Mass-Transfer Efficiency of Sieve Tray Extraction Columns

From a detailed analysis of five sets of experimental data on mass-transfer efficiencies in sieve tray liquid–liquid extraction columns, we point out the shortcomings of the recently published model by Rocha et al. In particular, their model overestimates the importance of the contribution due to drop formation. An improved procedure for estimation of the overall column efficiency, relying entirely on published correlations for drop size and mass-transfer coefficients, is suggested.

In a recent paper, Rocha et al. (1986) have presented a model for the prediction of the efficiency of sieve tray extraction columns wherein particular emphasis was placed on the contribution to mass transfer during drop formation. They used their own experimental data to tune some of the model parameters and tested their proposed model with their own experiments and some of the published data. In the present communication, we reexamine the accuracy of Rocha et al.'s model using an experimental data bank of 230 observations, including the measurements of Pilhofer and Mewes (1979), which had been omitted by Rocha et al. (1986) in their study; Table I gives salient details of the experimental data set. We propose an improved model for estimation of the column efficiency.

Our analysis of the set of experimental data in Table I shows that, while the method proposed by Rocha et al. (1986) gives a good fit of their own experimental data set (B and C), the predictions of the overall column efficiency for the systems measured by other workers (systems A, D, and E) are much worse; Table II gives values of the relative absolute percent deviation for each data set and also of the total set. For systems D and E, the average absolute deviation is in excess of 44%. The major reason for the large deviations for systems D and E is that Rocha et al. include the correction term

$$C_f = (-6.0 + 0.07We + 6.5\sigma_{ref}/\sigma) \qquad (1)$$

in their calculation of the overall mass-transfer coefficient for drop formation (cf. their eq IV-2). This correction term assumes large values for systems with low interfacial tension, such as systems D and E. Put another way, the Rocha et al. model grossly overestimates the contribution due to drop formation for systems with low interfacial tension. For system E, which has an extremely large area of drop formation, $A_f = N_o \pi d_p^2$, this situation is further exacerbated. As can be seen from Figure 1, the predicted column efficiency values, E_O, for systems D and E are consistently higher than the experimentally measured values.

Apparently to compensate for the overestimation of the contribution to mass transfer due to drop formation, Rocha et al. further introduced the correction factor

$$C_r = (0.70 + 0.02We) \qquad (2)$$

into the calculation of the overall mass-transfer coefficient for drop rise (cf. their eq IV-5). For operations with a high rise zone ($H_t - h_c$), the introduction of this correction factor will have the effect of giving a lower predicted value for the column efficiency; this is indeed the case for system A (cf. Figure 2) for which the underprediction of the overall column efficiency, E_O, is seen to increase with increasing $H_t - h_c$.

Suggested Improvements in the Rocha et al. Model

In attempting to improve the predictions of the overall column efficiency for all systems, we examined every factor in the prediction model. On the basis of this examination, we recommend the following changes in the Rocha et al. model.

(a) Improved Correlation for Drop Size Prediction. Rocha et al. (1986) use the Kumar and Hartland (1982) correlation for drop size in their model. More recently, Kumar and Hartland (1984) have proposed an improved drop size correlation which yields an average deviation of 7.3% as compared to 9.7% with the earlier correlation. Their improved correlation is

$$d_p = d_o E\ddot{o}^{-0.4}[2.13(\Delta\rho/\rho_d)^{0.67} + \exp(-0.13Fr)] \quad \text{for } E\ddot{o} < 0.4 \qquad (3)$$

and

$$d_p = d_o E\ddot{o}^{-0.42}[1.24 + \exp(-Fr^{0.42})] \quad \text{for } E\ddot{o} \geq 0.4 \qquad (4)$$

(b) Correction Factor for the Overall Mass-Transfer Coefficient for Drop Formation (Cf. Equation IV-2 of Rocha et al. (1986)). We recommend that this correction factor, C_f, be set equal to 1.5, following Treybal (1980).

(c) Correction Factor for the Overall Mass-Transfer Coefficient for Drop Rise (Cf. Equation IV-5 of Rocha et al. (1986)). We recommend that this correction factor, C_r, be set equal to unity.

(d) Calculation of the Continuous-Phase Mass-Transfer Coefficient during Drop Rise, k_{cr}. Rocha et al. (1986) use the Ruby and Elgin (1955) correlation for the calculation of k_{cr}. Our detailed analysis shows that this correlation underpredicts the value of k_{cr}, and we recommend the use of the penetration model (cf. Schulz and Pilhofer (1982))

$$k_{cr} = 2(D_c V_s/\pi/d_p)^{0.5} \qquad (5)$$

(e) Calculation of the Murphree Stage Efficiency. The number of transfer units due to drop formation is

$$\mathrm{NTU}_{Od,f} = 6K_{Od,f}t_f/d_p \qquad (6)$$

where t_f is the time for formation (Treybal, 1980)

$$t_f = (\pi d_p^3/6)/(Q_d/N_o) \qquad (7)$$

and the number of transfer units due to drop rise is

$$\mathrm{NTU}_{Od,r} = 6K_{Od,r}(H_t - h_c)/V_s/d_p \qquad (8)$$

It is common to assume that the number of transfer units during drop coalescence is 10% of the value due to drop formation (Treybal, 1980); i.e.,

$$\mathrm{NTU}_{Od,c} = 0.1\mathrm{NTU}_{Od,f} \qquad (9)$$

With the $\mathrm{NTU}_{Od,c}$'s calculated from eq 6–9, the stage efficiencies can be calculated from

$$E_{Md} = 1 - (1 - E_{Md,f})(1 - E_{Md,r})(1 - E_{Md,c}) \qquad (10)$$

$$E_{Md,f} = 1 - \exp(-\mathrm{NTU}_{Od,f}) \qquad (11)$$

$$E_{Md,r} = 1 - \exp(-\mathrm{NTU}_{Od,r}) \qquad (12)$$

$$E_{Md,c} = 1 - \exp(-\mathrm{NTU}_{Od,c}) \qquad (13)$$

Rocha et al. (1986), following Treybal (1980), use an approximation to eq 10 that supposes an arithmetic average driving force in place of the actual logarithmic mean; we

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Table I. Set of Systems Used in the Data Correlations and Analysis[a]

set	author	no. of exptl data pts	column diameter, m	plate spacing, m	hole diameter, mm (no. of holes)	fractional downcomer area	velocity: continuous phase, mm/s	velocity: dispersed phase, mm/s	velocity: hole, m/s	interfacial tension, mN/m
A: toluene–acetone–water	Pilhofer and Mewes, 1979	74	0.080	0.15–0.60	2 (48) 3 (21)	0.041	2.5–5.0	2.5–12.5	0.08–0.42	25
B: toluene–acetone–water	Rocha, 1984; Rocha et al., 1986	41	0.100	0.16–0.51	2.4 (123) 3.2 (33) 3.2 (54) 4.8 (33)	0.026	2.7–4.3	3.4–14.1	0.06–0.27	25
C: MIBK–acetic acid–water	Rocha, 1984; Rocha et al., 1986	39	0.100	0.16–0.32	3.2 (54) 4.8 (21) 6.3 (13)	0.026	2.8–8.4	2.9–18.2	0.05–0.33	8
D: MIBK–adipic acid–water	Garner et al., 1956	44	0.102	0.152	3.3 (59)	0.053	1.6–16.4	1.2–13.2	0.02–0.21	13
E: diethyl ether–acetic acid–water	Pyle et al., 1950	32	0.219	0.117–0.508	2.79 (109) 2.79 (205) 2.79 (310) 1.61 (646) 5.11 (62)	0.013	0.9–3.6	0.9–6.2	0.02–0.35	10.7

[a] Reported stage efficiency data for sets A and E were converted to column efficiencies in the data analysis given in Table II.

Table II. Relative Absolute Percent Deviations in the Predictions of the Column Efficiency (E_O = [abs ($E_{O,exptl}$ − $E_{O,pred}$)/$E_{O,exptl}$]100): Arithmetic Averages for Each Data Set and Total Set

system / model	A	B	C	D	E	total
Rocha et al.	34.6	21.0	17.1	48.3	52.5	34.3
improved	23.4	23.2	26.5	25.3	20.0	23.8
improved (neglecting $NTU_{Od,f}$ and $NTU_{Od,c}$)	25.3	22.7	27.4	26.0	21.9	24.9
simplified using eq 15	15.4	31.9	26.0	46.5	31.0	28.3

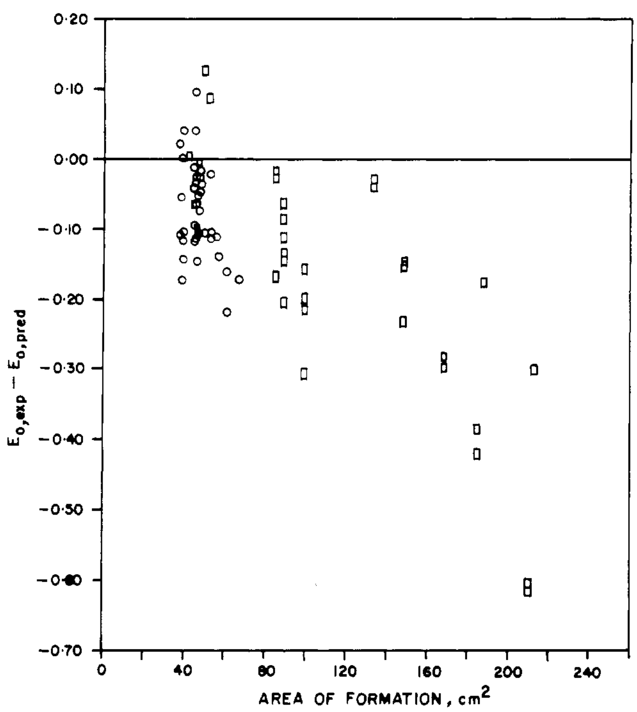

Figure 1. Deviation between experimental and predicted overall column efficiency values for systems D (○) and E (□), as a function of the area of formation, A_f.

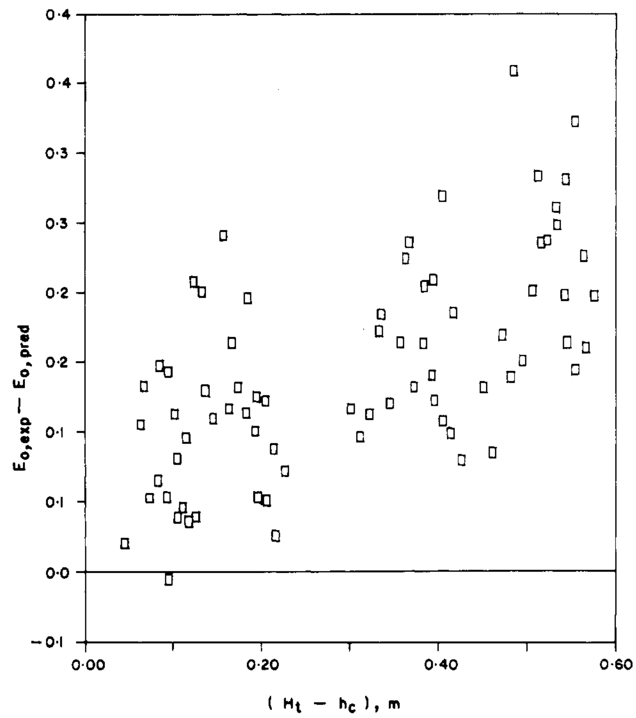

Figure 2. Deviation between experimental and predicted overall column efficiency values using the Rocha et al. model, for system A, as a function of the height of the rise zone, $H_t - h_c$.

find that this approximation is, in general, not of adequate accuracy.

For a linearized equilibrium relationship and constant extraction factor, λ, the overall column efficiency can be calculated from the Murphree stage efficiency by

$$E_O = \ln [1 + E_{Md}(\lambda - 1)]/\ln \lambda \quad (14)$$

Results and Discussion

With modifications a–e given above, the values of the average absolute deviations for each of the five systems are brought to the same level of around 24%; see Table II. We further note that the deviations are hardly affected even if we neglect the contributions due to drop formation and coalescence, as can be seen from Table II. The conclusion to be drawn is that the contribution due to drop formation, and coalescence, is not very significant for systems A–E, contrary to the findings of Rocha et al. (1986).

We also found from a statistical analysis of the total data set in Table I that for quick estimations of E_O we may take

$$K_{Od,r}/V_s = 0.0014 \quad (15)$$

and neglect the contributions due to drop formation and coalescence; the results of Table II show that even with this simplification the deviations are smaller than obtained by the model of Rocha et al. (1986).

Nomenclature

A_f = area of formation, m^2
C_f = correction factor defined by eq 1
C_r = correction factor defined by eq 2
d_o = hole or perforation diameter, m
d_p = droplet diameter, m
D_c = diffusivity in the continuous phase, m^2/s
E_{Md} = Murphree stage efficiency
E_O = overall column efficiency
$Eö$, = Eötvos number, $=\Delta\rho d_o^2 g/\sigma$
Fr = Froude number, $=U_o^2/g/d_o$
g = acceleration due to gravity, 9.81 m/s^2
h_c = height of coalesced layer, m
H_t = spacing between trays, m
k_{cr} = continuous-phase mass-transfer coefficient during drop rise, m/s
$K_{Od,f}$ = overall mass-transfer coefficient due to drop formation, m/s
$K_{Od,r}$ = overall mass-transfer coefficient due to drop rise, m/s
m = linearized slope of equilibrium line
N_o = number of holes per tray
$NTU_{Od,c}$ = number of transfer units due to drop coalescence
$NTU_{Od,f}$ = number of transfer units due to drop formation
$NTU_{Od,r}$ = number of transfer units due to drop rise
Q_d = volumetric flow rate of the dispersed phase, m^3/s
t_f = contact time for drop formation, s
U_c = superficial velocity of continuous phase (based on empty column cross section), m/s
U_d = superficial velocity of dispersed phase (based on empty column cross section), m/s
U_o = velocity through orifice (hole velocity), m/s
V_s = slip velocity, m/s
We = Weber number, $=\rho_d d_o U_o^2/\sigma$

Greek Letters

λ = extraction factor, mU_d/U_c
ρ = phase density, kg/m^3
$\Delta\rho$ = absolute difference in phase densities, kg/m^3
σ_{ref} = interfacial tension of reference system, =0.035 N/m
σ = interfacial tension, N/m

Subscripts

C = continuous phase; coalesced layer
d = dispersed phase
f = droplet formation contribution
M = Murphree
o = orifice (perforation)
O = overall
Od = overall coefficient based on dispersed phase
r = droplet rise contribution
s = slip
t = tray

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