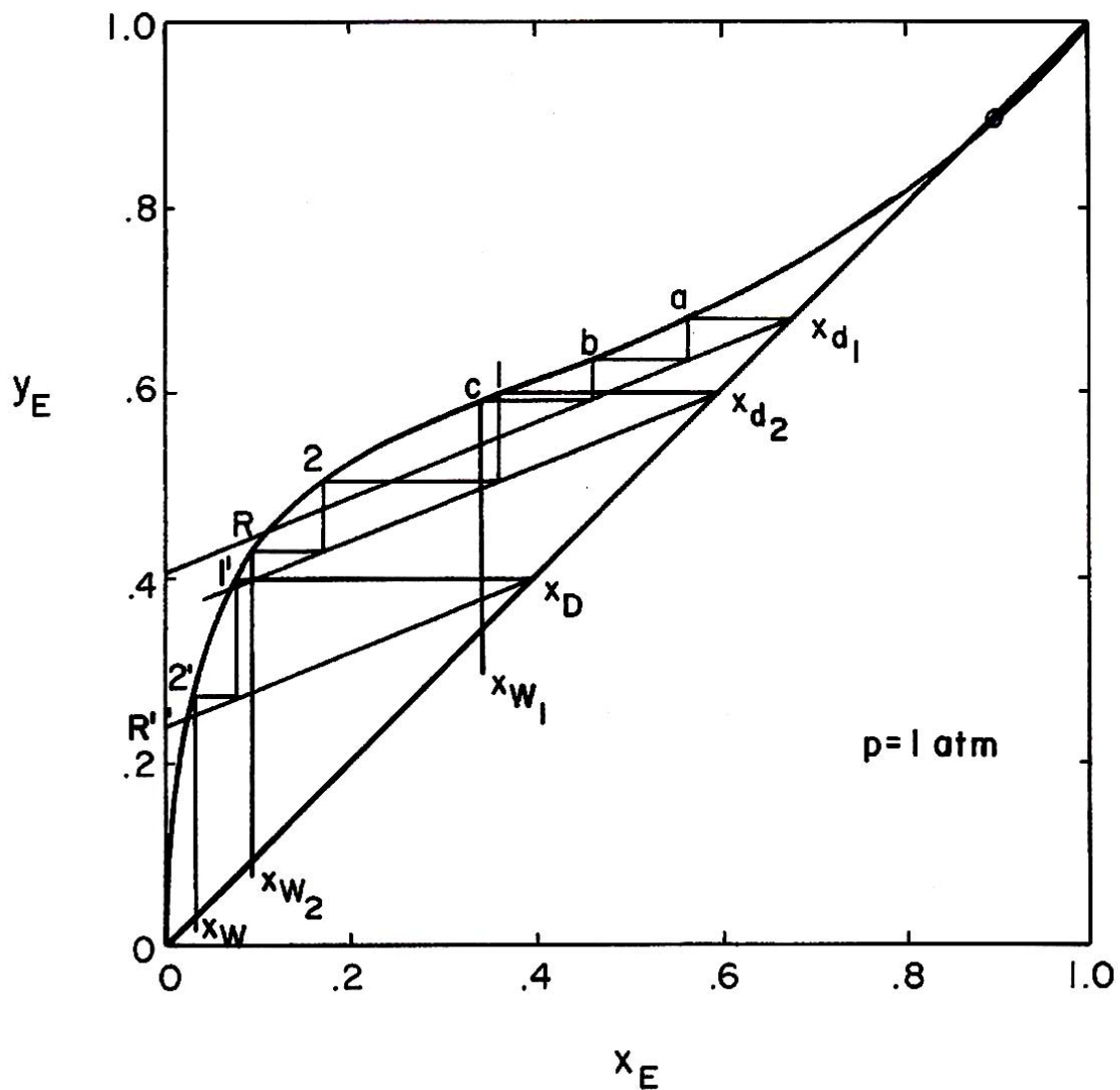
The schematic diagram of the batch distillation in this Example is as shown below



(from “Separation Process Engineering” by Wankat, 2007)

Since the operation is at 1 atm, the equilibrium curve of EtOH can be obtained from the $x - y$ equilibrium data of the EtOH-water mixture at 1 atm

A value of x_D is selected (specified), and the corresponding value of x_w for each selected value of x_D (or for each operating line) for the **number of stages of 3** (why “3”?) is obtained, as shown in the following McCabe-Thiele diagram



(from “Separation Process Engineering” by Wankat, 2007)

From each pair of x_D and x_w , the value of $\frac{1}{x_D - x_w}$ is calculated

Eventually, a graph between $\frac{1}{x_D - x_w}$ and x_w is plotted from $x_{w, \text{final}} = 0.045$ (4.5%) to $x_F = 0.32$ (32%), as shown on the next Page, and the **area under the curve** is found to be **0.608**

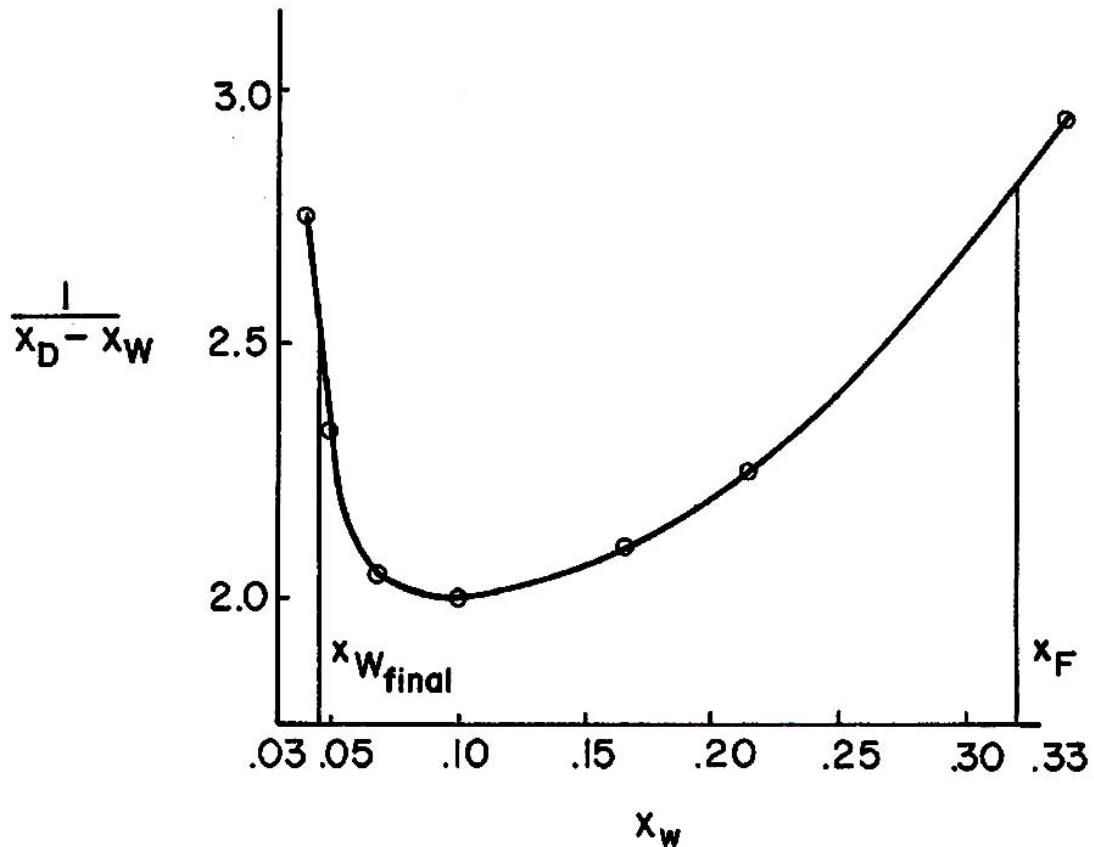
Hence,

$$\begin{aligned} W_{\text{final}} &= F \exp(-\text{area under the curve}) \\ &= (50) \exp(-0.608) \end{aligned}$$

$$W_{\text{final}} = 27.21$$

and

$$D_{\text{total}} = F - W_{\text{final}} = 50 - 27.21 = 22.79$$



(from “Separation Process Engineering” by Wankat, 2007)

The value of $x_{D,avg}$ can, thus, be calculated as follows

$$\begin{aligned}
 x_{D,avg} &= \frac{x_F F - x_{w,final} W_{final}}{D_{total}} \\
 &= \frac{[(0.32)(50)] - [(0.045)(27.21)]}{(22.79)} \\
 x_{D,avg} &= 0.648
 \end{aligned}$$

7.4.2 Variable reflux ratio (Constant x_D)

In this batch distillation mode, the distillation is carried out such that the value of x_D is fixed,

while the *reflux ratio* $\left(\frac{L}{D}\right)$ is *varied*

As the *reflux ratio* is *varied*, the *slope* of the *operating line* keeps changing as illustrated in Figure 7.4

Note that the point where the operating line intersects with the $y = x$ line at x_D is fixed (as the value of x_D is kept constant)

Similar to the constant reflux ratio batch distillation (**but not exactly the same**), to solve this

problem, we step off stages (for a given number of equilibrium stages) from the point where $y = x = x_D$ for each operating line, and the corresponding value of x_w is obtained; then, the graph between

ween $\frac{1}{x_D - x_w}$ and x_w is plotted

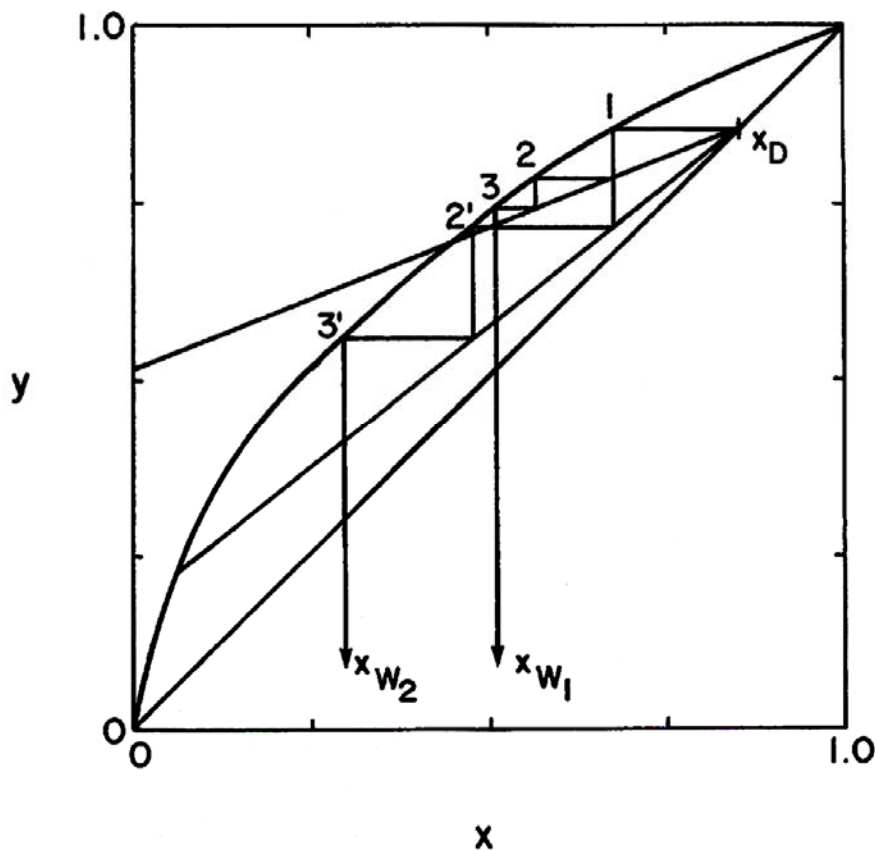


Figure 7.4: The batch distillation with varying reflux ratio

(from “Separation Process Engineering” by Wankat, 2007)

7.5 Operating Time for Batch Distillation

The *overall* operating time for batch distillation includes the *operating* time and the *down* time:

$$t_{\text{batch}} = t_{\text{operating}} + t_{\text{down}} \quad (7.32)$$

The *actual* operating time for batch distillation ($t_{\text{operating}}$) can be computed using the following equation:

$$t_{\text{operating}} = \frac{D_{\text{total}}}{\dot{D}} \quad (7.33)$$

where \dot{D} = the flow rate of the distillate

The value of \dot{D} **cannot** be set arbitrarily (อย่างไรก็ได้ or ตามใจชอบ), as the column must be

designed to accommodate a limited amount of vapour flow rate (V_{\max}), to avoid the *flooding* phenomenon

The *maximum* distillate flow rate (D_{\max}) can be computed as follows

$$\dot{D}_{\max} = \frac{V_{\max}}{1 + \frac{L}{D}} \quad (7.34)$$

Normally, the *optimal* or *operating* value of \dot{D} is $0.75\dot{D}_{\max}$

The down time (t_{down}) includes

- 1) the time required for *dumping* (draining out) the *remaining bottom product*
- 2) the *clean-up* time (to clean up the column)

- 3) the *loading* time for the next batch
- 4) the *heat-up* time until the reflux starts to appear

Note that the *energy requirements* for a *condenser* and a *re-boiler* can be calculated from the *energy balance* equations around the *condenser* and the *whole system*, respectively

If the *reflux* is a *saturated liquid*,

$$Q_C = -V_1 (H_1 - h_D) = -V_1 \lambda \quad (7.35)$$

where λ is the latent heat of vaporisation

The energy balance around the entire system yields the heating load (Q_R) as follows

$$Q_R = -Q_C + Dh_D \quad (7.36)$$