Plate Efficiency

The designer is concerned with real contacting stages, not the theoretical equilibrium stage assumed for convenience in the mathematical analysis of multistage processes.

Equilibrium will rarely be attained in a real stage. The concept of a stage efficiency is used to link the performance of practical contacting stages to the theoretical equilibrium stage.

Three principal definitions of efficiency are used:

- Murphree plate efficiency (Murphree, 1925), defined in terms of the vapor compositions by

$$E_{mV} = \frac{y_n - y_{n-1}}{y_e - y_{n-1}}$$

where y_e is the composition of the vapor that would be in equilibrium with the liquid leaving the plate.

The Murphree plate efficiency is the ratio of the actual separation achieved to that which would be achieved in an equilibrium stage.

In this definition of efficiency, the liquid and the vapor stream are taken to be perfectly mixed; the compositions in equation are the average composition values for the streams.

- Point efficiency (Murphree point efficiency).

If the vapor and liquid compositions are taken at a point on the plate, equation gives the local or point efficiency, E_{mv}.

- Overall column efficiency.

This is sometimes confusingly referred to as the overall plate efficiency.

$$E_o = \frac{\text{number of ideal stages}}{\text{number of real stages}}$$

An estimate of the overall column efficiency will be needed when the design method used gives an estimate of the number of ideal stages required for the separation.

In some methods, the Murphree plate efficiencies can be incorporated into the procedure for calculating the number of stages and the number of real stages determined directly.

For the idealized situation in which the operating and equilibrium lines are straight, the overall column efficiency and the Murphree plate efficiency are related by an equation derived by Lewis (1936):

$$E_0 = \frac{\log\left[1 + E_{mV}\left(\frac{mV}{L} - 1\right)\right]}{\log\left(\frac{mV}{L}\right)}$$

where
m = slope of the equilibrium line; V = molar flow rate of the vapor;
L = molar flow rate of the liquid.

Equation is not of much practical use in distillation, as the slopes of the operating and equilibrium lines will vary throughout the column. It can be used by dividing the column into sections and calculating the slopes over each section.

Prediction of Plate Efficiency

Whenever possible, the plate efficiencies used in design should be based on experimental values for similar systems obtained on full-sized columns.

There is no entirely satisfactory method for predicting plate efficiencies from the system physical properties and plate design parameters.

However, the methods given can be used to make a rough estimate where no reliable experimental values are available.

Plate and overall column efficiencies will normally be between 30 and 80%, and as a rough guide, a figure of 70% can be assumed for preliminary designs.

Efficiencies will be lower for vacuum distillations, as low weir heights are used to keep the pressure drop small.

For Multicomponent Systems

The prediction methods given in the following sections, and those available in the open literature, are invariably restricted to binary systems.

It is clear that in a binary system the efficiency obtained for each component must be the same. This is not so for a multicomponent system; the heavier components will usually exhibit lower efficiencies than the lighter components.

The following guide rules, adapted from a paper by Toor and Burchard (1960), can be used to estimate the efficiencies for a multicomponent system from binary data:

1. If the components are similar, the multicomponent efficiencies will be similar to the binary efficiency.
2. If the predicted efficiencies for the binary pairs are high, the multicomponent efficiency will be high.
3. If the resistance to mass transfer is mainly in the liquid phase, the difference between the binary and multicomponent efficiencies will be small
4. If the resistance is mainly in the vapor phase, as it normally will be, the difference between the binary and multicomponent efficiencies can be substantial.

For mixtures of dissimilar compounds, the efficiency can be very different from that predicted for each binary pair, and laboratory or pilot-plant studies should be made to confirm any predictions.

O'Connell's Correlation

A quick estimate of the overall column efficiency can be obtained from the correlation given by O'Connell (1946), which is shown in Figure.

The overall column efficiency is correlated with the product of the relative volatility of the light key component (relative to the heavy key) and the molar average viscosity of the feed, estimated at the average column temperature.

The correlation was based mainly on data obtained with hydrocarbon systems but includes some values for chlorinated solvents and water-alcohol mixtures.

It has been found to give reliable estimates of the overall column efficiency for hydrocarbon systems and can be used to make an approximate estimate of the efficiency for other systems.

The method takes no account of the plate design parameters and includes only two physical property variables.

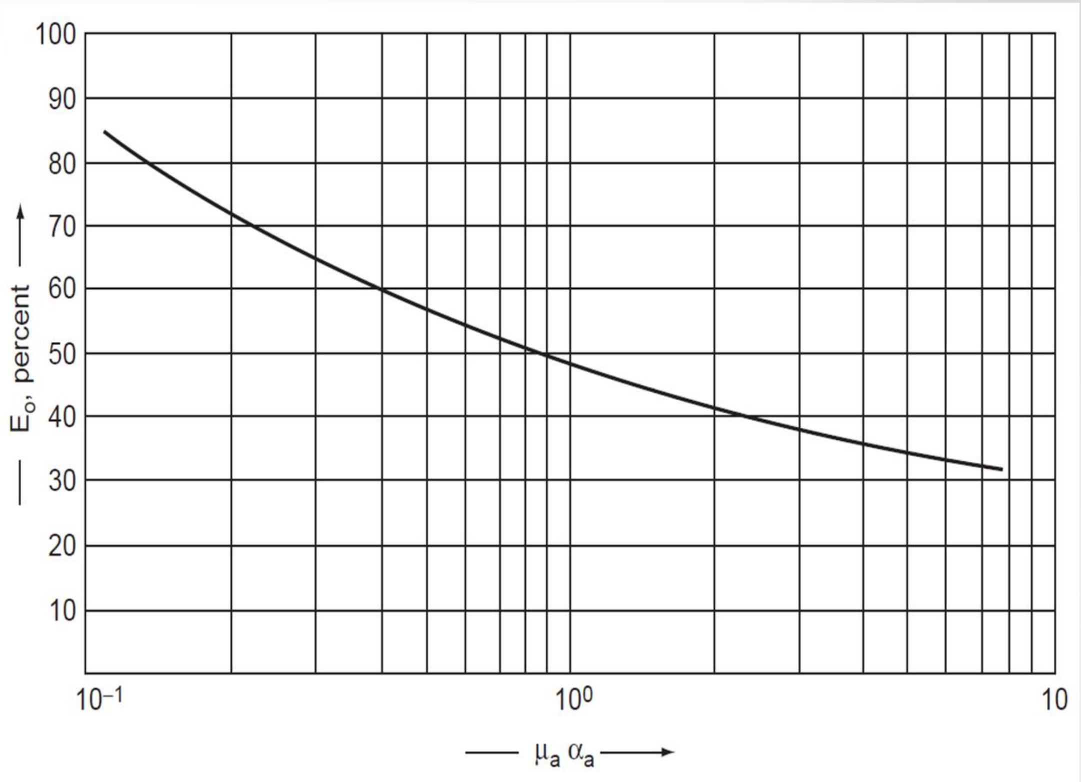
Eduljee (1958) has expressed the O'Connell correlation in the form of an equation:

$$E_o = 51 - 32.5\log(\mu_a\alpha_a)$$

where

μ_a = the molar average liquid viscosity, mNs/m2;

α_a = average relative volatility of the light key.



For Absorbers

O'Connell gave a similar correlation for the plate efficiency of absorbers; see Figure.

Appreciably lower plate efficiencies are obtained in absorption than in distillation.

In O'Connell's paper, the plate efficiency is correlated with a function involving Henry's constant, the total pressure, and the solvent viscosity at the operating temperature.

To convert the original data to SI units, it is convenient to express this function in the following form:

$$x = 0.062\left[\frac{\rho_s P}{\mu_s \mathcal{H} M_s}\right] = 0.062\left[\frac{\rho_s}{\mu_s K M_s}\right]$$

where

'H = the Henry's law constant, Nm^{-2}/mol fraction;

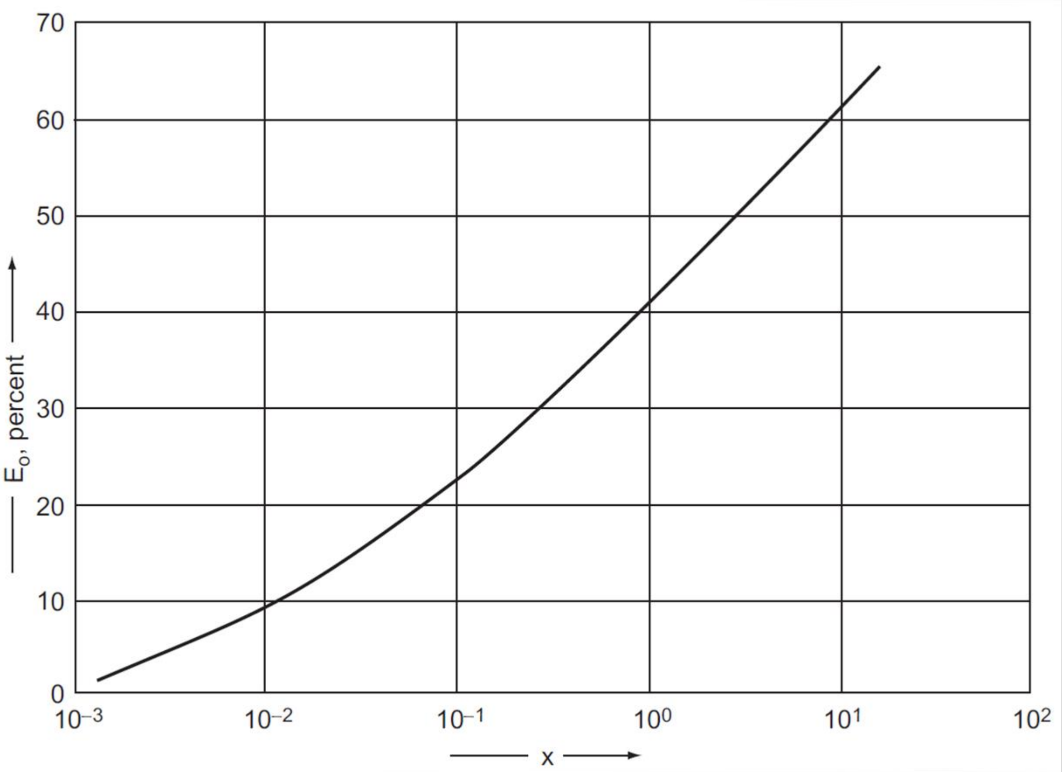
P = total pressure, N/m^2;

μ_s = solvent viscosity, mNs/m^2;

Ms = molecular weight of the solvent;

ρ_s = solvent density, kg/m3;

K = equilibrium constant for the solute.



Van Winkle's Correlation

Van Winkle et al. (1972) have published an empirical correlation for the plate efficiency which can be used to predict plate efficiencies for binary systems.

Their correlation uses dimensionless groups that include those system variables and plate parameters that are known to affect plate efficiency.

They give two equations; the simplest, and that which they consider the most accurate, is given here.

The data used to derive the correlation covered both bubble-cap and sieve plates.

$$E_{mV} = 0.07\mathrm{Dg}^{0.14}\mathrm{Sc}^{0.25}\mathrm{Re}^{0.08}$$

where

Dg = surface tension number = ($\sigma_L/\mu_L u_v$);
σ_L = liquid surface tension;
Sc = liquid Schmidt number $\frac{1}{4}$ (mL/rLDLK);
D_{LK} = liquid diffusivity, light key component;
h_w = weir height;
$u{\cdot}_v$ = superficial vapor velocity;
μ_L = liquid viscosity;
ρ_L = liquid density;
Re = Reynolds number = ($h_w u_v \sigma_v/\mu_L$ (FA));
σ_v = vapor density;

$$(\text{FA}) = \text{fractional area} = \frac{(\text{area of holes or risers})}{(\text{total column cross-sectional area})}$$

AIChE Method

The AIChE method of predicting plate efficiency, published in 1958, was the result of a 5-year study of bubble-cap plate efficiency directed by the Research Committee of the American Institute of Chemical Engineers.

The AIChE method is the most detailed method for predicting plate efficiencies that is available in the open literature. It takes into account all the major factors that are known to affect plate efficiency; this includes

- The mass transfer characteristics of the liquid and vapor phases;
- The design parameters of the plate;
- The vapor and liquid flow rates;
- The degree of mixing on the plate.

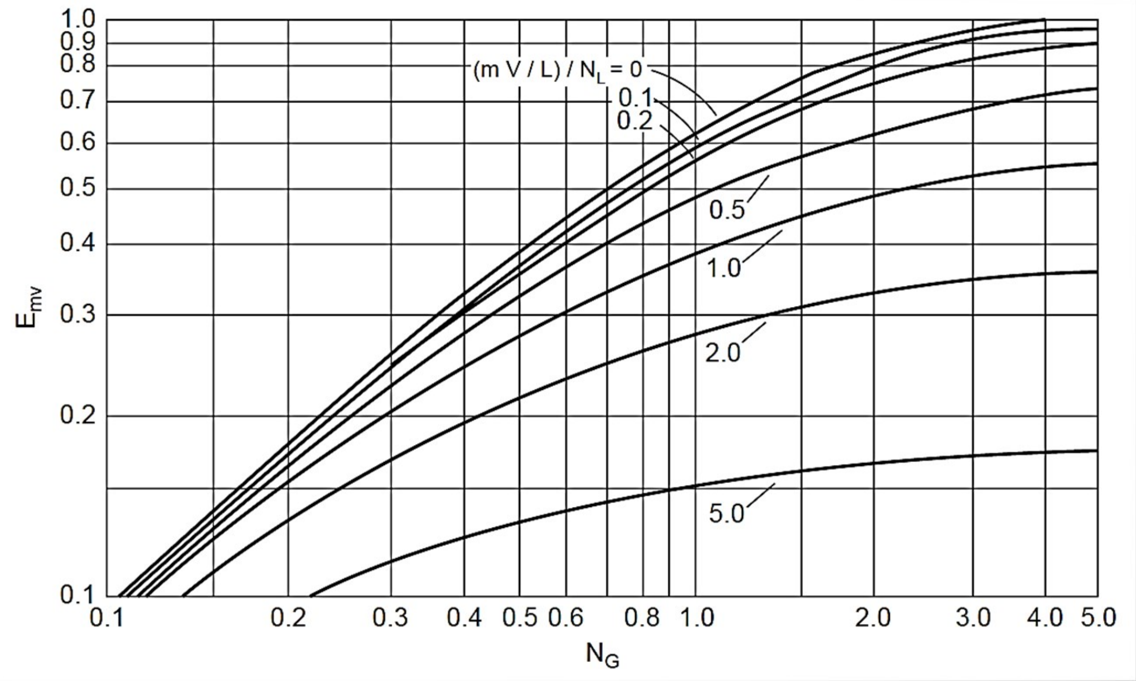
The method is well established and, in the absence of experimental values or proprietary prediction methods, should be used when more than a rough estimate of efficiency is needed.

The mass transfer resistances in the vapor and liquid phases are expressed in terms of the number of transfer units, N_G and N_L. The point efficiency is related to the number of transfer units by the equation

$$\frac{1}{\ln(1-E_{mv})} = -\left[\frac{1}{N_G} + \frac{mV}{L} \times \frac{1}{N_L}\right]$$

where m is the slope of the operating line, and V and L the vapor and liquid molar flow rates.

Equation is plotted in Figure.



The number of gas phase transfer units is given by

$$N_G = \frac{(0.776 + 4.57 \times 10^{-3} h_w - 0.24 F_v + 105 L_p)}{\left(\frac{\mu_v}{\rho_v D_v}\right)^{0.5}}$$

where

h_w =weir height, mm;

Fv =the column vapor "F" factor = $u_a\sqrt{\rho_v}$

U_a = vapor velocity based on the active tray area (bubbling area); m/s;

L_p = the volumetric liquid flow rate across the plate, divided by the average width of the plate,m^3/sm. The average width can be calculated by dividing the active area by the length of the liquid path Z_L;

μ_v= vapor viscosity, Ns/m^2;

ρ_v = vapor density; kg/m^3;

D_v = vapor diffusivity, m^2/s.

The number of liquid phase transfer units is given by

$$N_L = (4.13 \times 10^8 D_L)^{0.5} (0.21 F_v + 0.15) t_L$$

where

D_L = liquid phase diffusivity, m^2/s;

t_L = liquid contact time, s;

given by

$$t_L = \frac{Z_c Z_L}{L_p}$$

where

Z_L = length of the liquid path, from inlet downcomer to outlet weir, m;

Z_c = liquid holdup on the plate, m^3 per m^2 active area,

given by

for bubble-cap plates:

$$Z_c = 0.042 + 0.19 \times 10^{-3} h_w - 0.014 F_v + 2.5 L_p$$

for sieve plates:

$$Z_c = 0.006 + 0.73 \times 10^{-3} h_w - 0.24 \times 10^{-3} F_v h_w + 1.22 L_p$$

The Murphree efficiency E_{mV} is equal to the point efficiency E_{mv} only if the liquid on the plate is perfectly mixed.

On a real plate this will not be so, and to estimate the plate efficiency from the point efficiency, some means of estimating the degree of mixing is needed.

The dimensionless Peclet number characterizes the degree of mixing in a system. For a plate, the Peclet number is given by

$$Pe = \frac{Z_L^2}{D_e t_L}$$

where D_e is the eddy diffusivity, m^2/s.

A Peclet number of zero indicates perfect mixing, and a value of ∞ indicates plug flow.

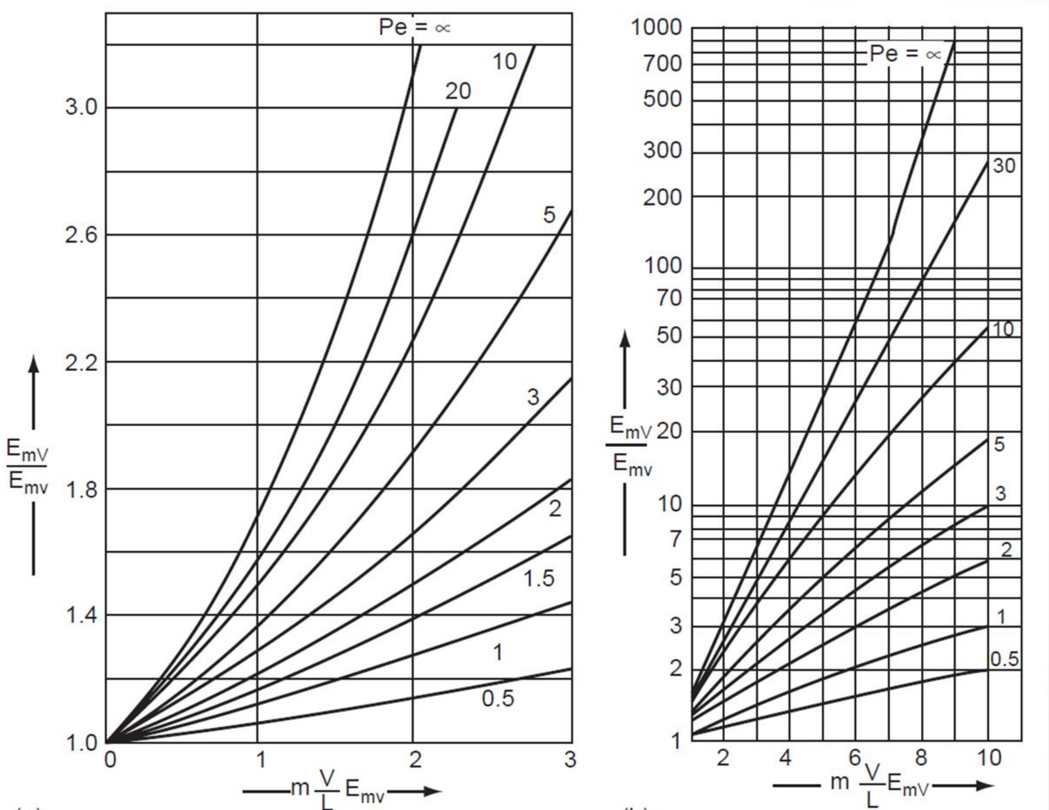
For bubble-cap and sieve plates, the eddy diffusivity can be estimated from the equation:

$$D_e = (0.0038 + 0.017u_a + 3.86L_p + 0.18 \times 10^{-3}\ h_w)^2$$

The relation between the plate efficiency and point efficiency with the Peclet number as a parameter is shown in Figure a and b.

The AIChE method was developed from measurements on binary systems.

The AIChE manual should be consulted for advice on its application to multicomponent systems.



(a) (b)

Entrainment

The AIChE method and that of Van Winkle predict the "dry" Murphree plate efficiency.

In operation some liquid droplets will be entrained and carried up the column by the vapor flow, and this will reduce the actual, operating efficiency.

The dry-plate efficiency can be corrected for the effects of entrainment using the equation proposed by Colburn (1936):

$$E_a = \frac{E_{mV}}{1 + E_{mV}\left[\frac{\psi}{1-\psi}\right]}$$

where

Ea = actual plate efficiency, allowing for entrainment;

ψ = the fractional entrainment = $\frac{\text{entrained liquid}}{\text{gross liquid flow}}$

Methods for predicting the entrainment from sieve plates are given in following slides; a similar method for bubble-cap plates is given by Bolles (1963).