Multipass Flow Distribution and Mass Transfer Efficiency for Distillation Plates

A new model for predicting the hydrodynamics, flow distribution, and mass transfer efficiency of multipass distillation trays is presented. Separate submodels apply to two-, three-, and four-pass trays, which may be any type of cross flow tray with downcomers: sieve, valve, or bubble cap.

It was found that the liquid/vapor flow ratio in one pass of a poorly designed multipass tray can be several times that in adjacent passes, and that the mean tray efficiency of such a tray is substantially less than the optimum possible. It is shown that multipass trays can be designed with essentially perfect flow distribution and optimum (maximum) overall tray efficiency.

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SCOPE

The simplest type of cross flow tray for vapor liquid contacting with mass transfer as used for distillation is the one-pass configuration. However, when the liquid load is proportionately high (compared to the vapor), or where the tower diameter is large, it is necessary to employ multipass trays of two, three, four, and sometimes more passes in order to accommodate the hydrodynamic flow characteristics.

The objectives of this study were to determine the effect of tray geometry on the liquid and vapor flow distribution among the various passes, to determine the effect of liquid/vapor flow distribution on mean plate efficiency, and to determine how to design a multipass tray with optimum flow distribution and plate efficiency.

These objectives were met by deriving a mathematical model for multipass flow distribution and mean Murphree plate efficiency. This model was then programmed for digital computer solution so that any multipass tray could be rated on its hydrodynamic and efficiency characteristics. The model was then executed on over 150 multipass tray geometry configurations to find the basic principles of optimum multipass tray design.

The scope of the present work included two-, three-, and four-pass trays. However, trays of any number of passes may be analyzed by following the same principles.

The multipass model requires hydrodynamic and mass transfer efficiency submodels for single passes where the liquid and vapor flow rates are known. These single-pass submodels were taken from the prior literature.

However, prior to this work there were no publications of any studies of overall mass transfer efficiency in multipass trays.

This study is theoretical and is not backed up by experimental data. However, the models employed are theoretically sound, and it is believed that the conclusions are valid and sound.

CONCLUSIONS AND SIGNIFICANCE

Two-pass trays present no special problems. Liquid and vapor streams distribute equally between the passes, and the mean Murphree plate efficiency is essentially equal to the arithmetic average of the Murphree efficiencies of the individual passes.

In the case of three and four pass trays, certain tray geometries can lead to very bad flow distribution, with liquid/vapor flow ratio in one pass several times that in other passes. Such flow maldistribution will result in premature flooding and a mean Murphree plate efficiency considerably less than the optimum obtainable.

Multipass trays can be designed for uniform flow distribution and optimum efficiency. One good design principle is to make the passes of equal area and the bubbling area within each also equal. Another is to employ inlet weirs. Best results are achieved with a combination of these and other design principles. When these recommended design principles are employed, no vapor equalization tunnels (through the intermediate downcomers) are required, and the mean Murphree plate efficiency is essentially equal to the arithmetic average of the predicted pass Murphree efficiencies.

The most common type of vapor liquid contacting tray is the one-pass, or single cross flow tray because of its simplicity, low cost, and known design methods. However, for large columns many designers employ the multipass configuration, as illustrated in Figure 1. A guide to selection of tray type was suggested by Bolles (1963) in which multipass trays were recommended for large column diameters and high liquid loads.

Commercial columns have been built with trays up to 15 m (50 ft) in diameter. Two-pass trays are common in columns 3 to 6 m in diameter, and three-pass and four-pass trays have been used in larger columns.

One reason for selecting a multipass tray is to provide for relatively high liquid load as compared to vapor load. With the multipass tray, both the liquid velocity and the length of liquid flow path are simultaneously cut to roughly 1/N of what they would be for a one-pass tray, where N is the number of passes. This results in lower weir crests and liquid gradients. Even where the liquid load is not relatively great, the multipass tray may be necessary for large column diameters, since liquid capacity is roughly proportional to weir length (first power of linear dimension), whereas vapor capacity is roughly proportional to column cross-sectional area

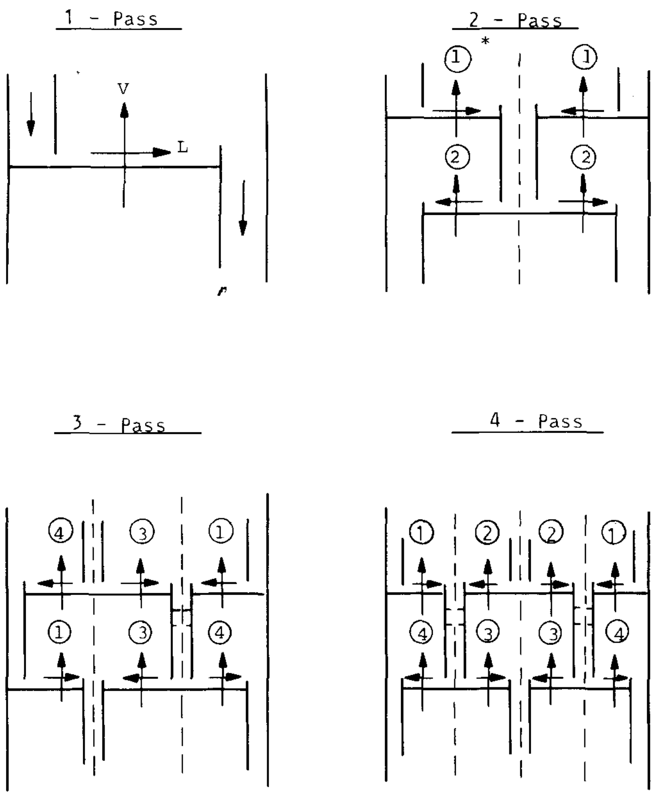

Fig. 1. Types of multipass trays.

(second power of linear dimension).

Furthermore, there is new evidence from Bell (1972), and Porter (1972) that long flow paths may lead to liquid channeling and reduced plate efficiency, particularly for large column diameters. This problem may be minimized through the specification of multipass trays, where the length of flow path is short compared to the width of the flow channel.

The operating mechanism and design of multipass trays have heretofore been little understood. At the time (1970) the author originally developed the model presented here; there had been no prior publications of analyses of hydrodynamics, flow distribution, and mass transfer efficiency of multipass trays. Indeed, the distillation practitioner had no recourse other than to assume that the liquid and vapor streams distribute themselves equally among the contacting passes and that the mean efficiency of the overall tray is equal to the arithmetic average of the efficiencies of the individual passes. Subsequently Becker (1974) published an analysis of the multipass hydraulics problem but excluding any treatment of the mass transfer efficiency relationships.

Actually, as will be shown, the liquid and vapor flow rates in the various contacting passes of a multipass tray are not necessarily equal. When the vapor velocity is higher in one pass than in others, the column may flood prematurely in the pinched pass because one pass may flood while others have surplus capacity. Also, where the liquid/vapor flow ratios differ among passes, the effective (mean) mass transfer efficiency for the overall tray may be less than that obtained when the phases are equally distributed.

MODEL

Fundamental Relations

Murphree efficiency, in terms of vapor compositions, defines the mass transfer approach to equilibrium in each pass:

$$E_{n,p} = \frac{y_{n,p} - y_{(n-1),pb}}{y^*_{n,p} - y_{(n-1),pb}} \quad (1)$$

Phase equilibrium is defined by the equilibrium line which may, alternatively, be represented by

$$y^*_{n,p} = mx_{n,p} + b \quad (2a)$$

$$y^*_{n,p} = \frac{\alpha x_{n,p}}{1 + (\alpha - 1)x_{n,p}} \quad (2b)$$

The intrapass mass balance within a pass is defined by the operating line:

$$V_{n,p}[y_{n,p} - y_{(n-1),pb}] = L_{n,p}[x_{(n+1),pa} - x_{n,p}] \quad (3)$$

Interpass mass balances define the interfaces among passes on an overall basis

$$\sum_{p=1}^{N} (L_p)_n = L_n \quad (4a)$$

$$\Sigma (V_p)_n = V_n \quad (4b)$$

and on a component basis:

$$\Sigma (L_p x_p)_n = L_n x_n \quad (5a)$$

$$\Sigma (V_p y_p)_n = V_n y_n \quad (5b)$$

Two-Pass Trays

Figure 1 gives a diagram of a two-pass tray. Since there are two different tray designs, installed alternately, it is necessary to analyze one whole repeater unit consisting of two trays.

Since the tray geometry is symmetrical with respect to the center line, then all variables should also be symmetrical.

The hydrodynamics are defined by application of Equation (4):

$$L_1 = L/2 \quad (6a)$$

$$L_2 = L/2 \quad (6b)$$

$$V_1 = V/2 \quad (6c)$$

$$V_2 = V/2 \quad (6d)$$

Murphree efficiencies for passes 1 and 2 are defined by application of Equation (1):

$$E_1 = \frac{y_{n+1} - y_n}{y^*_{n+1} - y_n} \quad (7)$$

$$E_2 = \frac{y_n - y_{n-1}}{y^*_n - y_{n-1}} \quad (8)$$

Phase equilibrium relations are defined by application of Equation (2a):

$$y^*_n = mx_n + b \quad (9)$$

$$y^*_{n+1} = mx_{n+1} + b \quad (10)$$

The mass balance is defined by application of Equation (3):

$$V_2(y_n - y_{n-1}) = L_2(x_{n+1} - x_n) \quad (11)$$

Equations (7) to (11) represent five simultaneous, linear equations in five unknowns: x_{n+1}, y_n, y^*_n, y_{n+1}, and y^*_{n+1}. These may be solved for y_{n+1} as a function of y_{n-1} and x_n with the following result:

$$y_{n+1} = y_{n-1} + (E_1 + E_2 - E_1E_2 + \lambda E_1E_2)(-y_{n-1} + mx_n + b) \quad (12)$$

where

$$\lambda = mV/L \quad (13)$$

Now, the mean plate efficiency E_m is defined such that replacing E_1 and E_2 with E_m will not alter the value of y_{n+1} in Equation (12). Making this substitution, we get

$$y_{n+1} = y_{n-1} + (E_m + E_m - E_m^2 + \lambda E_m^2)(-y_{n-1} + mx_n + b) \quad (14)$$

Equations (12) and (14) can be combined and reduced to

$$E_m^2 + 2\left(\frac{1}{\lambda - 1}\right) E_m - \left[\frac{E_1 + E_2}{(\lambda - 1)} + E_1 E_2\right] = 0 \quad (15)$$

Equation (15) is quadratic in E_m, whose solusion is

$$E_m = -\frac{1}{\lambda - 1} \pm \sqrt{\left(\frac{1}{\lambda - 1} + E_1\right)\left(\frac{1}{\lambda - 1} + E_2\right)} \quad (16)$$

Equations (6) and (16) represent the final hydrodynamic and efficiency model for two-pass trays.

Four-Pass Trays

A diagram of a four-pass tray is given in Figure 1. Since the tray geometry is symmetrical with respect to the center line, then all variables are also symmetrical. Note that the optional vapor communication tunnels through the intermediate downcomers for the purpose of pressure equalization.

First, let us consider the hydrodynamics of the four-pass tray. Application of Equation (4) results in

$$L_1 + L_2 = L/2 \quad (17)$$

$$L_3 + L_4 = L/2 \quad (18)$$

$$V_1 + V_2 = V/2 \quad (19)$$

$$V_3 + V_4 = V/2 \quad (20)$$

$$V_{34} = V_1 - V_4 \text{ (vapor tunnel)} \quad (21a)$$

$$V_{34} = 0 \text{ (no vapor tunnel)} \quad (21b)$$

where V_{34} = vapor flow through tunnel from pass 3 to pass 4.

Since there is only one downcomer from pass 4 to pass 1

$$L_1 = L_4 \quad (22)$$

Since passes 3 and 4 share the same downcomer

$$h_3 = h_4 \quad (23)$$

With vapor tunnels there is complete equalization of pressure between adjacent zones:

$$\Delta P_1 = \Delta P_2 \quad (24)$$

$$\Delta P_3 = \Delta P_4 \quad (25)$$

On the other hand, without vapor tunnels, a simple derivation results in

$$\Delta P_1 + \Delta P_4 = \Delta P_2 + \Delta P_3 \quad (25a)$$

Equations (17) to (25) represent nine equations in nine unknowns: L_1, L_2, L_3, L_4, V_1, V_2, V_3, V_4, and V_{34}. These may be solved by any hydrodynamic model capable of calculating h_3, h_4, ΔP_1, ΔP_2, ΔP_3, ΔP_4 for single passes where L_p and V_p are known.

Now let us consider the mass transfer efficiency of the four-pass tray. Although two four-pass trays complete a repeater unit, it was found necessary to analyze three trays in order that the number of equations equals the number of unknowns.

Although the flow of vapor through the vapor communication tunnel alters somewhat the composition of the vapor stream, this effect will be ignored. In other words, it will be assumed that vapors in all passes are isolated sofar as composition is concerned. This is a conservative assumption, because any mixing will reduce maldistribution and improve plate efficiency.

Murphree efficiencies for each pass are defined by application of Equation (1):

$$E_1 = \frac{y_{(n+1),1} - y_{n,4}}{y^*_{(n+1),1} - y_{n,4}} \quad (26)$$

$$E_2 = \frac{y_{(n+1),2} - y_{n,3}}{y^*_{(n+1),2} - y_{n,3}} \quad (27)$$

$$E_3 = \frac{y_{n,3} - y_{(n-1),2}}{y^*_{n,3} - y_{(n-1),2}} \quad (28)$$

$$E_4 = \frac{y_{n,4} - y_{(n-1),1}}{y^*_{n,4} - y_{(n-1),1}} \quad (29)$$

$$E_3 = \frac{y_{(n+2),3} - y_{(n+1),2}}{y^*_{(n+2),3} - y_{(n+1),2}} \quad (30)$$

$$E_4 = \frac{y_{(n+2),4} - y_{(n+1),1}}{y^*_{(n+2),4} - y_{(n+1),1}} \quad (31)$$

Phase equilibria relations are obtained by application of Equation (2b):

$$y^*_{(n+1),1} = \frac{\alpha x_{(n+1),1}}{1 + (\alpha - 1)x_{(n+1),1}} \quad (32)$$

$$y^*_{(n+1),2} = \frac{\alpha x_{(n+1),2}}{1 + (\alpha - 1)x_{(n+1),2}} \quad (33)$$

$$y^*_{n,3} = \frac{\alpha x_{n,3}}{1 + (\alpha - 1)x_{n,3}} \quad (34)$$

$$y^*_{n,4} = \frac{\alpha x_{n,4}}{1 + (\alpha - 1)x_{n,4}} \quad (35)$$

$$y^*_{(n+2),3} = \frac{\alpha x_{(n+2),3}}{1 + (\alpha - 1)x_{(n+2),3}} \quad (36)$$

$$y^*_{(n+2),4} = \frac{\alpha x_{(n+2),4}}{1 + (\alpha - 1)x_{(n+2),4}} \quad (37)$$

Intrapass mass balances are obtained by application of Equation (3):

$$V_1[y_{(n+1),1} - y_{n,4}] = L_1[x_{(n+2),4} - x_{(n+1),1}] \quad (38)$$

$$V_2[y_{(n+1),2} - y_{n,3}] = L_2[x_{(n+2),3} - x_{(n+1),2}] \quad (39)$$

$$V_3[y_{n,3} - y_{(n-1),2}] = L_3(x_{n+1} - x_{n,3}) \quad (40)$$

$$V_4[y_{n,4} - y_{(n-1),1}] = L_4(x_{n+1} - x_{n,4}) \quad (41)$$

$$V_3[y_{(n+2),3} - y_{(n+1),2}] = L_3[x_{n+3} - x_{(n+2),3}] \quad (42)$$

$$V_4[y_{(n+2),4} - y_{(n+1),1}] = L_4[x_{n+3} - x_{(n+2),4}] \quad (43)$$

Interpass mass balances are obtained by application of Equation (4):

$$(V_1 + V_2)y_{n-1} = V_1 y_{(n-1,)1} + V_2 y_{(n-1),2} \quad (44)$$

$$(V_1 + V_2)y_{n+1} = V_1 y_{(n+1,)1} + V_2 y_{(n+1),2} \quad (45)$$

$$(L_3 + L_4)x_n = L_3 x_{n,3} + L_4 x_{n,4} \quad (46)$$

$$(L_1 + L_2)x_{n+1} = L_1 x_{(n+1),1} + L_2 x_{(n+1),2} \quad (47)$$

In addition, the following boundary conditions may be specified:

$$x_n = x_{n,\text{spec}} \tag{48}$$

$$y_{(n-1)} = (L/V)x_n + B \tag{49}$$

$$y_{(n-1),1} = y_{(n-1)} + \Delta R_{y(n-1)} \tag{50}$$

Equations (26) to (50) represent twenty-five simultaneous equations in the following twenty-five unknowns:

	y_{n-1}	
	$y_{(n-1),1}$	
	$y_{(n-1),2}$	
x_n		
$x_{n,3}$	$y_{n,3}$	$y^*_{n,3}$
$x_{n,4}$	$y_{n,4}$	$y^*_{n,4}$
x_{n+1}	y_{n+1}	
$x_{(n+1),1}$	$y_{(n+1),1}$	$y^*_{(n+1),1}$
$x_{(n+1),2}$	$y_{(n+1),2}$	$y^*_{(n+1),2}$
$x_{(n+2),3}$	$y_{(n+2),3}$	$y^*_{(n+2),3}$
$x_{(n+2),4}$	$y_{(n+2),4}$	$y^*_{(n+2),4}$
x_{n+3}		

These twenty-five equations will then yield a unique solution.

In order to determine the mean efficiency E_m for the two-tray, four-pass repeater unit, it is necessary to analyze a two-tray, one-pass repeater unit having the same boundary conditions of compositions x_n, y_{n-1}, and y_{n+1}, and total flow rates L and V.

Murphree efficiencies for each tray are obtained by application of Equation (1):

$$E_m = \frac{y_n - y_{n-1}}{y^*_n - y_{n-1}} \tag{51}$$

$$E_m = \frac{y_{n+1} - y_n}{y^*_{n+1} - y_n} \tag{52}$$

Phase equilibria relations are obtained by application of Equation 2b):

$$y^*_n = \frac{\alpha x_n}{1 + (\alpha - 1)x_n} \tag{53}$$

$$y^*_{n+1} = \frac{\alpha x_{n+1}}{1 + (\alpha - 1)x_{n+1}} \tag{54}$$

Intrazone mass balance is obtained by application of Equation (3):

$$V(y_n - y_{n-1}) = L(x_{n+1} - x_n) \tag{55}$$

In addition, the following boundary conditions prevail:

$$x_n = x_{n,\text{spec}} \tag{56}$$

$$y_{n-1} = y_{(n-1),\text{spec}} \tag{57}$$

$$y_{n+1} = y_{(n+1),\text{spec}} \tag{58}$$

Equations (51) to (58) represent eight simultaneous equations in eight unknowns: E_m, x_n, x_{n+1}, y_{n-1}, y_n, y_{n+1}, y^*_n, and y^*_{n+1}. Therefore, a unique solution is possible for E_m.

The boundary conditions expressed by Equations (48) to (50) require special attention. Equation (48) is obvious, we simply wish to specify the tray liquid composition as one of the input variables.

Equation (49) represents the overall column material balance. Although the value of B could be made available to the model, it was decided to keep the model independent of any input data not available on the tray itself. A study of the model response for many numerical examples showed that the computed mean efficiency is essentially independent of the value of B. Hence a decision was made to arbitrarily set $B = 0$ in the model.

Equation (50) describes the bias of the vapor composition in pass 1 relative to that of the bulk stream. The value of R_y is zero for $n = 1$ since all vapor from the reboiler is of the same composition. As n increases, R_y takes on a small absolute value and eventually becomes constant. It seems reasonable to assume that, at equilibrium, the value of R_y for vapor entering a repeater unit should be equal to the value for that leaving; that is

$$R_{y,(n-1)} = R_{y,(n+1)} \tag{50}$$

where

$$R_{y,(n+1)} = [y_{(n+1),1} - y_{(n+1)}]/\Delta \tag{51}$$

The value of the constant Δ is arbitrary, but it is advantageous if the value is proportional to the order of magnitude of concentration increments among passes computed by the model. For this purpose, it was found that a good value of Δ is given by

$$\Delta = y^*_n - x_n = (\alpha x_n)/[1 + (\alpha - 1)x_n] - x_n \tag{52}$$

Algorithm

The algorithm for solving the hydrodynamic model for four-pass trays starts with assuming values for two or three* trial variables: L_1, V_1, and V_4. Reasonable starting values are one-quarter of total stream flow rates. All other input flow variables are then computed directly from Equations (17) to (22).

The detailed hydrodynamic model for each pass is then executed to compute the values of the dependent variables: h_3, h_4, ΔP_1, ΔP_2, ΔP_3, and ΔP_4. These output values are then tested to see if they satisfy the two or three* Equations (23) to (25). The remainder of the hydrodynamic algorithm consists of iterating on the trial variables until the convergence is achieved.

The algorithm for the mass transfer efficiency model starts with assuming that the value of $R_{y,(n-1)}$ is zero. It is then possible to solve Equations (26) to (50) directly, provided they are ordered in proper sequence so as to work upwards through three trays. The pass Murphree efficiencies, E_1, E_2, E_3, and E_4, are predicted by a mass transfer model executed on the individual passes. At the end, $R_{y,(n+1)}$ is computed by Equation (51). Iterations are then performed on trial variable $R_{y,(n-1)}$ until Equation (50) is satisfied. At this point, we have the compositions of all liquid and vapor streams of all passes.

Finally, mean Murphree efficiency E_m is computed by solving Equations (51) to (58) by an iterative procedure.

Three-Pass Trays

Limitations on space do not permit presenting the model for three-pass trays. However, the approach is the same as for four-pass trays.

Detailed Pass Model

The new multipass model herein developed is concerned only with the hydrodynamics and mass transfer efficiency relationships between and among the contacting passes of the multipass tray. In order to study the behavior and response of the new model, it is necessary to couple it with a basic pass model for the hydrodynamics and mass transfer efficiency within each contacting pass.

The pass model for this purpose was chosen for sieve trays from Smith (1963). The hydrodynamic model is essentially that of Fair (1963), and the efficiency model that of AIChE (1958), as described by Smith (1963,

* Vapor communication tunnels involve three trial variables and three equations, absence of tunnels involves two.

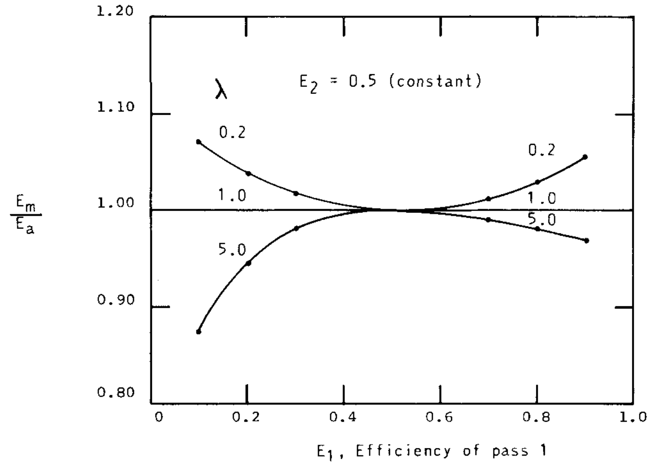

Fig. 2. Examples of efficiencies for two-pass trays.

chapter 16). One exception from the Fair-AIChE model is in regard to entrainment; its magnitude and effect on efficiency were ignored. This was done deliberately to avoid masking the effect of multiple passes on mass transfer efficiency.

The total model was then programmed for execution on a large digital computer.

TRAY DESIGN STUDIES

A base case was chosen for multipass tray design studies. This case involved the distillation of a system involving benzene and toluene at atmospheric pressure, similar to the example calculation of Fair (1963). The model study then consisted of perturbing one or more values of the independent geometric variables from the base case and then observing the model response with respect to the dependent variables. More than 150 cases were solved in detail with the complete model and computer program. The results from a few of these cases will be presented herein for illustrative purposes.

The response of the model for two-pass trays is best understood by graphing Equation (20), as illustrated in Figure 2. Here the ordinate is E_m/E_a, where mean efficiency E_m is from Equation (20), and average efficiency is defined by $E_a = (E_1 + E_2)/2$. In the example, E_2 is held constant at 50%, while E_1 is varied with parametric values of λ. It can be seen that the value of efficiency ratio E_m/E_a is essentially unity unless there is a very wide difference between pass efficiencies.

For two-pass trays, it was found that to effect a significant difference in pass efficiencies required assuming a radical difference in pass geometries. For example, by making the weir heights differ by 15 cm, the predicted Murphree pass efficiencies were 70 and 81%, and the mean efficiency was 75% as compared to an optimum (maximum) of 76%. A more prominent effect was found in inactive area, defined as that portion of tray area deliberately blanked and assumed to support no mass transfer. Blanking one pass by 50% resulted in predicted pass efficiencies of 76 and 47% and a tray mean efficiency of only 62% for the same service. However, it is not expected that such an unusual tray geometry would ordinarily be encountered in practice.

It was concluded from these as well as other studies that the mean efficiency for any reasonable two-pass tray design is essentially equal to the arithmetic average of the predicted efficiencies for the passes.

The numerical study of the four-pass model began with the example data of Fair (1963), except that the design loads were increased tenfold so as to require a column of sufficient size to justify four-pass trays. The base case was for a sieve tray 10.7 m in diameter, all pass areas equal at 25% of column area, downcomers at 6% of pass area, hole area at 10% of active area, outlet weirs of height 75 mm and length equal to that of the segment chords, and no inlet weirs. The computed performance for this tray, identified as case 1, may be summarized as follows:

Pass	1	2	3	4
L/V	0.53	1.14	1.14	0.53
% flood	68	70	70	68
% efficiency	91	80	80	91
Distribution ratio, ϕ		2.15		
Average efficiency, E_a		85%		
Mean efficiency, E_m		67%		
Mean/average, E_m/E_a		0.79		

Distribution ratio ϕ is defined as the ratio of the maximum to the minimum pass L/V ratio: $1.14/0.53 = 2.15$. Thus, distribution ratio is an index to the uniformity of flow distribution, with unity as the measure of perfect distribution. Average efficiency is the arithmetic average of the predicted pass efficiencies. Mean efficiency is E_m as computed by the multipass model.

Case 2 was developed from case 1 by adding inlet weirs to all passes, with the following results:

Pass	1	2	3	4
L/V	0.82	0.84	0.84	0.82
% flood	69	69	69	69
% efficiency	81	81	81	81
Distribution ratio		1.02		
Average efficiency		81%		
Mean efficiency		81%		
Mean/average efficiency		1.00		

As can be seen, the distribution is almost perfect, and the mean efficiency is equal to the arithmetic average. Based on the total study of over 150 tray configurations, it was concluded that 81% is the maximum (optimum) Murphree plate efficiency possible for this system in a four-pass tray.

Analysis of detailed data revealed the reason for the remarkable difference between cases 1 and 2. In both cases the hole area is the same in all passes, which causes the vapor to distribute approximately equally. However, in case 1 the liquid loads are controlled by the outlet weirs, and since side weirs are much shorter than intermediate weirs, the liquid does not distribute uniformly. In case 2, however, the liquid loads are controlled by the inlet weirs. Since inlet weirs on either side of intermediate downcomers are approximately equal in length, the liquid flow rates are also approximately equal.

Other cases in the study included design changes deliberately intended to result in poor performance in order to develop understanding and insight. For example, case 3 was generated from case 2 by cutting the effective length of the inlet weir to pass 4 to one-half the length of the segment. Case 3 results were as follows:

Pass	1	2	3	4
L/V	0.56	1.11	1.11	0.56
% flood	68	70	70	68
% efficiency	88	78	78	88
Distribution ratio		1.96		
Average efficiency		83		
Mean efficiency		69		
Mean/average efficiency		0.83		

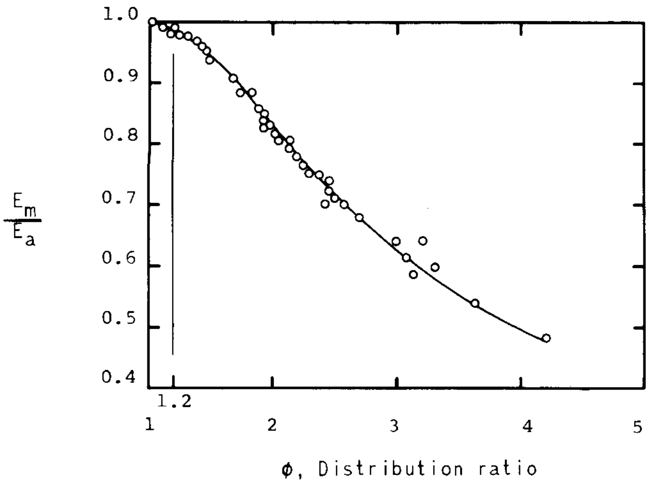

Fig. 3. Empirical correlation of multipass efficiency.

Case 4 was generated from case 3 by cutting the hole area in passes 2 and 3 from 10 to 7%, with the following results:

Case	1	2	3	4
L/V	0.47	1.40	1.40	0.47
% flood	82	71	71	82
% efficiency	91	86	86	91
Distribution ratio		2.98		
Average efficiency		88		
Mean efficiency		56		
Mean/average efficiency		0.64		

In case 4 not only is the mean plate efficiency low, but also the pass loads are poorly balanced. Consequently, as the overall loads on this tray are increased, passes 1 and 4 will flood while passes 2 and 3 have surplus capacity. This indicates a waste of tower area and capacity.

The other cases in the design study included the effect of the number of passes, column diameter, system properties, vapor load, liquid load, pass area distribution, downcomer area, inlet weirs, outlet weirs, hole area, and vapor tunnels.

DISCUSSION

One of the outcomes of the design studies is the correlation shown in Figure 3, which shows that mean efficiency falls as distribution ratio rises. Although this correlation is admittedly empirical, it seems reasonable to conclude that if the distribution ratio is less than 1.2, the multipass mean plate efficiency is essentially equal to the arithmetic average of the pass efficiencies. With this conclusion one can bypass the complex multipass efficiency model.

Furthermore, it was found that low distribution ratios (less than 1.2) can usually be obtained by following certain design principles. One is to subdivide the column into equal pass areas and to provide equal hole area (or number of valves or bubble caps) within each pass. Another is to provide inlet weirs. If these principles are followed, no vapor equalization tunnels will be necessary.

In the event that the pass areas are not equal, good flow distribution can be achieved by proper selection of the lengths of the inlet weirs for each pass. Furthermore, if inlet weirs are undesirable, good flow distribution can be achieved by tuning the lengths of the outlet weirs.

The simplest method for modifying the effective length of a weir is to employ a picket fence configuration. This means that the weir height is staggered between two elevations. Since liquid can flow only through the spaces at low elevation, the effective weir length can be adjusted to any desired value by the number and width of the pickets.

NOTATION

B = intercept of operating line tangent
b = intercept of equilibrium line tangent
E = Murphree plate efficiency
h = head of liquid in downcomer
L = liquid molar flow rate
m = slope of equilibrium line
N = number of passes
ΔP = pressure differential through tray pass
R = ratio of concentrations
V = vapor molar flow rate
x = mole fraction of key component in liquid leaving tray pass
y = mole fraction of key component in vapor leaving tray pass
α = relative volatility between key components
Δ = composition increment constant
λ = mV/L
ϕ = distribution ratio, $(L/V)_{max}/(L/V)_{min}$

Subscripts

a = average (arithmetic)
n = plate number, counting upwards
m = mean (true, effective)
p = index to pass
1 = pass with inlet side downcomer
2 = pass with inlet center downcomer
3 = pass with inlet intermediate downcomer nearest to tray center
4 = pass with inlet intermediate downcomer farthest from tray center
pa = pass above pass p
pb = pass below pass p
spec = specified

Superscripts

$*$ = equilibrium

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