

# Introduction to Chemical Engineering for Lecture 7: Flash Distillation

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## 1. Flash distillation

Flash evaporation is one of the simplest separation processes. A liquid stream containing several components is partially vaporised in a "flash drum" at a certain pressure and temperature. This results in two phases: a vapor phase, enriched in the more volatile components, and a liquid phase, enriched in the less volatile components.

The fluid is pressurized and heated and is then passed through a throttling valve or nozzle into the flash drum. Because of the large drop in pressure, part of the fluid vaporizes. The vapor is taken off overhead, while the liquid drains to the bottom of the drum, where it is withdrawn. The system is called "flash" distillation because the vaporization is extremely rapid after the feed enters the drum. Because of the intimate contact between liquid and vapor, the system in the flash chamber is very close to an equilibrium stage. Figure 1 shows a schematic drawing of a flash unit.

As long as the feed consists of only 2 components, we have a *binary* flash. We will consider this case first, then we will see how to calculate bubble- and dew-points of binary mixtures. Further reading for this part of the lecture can

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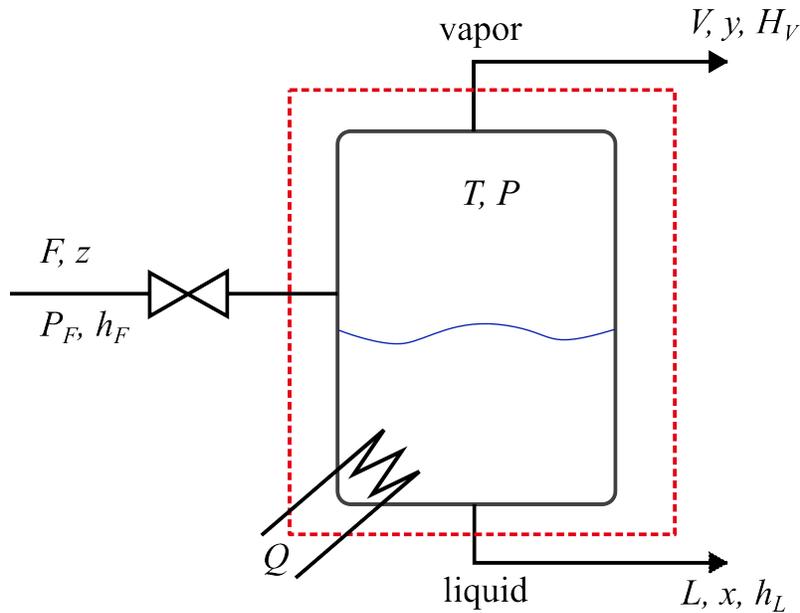


Figure 1: Schematic drawing of a flash distillation unit

be found in chapter 2 of Wankat's "Separation Process Engineering"<sup>1</sup>.

### 1.1. Binary flash

In a binary flash there are two components, 1 and 2. Unless stated otherwise, the compositions  $x, y$  and  $z$  refer to the molar fraction of the more volatile component. The variable  $x$  is normally used for the liquid phase,  $y$  for the vapor phase and  $z$  for the feed instead of  $x_1, y_1, z_1$  as used in lectures 1-4. The composition of the less volatile component is easily obtained from this value. For example, if 2 is the less volatile component,  $x_1 = 1 - x$ ,  $y_1 = 1 - y$ .

<sup>1</sup>Wankat, P.C. Separation Process Engineering, second edition; Prentice Hall, 2006. This is the revised edition of Wankat, P. C. Equilibrium staged separations; Separations in Chemical Engineering; Prentice Hall, 1988. In the old edition, the corresponding chapters are 3.2 (binary flash), 2.6 (bubble- and dew-point calculation), and 2 (vapor-liquid equilibria)

### 1.1.1. Phase diagrams

In Figure 2(a), a  $T - xy$  diagram for a flash distillation is shown. In this example, the feed is a liquid with a composition  $z$ , at a temperature  $T_F$ . When the feed enters the flash drum, its temperature is increased to the temperature of the flash unit,  $T$ . At this point, the feed is out of equilibrium. Therefore, it will split into a vapor and a liquid phase, whose compositions are given by the two green equilibrium lines. The point on the left represents the liquid phase, with the composition  $x$ , while the point on the right represents the vapor phase, with a composition  $y$ . From this diagram it can be seen that if the temperature of the flash is increased,  $x$  and  $y$  will decrease, and if the temperature is decreased,  $x$  and  $y$  will increase.

Figure 2(b) shows a  $P - xy$  diagram for the case of a flash distillation at a specified temperature. The feed enters at a pressure  $P_F$  and composition  $z$ , in this case as a liquid. In the flash drum, the pressure is decreased to a new value  $P$ , and the feed enters the two-phase region, leading to a separation. The new liquid phase has composition  $x$ , and the new vapor phase has composition  $y$ .

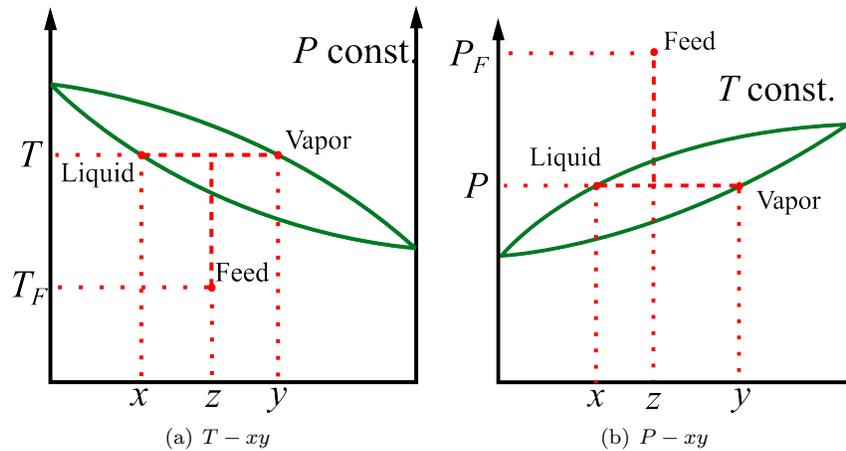


Figure 2: Phase diagrams for a flash distillation

### 1.1.2. Design of flash units

The designer of a flash system needs to know the pressure and temperature of the flash drum, the size of the drum and the liquid and vapor compositions and flow rates. Which of these variables are specified and which need to be chosen depend on the application<sup>2</sup>. Normally, the feed is specified, ie. the flow rate  $F$ , composition  $z$ , pressure  $P_F$  and enthalpy  $h_F$  are known<sup>3</sup>. The other variables are the vapor flow rate  $V$ , vapor composition  $y$ , liquid flow rate  $L$ , liquid composition  $x$ , temperature  $T$  and pressure  $P$  in the flash unit and heat input  $Q$ . These can not be chosen freely. To see how they are related to each other, we write material and energy balances for the system. The boundary of the system is shown by the dashed, red line in Figure 1.

As stated above, the two phases in the flash drum are at equilibrium (iso fugacity condition). Therefore, we can write the following equations for the phase equilibria<sup>4</sup> (we assume an liquid and vapor phase):

$$\begin{aligned}f_i^{V*} &= f_i^{L0} & i &= 1, 2 \\yP &= xP_1^v(T) & \text{for } i &= 1 \\(1-y)P &= (1-x)P_2^v(T)\end{aligned}$$

These equations can also be written using equilibrium constants:

$$y = K_1(P, T)x \tag{1}$$

$$(1-y) = K_2(P, T)(1-x) \tag{2}$$

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<sup>2</sup>Flash drums are operated continuously. Therefore, we will only consider the equilibrium solution.

<sup>3</sup>The enthalpy is a function of the temperature and composition. In this section, we assume this functional dependence is known.

<sup>4</sup>Refer to the first chapters of the lecture script for details on where these equations come from

Furthermore, we have material balances for the whole flash unit, and for one of the components:

$$F = V + L \quad (3)$$

$$Fz = Vy + Lx \quad (4)$$

and an energy balance based on the enthalpies ( $h_F, h_L, H_V$ ) of the various streams:

$$Fh_F + Q = Lh_L + VH_V \quad (5)$$

We have 7 unknowns ( $V, L, Q, x, y, P, T$ ) and 5 equations (eqs. 1-5), which means that we have 2 degrees of freedom. Often, the pressure is given. This leaves a few possibilities for setting the design specifications of a flash unit:

- a)  $x$
- b)  $y$
- c)  $V/F$  or  $L/F$
- d)  $T$
- e)  $Vy/Fz$  : split factor
- f)  $Q$ , eq. adiabatic flash with  $Q = 0$ .

For cases a)-e), we can apply a sequential solution procedure, which means that we first solve the phase equilibria and material balances, and then calculate  $Q$  through an energy balance. As an example, we will consider the cases where the vapor or liquid fraction ( $V/F$  or  $L/F$ , case c) is specified, and the case where the temperature is given (case d).

*c)  $V/F$  or  $L/F$  is given.*  $V/F$  is referred to as the vapor fraction, while  $L/F$  is the liquid fraction. From the overall material balance eq. 3 we see that when

one is given, the other is also set:

$$\frac{L}{F} = 1 - \frac{V}{F} \quad (6)$$

From the material balance for component 1 (eq. 4) we obtain the so-called working line:

$$y = -\frac{L}{V}x + \frac{F}{V}z \quad (7)$$

For a graphical solution of this problem, we plot the working line along with the equilibrium curve in the  $x$ - $y$  diagram, as shown in Figure 3. Note that the slope of the working line is  $-L/V$ , and that it intersects the diagonal  $x = y$  line at  $y = z$ . At the intersection between the working line and the equilibrium line, we find the values of  $x$  and  $y$ . Once these are known, we solve the equilibrium condition (eq. 1) numerically to find the corresponding temperature.

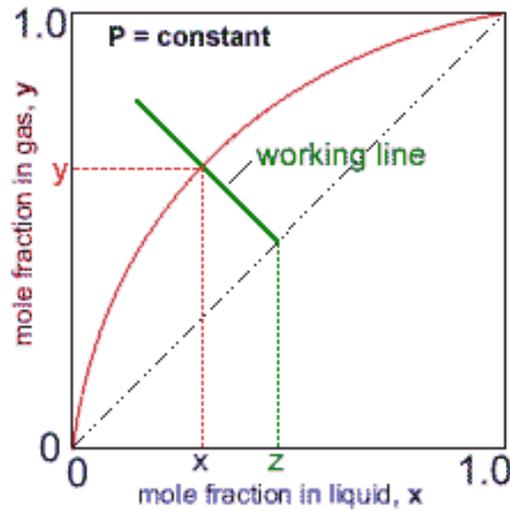


Figure 3:  $x$ - $y$  diagram with equilibrium curve and working line

d)  $P, T$  is given. If the pressure and temperature are known, we can easily find  $y$  and  $x$  by solving the set of equations

$$\begin{cases} y = K_1(P, T)x \\ 1 - y = K_2(P, T)(1 - x) \end{cases} \quad (8)$$

f)  $P, Q$  is given: *simultaneous solution*. When the heat input is given, eg. as for an adiabatic flash where  $Q = 0$ , all the equations are coupled and we must apply the simultaneous solution procedure. These equations can either be solved numerically (works; but may be difficult, since several equations are non-linear) or by an iterative approach. For this, we choose a trial variable, for example the temperature  $T$ . Then the procedure is as follows:

1. Guess a value for the trial variable
2. Calculate the values for all other variables, eg.  $x, y, V, L$  using the equations introduced above.
3. Check the energy balance: is equation 5 fulfilled?
4. If not, repeat

This problem can also be solved graphically. For this, we use the  $H - xy$  diagram, as shown in Figure 4. The coordinates of a point in the diagram give the composition and enthalpy of a stream. The lower green line represents points where the stream is at the boiling point, and the upper green line represents points at which the stream is a saturated vapor (i.e. at the dew point). Two streams which are in equilibrium are connected by tie-lines. Therefore, the liquid and vapor phases in a flash unit lie on the same tie-line and on the corresponding green line. The point representing the mixture also lies on the tie-line. This point is given by the feed - the composition is given; as is the enthalpy. Starting with the feed enthalpy, a certain amount of heat is added ( $Q/F$ , since we need to consider the specific heat), giving a point  $\mathbf{M}$  with coordinates  $(z, h_F + Q/F)$ .

By using the tie-line passing through **M**, we can find the compositions  $x$  at the end-point **A** and  $y$  at the end-point **B**. The flow rates  $L$  and  $V$  can be found using the lever-arm rule:

$$\frac{\overline{AM}}{\overline{BM}} = \frac{V}{L} \quad (9)$$

For more details on  $H - xy$  diagrams, check the first sections of the lecture script.

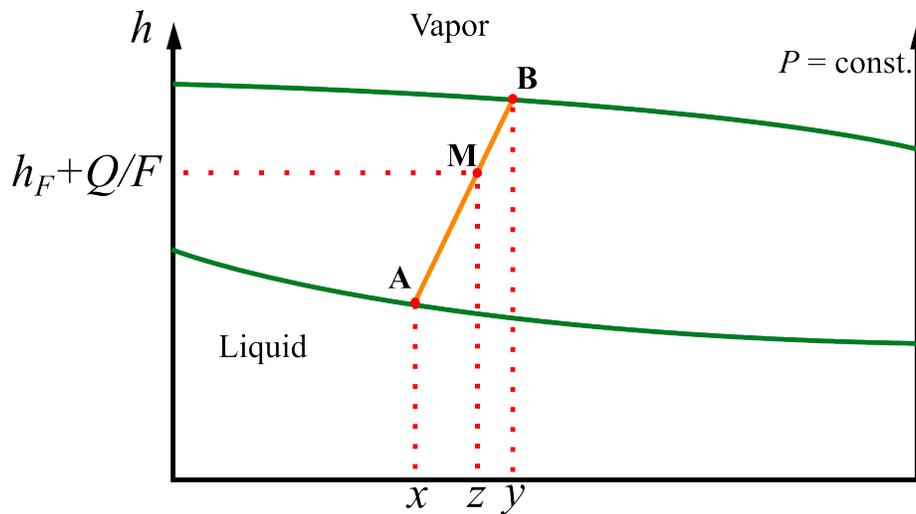


Figure 4: Use of the enthalpy-composition diagram to graphically solve for  $x, y, L, V$  in a flash when  $Q$  is given

### 1.1.3. Calculation of bubble and dew points

The dew point of a mixture is the point (temperature and pressure) at which a vapor will start condensing. Similarly, the bubble point is the point at which a liquid starts boiling. In other words, the vapor fraction at the dew point is 1, while it is 0 at the bubble point.

To calculate the dew and bubble point, we again look at the material balances and equilibrium conditions.

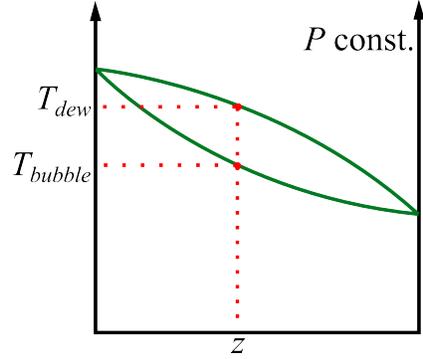


Figure 5: Bubble point  $T_{bubble}$  and dew point  $T_{dew}$  at pressure  $P$ , for a mixture of composition  $z$

*Bubble point.* At the dew point,  $V = 0$ . The material balance then gives us that  $F = L$  and  $z = x$ . If we sum up equations 1 and 2, we obtain

$$K_1(P, T)x + (1 - x)K_2(P, T) = 1 \quad (10)$$

and with  $z = x$

$$K_1(P, T)z + (1 - z)K_2(P, T) = 1 \quad (11)$$

To find the bubble point, we need to find the temperature and pressure (one of which is given) at which equation 11 is fulfilled. Normally, this can only be done numerically.

*Dew point.* At the dew point,  $L = 0$ . From the material balance we obtain  $F = V$  and  $z = y$ . In this case, we write the equilibrium conditions (equations 1 and 2) in terms of  $x$ :

$$x = \frac{y}{K_1} \quad (12)$$

$$1 - x = \frac{1 - y}{K_2} \quad (13)$$

By summing equations 12 and 13 we obtain

$$\frac{y}{K_1} + \frac{1-y}{K_2} = 1 \quad (14)$$

and with  $z = y$

$$\frac{z}{K_1(P,T)} + \frac{1-z}{K_2(P,T)} = 1 \quad (15)$$

Again, we need to solve equation 15 numerically to find the dew point temperature and pressure.