Influence of Tray Geometry on Scaling Up Distillation Efficiency from Laboratory Data

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This paper studies the effect of tray geometry (especially hole diameter) and liquid tray composition on tray efficiency in a bench-scale distillation column. The results of this study are used for scaling up tray efficiency. Two binary systems, ethanol/water and cyclohexane/n-heptane, were considered. The operating conditions were atmospheric pressure and total reflux. For each one, two different hole diameters (small and large) were also tested. Kirschbaum's industrial data (1962) for the ethanol/water system and of Yanagi and Sakata's (1982) for the cyclohexane/n-heptane system were considered as reference values. The results show the importance of reproducing the hole diameter and liquid tray composition in small trays for using laboratory data to predict large tray efficiency.

Introduction

The prediction of industrial tray efficiencies on distillation columns is usually made by the following procedures: (1) Comparison with the tray efficiency of similar operating columns; (2) scaling up from laboratory columns; (3) empirical correlation; (4) theoretical to semitheoretical mass-transfer models.

The best and surest method of efficiency calculation today is to use the value of a similar column as a reference.[1] Then, when laboratory data are available, satisfactory results can be obtained by scaling up these values to an industrial tray. If no experimental reference is available, the latest prediction methods can provide efficiency values, the validity of which depends on the suitability and quality of the correlation. Reviews of prediction models for tray efficiency can be found in Chan and Fair,[2] Dribika and Biddulph,[3] Chen and Chuang,[4] Klemola and Ilme,[1] and Bennett et al.[5] The papers of Chen and Chuang[4] and Bennett et al.[5] present new improved correlations to estimate the point efficiency.

The second method, the scaling-up procedure, i.e., the relationship between tray efficiency in small and large trays, is considered in detail in this paper.

Different procedures of scaling up exist in freely available literature. Among them, Finch and Van Winkle,[6] Garrett et al.,[7] and Fair et al.[8] seem to be the most developed methods.

On one hand, the Finch and Van Winkle method defines the small tray as the most similar to the industrial tray, but its scaling-up procedure has a high empiricism. On the other hand, the Garrett et al. and de Fair et al. methods use Oldershaw columns with small hole diameters to obtain the point efficiency and then they predict tray efficiency by using a flux model.

The Dribika and Biddulph[3] and Biddulph et al.[9] studies, which compare the results obtained in a small column with tray efficiencies in a large tray (with similar hole diameters, 1.8 and 1.1 mm for the large and small trays, respectively), demonstrate that the results obtained in small columns can be used by a flow model to predict the tray efficiency of large trays from laboratory data.

Biddulph et al.[10] analyze the scaling up between a 0.43-m column diameter with one of 1.2 m for the cyclohexane/n-heptane system at different operation pressures. In the normal operation range in the small column there is no discernible effect of pressure on point efficiency. The weir height is the same for both columns, but the hole diameters were 4.8 and 12.7 mm for the small and large columns, respectively. Although data are at a minimum, the scaling-up results are acceptable.

The aim of this paper is to corroborate the importance of tray geometry and liquid composition in small trays, whose point efficiency data will be used in tray efficiencies scaling up. The data from small trays, such as froth height, ensure a better prediction. Another advantage of reproducing the tray geometry and liquid tray composition is that one can define the operation range for industrial columns from the small tray.

Experimental Section

Large Tray Efficiency Data. We have taken data from large trays as a reference. Kirschbaum's data[11] have been used for the ethanol/water system (EtOH/H_2O) at two different tray spacings (Figure 1) and Yanagi and Sakata's data[12] for the cyclohexane/n-heptane system (c-C6/n-C7) at two different pressures (Figure 2). The tray characteristics of large trays are presented in Table 1.

Experimental Equipment. A glass column with an inside diameter of 75 mm and containing two or three easily replaceable stainless steel trays was assembled to measure the tray efficiency. A glass-walled column was chosen in preference to the other insulated materials so that the tray and column performances could be viewed. The equipment is insulated with 40-mm-thick glass fiber material, except for the experimental area, which is built with a double-glass wall, on the inside of which the vacuum is used. Essential layout features of the column are shown in Figure 3.

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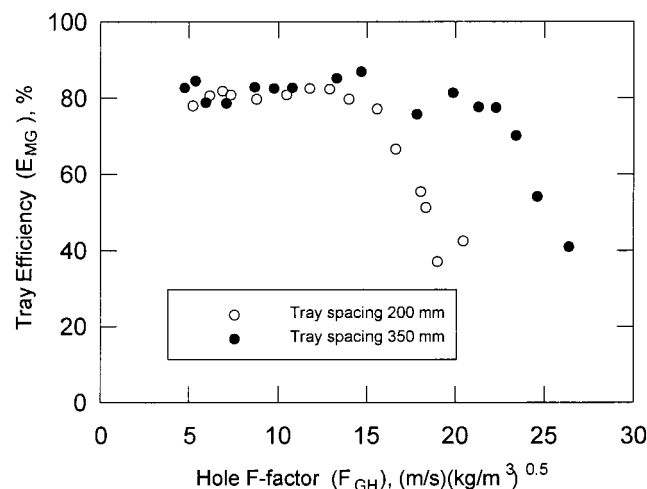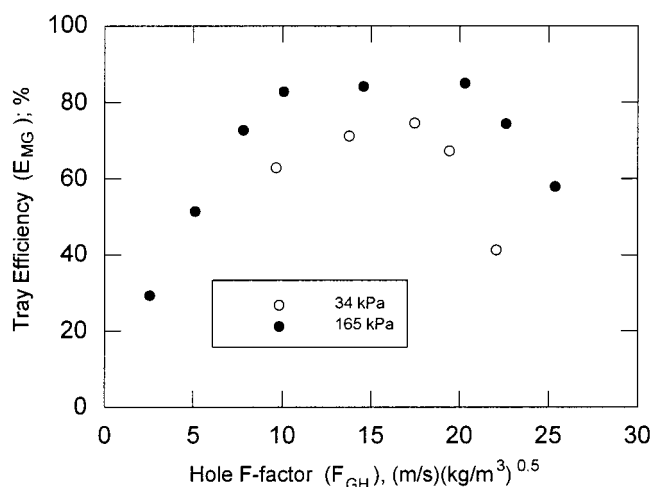
Figure 1. Kirschbaum tray efficiencies.

Figure 2. Yanagi and Sakata tray efficiencies.

Table 1. Characteristics of Kirschbaum and Yanagi and Sakata Trays

	Kirschbaum	Yanagi and Sakata
tray diameter (m)	0.75	1,2
hole diameter (mm)	10	12.7
weir length (m)	0.545	0.94
tray spacing (mm)	200/350	0.61
outlet weir height (mm)	25	50.8
flow path length (m)	0.515	0.762
pitch/hole diameter ratio	2.8	2.4
downcomer area (m^2)	0.0447	0.14
active area (m^2)	0.3524	0.859
hole area (m^2)	0.0364	0.118
system	EtOH/H$_2$O	c-C6/n-C7
pressure (kpa)	101	165/34
reflux	total	total

Two different hole diameters have been used in this study for each binary system. The weir height was adjustable. The tray geometries are summarized in Table 2.

Measurements. Experiments under atmospheric conditions and total reflux were performed. At the beginning of each experiment, the column was operated until it reached the steady state. The liquid composition was the same as that for the industrial tray, i.e., 50% for the EtOH/H$_2$O system and 60% for the c-C6/n-C7 system.

Samples of the inlet and outlet vapor, liquid tray, and reflux were collected simultaneously in precooled bottles and analyzed by gas chromatography, with an accuracy
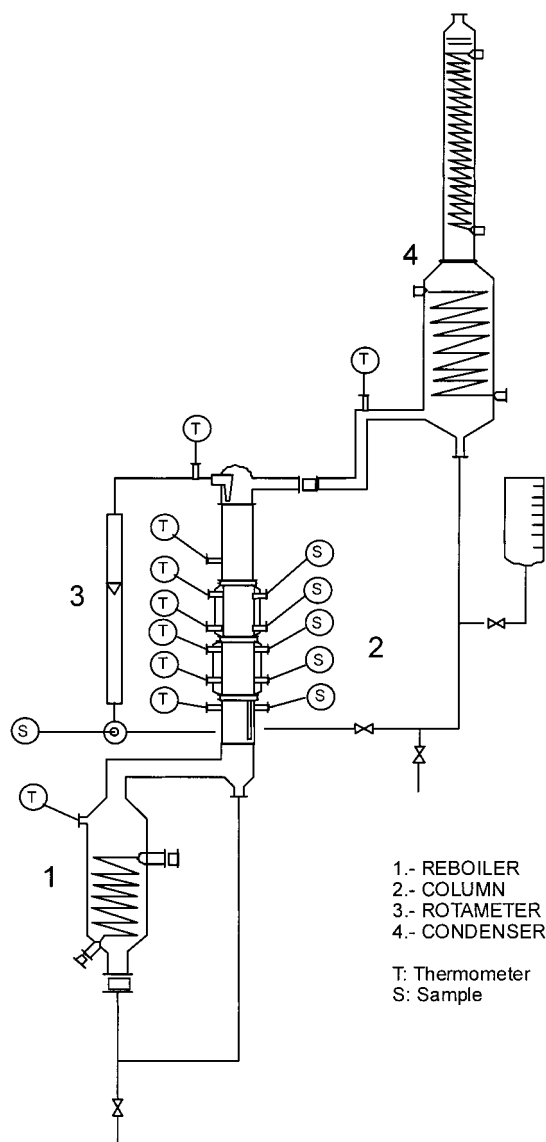

Figure 3. Simplified diagram of a laboratory distillation column.

Table 2. Characteristics of Trays Used in the Experimental Work

tray	T-1	T-2	T-3	T-4
tray diameter (mm)	75	75	75	75
hole diameter (mm)	2.5	10	2	12.5
downcomer diameter (mm)				
ID	12	12	12	12
OD	10	10	10	10
tray spacing (mm)	158	158/330	347	347
weir height (mm)	25	25	50.5	50.5
hole number	67	7	119	4
pitch/hole diameter ratio	2.8	2.8	2.5	2.4
perforated sheet, thickness (mm)	2	2	2	v
perforated sheet, material	316 SS	316 SS	316 SS	316 SS
clearance (mm)	4	4	4	4
total area (cm^2)	44.2	44.2	44.2	44.2
downcomer area (cm^2)	1.13	1.13	1.13	1.13
active area (cm^2)	41.9	41.9	41.9	41.9
hole area (cm^2)	3.29	5.50	3.74	4.91

of ±0.0012 mole fraction for the EtOH/H$_2$O and ±0.0023 mole fraction for the c-C6/n-C7.

The temperatures of the liquid and the inlet and outlet vapor of the measuring tray and reflux were measured by PT-100 thermocouples.

The froth height was measured against a scale placed behind the column, and the reflux flow rate was measured by a calibrated rotameter.

Table 3. Summary of Experimental Sets

set	tray	binary system	liquid composition (mol %)	liquid density (kg/m³)	vapor density (kg/m³)	flood point[b] F_{GH}	entrainment[c] E
1	T-1	EtOH−H₂O	50	850	1.1	15.4	0.023
2	T-2 (158)[a]	EtOH−H₂O	50	850	1.1	12.8	0.040
3	T-2 (330)[a]	EtOH−H₂O	50	850	1.1	21.9	0.019
4	T-3	c-C6/n-C7	60	675	3.1	21.6	0.008
5	T-4	c-C6/n-C7	60	675	3.1	13.3	0.010

[a] Tray spacing. [b] Extrapolated value. [c] Maximum value calculated.

The flooding point was determined experimentally by increasing the vapor velocity until flooding.

Vapor−Liquid Equilibria and Physical Properties. The vapor pressures of pure components are determined by the Antoine equation, while the activity coefficients of the liquid mixtures are evaluated using Van Laar's equation and gas equation of state (EOS). The vapor−liquid equilibrium (VLE) was calculated by Gibbs free energy minimization using Hoche−Jeeves' algorithm. Antoine's constants, molar volumes of pure liquid components, and Van Laar's parameter are taken from Gmehling and Onken.[13]

The liquid densities and liquid viscosities of pure components were obtained from Yaws et al.[14]

The vapor viscosities of pure components were obtained by using Brokaw's equation. Wilke's method is applied for liquid mixtures.[15]

The surface tension at the boiling temperature under atmospheric pressure was obtained for each system from the surface tensions of pure components reported by Yaws et al.[14] and then calculated according to mixing rules recommended by Reid et al.[15]

The binary diffusion coefficient of vapor is estimated from the Wilke and Lee equation while the binary coefficient of liquid is calculated by the Wilke and Chang method reported by Reid et al.[15]

Experimental Procedure. In the experiment we ran two binary mixtures in the column described above and measured the tray efficiency and froth height. For each binary system, the flooding point was determined for the tray used. Samples were obtained so that the operation of the tray could be studied over a wide range of operating conditions.

The different experimental sets are summarized in Table 3 (tray reference, binary system, liquid composition, flooding point, and entrainment).

Scaling-Up Procedure. The scaling-up procedure used to calculate the tray efficiency for the large trays is accurately described in the Appendix.

Results and Discussion

Influence of Hole Diameter. For the EtOH/H₂O system three sets of experiments were carried out under the same operating conditions (pressure and total reflux) as Kirschbaum's trays. A similar tray geometry to Kirschbaum's was considered. In the first one, with tray T-1, the main difference between tray T-1 and Kirschbaum's tray was the hole diameter (2.5 mm versus 10 mm). In the second and third sets, tray T-2 with two different tray spacings, 158 and 330 mm, were used (see Table 2). This tray has the same hole diameter (10 mm), weir height (25 mm), and pitch/hole diameter ratio (2.8) as the Kirschbaum tray, so they can be considered part of the Kirschbaum tray.

If tray efficiency profiles versus hole F factor (F_{GH}) for the trays T-1 and T-2 are analyzed (see Figure 4), then the difference between the efficiency of trays T-1
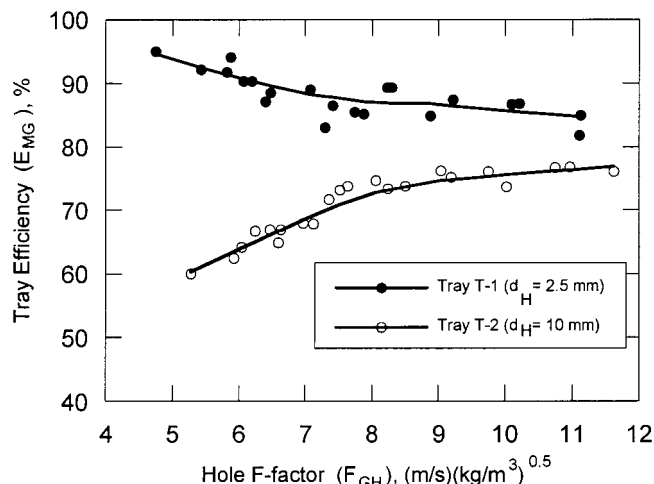

Figure 4. Comparison between small trays T-1 and T-2 (liquid composition on tray 50 mol %).

and T-2 is significant. These results demonstrate first of all that the hole diameter has a very important effect on the tray efficiency of small test trays. For low vapor velocities (e.g., F_{GH} = 6 (m/s) (kg/m³)$^{0.5}$), the tray with the large hole has an efficiency of 65% and the small tray has an efficiency of 90%. This fact must be taken into consideration since most of the experimental data determined in pilot columns have been obtained with Oldershaw columns using small holes trays. Lockett[16] said that the estimations of E_{OG} to scaling-up studies appear to depend on a fortunate combination of circumstances. Kalbassi et al.[17] found that there was an increase in tray and point efficiency with decreasing perforation size.

The difference in behavior between trays T-1 and T-2 can be explained by the different tray-operating regimes.[18] While tray T-1 (small hole diameter) operates at a hole Reynolds number of between 1000 and 3000, tray T-2 (large hole diameter) operates at a hole Reynolds number of between 4000 and 10000. Because the hole diameters are different, the vapor bubbles, froth characteristics, froth height (2-cm gap at the same flow), and the interfacial area are also different.

According to Biddulph et al.[10] as there is no discernible effect of pressure on point efficiency in the normal operation range in small columns, similar experimental work has been done for the c-C6/n-C7 system, operating at total reflux and atmospheric pressure. In this case the reference was the efficiency data of an industrial tray reported by Yanagi and Sakata.[12] These data were reported at 34 and 165 kPa. Two types of test trays were used, T-3 and T-4, the details of which are presented in Table 2. Both trays have similar geometries to those of the reference tray, but T-3 has a hole diameter of 2 mm, while the hole diameter of tray T-4 is practically equal to the reference tray (12.7 mm). The tray efficiency profiles are shown in Figure 5, and an important difference between the two trays can also be observed.
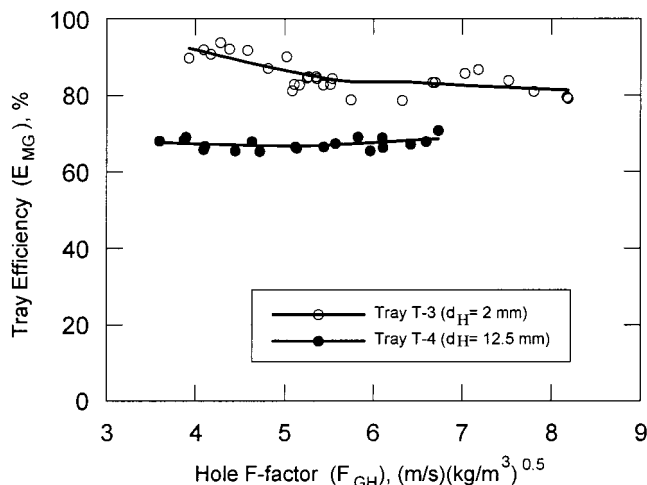
Figure 5. Comparison between small trays T-3 and T-4 (liquid composition on tray 60 mol %).
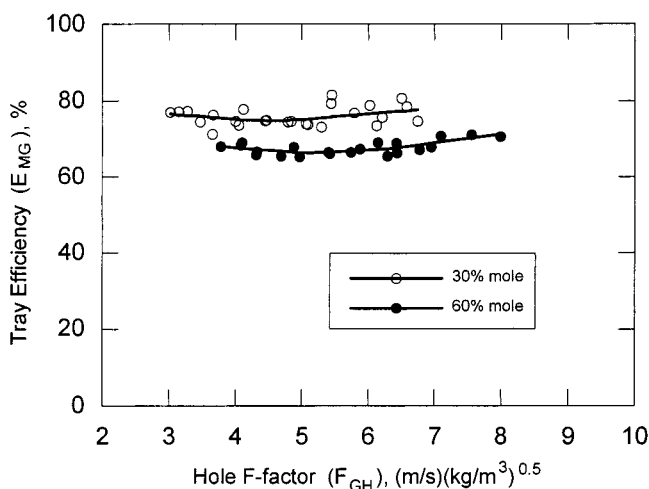

Figure 6. Effect of liquid composition on tray efficiency for c-C6/n-C7 system.

Figure 7. Variation on tray efficiency with tray spacing in tray T-2.
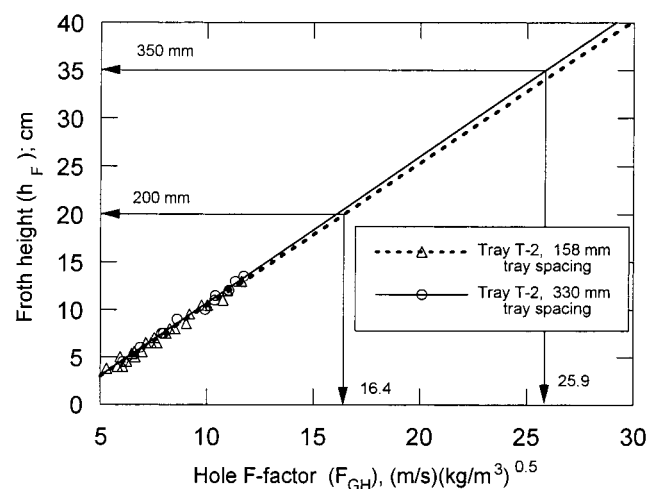
Figure 8. Determinations of flooding point with tray spacing in tray T-2.

Influence of Weir Height. The effect of weir height has previously been studied,[17,19,20] and for this reason the weir height in both trays, large and small, was maintained.

Influence of Liquid Composition. Given that the liquid tray composition has an important effect on tray efficiency in positive systems,[17,18,21,22] the liquid composition was maintained in both trays to reproduce the same operating conditions.

The c-C6/n-C7 system is a negative system, and an increase in tray efficiency with liquid composition due to the gradient of the surface tension (Marangoni effect) cannot be expected. Nevertheless, two sets of experiments were performed with tray T-4 at two different liquid tray compositions (30 and 60%). The results presented in Figure 6 demonstrate an important effect of liquid composition on tray efficiency. Therefore, it will be necessary to check if the liquid composition in negative systems has a significant influence on tray efficiency.

Influence of Tray Spacing. *Tray Efficiency.* The effect of tray spacing on tray efficiency was also considered. According to Kirschbaum's data[11] for industrial trays (Figure 1), at a normal operating range the tray efficiency is practically independent of tray spacing. The trend was the same in our experiments with small trays. Figure 7 shows the results of two sets of experiments
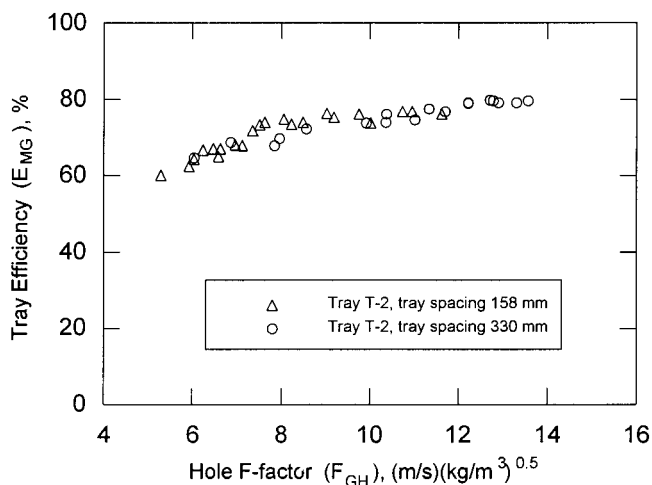
with tray T-2 (Table 2) at a tray spacing similar to that of Kirschbaum's trays (158 and 330 mm).

Tray spacing should have a significant effect if there is strong entrainment. In our case at normal operating conditions the entrainment was negligible (Table 2). The entrainment was calculated according to the Bennett et al. correlation.[23] The values presented in Table 3 show the maximum entrainment. This represents a variation of less than 1.5% in the point efficiencies in small trays.

In conclusion, tray spacing has no significant influence on tray efficiency in small trays.

Operating Ranges. In Figures 1 and 7 we can see that the lower operating limit (F_{GH} = 5 (m/s) (kg/m^3)$^{0.5}$) is practically the same, independent of tray spacing and tray size.

In the small column, it was not possible to measure the upper operating limit experimentally because the tray above the column flooded before reaching the flooding point in the tray below. However, it is possible to calculate the upper limit in the small tray by extrapolating froth height data as a function of tray spacing. In Figure 8 we can see a linearity between froth height and the hole F factor.

If we assume that the flooding point is reached when the froth height is equal to tray spacing, the flooding point, using froth height data of trays with 158- and

330-mm tray spacing, should occur at $F_{GH} = 16.4$ and 25.9 (m/s) (kg/ m³)^0.5 (see Figure 8). These results are similar to those obtained in Figure 1 with Kirschbaum trays, where the flooding point starts at 16 (m/s) (kg/m m³)^0.5 at 200 mm and 23 (m/s) (kg/m m³)^0.5 at 350 mm of tray spacing, respectively.

These results indicate that data from small trays can be used to determine the operating range in a large tray.

Scaling Up. In the scaling-up procedure described in the Appendix, the point tray efficiencies obtained experimentally in the small column are used to predict large tray efficiency with a tray flux model. It is well-known that large tray point efficiency is always smaller than the overall tray efficiency. Data obtained with tray T-1, with a hole diameter of 2.5 mm (see Figure 4), cannot be used to predict Kirschbaum tray efficiencies because of the differences in the hole diameter. Consequently, only the efficiency values obtained with tray T-2 ($d_H = 10$ mm) can be used for actual tray efficiency prediction. Bennett et al.[5] stress the importance that the clear liquid height on the tray has on the point efficiency. Normally, for small trays the liquid flow per length of outlet weir is smaller than that for large trays. This represents a lower clear liquid height at a given column flux. In our test trays the weir is circular and the clear liquid height is a function of weir diameter. The calculated values of clear liquid height in our trays are very similar to those of the industrial trays, since similar values of liquid flow per length of outlet weir are obtained on both scales.

A similar analysis could be made for the c-C6/n-C7 system (see Figure 5). The point efficiency values for the tray with small holes are again higher than industrial efficiency values, and so are unsuitable to predict. However, point efficiency values for tray T-4 (67% on average), lower than industrial values, can be used to predict the tray efficiency of large trays. Biddulph et al.[10] obtained values of point efficiencies for a 0.43-m column diameter in the 60−72% range for the c-C6/n-C7 system. In their scaling-up study, the authors used a mean value of point efficiency of 67%, which is the same value we obtained for the small column.

To predict the tray efficiency of large trays, the scaling-up procedure described in the Appendix was used.

Figure 9a,b shows the predictions of large tray efficiencies for the Kirschbaum reference trays from the data obtained from the corresponding test tray T-2 (at two different tray spacings).

In these figures we can see that the predicted values for the two cases fit correctly to the experimental values of the large trays, in the usual operating range.

Figure 10 shows the predictions of tray efficiencies for the Yanagi and Sakata reference tray at two different pressures. Also, for the c-C6/n-C7 system the predictions agree with the Yanagi and Sakata data in the normal operation range at two different pressures.

Conclusions

The diameter of the hole has an important effect on the experimental tray efficiency determined in small columns. Trays with large holes have a different hydrodynamic behavior and are less efficient than trays with small holes. Attention must therefore be paid when experimental results from test sieve trays with small holes are used as point efficiency values for predicting of the tray efficiency of industrial trays.
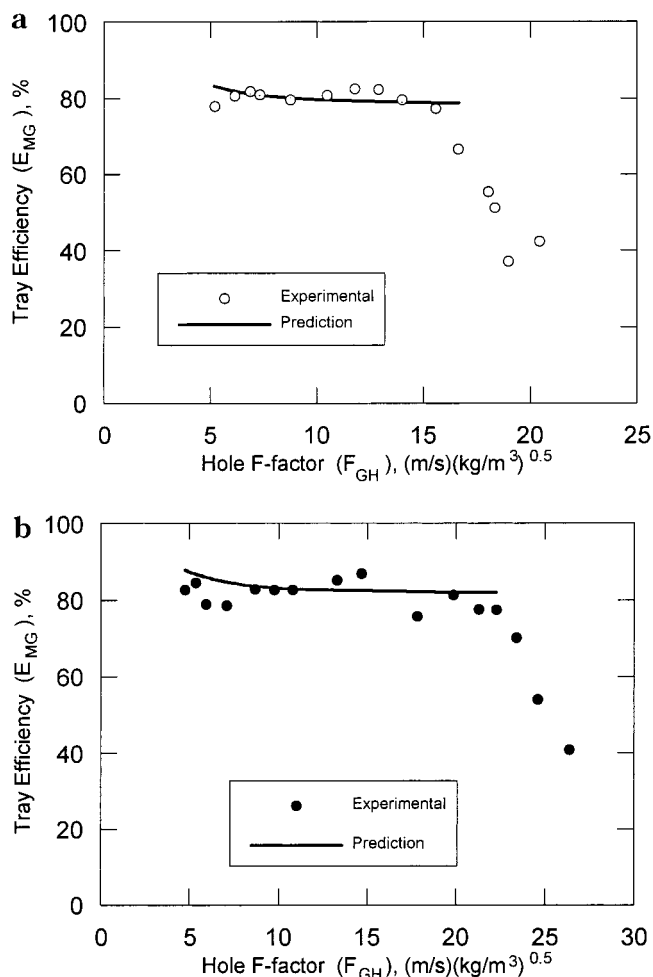

Figure 9. (a) Prediction of tray efficiency for Kirschbaum tray with 200-mm tray spacing. (b) Prediction of tray efficiency for Kirschbaum tray with 350-mm tray spacing.
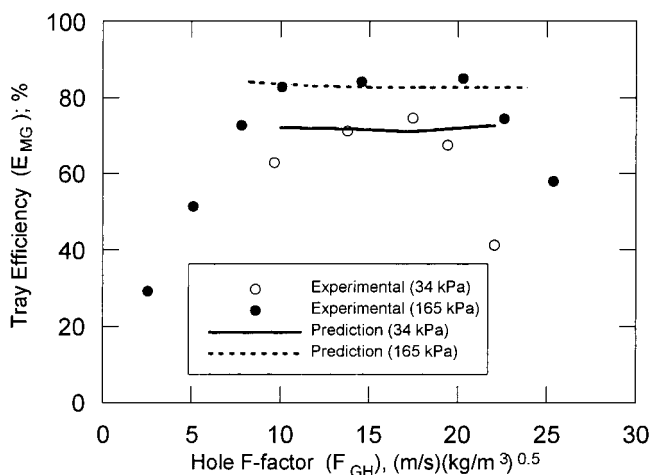

Figure 10. Prediction of tray efficiency for Yanagi and Sakata tray.

Tray spacing has no important effect on tray efficiency in small columns, but entrainment and weeping must be checked to select the values of point efficiency obtained from small columns, which can be used in scaling-up calculations.

The liquid composition in small trays is an important parameter that should be considered because of its influence on tray efficiency in positive systems, and perhaps in neutral and negative systems. If positive

systems are used, the scale-up calculations must be based on the same liquid compositions.

The experimental operating range obtained in small columns can be used to predict the operating conditions of the industrial tray.

We tested a scaling-up procedure to predict industrial tray efficiencies from test tray data. When laboratory trays with the same geometry as large trays are used, the estimated efficiency values can be reasonably applied for column design purposes.

Nomenclature

A_A = active area, m²
A_H = hole area, m²
C = parameter defined by eq 10
D_{EG} = eddy diffusivity for vapor mixing, m²/s
D_{EL} = eddy diffusivity for liquid mixing, m²/s
d_H = hole diameter, m
E = entrainment, kg/kg
E_{MG} = Murphree vapor-phase tray efficiency
E_{OG} = Murphree vapor-phase point efficiency
F_{GA} = active area F factor defined by $u_{GA}\rho_G^{1/2}$, (m/s) (kg/m³)⁰·⁵
F_{GH} = hole area F factor defined by $u_{GH}\rho_G^{1/2}$, (m/s) (kg/m³)⁰·⁵
F_{PL} = flow path length, m
Fr_G = vapor Froude number defined by eq 13
Fr_L = liquid Froude number defined by eq 4
g = gravity acceleration, 9.8 m/s²
G = vapor flow rate, kmol/s
h_F = froth height on tray, m
h_{Fe} = froth height on tray calculated by eq 8, m
h_L = clear liquid height on tray, m
h_W = outlet weir height, m
$h_{2\Phi}$ = froth height on tray calculated by eq 12, m
K_S = flow parameter defined by $u_{GA}[\rho_G/(\rho_L - \rho_G)]^{0.5}$
L = liquid flow rate, kmol/s
m = slope of equilibrium line
Pe_G = vapor Peclet number defined by eq 3, dimensionless
Pe_L = liquid Peclet number defined by eq 2, dimensionless
Q_L = liquid flow rate, m³/s
Q_G = vapor flow rate, m³/s
T_S = tray spacing, m
u_{GA} = vapor velocity with respect to active area, m/s
u_{GH} = hole vapor velocity, m/s
V_{ej} = vapor velocity defined by eq 14
W_L = weir length, m
x_N = liquid mole fraction at tray N
y_N = vapor mole fraction
y_{N-1} = vapor mole fraction
y_N^* = mole fraction in vapor in equilibrium with the liquid leaving the tray via the downcomer.

Greek Symbols

β = parameter defined by eq 18
η = parameter defined by eq 6
λ = stripping factor defined by m(G/L)
ρ_L = liquid density, kg/m³
ρ_G = vapor density, kg/m³
ϕ_e = foam density defined by eq 9
ϕ_{2e} = foam density defined by eq 17

Subscripts

I = for large tray (industrial)
S = for small tray (laboratory)

Appendix: Scaling-Up Procedure

(1) Murphree vapor efficiencies are calculated from experimental data obtained in laboratory trays:

$$E_{OG} = \frac{y_N - y_{N-1}}{y_N^* - y_{N-1}} \tag{1}$$

In small trays, if the liquid and vapor are well-mixed, the tray efficiency can be considered equal to the point efficiency. This is true if the liquid Peclet number (Pe_L) is less than 0.2 and the vapor Peclet number (Pe_G) less than 50. The definition of Peclet numbers are

$$Pe_L = \frac{Q_L F_{PL}^2}{A_A h_L D_{EL}} \tag{2}$$

$$Pe_G = \frac{u_{GA} F_{PL}^2}{(T_S - h_{2\phi}) D_{EG}} \tag{3}$$

where the liquid eddy diffusivity (D_{EL}) is calculated by the Bennett and Grimm correlation,[24] described above. According to Lockett[16] vapor eddy diffusivity (D_{EG}) can be assumed equal to 0.01 m²/s.

It would also be convenient to test the weeping point in the small trays, to select the available data to use in the scaling-up procedure. The validity of data in the small column is determined by the liquid Froude number (Fr_L). According to Lockett and Banik[25] if $Fr_L > 0.5$, there are no problems with weeping. The liquid Froude number is defined by

$$Fr_L = \sqrt{\frac{\rho_G u_{GH}^2}{\rho_L g h_L}} \tag{4}$$

The entrainment in the small trays should also be checked. The Bennett et al.[5] correlation, described later, has been used.

(2) As the tray geometry and clear liquid height in small trays are similar to those in large trays, it can be assumed that $(E_{OG})_I = (E_{OG})_S$.

(3) The next step is to apply a flux model to predict the vapor tray efficiency of the large tray. The diffusion flux model is applied. The equation is

$$\frac{E_{MG}}{E_{OG}} = \frac{1 - e^{-(\eta + Pe_L)}}{(\eta + Pe_L)\left[1 + \dfrac{\eta + Pe_L}{n}\right]} + \frac{e^\eta - 1}{\eta\left[1 + \dfrac{\eta}{\eta + Pe_L}\right]} \tag{5}$$

where

$$\eta = \frac{Pe_L}{2}\left[\sqrt{\left(1 + \frac{4\lambda E_{OG}}{Pe_L}\right)} - 1\right] \tag{6}$$

To apply the previous equations, we must calculate the clear liquid height (h_L) and liquid eddy diffusivity (D_{EL}).

According to Lockett,[16] the clear liquid height was calculated by the Bennett et al. correlation.[26]

$$h_L = h_{Fe}\phi_e \tag{7}$$

where

$$h_{Fe} = h_W + C\left(\frac{Q_L}{\phi_e}\right)^{2/3} \qquad (8)$$

and

$$\phi_e = \exp[-12.55 K_S^{0.91}] \qquad (9)$$

and

$$C = 0.501 + 0.439 \exp[-137.8 h_W] \qquad (10)$$

According to Klemola and Ilme,[1] the liquid eddy diffusivity is calculated by the Bennett and Grimm[24] correlation, which is modified by Bennett et al:[5]

$$D_{EL} = (4)(0.024)[gh_{2\phi}^3]^{1/2} \qquad (11)$$

where

$$\frac{h_{2\phi}}{h_{Fe}} = 1 + \left[1 + 6.9\left(\frac{h_L}{d_H}\right)^{-1.85}\right]\frac{Fr_G}{2} \qquad (12)$$

and

$$Fr_G = \frac{V_{ej}^2}{gh_{Fe}} \qquad (13)$$

and

$$V_{ej} = 3K_S\sqrt{\frac{\sqrt{3}}{(A_H/A_A)\phi_e}} \qquad (14)$$

The authors recommend using this correlation even if the froth height is larger than tray spacing.

If the froth height in the small trays is determined experimentally, it can be assumed that the froth height in the large tray is equal to the small tray (similar geometry). Kalbassi and Biddulph[27] corrected the wall effects in the measurements of the froth heights by enlarging the diameter of the Oldershaw column from 1 to 3 in. If the diameter of the small column is larger than 3 in., the wall effect can then be ignored.

(4) The effect on the tray efficiency of entrainment is corrected by the following equation:

$$\frac{E_{MG}(E=E)}{E_{MG}(E=0)} = 1 - 0.8 E_{OG}\lambda^{0.543}E\frac{G}{L} \qquad (15)$$

where the entrainment is calculated by the Bennett et al correlation:[5]

$$E = 0.0035\left(\frac{T_S}{h_{2\phi}}\right)^{-1.10}\left(\frac{\rho_L}{\rho_G}\right)^{0.5}\phi_{2\phi}^{\beta} \qquad (16)$$

where

$$\phi_{2\phi} = \frac{h_L}{h_{2\phi}} \qquad (17)$$

and

$$\beta = 0.5\left[1 + \tanh\left(1.3\ln\left(\frac{h_L}{d_H}\right) - 0.15\right)\right] \qquad (18)$$

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