Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

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R. B. Eldridge[a]; J. L. Humphrey[a]; J. R. Fair[a]
[a] Department of Chemical Engineering, the University of Texas at Austin, Austin, Texas

To cite this Article Eldridge, R. B. , Humphrey, J. L. and Fair, J. R.(1987) 'Continuous Phase Mixing on Crossflow Extraction Sieve Trays', Separation Science and Technology, 22: 2, 1121 — 1134

To link to this Article: DOI: 10.1080/01496398708069002

URL: http://dx.doi.org/10.1080/01496398708069002

SEPARATION SCIENCE AND TECHNOLOGY, 22(2&3), pp. 1121-1134, 1987

Continuous Phase Mixing on Crossflow Extraction Sieve Trays

R. B. ELDRIDGE, J. L. HUMPHREY, and J. R. FAIR

DEPARTMENT OF CHEMICAL ENGINEERING
THE UNIVERSITY OF TEXAS AT AUSTIN
AUSTIN, TEXAS 78712

ABSTRACT

Axial dispersion of a crossflowing continuous phase was studied in a special experimental system that simulated a "slice" from a large, commercial scale sieve tray extractor. The toluene-water system was used, and Peclet numbers were determined as functions of phase flow rates and tray geometry. It was concluded that for systems with relatively high interfacial tension, which give characteristically low point efficiencies, axial mixing is not an important issue in the design of sieve tray extractors.

INTRODUCTION

Separations by liquid-liquid extraction are receiving increased attention because of their possible energy economies and because they can permit processing of temperature-sensitive materials at essentially ambient conditions. A hindrance to the selection of extraction for new plant designs, however, is the inadequacy of reliable information for scaling pilot plant results to much larger commercial equipment. Typically, tests are made at the small scale and the conversion is made by experience-supported empirical techniques. There are needs for more rational and fundamentally-based approaches, and the work reported here is part of an effort to develop mechanistic models that might better serve this scaleup purpose.

Rocha et al. (1) modeled a small (four inch diameter) sieve tray column, and concluded that for such a small device the continuous phase is essentially well-mixed. Analogy to the behavior of gas-liquid systems in similar geometries would lead to the expectation that under certain flow conditions the continuous phase in the extraction column would depart from a well-mixed condition and might indeed approach a plug flow behavior. If such would be the case, then some enhancement of the well-mixed (local) efficiency might be possible. Judicious selection of the tray dimensions, to promote plug flow, might then be prudent. In turn, this could improve the economic attractiveness of extraction in sieve tray units.

Background

The geometry of an extractor sieve tray resembles that of a distillation sieve tray. As indicated in Figure 1, continuous phase enters the try through a downcomer (or upcomer) and passes across the field of moving dispersed phase drops. The mass transfer efficiency of tray n is conveniently expressed as a Murphree efficiency:

$$E_{md} = \frac{Y_n - Y_{n-1}}{Y^*_n - Y_{n-1}} \tag{1}$$

where the Y values refer to solute mole fractions in the dispersed phase and the Y* term refers to an equilibrium concentration with respect to the continuous phase leaving the tray:

$$Y^*_n = m_{dc} X_n \tag{2}$$

The direct analogy to vapor-liquid equilibrium on distillation trays is apparent.

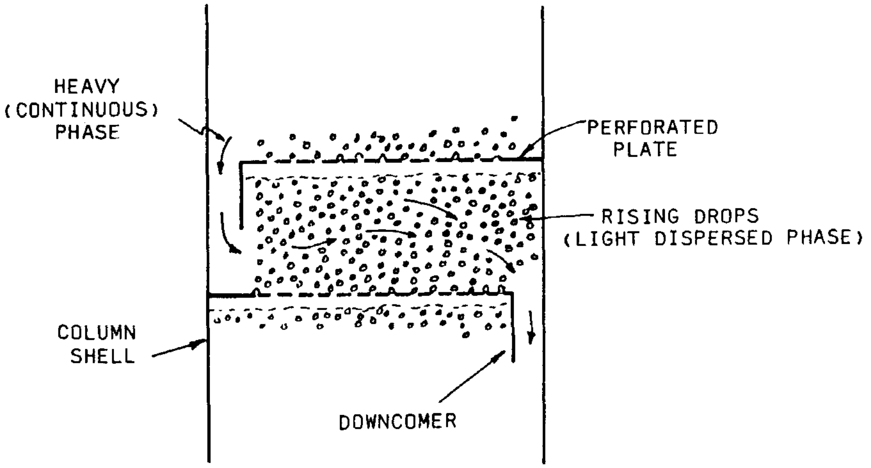

Figure 1. Crossflow sieve tray for extraction

Depending on phase mixing, the value of E_{md} will be equal to or greater than the local efficiency, which applies to a point on the tray and which can vary with location. For the case of complete continuous phase mixing, $E_{md} = E_{pd}$. For the case of plug flow of continuous phase,

$$E_{md} = \frac{\exp[E_{pd}\ \lambda] - 1}{\lambda} \tag{3}$$

where E_{pd} = *point efficiency, based on dispersed phase* concentrations

λ = extraction factor, $m_{dc}\ F_d/F_c$

F_d/D_c = molar ratio of dispersed to continuous flows

m_{dc} = slope of the equilibrium curve based on molar concentrations, dispersed phase on ordinate scale

For cases that are intermediate between complete mixing and plug flow, measures of departure from ideal flow are necessary. The pertinent background work leading to such measures has been done largely with homogeneous systems of with gas-liquid systems, and it is possible to utilize such work, by direct analogy, for liquid-liquid systems.

A useful method for expressing axial mixing effects is through the use of the diffusive backmixing model, which utilizes an eddy diffusion coefficient D_E. With reference to Figure 2, and considering a differential slice of two-phase mixture on the tray, a material balance yields:

$$D_E \frac{d^2X}{dZ^2} - \left(\frac{F_c}{A\ \rho_m}\right) \frac{dX}{dZ} + \frac{Y_{n-1} - Y_n}{A\ \rho_m} \left(\frac{F_d}{Z_t}\right) = 0 \tag{4}$$

where D_E = eddy diffusion coefficient

X = mole fraction solute in continuous phase

Y = mole fraction solute in dispersed phase

Z = distance in direction of crossflow (Z_T = total tray length)

F_c = continuous phase molar flow rate

F_d = dispersed phase molar flow rate

A = cross sectional area available for flow

ρ_m = mean molar density of tray mixture

If the point efficiency is constant and the equilibrium relationship can be approximated as linear, Equation 4 becomes:

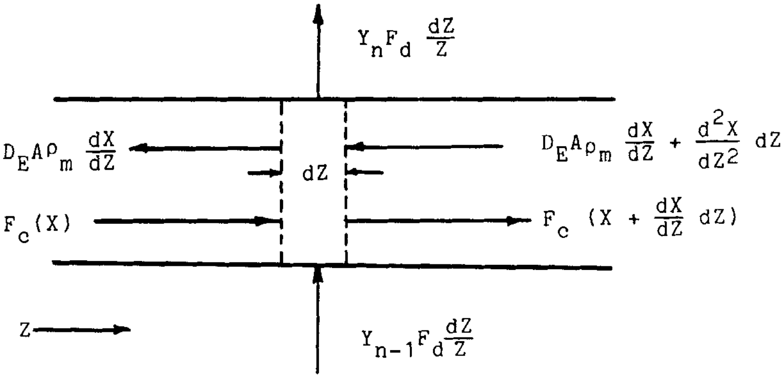

Figure 2. Material balance across tray element

$$\frac{1}{Pe}\left(\frac{d^2X}{dw^2}\right) - \frac{dX}{dw} - \lambda\, E_{pd}\,(X - X^*_e) \qquad (5)$$

where Pe = dimensionless Peclet number = $(F_c Z_T)/(A\ \rho_m D_E)$

w = dZ/Z

X^*_e = mole fraction of solute in continuous phase when in equilibrium with the dispersed phase entering the tray

For uniform concentration of dispersed phase entering the tray (from the coalesced layer below the tray), it may be shown that:

$$E_{md}/E_{pd} = \int_0^1 \frac{X - X^*_e}{X_n - X^*_e}\, dw \qquad (6)$$

Applying the following boundary conditions to Equation 5,

$$X = X_n \text{ and } dX/dW = 0 \text{ at } w = 1$$

and combining with Equation 6,

$$E_{md}/E_{pd} = \frac{1 - e^{-(\eta + Pe)}}{(\eta + Pe)(1 + \frac{\eta + Pe}{\eta})} + \frac{e^{\eta} - 1}{\eta\ (1 + \frac{\eta}{\eta + Pe})} \qquad (7)$$

where $\eta = \frac{Pe}{2}\ [\sqrt{1 + 4\lambda\ E_{pd}/Pe} - 1]$ (8)

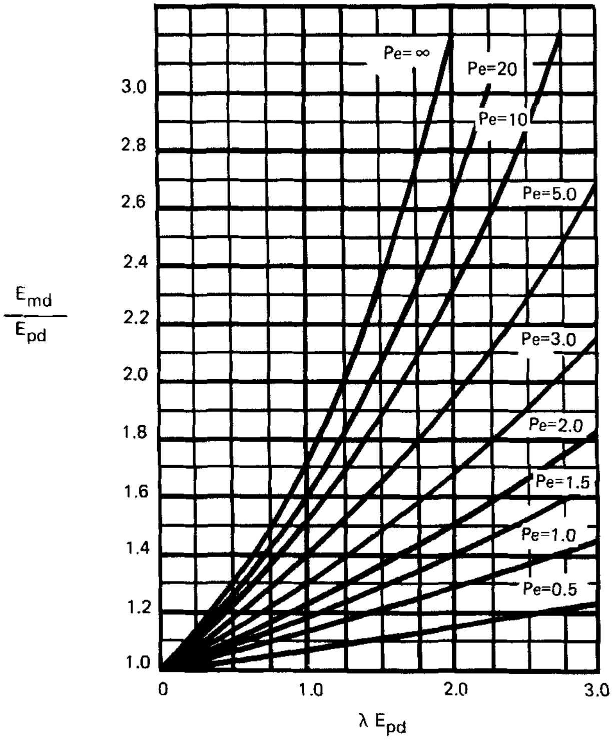

Figure 3. Effect of Peclet number on point efficiency enhancement (2).

This is a general expression relating tray efficiency E_{md}, point efficiency E_{pd}, extraction factor λ (= m_{dc} F_d/F_c) and Peclet number Pe. It is shown graphically in Figure 3, taken from the work of Gerster et al (2). More details on the development of Equation 7 are given in the same reference.

An alternate model for tray mixing is the stage model, where the phase in crossflow is presumed to flow through one or more well-mixed stages. This model, originally applied to distillation trays by Gautreaux and O'Connell (3), also relates point and tray efficiencies:

$$E_{md}/E_{pd} = \frac{\left(1 + \frac{\lambda E_{pd}}{s}\right)^{s} - 1}{\lambda E_{pd}} \tag{9}$$

where s = number of mixing stages on the tray

When s = 1, the continuous phase is completely mixed, and point efficiency equals tray efficiency. For pure plug flow of continuous phase, $s = \infty$. For intermediate cases, a blending of the diffusion and stage models is possible, and:

$$s \sim (Pe + 2)/2 \tag{10}$$

The Peclet number, $Pe = \frac{F_c Z_T}{A\rho_m D_E}$, thus becomes a key dimensionless parameter in assessing the effects of geometry on axial mixing and point efficiency enhancement.

Measurements of Peclet numbers (or eddy diffusion coefficients) for continuous phase flow on sieve trays have not been reported previously. Angelo and Lightfoot (4) considered liquid-liquid system mixing in such a geometry, but limited their work to the completely mixed region. For other extraction devices, however, some axial mixing studies have been reported, for example the notable work of Miyauchi and Vermeulen (5) for packed extractors. It is beyond the scope of the present paper to review mixing studies in the various available extraction devices, since the purpose here is to deal with mixing on crossflow sieve tray devices.

Experimental Equipment

A flow diagram of the experimental equipment is shown in Figure 4. The contacting unit was designed to simulate a slice from a large scale sieve tray extractor and to provide for maximum opportunity for viewing flows of the phases. The design also provides a broad range of phase flow rates, tray spacings, downcomer (or upcomer) dimensions and tray hole patterns. Dimensions of the contacting units are shown in Figure 5.

Phase interfaces are maintained by adjustment of the elevation of the atmospheric head tanks. Mesh pads aid in drop coalescence. The injection point for a dye tracer is in the inlet downcomer. A sampling device withdraws fluid from the exit downcomer and feeds the sample to a Beckman spectrophotometer for analysis. For the observation and measurement of mixing effects, a pulse testing approach is used, with the output from the spectrophotomer being shown on a strip chart recorder. The experimental unit is also equipped for the photographic determination of drop size distribution.

Data Analysis

The unsteady state unidirectional axial dispersion relationship, appropriate for the test method used, is:

$$\frac{\partial C}{\partial t} + V_z \frac{\partial C}{\partial Z} = D_E \frac{\partial^2 C}{\partial Z^2} + [\text{source term}] \tag{11}$$

where C = concentration of tracer

t = time

V_z = velocity in the axial direction

D_E = eddy diffusion coefficient

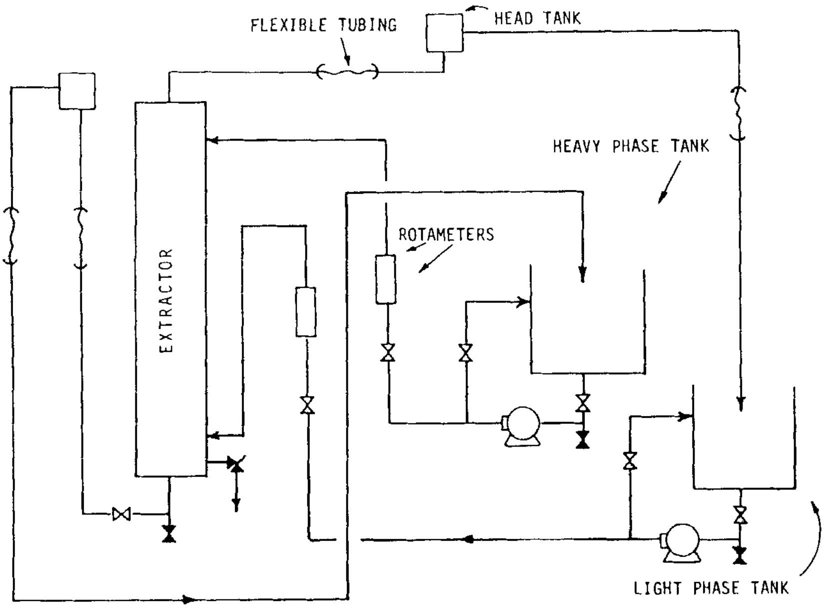

Figure 4. Flow diagram of experimental equipment

A "source term" is shown in Equation 11 to allow for the injection of tracer in the test section itself. In the present work, an impulse source term was used in the experimentation; this term approximated a perfect delta function.

Equation 12 is the dimensionless solution of Equation 11, subject to plug flow boundary conditions (i.e., no diffusion in the tray inlet and exit):

$$C_N = (1/t_r)\,(e^{Pe/2}) \sum_{n=1} \frac{(-1)^{n+1}\; 8\,\alpha_n^2}{4\,\alpha_n^2 + 4\,Pe + Pe^2} \exp[-A_n(t/t_r)] \qquad (12)$$

where C_N = normalized concentration time (time -1)

t_r = mean residence time

Pe = Peclet number

$$A_n = \frac{Pe^2 + 4\,\alpha_n^2}{4\,Pe} \qquad (13)$$

$$\tan \alpha_n = \frac{4\,Pe\,\alpha_n}{4\,\alpha_n^2 - Pe^2} \qquad (14)$$

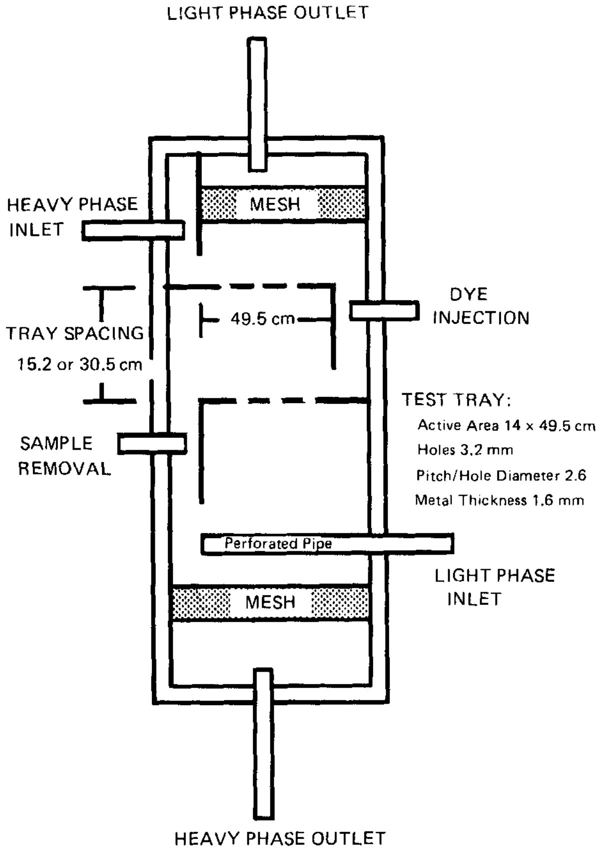

Figure 5. Dimensions of contacting unit

This solution has been taken from Himmelblau and Bischof (6).

Points were obtained from experimental traces of dye concentration, an example of which is shown in Figure 6. These points were fitted to Equation 12 through a nonlinear error minimization technique. This data regression yielded a Peclet number and a mean residence time which minimized the error between the experimental and calculated concentration profiles; the example shown in Figure 7 is a companion to the raw data of Figure 6. The Peclet number so obtained was combined with the tray length and the continuous phase flow rate to yield a value of the eddy diffusion coefficient.

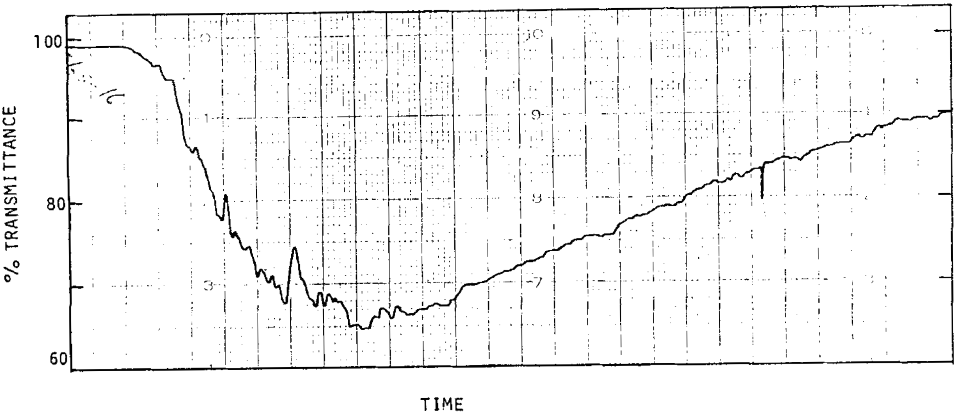

Figure 6. Typical plot of light transmittance vs. time V_c/V_d = 2.253; Pe = 1.83; $\bar{t}$ = 3.98 min.

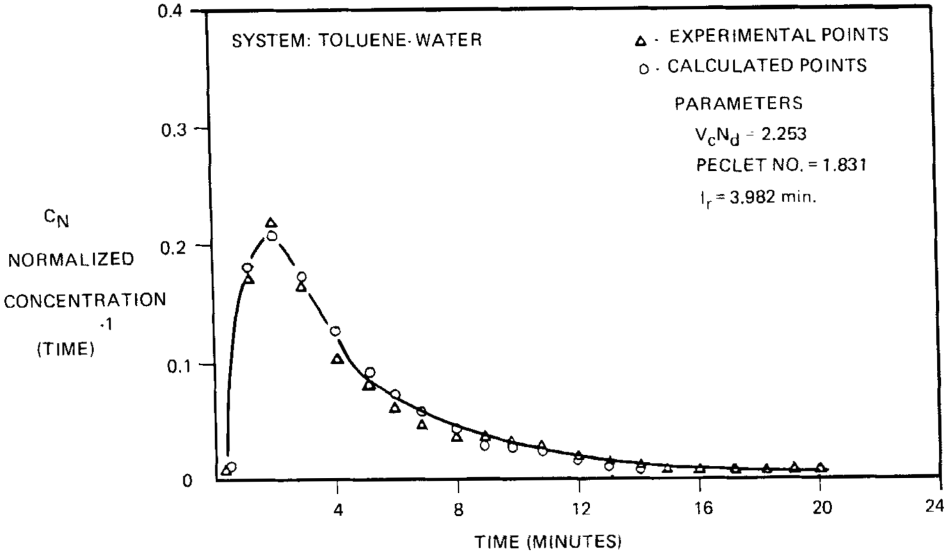

Figure 7. Typical regressed plot of experimental data

Results

Axial mixing results were obtained for operating sieve trays spaced at 6 and 12 inches, using the geometry shown in Figure 6. The immiscible phases were toluene and water at room temperature. This system has an interfacial tension of about 35 dynes/cm and with modest amounts of a transferring solute would be termed a "difficult" system with regard to mass transfer efficiency, i.e., one with characteristically low tray efficiencies. The relatively high interfacial tension leads to larger drop sizes and thus lower interfacial areas.

The experimental data are shown in Table 1 and are plotted as Peclet number versus phase flow ratio in Figure 8. As expected, the smaller tray spacing leads to a larger plug flow component (higher Peclet number, lower eddy diffusion coefficient). While only one tray length was investigated, by definition and by analogy to gas-liquid tray mixing results, one would expect larger Peclet numbers for longer flow paths of continuous phase.

The scatter of the data points in Figure 8 is in part characteristic of the measurement and reduction techniques used in the study, but may also indicate a need for additional correlating variables. However, the magnitude of the Peclet number as a function of tray spacing is well defined.

Summary and Conclusions

An experimental study has been made of the axial mixing of the continuous phase flowing across a sieve tray that is active with a rising field of light phase drops. Peclet numbers as high as 5 were obtained for a tray spacing of 6 inches. This indicates a significant amount of backmixing, even at high flow ratios of continuous to dispersed phase.

Under mass transfer conditions, and for typical extraction factor values in the range of 1 to 3, a "difficult" system is characterized by sieve tray point efficiencies in the range of 10 to 20 percent (1). Reference to Figure 3 leads to the conclusion that even with pure plug flow (infinite value of Peclet number) there is relatively little enhancement of point efficiency. Thus, for the higher interfacial tension systems, tray mixing is not likely to be a point of issue.

For the so-called "easy" mass transfer systems, such as the familiar test system methylisobutylketone/acetic acid/water, with characteristic point efficiencies in the range of 40 percent or higher, it may be possible for significant enhancement of point efficiency to occur. It remains to be seen whether the smaller drop sizes of such systems would affect significantly the axial mixing of the continuous phase, but if drop momentum is an important factor, then for the same volume of dispersed phase flow (producing a larger population of drops), the Peclet number data shown in Figure 8 should still apply. Planned work with lower interfacial tension systems should shed light on this issue.

Table 1

Experimental Data

		Phase Rates		Supfl. Vel.	Phase	Peclet	Diff.
Run No.	Tray Spacing cm	Cont. Q_c $M^3/s\cdot(10^4)$	Disp. Q_d $M^3/s\cdot(10^4)$	Cont. Phase V_c $M/s\cdot(10^2)$	Ratio V_c/V_d -	No. Pe -	Coeff. D_E cm^2/sec
6-1	15.2	1.20	1.14	0.46	4.04	2.64	8.7
6-2	15.2	1.20	0.82	0.50	6.18	2.46	10.3
6-3	15.2	1.77	0.82	0.75	9.26	2.62	14.5
6-4	15.2	2.40	0.82	1.00	12.34	6.78	7.5
6-5	15.2	1.20	1.20	0.46	3.77	1.96	11.8
6-6	15.2	1.77	1.64	0.79	4.92	2.23	18.0
6-7	15.2	1.77	2.02	0.88	4.41	2.79	16.0
6-8	15.2	1.77	1.20	0.75	6.20	2.66	14.3
6-9	15.2	2.40	1.64	1.18	7.31	2.55	23.3
6-10	15.2	2.40	1.20	1.18	9.69	4.71	12.6
6-11	15.2	1.58	0.51	0.59	11.95	4.55	6.6
6-12	15.2	1.90	0.51	0.73	14.70	4.36	8.5
6-13	15.2	2.40	0.44	1.12	25.52	5.61	10.1
6-14	15.2	2.97	0.51	1.47	29.63	3.46	21.5
6-15	15.2	1.07	2.02	0.45	2.25	1.83	12.5
12-1	30.4	1.20	0.82	0.22	2.69	1.05	10.5
12-2	30.4	1.77	1.20	0.35	2.88	0.91	19.5
12-3	30.4	1.77	0.82	0.33	4.07	1.12	14.9
12-4	30.4	1.20	0.82	0.22	2.76	1.29	8.8
12-5	30.4	2.40	0.82	0.47	5.73	1.28	18.5
12-6	30.4	1.77	1.64	0.37	2.26	0.59	31.3
12-7	30.4	1.20	1.64	0.22	1.39	0.81	14.0
12-8	30.4	1.58	0.51	0.28	5.70	1.22	11.8
12-9	30.4	1.90	0.51	0.38	7.50	0.99	19.2
12-10	30.4	2.40	0.44	0.49	10.70	1.32	18.7
12-11	30.4	1.51	0.82	0.27	3.36	0.82	16.9
12-12	30.4	0.69	1.64	0.14	0.86	0.62	11.2
12-13	30.4	1.77	0.63	0.36	5.47	1.03	17.7

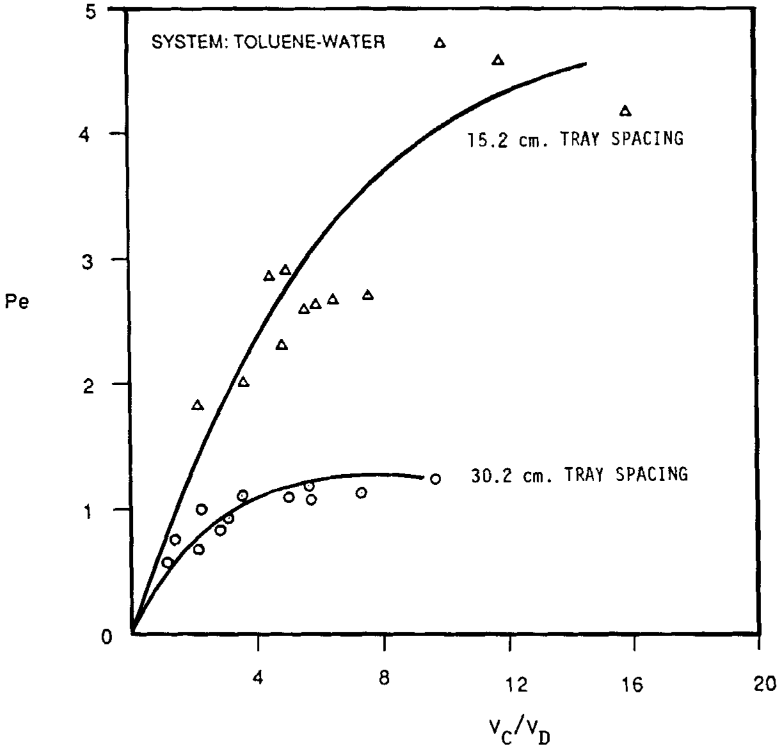

Figure 8. Peclet number as a function of phase flow ratio

One may conclude from this work that for systems with relatively high interfacial tension, which give characteristically low point efficiencies, axial mixing is not an important issue in the design of sieve tray extractors. Additional work is required to validate the effects of lower interfacial tension and alternate tray geometries, but the indication is that for the systems giving typically high mass transfer efficiencies, axial mixing could play a role in the optimum design of sieve tray extractors.

SYMBOLS

A	cross sectional area available for continuous phase flow (L)
A_n	variable defined by Equation 13 (dimensionless)
C	concentration of tracer (moles/L^3)

C_N	normalized tracer concentration $(1/\theta)$
D_E	eddy diffusion coefficient (L^2/θ)
E_{md}	Murphree dispersed phase tray efficiency (fractional)
E_{pd}	point dispersed phase efficiency (fractional)
F_c	continuous phase molar flow rate (moles/θ)
F_d	dispersed phase molar flow rate (moles/θ)
m_{dc}	equilibrium distribution coefficient, Y^*/X (dimensionless)
Pe	Peclet number (dimensionless)
s	number of mixing stages on tray
t	time (θ)
t_r	mean residence time of tracer on tray (θ)
V_c	superficial velocity of continuous phase based on area for crossflow (L/θ)
V_d	superficial velocity of dispersed phase based on active tray area (L/θ)
V_z	velocity of continuous phase in axial direction (L/θ)
w	dimensionless tray length dZ/Z (dimensionless)
X	mole fraction of solute in continuous phase
X_e^*	mole fraction of solute in continuous phase, in equilibrium with dispersed phase entering the tray
Y	mole fraction of solute in dispersed tray
Y^*	mole fraction of solute in dispersed phase, in equilibrium with continuous phase mole fraction X
Z	distance in direction of continuous phase flow (L)
Z_T	total length of tray (L)

Greek letters

α_n	variable defined by Equation 14 (dimensionless)
η	variable defined by Equation 8 (dimensionless)
λ	extraction factor, $m_{dc}F_d/F_c$ (dimensionless)
ρ_m	mean molar density of tray mixture (moles/L^3)

Subscripts

n	tray n
$n-1$	tray $n-1$ (below tray n)

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