Point Efficiencies on Sieve Trays

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The flow characteristics across a circular, chordal-weir distillation tray have a considerable effect on the mass transfer efficiency of the tray. Since these characteristics depend on column diameter, it is inevitable that columns of different diameters operate with different efficiencies, even if all other conditions are identical. This being the case, it is essential to separate the mass transfer aspects from the flow aspects in attempting scale-up column design. One way of doing this is to use point efficiencies in conjunction with a model that takes into account the extent of backmixing in the liquid phase on the tray. For similar systems under similar conditions, it might be expected that point efficiencies should be similar. Thus, point efficiencies could be combined with the appropriate flow conditions to provide accurate scale-up of design.

The use of this approach involves some difficulties that are still under investigation. One of these difficulties is the fact that liquid flow across chordal-weir, circular trays is generally nonuniform. This nonuniformity usually takes the form of preferential flow across the center of the tray, from inlet to outlet, with reduced flow around the tray edges. This phenomenon has been extensively studied in recent years, with the general conclusion being that the nonuniformity of flow will only adversely affect efficiency at column diameters larger than about two meters. It then follows that at smaller column diameters a model assuming uniform liquid flow should provide a good simulation of tray behavior. Another difficulty in the use of this approach is in the availability of point efficiency values, and this is the aspect under consideration in the present work.

Point efficiencies come from two sources. They may come from measurements made in very small laboratory-scale columns. Pertinent to the present work, Fair et al. (1983) reported cyclohexane/*n*-heptane efficiencies for a 28-mm Oldershaw laboratory column. Although a vast amount of such data has accumulated over many years, there is always some doubt about how well the conditions on such a small tray represent those at the center of a large commercial tray. Hole size and clear liquid head are generally much smaller in the small column, although this has been improved recently by the development of a new design of a point efficiency column (Kalbassi and Biddulph, 1987; Biddulph and Kalbassi, 1990).

Alternatively, point efficiencies may come from medium-scale column measurements by careful simulation and back-calculation. This has been achieved in a series of studies of a rectangular column (Biddulph and Ashton, 1977; Biddulph and Dribika, 1986; Dribika and Biddulph, 1986; Kalbassi et al., 1987; Biddulph et al., 1988) at the University of Nottingham for alcohol-alcohol and alcohol-water systems. The availability of new data on a 0.43-m-diameter column at The University of Texas at Austin for the system cyclohexane/*n*-heptane provided the opportunity to extend this study. Furthermore, data from Fractionation Research, Inc. (FRI) for the same system in a 1.2-m-diameter column provided a chance to test the scale-up potential of point efficiencies.

Mathematical Model

The mathematical model that relates the degree of mixing on a tray to the composition and enthalpy profiles has been described in some detail previously (Biddulph, 1975). Briefly, it considers a mass and enthalpy balance on successive elements of a biphase (froth or spray) on the tray. The differential equations are solved numerically moving from the outlet weir against the direction of liquid flow. The liquid- and vapor-phase concentration profiles on the tray are thus predicted using point efficiencies at each point across the tray. The eddy diffusion model is used to introduce backmixing in the liquid phase, and a simple partial averaging model is used to account for the relatively less important influence of mixing in the vapor phase.

The model is applied as follows. Starting from a known reboiler composition, the vapor composition leaving the reboiler is calculated assuming equilibrium, and this composition is assumed uniform everywhere below the bottom tray in the column. The composition of the liquid leaving the bottom tray is obtained from a mass balance. The differential equations describing the component compositions and liquid flow numerically are solved stepwise across the bottom tray from outlet to inlet. At each step, an appropriate point efficiency is used to calculate the vapor composition leaving the tray at that point. When the inlet to the bottom tray is reached, a mass balance is used to establish the composition of the liquid leaving the next tray. If necessary, the effect of mixing in the vapor

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phase is included by modifying the vapor composition profiles above the bottom tray before proceeding to the calculation of the next tray. The procedure is now repeated for the next tray and so on up the column, allowing for feeds and side streams as necessary. Data required for the simulation are K values and enthalpies and a Peclet number for each tray to account for the effects of backmixing in the liquid phase. Point efficiencies are also required.

The Peclet Number

The Peclet number describes the extent of backmixing in the liquid phase on a tray. A Peclet number of zero indicates complete mixing and a value of infinity indicates plug flow. Under conditions of complete mixing the Murphee tray efficiency equals the point efficiency, whereas for plug flow conditions the tray efficiency exceeds the point efficiency due to the effects of the composition gradients across the tray. A real tray usually operates somewhere between these extremes.

A number of studies have provided correlations for the prediction of the Peclet number (Barker and Self, 1962; Shore and Haselden, 1969; Bennett and Grimm, 1991). Predictions of the Peclet number for the conditions existing in a typical run in the 0.43-m column were checked. The correlation of Bennett and Grimm fell in the middle of the small range of values, the extreme values making only about 1% difference in the inferred point efficiency. It was, therefore, decided to use this correlation for all simulations. Uniform flow in the liquid phase was assumed.

Vapor mixing is known to have only a minor effect on efficiency (Diener, 1967; Biddulph, 1975). The 0.43-m column was assumed to be small enough to give complete lateral mixing in the vapor phase, while the larger 1.22-m-diameter FRI column vapor was assumed to have no lateral mixing. This effect was checked for the 0.43-m column and found to be less than 0.5% in efficiency over the range of vapor mixing.

The simulations were carried out by trial-and-error on point efficiency until a good agreement between predicted and measured compositions was achieved, all the runs being at total reflux.

Description of the Columns

The smaller of the two columns studied is at The University of Texas at Austin and is nominally 0.43-m inside diameter.

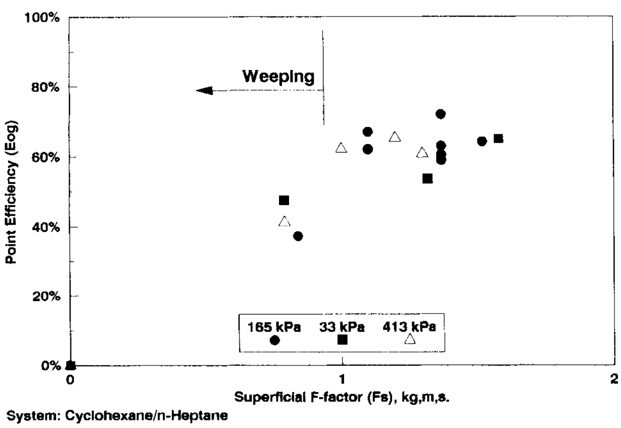

Figure 1. Point efficiencies for the 0.43-m column.

The trays have 4.8-mm-diameter holes on a 9.52-mm triangular pitch, giving a hole area of 8%. The outlet weir height is 50.8 mm. There are 14 trays with sample connections at the bottom, middle and top of the column.

For the FRI column, the trays have a diameter of 1.22 m and have 12.7-mm-diameter holes on a 38.11-mm triangular pitch, again providing a hole area of 8%. The outlet weir is 50.8 mm and the column has ten trays with samples at all tray outlets as well as reboiler and reflux liquid.

The system studied in both columns was cyclohexane/*n*-heptane at pressures of 28-33 kPa and 165 kPa. Equilibrium data for this system have been reported by Lenoir and Sakata (1978). Samples from both columns were analyzed by gas chromatography.

Small Column Results

Experimental results were available from a total of 15 runs in the 0.43-m-diameter column, carried out at pressures of 33, 165 and 413 kPa. The simulations were made using the measured bottom and top compositions, with the middle sample being used as a check. In most cases, the predicted middle composition agreed closely with the measured value, indicating a similar point efficiency in the two sections. The results are plotted in Figure 1. It can be seen that the inferred point efficiencies are generally in the range 60–72%.

Experiments at F factors below 1.0 $m/s(kg/m^3)^{1/2}$ showed weeping problems, and hence the efficiencies were low. There is some scatter in the values due perhaps to a composition effect on point efficiency, the runs being carried out at various reboiler compositions. Over a range of 14 trays, however, this is very difficult to substantiate. In general, for superficial F factors between about 1.0 and 2.0, there is no discernible effect of pressure on point efficiency.

A comparison with results obtained by Kalbassi et al. (1987) for the system methanol/water and similar hole sizes shows that the alcohol/water system gives somewhat higher point efficiencies, around 85%. This is to be expected due to the surface-tension-positive character of that system. The cyclohexane/*n*-heptane system is slightly surface-tension-negative. The highly surface-tension-positive system provides greater interfacial area under froth conditions.

Larger and Smaller Results Comparisons

One of the benefits of the new data available from the smaller column is that the 33-kPa and 165-kPa runs match the conditions for extensive data published by FRI (Sakata and Yanagi, 1979). A comparison of these data should enable testing the feasibility of scale-up using point efficiency. The larger tray results in higher values of Peclet number and consequently a greater efficiency enhancement.

The simulation of the 1.22-m-diameter column was made between the reboiler and the outlet tray 8. The FRI results are plotted in Figure 2, together with the 0.43-m column results at the same pressure. One difference between the trays studied was in the hole size. The smaller column had 4.76-mm-diameter holes, while the larger column had 12.7-mm holes. Most studies, however, have shown (e.g., Kalbassi et al., 1987) that variation in hole size has little effect on point efficiency. Both columns had an outlet weir height of 50.8 mm.

Figure 2 shows that the point efficiencies inferred from the

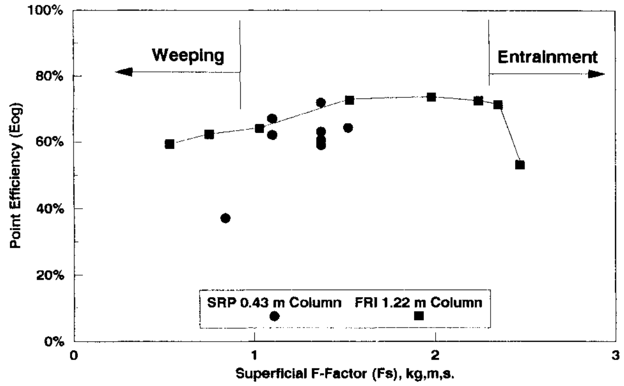

Figure 2. Point efficiencies for the two columns at 165 kPa.

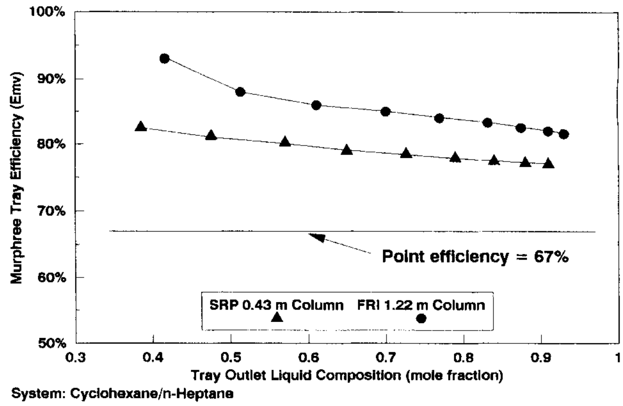

Figure 4. Predicted tray efficiencies for the two columns with the same point efficiency.

two columns are remarkably similar in the correct range of $1.0<F_s<2.0$. Outside these limits, either weeping or entrainment has an adverse effect on efficiency. Certainly the point efficiencies inferred from the larger column are not lower than those inferred from the smaller column, indicating that the 1.22-m-diameter column was not suffering any adverse effects of flow nonuniformities. If this had been the case, it would have shown up as apparently depressed point efficiencies in the larger column. This finding appears to confirm the conclusion of Yanagi and Scott (1973), who studied the FRI 1.22-m-diameter column, both with and without modified trays. The modifications to the normal cross-flow arrangement were designed to produce uniform flow across the tray. They reported little difference between the unmodified and the modified trays under identical distillation conditions. Although their conclusion was questioned by Lockett (1986), the study reported here appears to support their opinion.

The similarity of the inferred point efficiencies from the two columns means that it should be possible to obtain a good simulation of the performance of larger columns by using a point efficiency from smaller columns. Such a comparison is shown on Figure 3, where the simulation represents the FRI sample compositions very well. Figure 4 shows a comparison of the predicted tray efficiencies through the two columns, both for a point efficiency of 67%; it is evident that the larger column has a greater enhancement of point efficiency.

Results for the two columns are compared in Figure 5. With only three data points on the small column, comparison is difficult, but again the point efficiencies inferred from the large column are certainly not lower than those from the small column. This confirms the earlier conclusion.

Other Relevant Data

Other data available to the authors from various sources have been summarized in Table 1, together with the data from the studies mentioned above. The values for point efficiencies indicated under the E_{og} heading were inferred from tray or column efficiency data, as described previously. Additional point efficiency data for the methanol-water system, taken in a 0.59-m sieve tray column, were measured directly by Lockett and Ahmad (1983). Their point efficiencies ranged from 60 to 89% depending on concentration.

It can be observed that the results on hydrocarbon systems in two sizes of sieve trays and one valve tray indicate similar values in the range of 60 to 70%. These values are in very good agreement with those measured for the same systems in Oldershaw equipment by Fair et al. (1983). The point efficiencies in the markedly surface-tension-positive system methanol/water are significantly higher, as should be expected. The

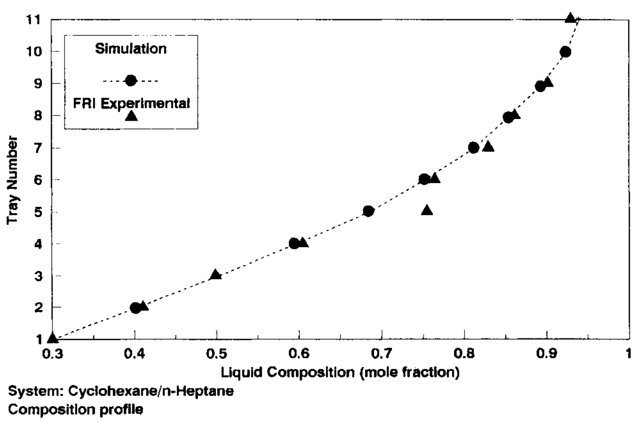

Figure 3. Use of point efficiency from a 0.43-m column to simulate a 1.22-m column composition profile.

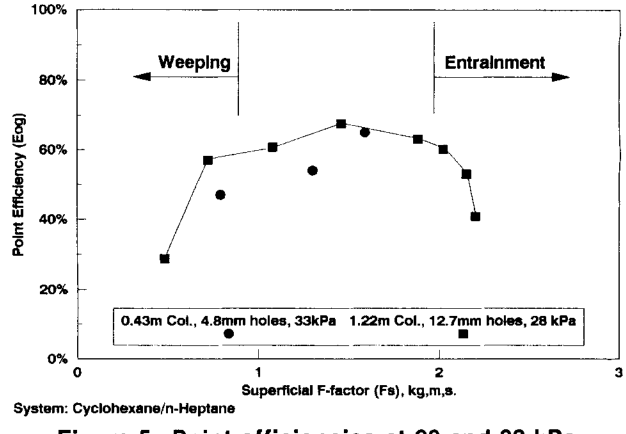

Figure 5. Point efficiencies at 28 and 33 kPa.

Table 1. Inferred Point Efficiency Data

System	Column Description	Point Efficiency	Source
Cyclohexane/*n*-Heptane	0.43-m sieve trays 4.8-mm holes 33, 165 and 413 kPa	60–70%	Univ. Texas (1990)
Cyclohexane/*n*-Heptane	1.2-m sieve trays 12.7 mm-holes 28 and 165 kPa	65–73%	Sakata & Yanagi (1979)
Benzene/Toluene/Xylene	2.4-m valve trays Koch T-type Flexitrays	66%	Biddulph & Ashton (1977)
Methanol/Water	0.91-m-long rectangular sieve tray 1, 1.8, 3.2 and 6.4 mm holes	85–95%	Kalbassi et al. (1986)
Methanol/Ethanol *n*-Propanol	0.91-m-long rectangular sieve tray 1.8-mm holes	77–81%	Biddulph & Dribika (1986) Biddulph et al. (1988)
Ethanol/*n*-Propanol; Methanol/*n*-Propanol	0.91-m-long rectangular sieve tray 1.91-mm holes	70–80%	Biddulph & Dribika (1986) Biddulph et al. (1988)

values in the alcohol/alcohol systems with small hole sizes are also high, on the order of 70 to 80%. This is presumably due to reduced entrainment.

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Notation

D_e = eddy diffusion coefficient, m^2/s
F = froth height, m
F_s = superficial F factor, $U_s\rho v^{1/2}$, $m/s(kg/m^3)^{1/2}$
L = liquid rate, kg/s·m width
Pe = Peclet number $= Z_L L/(D_e F \rho_L Q_F)$
Q_F = relative froth density, volume of liquid/volume of froth
U_s = superficial vapor velocity, m/s
Z_L = liquid path length, m
ρ_L = liquid mass density, kg/m^3
ρ_v = vapor mass density, kg/m^3

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