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TECHNICAL NOTE

Phase Temperature Differences in Binary Distillation

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ABSTRACT

Assuming bubble point liquid and dew point vapor to coexist in a simple distillation column, equations are given describing the maximum sectional phase temperature differences for binary systems which are assumed to be completely separated.

If, in a packed distillation column, we assume that vapor is at its dew point and liquid at its bubble point, we find that the temperature (t_v) of the vapor leaving a differential element of packing is higher than the temperature of the liquid (t_l) leaving that same element. Plug flow is assumed. This phenomenon also occurs, to a lesser extent, for perfectly mixed trayed columns, particularly those with low Murphree efficiency (E_M). That is, the temperature of the vapor leaving a tray is greater than that of the liquid leaving the same tray. This phase temperature difference arises because the phases are not in equilibrium. For a binary system, the temperature difference is present at all reflux rates, is greatest at total reflux, and increases with increasing alpha value. For a perfect binary separation, the phase temperature difference is zero at the top and bottom of a column because we have pure components at these points. The temperature difference is always zero for a theoretical equilibrium stage (TES) anywhere in the column.

We see now that, while there is only a single temperature profile for a staged column, there are two temperature profiles for a packed or trayed column; one for the vapor phase and one for the liquid phase. We may estimate the magnitude of the maximum temperature difference for a packed column as well as for an actual trayed column if we assume a perfect binary separation. As a K-value generator, we choose

$$\ln(K) = a + b't \tag{1}$$

as a compromise between physical reality and mathematical convenience. The resulting equation for the stripping section is given in terms of the fraction of the difference between distillate (t_d) and bottoms (t_b) temperatures, which are here the boiling points of the light key (LK) and heavy key (HK) at system conditions.

$$\frac{(t_v - t_l)_{SS}^{max}}{t_b - t_d} = \frac{\ln\left[1 + \dfrac{(1 - E_{MV})\left(\alpha - \dfrac{L}{V}\right)^2}{4\alpha(L/V)}\right]}{\ln \alpha} \tag{2}$$

The E_{MV} term allows estimation of $(t_v - t_l)$ for perfectly mixed actual trays. E_{MV} is zero for packed columns and unity for TES columns (perfectly mixed phases in equilibrium). For the latter case, the maximum temperature difference is found to be zero, as expected. For perfectly mixed actual trays, E_{MV} is between zero and one. The L/V term permits calculation at partial reflux. At total reflux L/V is unity. The value of x_{LK} at the maximum temperature difference gives an indication of the location of the maximum. For the stripping section

$$\underset{@\max\Delta t_{SS}}{x_{LK}} = [\alpha V/L - 1]/[2(\alpha - 1)] \tag{3}$$

Note that E_{MV} does not appear in Eq. (3).

For the rectifying section in a perfect binary separation we obtain for the maximum value of $(t_v - t_l)$:

$$\frac{(t_v - t_l)_{RS}^{max}}{t_b - t_d} = \frac{\ln\left[1 + \dfrac{(1 - E_{MV})\left(\dfrac{\alpha L}{V} - 1\right)^2}{4\alpha(L/V)}\right]}{\ln\alpha} \tag{4}$$

The value of x_{HK} at the point of maximum temperature difference is given by

$$\underset{@\max\Delta t_{RS}}{x_{HK}} = [\alpha - V/L]/[2(\alpha - 1)] \tag{5}$$

When K_l are represented by Eq. (1), the maximum values of the left-hand sides of Eqs. (2) and (4) occur at total reflux. These "maximum maximum" values are given by

$$\frac{(t_v - t_l)_{\text{max}}^{\text{max}}}{t_b - t_d} = \frac{\ln\left[1 + \dfrac{(1 - E_{\text{MV}})(\alpha - 1)^2}{4\alpha}\right]}{\ln\alpha} \tag{6}$$

At total reflux, the value of x_{LK} associated with Eq. (6) is always 0.5 and is independent of E_{MV}.

Values estimated by Eq. (6) vary from zero at an alpha of unity to unity at an alpha of infinity. If the E_{ML} model is used for actual trays or packing, merely replace E_{MV} in Eqs. (2), (4), and (6) with E_{ML}.

EXAMPLE PROBLEM

A binary with equimolal feed composition at its boiling point is being separated by a packed column into 99.9% pure top and bottom products. This approximates perfect binary separation. Assuming Eq. (1) to hold, we will determine the maximum phase temperature difference $(t_v - t_l)$ in A) the rectifying section and B) the stripping section if the reflux-to-feed molal ratio is 1.5 and the relative volatility ratio (alpha) is 2.0. Then, C) at total reflux, we will determine the maximum temperature difference for the system. We will choose the E_{MV} model and assume constant molal overflow.

A. For a packed column, E_{MV} is zero. The top product rate is 0.5 mole per mole of feed. L/V_{RS} is 1.5/(1.5 + 0.5) = 0.75. From Eq. (4), $(t_v - t_l)_{\text{max}}$ is 5.9% of the temperature difference between top and bottom products. The value of x_{HK} at this maximum is 0.3333 by Eq. (5).

B. L/V_{SS} is (1.5 + 1.0)/2.0 = 1.25. From Eq. (2), $(t_v - t_l)_{\text{max}}$ is 7.9% of the temperature difference between top and bottom products. The value of x_{LK} at this maximum is 0.3000 by Eq. (3).

C. From Eq. (6), $(t_v - t_l)_{\text{max}}^{\text{max}}$ is 17.0% of the products temperature difference.

NOMENCLATURE

a, b'	generic constants in equilibrium constant equation
alpha, α	volatility of light key relative to heavy key, assumed to be a constant value

delta, Δ	difference (temperature)
b	in bottoms
d	in distillate
E_{ML}	Murphree liquid efficiency
E_{MV}	Murphree vapor efficiency
HK	heavy key component (also used as a subscript)
i	general component designator
K	equilibrium constant of a component $= y(i)/x(i)$
l	liquid phase designator
L	liquid flow, mol/time
L/V	slope of the operating line (molar)
LK	light key component (also used as a subscript)
RS	denotes rectifying section
SS	denotes stripping section
t	temperature
v	vapor phase designator
V	vapor flow, mol/time
x	liquid phase mole fraction of a component

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