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

Evaluation of Packings for Use in Liquid-Liquid Extraction Columns

A. F. Seibert[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 Seibert, A. F. , Humphrey, J. L. and Fair, J. R.(1987) 'Evaluation of Packings for Use in Liquid-Liquid Extraction Columns', Separation Science and Technology, 22: 2, 281 — 314
To link to this Article: DOI: 10.1080/01496398708068953
URL: http://dx.doi.org/10.1080/01496398708068953

SEPARATION SCIENCE AND TECHNOLOGY, 22(2&3), pp. 281-314, 1987

Evaluation of Packings for Use in Liquid-Liquid Extraction Columns

A. F. SEIBERT, J. L. HUMPHREY, and J. R. FAIR

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

ABSTRACT

Experimental investigations of packing performance in extraction service were conducted in a 10.2 cm. diameter column. Both random and structured packing elements were covered in separate studies. Test systems were toluene/acetone/water and n-butanol/succinic acid/water. Measurements were made of dispersed phase holdup and mass transfer rate. A tentative correlation was developed, based on a modification of basic tests using an empty column, involving an effective drop diameter.

INTRODUCTION

The increasing interest in liquid-liquid extraction for industrial processes has created a need for more basic design knowledge of extraction equipment. The objective of the work reported here was to provide such information in the form of evaluated relative effectiveness of a number of packing materials used in extraction service. The packed extractor was considered to be a simple modification of the counterflow spray column, with the packing elements providing additional drop holdup, increased probability of drop break up, and reduced axial mixing of the flowing phases. Wettability of the packing surfaces was also thought to play a role in the mass transfer performance of the packed extraction column.

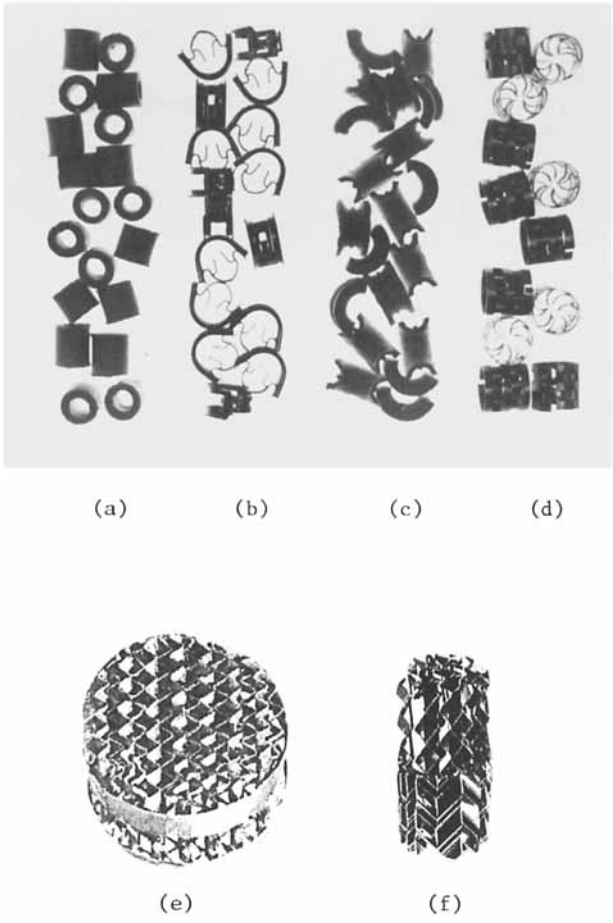
Packings for extraction are the same as those for distillation and absorption. They fall into two categories: random and ordered. In the first category fall the familiar ring and saddle elements. In the latter category fall the newer structured elements, usually in the form of corrugated metal sheets arranged carefully for controlling the flows of the phases. Examples of packing elements are shown in Figure 1. A particular objective of the present work was to ascertain the performance characteristics of several of these packings that have been developed only recently, and which have been found to give high efficiency in distillation service but which have not yet been tested in extraction service.

Previous Work

Raschig ring and Berl saddle packings have been studied rather extensively under extraction conditions, but this is far from the case for the other packings. The spray column, thought to be a base case for the packed column, has also received a great deal of attention. In some cases, spray and packed columns have been studied jointly: Appel and Elgin (1) compared 0.5 in. (12.7 mm.) Berl saddle results with those of a spray column and Sherwood et al. (2) studied 0.5 in. (12.7 mm.) and 1.0 in. (25.4 mm.) carbon Raschig rings as well as 0.5 in. (12.7mm.) Berl saddles in comparison with spray column operations under the same conditions. The latter concluded that packing has a negligible effect on the mass transfer coefficient but is effective in increasing the available interfacial area. Nemunaitis et al. (3) and Eckert (4) likewise investigated the effect of using packing instead of the empty spray column and found that the overall mass transfer efficiency was increased by as much as 50%. These workers used an 18 in. (0.46mm.) diameter column and ring and saddle packings in the 1.0 in. (25 mm.) nominal size, and thus provided valuable information for scaleup purposes. A summary of previous work with packings in extraction service is shown in Table 1.

Because of its simple nature, the spray column has also been studied extensively. A complicating factor, however, has been the tendency for the phases, especially the continuous phase, to undergo axial mixing and thus alter the effective concentration driving force at various points in the column. Steiner and Hartland (5) have presented a comprehensive review of the hydrodynamics of spray columns, and Kumar and Hartland (6) have provided a general correlation for determining average drop sizes in such columns. Table 2 shows sources and conditions of experimental studies of drop sizes in packed columns.

In his 1963 monograph, Treybal (7) analyzed data for spray columns and recommended the mass transfer correlations of Handlos and Baron (8) for the dispersed phase and of Ruby and Elgin (9) for the continuous phase. In a recent investigation, Rocha et al. (10, 11) concluded that these correlations are representative of later work and are thus reasonable for use in continuing studies of spray column performance.



(a) Ceramic Raschig rings
(b) Metal Intalox saddles
(c) Ceramic Intalox saddles
(d) Metal Pall rings
(e) BX gauze packing
(f) SMV structured packing

Figure 1. Packings tested

TABLE 1. OVERALL MASS TRANSFER EFFICIENCY DATA BANK FOR PACKED COLUMNS

Researcher	System	Column Dia, in	Zp ft	Packing	Ref.
Allerton et al.	Kerosene/Benzoic Acid/Water	3.6	5.3	1/2" RR	(20)
Appel and Elgin	Toluene/Benzoic Acid/Water CCl4/Acetic Acid/Water	2	4	1/2" BS	(1)
Billet and Mackowiak	Toluene/Acetic Acid/Water	1,8.8	1.5,10	Bialeckerings	(21)
Chu et al.	Benzene/Benzoic Acid/Water Benzene/Acetic Acid/Water	2	6.5	1/4" RR	(22)
Claffey et al.	Kerosene/Nicotine/Water	4	12	1/2" RR	(23)
Clegg and Bearse	2-Butanone/Thio-diacetic Acid/Water	4	6.1	1/2" RR	(24)
Commings and Briggs	Benzene/Benzoic Acid/Water	0.5,7.5	4	1/2" RR	(25)
Degaleesan and Laddha	Toluene/Acetone/Water Butyl Acetate/Acetone/Water	3	unknown	1/2" RR 3/4" RR	(26)
Eaglesfield et al.	Ethyl Acetate/Acetic Acid/Water Methylcyclohexane/Acetic Acid/Water I-propyl Acetate/Acetic Acid/Water	1	na	6 mm BS 1/2" RR	(27)
Eckert	MEK/Kerosene/Water	18	5	1" RR,CI,PR	(4)
Garwin and Barber	Furfural/Lube Oil (Fract.)/lube oil	2	9.6	1/4" RR	(28)
Gayler and Pratt	Butyl Acetate/Acetone/Water Ethyl Acetate/Acetone/Water Chlorex/Acetone/Water Toluene/Acetone/Water	4,6,9,12 4 4 4	10 10 10 10	1/2,3/4,1,1.5" RR 1/2" RR 1/2" RR 1/2" RR	(19)
Knight	Toluene/Furfural/Water	4	13.7		(29)
Leibson and Beckman	Toluene/Diethylamine/Water	3,4,6	3.9	1/4,1/2,3/4,1"	(30)

Meissner	MEK/Water/CACL2 Brine	3.6	5.5	1/2" RR,BS	(31)
Morello and Poffenberger	Butylene/Ammonia/Water MEK/Di-acetic Acid/Water				
Nemunaitis et al.	MEK/Kerosene/Water	18	0.5,5	1" RR,CI,PR	(3)
Pratt and Glover	Vinylacetate/Acetaldehyde/Water Vinylacetate/Acetone/Water	1.8	unknown	10 mm RR	(32)
Rao and Rao	Toluene/Acetone/Water Kerosene/Acetone/Water Pegasol/Acetone/Water	1.8	2.5	3/8" RR	(33)
Row	Toluene/Benzoic Acid/Water	8.8	5.8	1/2" RR,BS	(34)
Sherwood et al.	Benzene/Acetic Acid/Water MIBK/Acetic Acid/Water	3.6	5.6	1/2" RR 6 mm BS	(2)
Sitaramaya and Laddha	Kerosene/Acetone/Water Butyl Acetate/Acetone/Water Benzene/Acetone/Water	2	3	1/4,3/8" RR 1/4,3/8" LR 1/4" BS	(35)
Streiff and Janic	Toluene/Acetone/Water n-Butanol/Succinic Acid/Water CCL4/Propionic Acid/Water	4	16.4	SMV	(36)

BS Berl saddles
CI Ceramic Intalox saddles
LR Lessing rings
PR Metal Pall rings
RR Ceramic Raschig rings
SMV SMV structured packing

Table 2. Dropsize Studies for Packed Columns

Researcher	System	Column Dia, in	Zp ft	Packing	Ref.
Gayler and Pratt	Dichloroethyl Ether/Water Toluene/Water	3,6,12	10	1/2,3/4,1,1.5" RR	(37)
Hamilton and Pratt	MIBK/Water	2.85	1	1/2" RR	(38)
Komasawa and Ingham	Toluene/Acetone/Water Toluene/Water MIBK/Acetic Acid/Water MIBK/Water	2.8	3.3	1/2" glass RR	(39)
Lewis et al.	Butyl Acetate/Water Chlorex/Water Benzene/Water Dibutyl Carbitol/Water MIBK/Water i-Octane/Water	2	3	1/4,3/8,1/2,3/4" RR 3/8" RR 1/2" BS	(40)

BS Berl saddles
RR Ceramic Raschig rings (except for glass rings)

Theory

For a differential contactor, the height Z required to obtain a given separation may be calculated from:

$$Z = (NTU)_{oc} \cdot (HTU)_{oc} \tag{1}$$

where $(NTU)_{oc}$ is the number of overall transfer units based on the continuous phase concentration. This parameter may be determined from equilibrium data and material balance (operating line) information:

$$(NTU)_{oc} = \int_{C_{c1}}^{C_{c2}} \frac{dC_c}{C_c - C_c^*} \tag{2}$$

An analytical expression for $(NTU)_{oc}$, based on dilute solute concentration and plug flow of both phases, was developed by Treybal (7):

$$(NTU)_{oc} = \frac{\left[\ln \frac{C_{c,\,feed} - C_{d,\,feed}/m_{dc}}{C_{c,\,exit} - C_{d,\,feed}/m_{dc}} \left(1 - \frac{1}{\lambda}\right) + \frac{1}{\lambda}\right]}{(1 - 1/\lambda)} \tag{3}$$

where λ is the extraction factor ($= \rho_d V_d m_{dc}/(\rho_c V_c)$.

Equation 3 may be used when axial mixing is present, with the correction being taken up in the value of the height of a transfer unit $(HTU)_{oc}$. This latter term may be defined as:

$$(HTU)_{oc} = V_c/(K_{oc}\, a_i) \tag{4}$$

where V_c = superficial velocity of the continuous phase

K_{oc} = overall mass transfer coefficient, based on continuous phase concentrations

a_i = interfacial area for mass transfer

Often, values of $K_{oc}a_i$ (a volumetric coefficient) are reported when describing the mass transfer efficiency of a counterflow, differential contactor. The overall coefficient may be determined from two-film theory as:

$$1/K_{oc} = 1/k_c + 1/(m_{dc}\, k_d) \tag{5}$$

where m_{dc} = distribution coefficient, or slope of the equilibrium curve, plotted on a concentration basis and with dispersed phase concentration as the ordinate scale

k_c = individual film mass transfer coefficient outside the drop

k_d = individual film mass transfer coefficient inside the drop

The interfacial area a_i may be calculated assuming the dispersed phase travels as spherical drops with an average diameter:

$$a_i = (6\varepsilon\ \phi_d)/d_{vs} \tag{6}$$

where ε = void fraction of packing

ϕ_d = volume fraction of the dispersed phase moving through the packing

d_{vs} = Sauter mean (volume-surface) drop diameter

Previous work on dispersed phase holdup in packed columns is summarized in Table 3.

The Handlos and Baron correlation for the individual film mass transfer coefficient inside the drop is:

$$k_d = 0.00375\ \left(\frac{V_s}{1 + \mu_d/\mu_c}\right) \tag{7}$$

where V_s = slip velocity between the phases, defined as:

$$V_s = \frac{V_c}{\varepsilon(1 - \phi_d)} + \frac{V_d}{\varepsilon\ \phi_d} \tag{8}$$

The Ruby and Elgin correlation for the individual film mass transfer coefficient outside the drop, as modified by Treybal (7), is:

$$k_c = 0.725\left(\frac{D_c}{d_{vs}}\right)\ (Re_c^{\ 0.57})\ (Sc_c^{\ 0.42})\ (1 - \phi_d) \tag{9}$$

The dimensionless Reynolds and Schmidt groups in Equation 9 are defined as:

$$Re_c = \frac{d_{vs}\ V_s\ \rho_c}{\mu_c} \tag{10}$$

$$Sc_c = \frac{\mu_c}{\rho_c\ D_c} \tag{11}$$

Table 3. Holdup Studies for Packed Columns

Researcher	System	Column Dia, in	Zp ft	Packing	Ref.
Gayler and Pratt	Benzene/Water Butylacetate/Water Dibutyl Carbitol/Water MIBK/Water i-Octane/Water Dichlorodiethyl/Water CCL4/Water	3	10	1/4,1/2,3/4" RR 1/4,1/2" BS	(41) (42)
Gayler and Pratt	Butyl Acetate/Acetone/Water Ethyl Acetate/Acetone/Water Chlorex/Acetone/Water Toluene/Acetone/Water	4,6,9,12 4	10 10	1/2,3/4,1,1.5" RR 1/2" RR	(19)
Venkataraman et al.	MIBK/Water Kerosene/Water Toluene/Water Nitrobenzene/Water 10 % Glycerol/Water 20 % Glycerol/Water	2	3	1/4,3/8" RR 3/16,1/4,3/8" LR 1/4" BS	(43)

BS Berl saddles
LR Lessing rings
RR Ceramic Raschig rings

Axial Mixing

Packed extraction columns are usually designed on the basis that there is plug flow in both phases. As noted earlier, the spray column has been found to exhibit considerable departure from this ideal flow situation, especially with regard to backmixing in the continuous phase. It is expected that the presence of packing elements serves to minimize axial mixing in packed columns, and the assumption of plug flow is an expedient that has some basis in experimental findings. Spray column mixing models have been summarized by Steiner and Hartland (5); the most notable model is due to Miyauchi and Vermeulen (12). Mixing data for packed extractors are scarce, and are limited to Raschig ring and Berl saddle random packings (13, 14).

Flooding

Investigations of flooding in packed extraction columns have been carried out in the absence of a transferring solute, and thus correlations based on such work may not be reliable for conditions when mass transfer takes place. The correlation of Dell and Pratt (15) is most often recommended, but those of Hoffing and Lockhart (16) and Crawford and Wilke (17) have some credence. Eckert (4) has proposed a flooding prediction method that incorporates some of his own data for larger diameter packed extractors. In all cases, the flooding models are largely empirical. Sources of flooding data for packed extraction columns are shown in Table 4.

Experimental Work

The experimental extraction system used in the present work utilized a conventional flow diagram (Figure 2). The column comprised 4 in. (10.2 cm.) (i.d.) flanged glass sections capable of containing up to 5 ft. (1.5 m.) of packing. The packing support was an open four-mesh screen. The distributor, located approximately 6 in. (15.2 cm.) from the packing, was a ring sparger with nine 3/16 in. (4.8 mm.) diameter holes, uniformly spaced to ensure proper flow distribution.

The packings studied are listed in Table 5, together with their geometrical characteristics. It will be noted that two of the random packings (Pall rings, metal Intalox saddles) and the two structured packings (Sulzer BX and Sulzer SMV) are usually included in the "high-efficiency" category when considered for distillation applications.

Two test systems were selected on the basis of recommendations by the European Federation of Chemical Engineering (18). The toluene/acetone/water system has a relatively high interfacial tension, thus producing fairly large drops. The n-butanol/succinic acid/water system has a very low interfacial tension with corresponding small drop sizes. Concentrations of the solutes acetone and succinic acid were determined by titration. Properties of the test systems are shown in Table 6.

Table 4. Flooding Data Bank for Packed Columns

Researcher	System	Column Dia, in	Zp ft	Packing	Ref.
Crawford and Wilke	Gasoline/Water CCL4/Water MIBK/Water Naptha/Water	12	2	1/2,3/4,1"RR 1/2,1" BS	(17)
Dell and Pratt	Benzene/Water Butylacetate/Water Dibutyl Carbitol/Water MIBK/Water i-Octane/Water Dichlorodiethyl ether/Water CCL4/Water	3 6	5 5	1/4,3/8,1/2,3/4,1" RR 1/4" RR 3/8,1/2" LR 1/4,1/2,1" BS	(15)
Gayler and Pratt " " " "	Butyl Acetate/Acetone/Water Ethyl Acetate/Acetone/Water Chlorex/Acetone/Water Toluene/Acetone/Water	4,6,9,12 4 " "	10 10	1/2,3/4,1,1.5"RR 1/2" RR	(19)
Hoffing and Lockhart	MEK/Water	6	6	1/2,3/4,1" RR	(16)
Nemunaitis et al.	MEK/Kerosene/Water	18	5	1" RR,CI,PR	
Sakiadis and Johnson	Benzene/Water Dibutyl Carbitol/Water MIBK/Water	unknown	unknown	1/4,3/8,1/2,3/4,1"RR 1/2,1" BS	(44)
Venkataraman and Laddha	MIBK/Water Kerosene/Water Toluene/Water Nitrobenzene/Water 10 % Glycerol/Water 20 % Glycerol/Water	2	3	1/4,3/8" RR 3/16,3/8,1/4" LR 1/4" BS	(43)

BS Berl saddles
CI Ceramic Intalox saddles
LR Lessing rings
PR Metal Pall rings
RR Ceramic Raschig rings

Table 5

Characteristics of Packings Tested

	Packing Surface ft^2/ft^3	Void Fraction	Pieces per cu. ft.
Ceramic Raschig rings, 1/2 inch	106	0.64	8,400
Metal Pall rings, 5/8 inch	87	0.93	5,070
Ceramic Intalox saddles, 1/2 inch*	110	0.72	12,500
Metal Intalox saddles, No. 15*	79	0.94	8,100
BX Gauze packing**	140	0.88	-
SMV Structured packing**	104	0.95	-

*Product of Norton Company, Akron, Ohio U. S. A.

**Product of Sulzer Brothers, Ltd., Winterthur, Switzerland; marketed in U. S. A. by Koch Engineering, Inc., Wichita, Kansas.

Table 6

Physical Properties of Systems Studied (18)

Temperature = 20 C

Continuous Phase	Toluene/Acetone/ Water*	n-Butanol/Succinic acid/Water**
Viscosity, cp	1.14	1.45
Density, gm/cm^3	0.992	0.988
Diffusion coefficient, cm^2/sec.	$1.01(10^{-5})$	$0.55(10^{-5})$
Dispersed Phase		
Viscosity, cp.	0.57	3.41
Density, gm/cm^3	0.864	0.852
Diffusion coefficient, cm^2/sec	$2.51(10^{-5})$	$0.23(10^{-5})$
Slope of equilibrium curve, m_{dc}	0.85	1.25
Interfacial tension, dynes/cm	23.1	1.5

*5.0 wt-% **0.8 wt-%

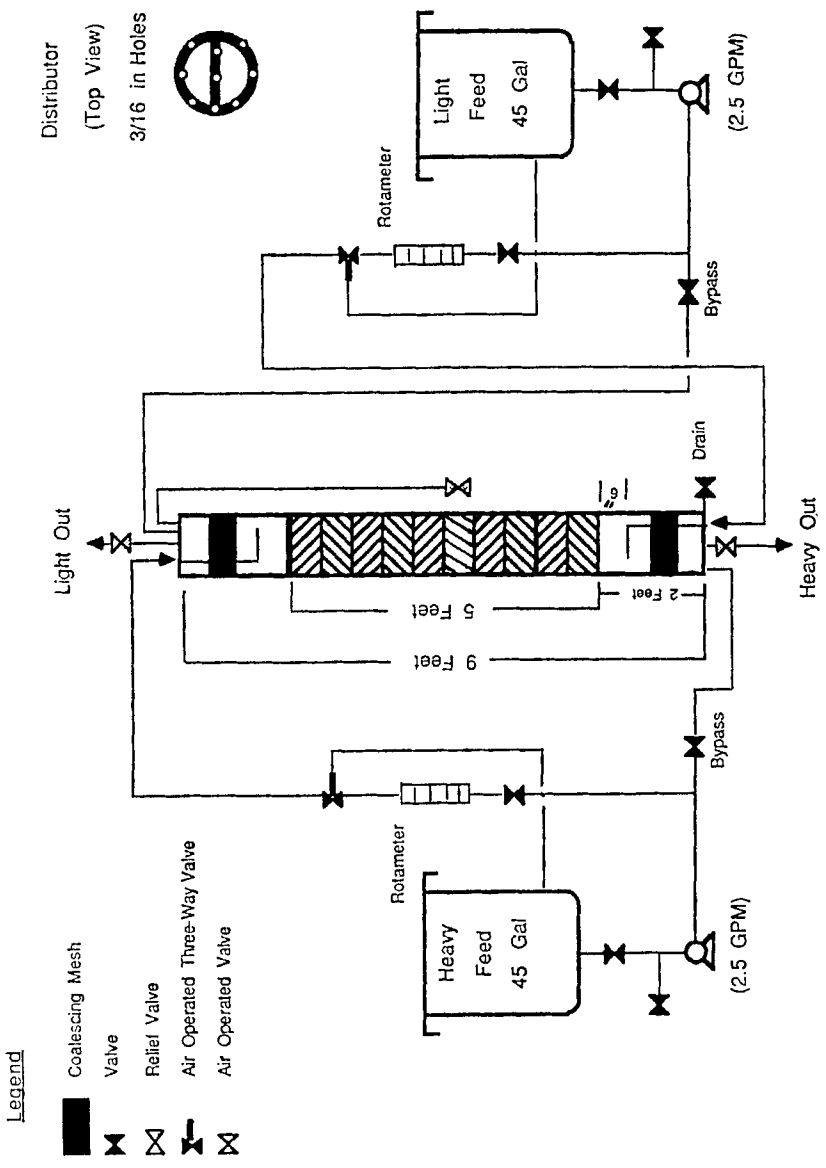


Figure 2. Flow diagram of experimental equipment

Experimental Results

The results of the experimental work are tabulated in Table 7 and are summarized in Figures 3 through 10. Values of the volumetric mass transfer coefficient, $K_{oc}a_i$, were obtained from Equations 3 and 4. Dispersed phase holdup values were measured directly by the quick shut-off technique. For both $K_{oc}a_i$ and holdup, effects of system properties, phase flow rates and mass transfer direction are shown for each of the packings tested and for the empty (spray) column. Also, each packing was operated up to its flood point, so relative capacities of the packings may be obtained from the data plots.

Figures 3 - 8 show that the transfer coefficient varies directly with phase flow rate and is more influenced by the dispersed phase rate than by the continuous phase rate. This may be attributed to the increased holdup associated with the increased drop population at higher dispersed phase flows; the measured holdup data are shown in Figure 10. Visual observations showed that drop size did not change materially with dispersed phase rate, except as flooding was approached. It is quite clear that the butanol/succinic acid/water system, with its low interfacial tension and characteristically small drop size, has superior mass transfer efficiency. More will be said later about the relative sizes of drops deduced for the different packings.

Figures 6, 7 and 8 deal with the newer packings that provide high efficiencies in distillation service. These packings also give good mass transfer results for extraction, but depending on their dimensions can have limited throughput capacity. For example, the BX gauze structured material has very close element spacing (about 10.2 cm.) and thus can accommodate relatively few of the larger size drops that are characteristic of the toluene/acetone/water system. The SMV sheet metal and metal Intalox packings show high efficiencies and capacities relative to the older, conventional ring and saddle packings.

Because of system and packing variations, it is difficult to compare the results of the present work with those of previous workers. Approximate comparisons, for example with the Raschig ring data of Gayler and Pratt (19), show quite good agreement.

Dispersed phase holdup data are plotted in Figure 10, with the various packing materials seen to have somewhat different influences on holdup. The variations follow through to the mass transfer coefficient variations shown earlier. When solute was transferred from the continuous to the dispersed phase, there was a tendency for the mass transfer efficiency to be higher than for solute movement in the reverse direction. However, this was not a consistent effect and at present is not explained. It would appear that in some cases there was sufficient solute movement to cause an increase in dispersed phase holdup and therefore interfacial area.

TABLE 7. DATA OBTAINED IN THIS WORK

COLUMN DIAMETER = 4 INCHES
PACKED HEIGHT = 5 FEET
CONTINUOUS PHASE = AQUEOUS

RUN	PACKING	SUP. VELOCITY (FT/HR) VC	VD	MASS FRACTION OF SOLUTE XO	XE	YO	YE	OD	NTUOC	HTUOC (FT)	HETS (FT)	KOCA (HR)
1-I	RR	24.8	31.0	0	0.0312	0.0539	0.0250	.08	0.89	5.61	5.25	4.42
2-I	RR	24.8	56.1	0	0.0456	0.0553	0.0328	.15	1.36	3.67	4.59	6.75
3-I	RR	23.3	11.0	0	0.0175	0.0605	0.0182	.03	0.36	13.81	7.30	1.68
4-I	RR	24.8	62.5	0	0.0506	0.0605	0.0371	.25	1.58	3.15	4.21	7.89
5-I	RR	24.8	45.2	0	0.0468	0.0620	0.0321	.13	1.22	4.07	4.54	6.09
6-I	RR	58.3	45.2	0	0.0275	0.0620	0.0210	.15	0.69	7.27	5.24	8.02
7-I	RR	27.1	41.6	0	0.0420	0.0620	0.0307	.13	1.05	4.77	4.94	5.68
8-I	RR	7.0	42.5	0	0.0671	0.0620	0.0490	.12	2.26	2.21	4.10	3.17
9-I	RR	21.9	18.5	0	0.0201	0.0469	0.0189	.05	0.61	8.20	6.10	2.71
10-II	RR	21.3	46.6	0.0547	0.0343	0.0175	0.0310	.35	1.58	3.16	3.36	6.74
11-II	RR	21.3	22.8	0.0532	0.0377	0.0160	0.0313	.14	1.04	4.81	4.17	4.42
12-II	RR	21.9	34.1	0.0532	0.0343	0.0160	0.0317	.26	1.50	3.33	3.16	6.57
13-II	RR	22.3	10.9	0.0566	0.0442	0.0056	0.0342	.06	0.51	9.81	5.31	2.27
14-II	RR	10.3	27.8	0.0639	0.0260	0.0100	0.0270	.16	1.86	2.69	3.44	3.83
15-II	RR	33.8	27.7	0.0639	0.0472	0.0100	0.0348	.20	0.60	8.33	5.95	4.06
16-III	RR	24.7	10.9	0	0.0022	0.0076	0.0022	.06	0.67	7.46	5.22	3.33
17-III	RR	24.8	32.1	0	0.0051	0.0076	0.0031	.28	2.96	1.70	2.01	14.58
18-III	RR	24.8	24.9	0	0.0027	0.0046	0.0015	.18	2.21	2.26	2.37	10.47
19-III	RR	10.5	14.6	0	0.0031	0.0046	0.0020	.08	2.90	1.72	2.08	6.10
20-III	RR	48.8	15.3	0	0.0012	0.0046	0.0001	.16	1.59	3.14	1.71	15.54
21-I	PR	25.6	17.3	0	0.0245	0.0608	0.0202	.04	0.67	7.47	4.97	3.42
22-I	PR	27.2	52.9	0	0.0534	0.0671	0.0360	.10	1.33	3.75	4.38	7.25
23-I	PR	27.1	87.4	0	0.0660	0.0665	0.0425	.15	1.98	2.53	3.66	10.79
24-I	PR	26.5	120.5	0	0.0922	0.0827	0.0602	.32	2.64	1.89	3.23	14.01
25-I	PR	22.3	26.5	0	0.0470	0.0778	0.0346	.06	0.95	5.27	4.91	4.23
26-I	PR	62.8	27.5	0	0.0120	0.0502	0.0190	.06	0.30	16.75	8.74	3.76
27-I	PR	94.7	41.0	0	0.0094	0.0346	0.0112	.11	0.40	12.55	6.75	7.58
28-II	PR	24.2	35.0	0.0640	0.0353	0.0057	0.0305	.12	0.97	5.15	4.94	4.70
29-II	PR	20.4	20.7	0.0504	0.0395	0.0160	0.0284	.08	0.58	8.62	8.04	2.36
30-II	PR	24.4	89.0	0.0504	0.0274	0.0160	0.0230	.42	1.63	3.07	4.79	6.64

RR = RASCHIG RINGS, PR = PALL RINGS, I,II = TOLUENE/ACETONE/WATER, III,IV = N-BUTANOL/SUCCINIC ACID/WATER

(CONTINUED)

TABLE 7. (CONT.)

COLUMN DIAMETER = 4 INCHES
PACKED HEIGHT = 5 FEET
CONTINUOUS PHASE = AQUEOUS

RUN	PACKING	SUP. VELOCITY (FT/HR) VC	VD	MASS FRACTION OF SOLUTE XO	XE	YO	YE	OD	NTUOC	HTUOC (FT)	HETS (FT)	KOCA (HR)
31-II	PR	49.8	25.8	0.0615	0.0500	0.0118	0.0400	.12	0.49	10.15	5.51	4.91
32-II	PR	105.0	25.9	0.0615	0.0550	0.0118	0.0420	.16	0.25	20.06	7.31	5.25
33-III	PR	23.8	21.6	0	0.0041	0.0089	0.0033	.06	1.19	4.21	4.00	5.48
34-III	PR	22.7	30.9	0	0.0058	0.0089	0.0039	.11	2.41	2.07	2.49	10.97
35-III	PR	22.7	51.4	0	0.0040	0.0055	0.0033	.23	2.92	1.71	2.51	13.27
36-III	PR	22.6	3.5	0	0.0007	0.0055	0.0005	.01	0.39	12.81	4.76	1.77
37-III	PR	55.4	27.0	0	0.0011	0.0037	0.0011	.15	0.71	7.04	5.03	7.86
38-III	PR	6.0	27.7	0	0.0029	0.0037	0.0030	.10	4.22	1.18	2.41	5.08
39-IV	PR	16.0	22.0	0.0104	0.0028	0.0017	0.0085	.08	3.02	1.65	1.94	9.69
40-IV	PR	50.1	20.0	0.0104	0.0068	0.0017	0.0125	.11	1.46	3.42	2.16	14.61
41-I	CI	23.9	27.7	0	0.0233	0.0450	0.0220	.06	0.69	7.25	6.51	3.29
42-I	CI	24.0	75.0	0	0.0448	0.0510	0.0347	.15	1.39	3.57	5.16	6.72
43-I	CI	24.2	102.0	0	0.0615	0.0621	0.0451	.20	1.71	2.92	4.74	8.28
44-I	CI	24.2	45.2	0	0.0393	0.0551	0.0302	.11	1.07	4.67	5.83	5.18
45-I	CI	14.9	24.2	0	0.0423	0.0691	0.0392	.06	0.87	5.74	6.10	2.43
46-I	CI	64.1	22.1	0	0.0106	0.0503	0.0139	.06	0.31	15.90	7.03	4.03
47-I	CI	115.4	20.7	0	0.0056	0.0471	0.0108	.07	0.19	26.30	7.61	4.37
48-II	CI	25.0	75.4	0.0413	0.0290	0.0181	0.0290	.40	1.31	3.70	6.19	6.71
49-II	CI	25.0	32.4	0.0801	0.0556	0.0232	0.0450	.14	0.71	7.04	6.67	3.57
50-II	CI	84.5	24.2	0.0808	0.0729	0.0230	0.0550	.25	0.25	16.67	6.59	5.03
51-III	CI	23.0	30.8	0	0.0108	0.0162	0.0060	.21	2.99	1.67	1.91	13.77
52-III	CI	23.7	58.2	0	0.0071	0.0119	0.0086	.39	1.36	3.67	5.77	6.45
53-III	CI	24.9	13.4	0	0.0044	0.0119	0.0021	.08	1.27	3.93	2.89	6.33
54-I	MI	18.8	21.0	0	0.0355	0.0623	0.0262	.05	0.90	5.55	4.91	3.31
55-I	MI	17.6	35.2	0	0.0511	0.0623	0.0325	.08	1.46	3.42	4.03	5.15
56-I	MI	19.3	74.2	0	0.0555	0.0518	0.0347	.16	2.39	2.09	3.24	9.23
57-I	MI	19.3	106.3	0	0.0590	0.0479	0.0343	.33	3.17	1.58	2.71	12.21
58-I	MI	19.1	84.5	0	0.0580	0.0478	0.0330	.29	3.05	1.64	2.65	11.61

PR = PALL RINGS, CI = CERAMIC INTALOX SADDLES, MI = METAL INTALOX SADDLES

TABLE 7.(CONT)

COLUMN DIAMETER = 4 INCHES
PACKED HEIGHT = 5 FEET
UNPACKED HEIGHT (NP) = 6 FEET
CONTINUOUS PHASE = AQUEOUS

RUN	PACKING	SUP. VELOCITY (FT/HR) VC	VD	MASS FRACTION OF SOLUTE XO	XE	YO	YE	OD	NTUOC	HTUOC (FT)	HETS (FT)	KOCA (HR)
59-I	MI	29.1	37.7	0	0.0235	0.0392	0.0182	.08	0.89	5.62	5.31	5.18
60-I	MI	58.2	39.0	0	0.0111	0.0294	0.0102	.10	0.54	9.26	6.14	6.28
61-I	MI	80.2	39.2	0	0.0050	0.0169	0.0047	.13	0.46	10.86	5.91	7.38
62-II	MI	29.8	58.0	0.0280	0.0152	0.0054	0.0130	.13	1.18	4.24	4.90	7.03
63-II	MI	29.9	127.1	0.0730	0.0223	0.0141	0.0280	.41	2.98	1.67	2.72	17.84
64-II	MI	30.8	72.8	0.0730	0.0347	0.0217	0.0400	.31	2.64	1.89	2.42	16.29
65-II	MI	16.3	50.2	0.0615	0.0195	0.0078	0.0244	.13	2.19	2.28	3.18	7.14
66-II	MI	77.2	50.3	0.0615	0.0490	0.0180	0.0420	.18	0.71	7.04	4.40	10.96
67-II	MI	93.2	50.7	0.0727	0.0588	0.0181	0.0496	.26	0.59	8.47	4.80	11.07
68-III	MI	25.5	36.7	0	0.0066	0.0117	0.0064	.09	1.47	3.40	4.21	7.50
69-III	MI	25.3	32.0	0	0.0065	0.0117	0.0058	.09	1.51	3.31	3.87	7.64
70-III	MI	24.9	8.5	0	0.0014	0.0064	0.0015	.03	0.49	10.20	5.83	2.44
71-III	MI	24.9	56.2	0	0.0046	0.0061	0.0037	.22	2.95	1.72	2.51	14.47
72-III	MI	27.7	70.1	0	0.0085	0.0108	0.0068	.32	3.61	1.39	2.15	19.95
73-III	MI	6.1	32.1	0	0.0047	0.0065	0.0054	.08	2.33	2.15	4.43	2.84
74-III	MI	56.8	32.1	0	0.0025	0.0057	0.0006	.13	1.91	2.60	2.10	21.89
75-III	MI	93.2	32.0	0	0.0009	0.0033	0.0003	.13	1.04	4.81	2.83	19.37
76-I	NP	23.2	34.7	0	0.0290	0.0713	0.0490	.025	0.48	12.56	12.81	1.85
77-I	NP	23.1	72.8	0	0.0455	0.0713	0.0533	.06	0.84	7.16	9.97	3.22
78-I	NP	23.3	97.6	0	0.0550	0.0680	0.0525	.10	1.21	4.96	7.97	4.69
79-I	NP	23.3	130.1	0	0.0680	0.0780	0.0700	.23	1.34	4.45	8.08	5.23
80-I	NP	47.2	29.2	0	0.0252	0.1200	0.0693	.02	0.24	24.89	15.15	2.20
81-I	NP	100.1	29.2	0	0.0150	0.1200	0.0570	.025	0.15	39.90	15.56	2.51
82-I	NP	140.3	29.2	0	0.0127	0.1200	0.0550	.03	0.13	46.81	16.09	2.99

MI = METAL INTALOX SADDLES, NP = NO PACKING

(CONTINUED)

Table 7.(cont)

Column Diameter = 4 inches
Packed Height = 5 feet
Continuous phase = Aqueous

Run	Packing	Sup. Velocity (ft/hr) Vc	VD	Mass Fraction of Solute Xo	Xe	Yo	Ye	OD	NTUoc	HTUoc (ft)	HETS (ft)	Koca (hr)
83-II	BX	27.3	30.5	0.1020	0.0410	0.0084	0.0760	.17	2.76	1.84	1.63	14.83
84-II	BX	27.3	43.3	0.0750	0.0360	0.0187	0.0480	.20	2.73	1.83	1.88	14.96
85-II	BX	27.3	8.9	0.0750	0.0620	0.0187	0.0627	.045	0.90	5.56	2.31	4.86
86-II	BX	27.3	67.5	0.0750	0.0287	0.0187	0.0415	.35	3.03	1.65	2.15	16.51
87-II	BX	52.7	30.6	0.0765	0.0516	0.0198	0.0650	.18	1.65	3.02	2.33	17.46
88-II	BX	14.4	27.3	0.0765	0.0370	0.0198	0.0480	.16	2.20	2.27	2.51	6.34
89-I	BX	16.0	25.2	0	0.0434	0.0551	0.0217	.09	1.89	2.64	2.77	6.06
90-I	BX	40.0	25.1	0	0.0240	0.0586	0.0158	.10	0.87	5.74	3.89	6.96
91-I	BX	82.0	24.6	0	0.0130	0.0586	0.0121	.13	0.27	12.60	5.42	6.51
92-I	BX	25.4	13.4	0	0.0272	0.0681	0.0155	.04	0.71	7.04	4.56	3.61
93-I	BX	26.6	33.1	0	0.0459	0.0681	0.0263	.09	1.30	3.85	3.65	6.91
94-I	BX	26.6	35.8	0	0.0581	0.0810	0.0351	.11	1.31	3.81	3.80	6.98
95-IV	BX	36.6	33.4	0.0124	0.0031	0	0.0121	.12	3.21	1.56	1.54	23.52
96-IV	BX	36.5	60.0	0.0124	0.0007	0	0.0087	.25	5.02	1.01	1.28	36.11
97-IV	BX	36.6	71.1	0.0124	0.0004	0	0.0069	.31	5.09	0.95	1.36	38.52
98-III	BX	37.0	71.6	0	0.0061	0.0078	0.0044	.29	5.30	0.94	1.31	39.36
99-III	BX	35.8	48.5	0	0.0055	0.0078	0.0033	.21	3.39	1.48	1.74	24.19
100-III	BX	37.6	9.7	0	0.0017	0.0082	0.0003	.03	0.92	5.43	2.71	6.92
101-III	BX	36.9	41.5	0	0.0052	0.0081	0.0024	.13	3.14	1.59	1.68	23.20
102-III	BX	60.0	33.3	0	0.0041	0.0091	0.0008	.16	2.42	2.06	1.59	29.10
103-III	BX	115.0	33.6	0	0.0023	0.0091	0.00015	.21	1.77	2.82	1.53	40.78
104-III*	BX	24.8	56.7	0	0.0030	0.0086	0.0009	.30	2.89	1.73	2.45	14.33
105-III*	BX	25.1	74.9	0	0.0025	0.0089	0.0041	.38	3.63	1.38	2.17	18.18
106-III*	BX	52.2	9.7	0	0.0048	0.0074	0.0067	.04	0.21	24.11	6.92	2.17

* = Aqueous phase is dispersed, BX = ordered guaze packing

TABLE 7.(CONT)

RUN	PACKING	SUP. VELOCITY (FT/HR) VC	VD	XO	MASS FRACTION OF SOLUTE XE	YO	YE	OD	NTUOC	HTUOC (FT)	HETS (FT)	KOCA (HR)
107-III	NP	17.9	26.0	0	0.0064	0.0119	0.0064	0.05	1.57	3.82	4.59	4.68
108-III	NP	16.5	66.9	0	0.0092	0.0119	0.0097	0.20	3.95	1.52	3.10	10.86
109-III	NP	19.1	85.6	0	0.0067	0.0086	0.0071	0.23	4.24	1.41	2.94	13.54
110-III	NP	19.2	124.2	0	0.0067	0.0081	0.0069	0.47	4.61	1.31	2.94	14.73
111-III	NP	19.4	42.2	0	0.0086	0.0134	0.0090	0.10	2.07	2.89	4.38	6.70
112-III	NP	57.3	25.4	0	0.0044	0.0152	0.0033	0.08	1.02	5.91	4.22	9.55
113-III	NP	86.6	25.9	0	0.0027	0.0101	0.0013	0.17	1.37	4.37	2.52	19.80
114-I	SMV	24.3	30.4	0	0.0660	0.1024	0.0445	0.08	1.05	4.76	4.54	5.11
115-I	SMV	25.0	65.2	0	0.0849	0.0965	0.0582	0.13	1.48	3.37	4.42	7.39
116-I	SMV	23.9	103.4	0	0.0658	0.0610	0.0431	0.27	2.91	1.72	2.81	11.71
117-I	SMV	33.3	115.3	0	0.0356	0.0321	0.0198	0.29	2.81	1.78	2.65	18.75
118-I	SMV	97.3	134.3	0	0.0450	0.0853	0.0461	0.29	0.84	5.91	5.79	14.37
119-I	SMV	118.3	145.5	0	0.0471	0.0851	0.0415	0.35	0.75	6.65	6.16	17.70
120-I	SMV	11.8	37.3	0	0.0698	0.0802	0.0562	0.07	1.40	3.57	5.28	3.30
121-I	SMV	52.5	38.8	0	0.0255	0.0673	0.0273	0.085	0.52	9.61	7.07	5.46
122-I	SMV	89.5	37.5	0	0.0169	0.0673	0.0182	0.09	0.36	13.88	6.77	6.45
123-I	SMV	147.8	41.1	0	0.0159	0.0859	0.0198	0.11	0.27	18.55	7.25	8.01
124-II	SMV	22.9	22.1	0.0640	0.0329	0.0049	0.0393	0.073	1.71	2.92	2.36	7.86
125-II	SMV	21.8	54.0	0.0653	0.0130	0.0049	0.0291	0.178	3.35	1.50	1.93	14.51
126-II	SMV	24.3	81.3	0.0724	0.0076	0.0014	0.0255	0.32	3.50	1.42	2.08	17.11
127-II	SMV	20.9	29.5	0.0551	0.0293	0.0083	0.0320	0.08	1.33	3.75	3.69	5.57
128-II	SMV	50.0	28.7	0.0703	0.0521	0.0083	0.0519	0.085	0.79	6.34	3.81	7.88
129-II	SMV	66.4	26.6	0.0547	0.0434	0.0068	0.0398	0.095	0.71	7.09	3.45	9.36
130-II	SMV	106.5	28.0	0.0691	0.0601	0.0146	0.0491	0.115	0.64	7.81	3.25	13.58
131-II	SMV	137.3	31.0	0.0625	0.0532	0.0075	0.0514	0.16	0.59	8.49	3.21	16.21
132-III	SMV	21.5	28.9	0	0.0041	0.0060	0.0021	0.10	2.81	1.78	1.95	14.21
133-III	SMV	20.9	53.9	0	0.0045	0.0060	0.0037	0.20	4.48	1.17	1.81	17.90
134-III	SMV	25.3	49.7	0	0.0071	0.0092	0.0052	0.17	3.80	1.31	1.85	19.31
135-III	SMV	23.7	73.1	0	0.0078	0.0096	0.0067	0.23	4.93	1.01	1.71	23.71
136-III	SMV	23.7	95.5	0	0.0070	0.0086	0.0065	0.32	5.07	0.98	1.82	24.18
137-III	SMV	23.7	130.0	0	0.0085	0.0103	0.0089	0.48	6.24	0.80	1.76	29.60
138-III	SMV	68.5	38.8	0	0.0038	0.0080	0.0007	0.16	2.15	2.33	1.78	29.41
139-III	SMV	141.8	43.2	0	0.0021	0.0080	0.00007	0.18	1.16	4.33	2.43	32.56

** = BUTANOL (D) WETS THE GREASY PACKING, NP = NO PACKING, SMV = ORDERED SHEET METAL PACKING

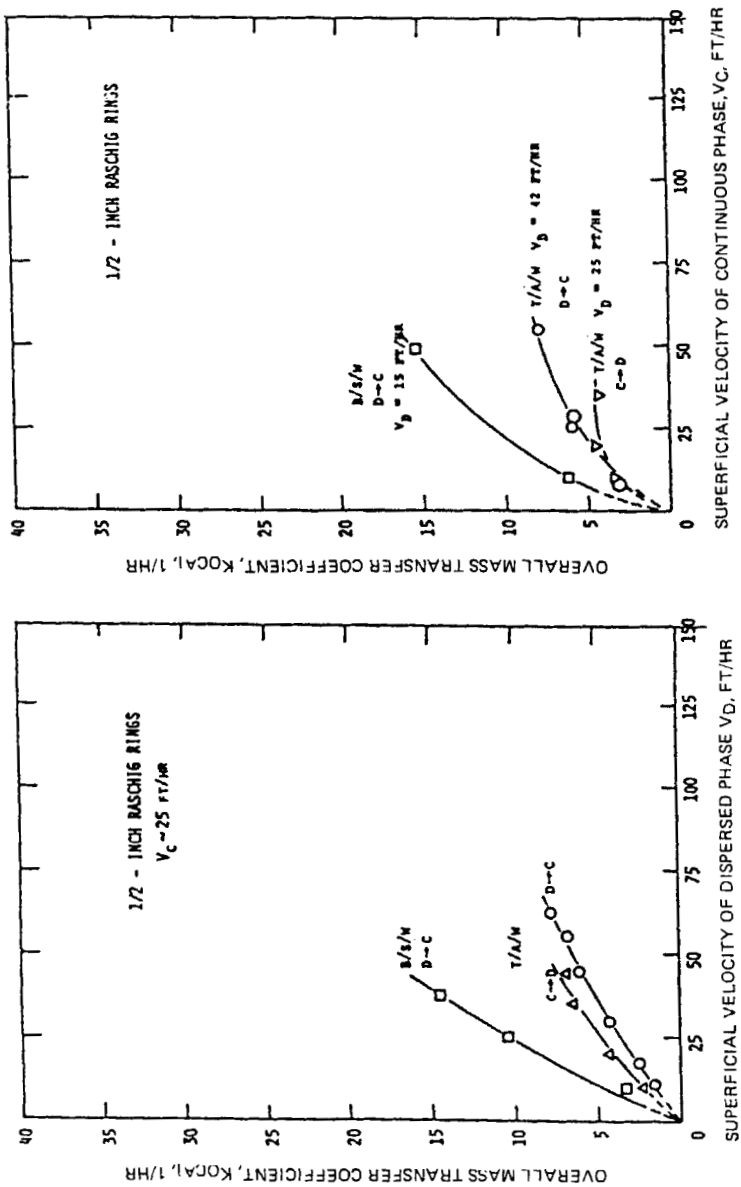


Figure 3. Mass transfer coefficients for 0.5 in. (12.7mm.) ceramic Raschig rings.

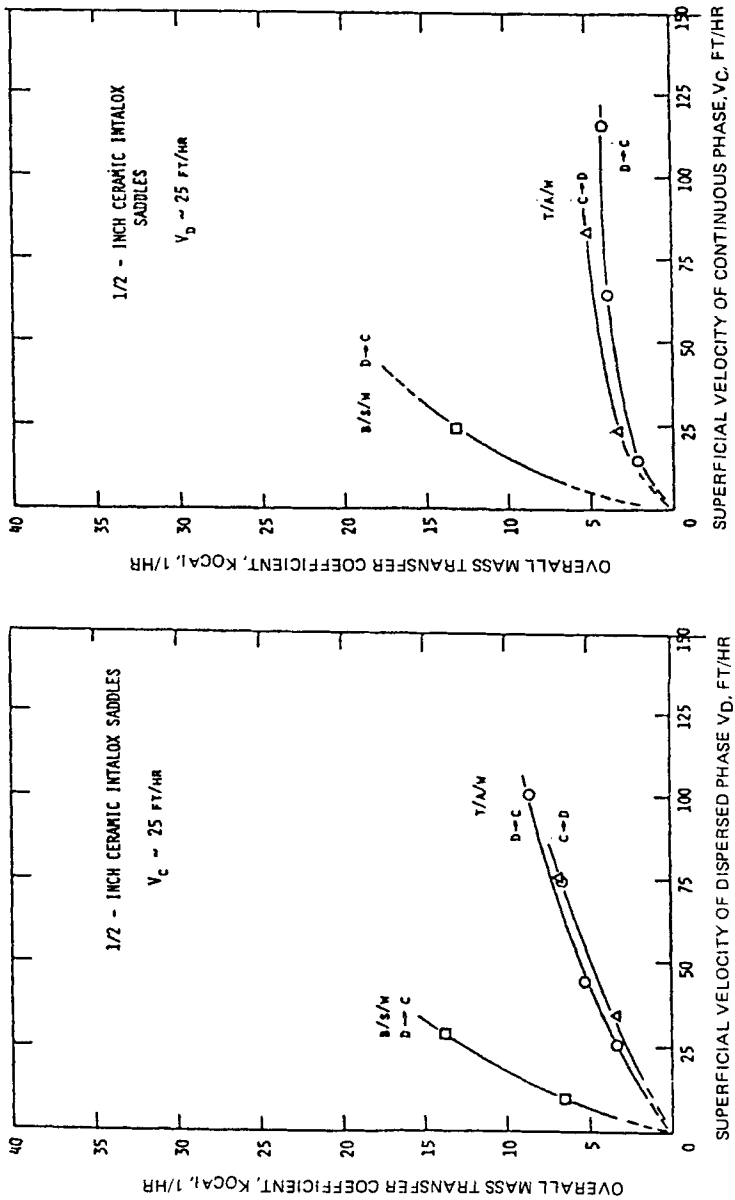


Figure 4. Mass transfer coefficients for 0.5 in. (12.7 mm.) ceramic Intalox saddles.

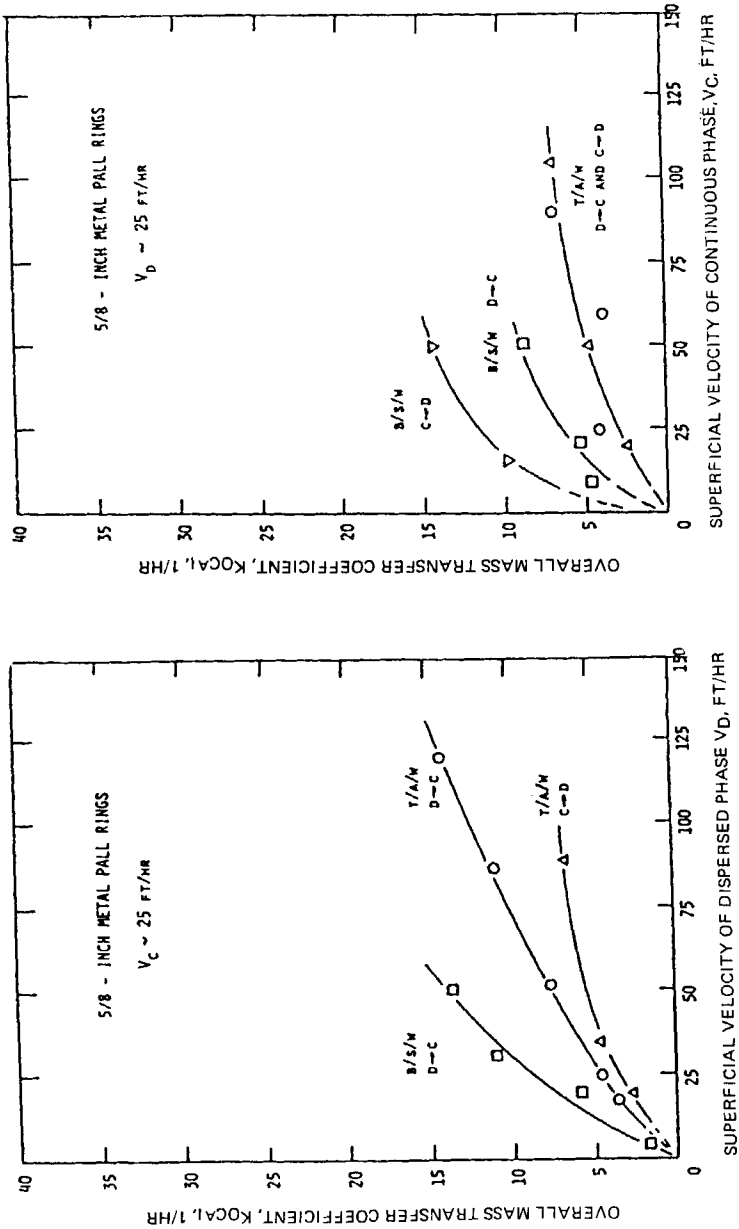


Figure 5. Mass transfer coefficients for 5/8-in. (15.9 mm.)

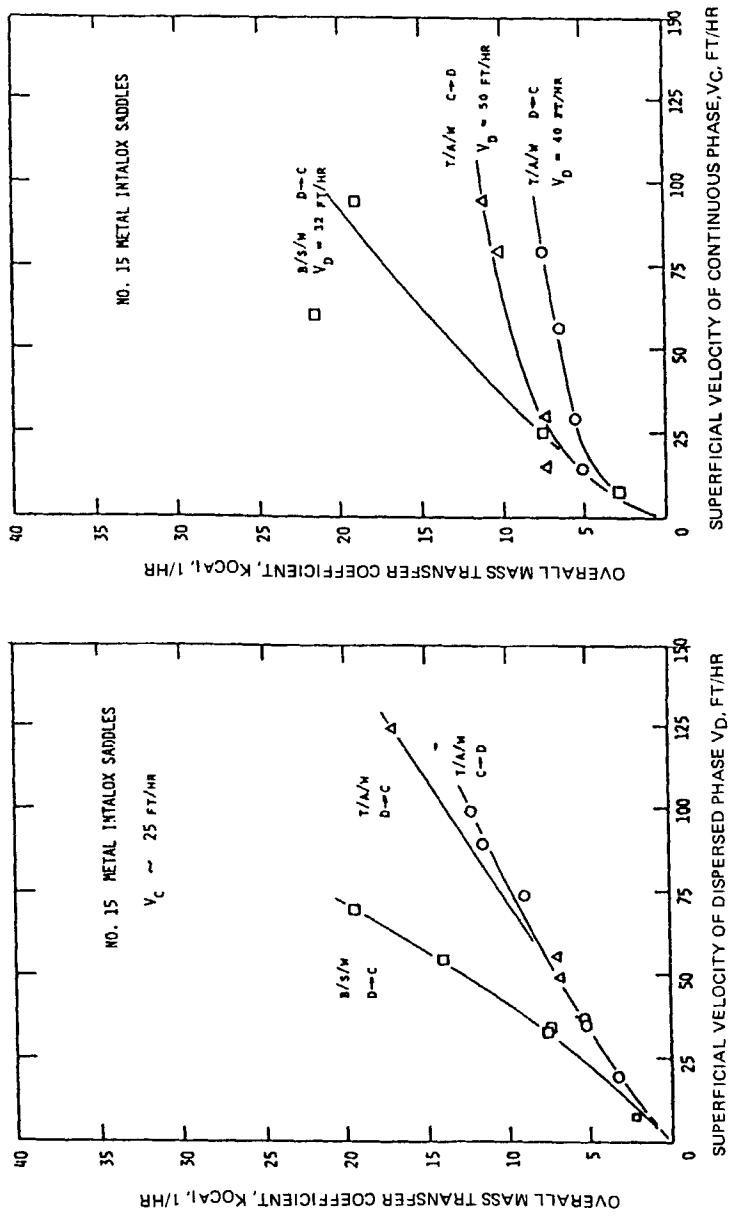


Figure 6. Mass transfer coefficients for No. 15 metal Intalox saddles.

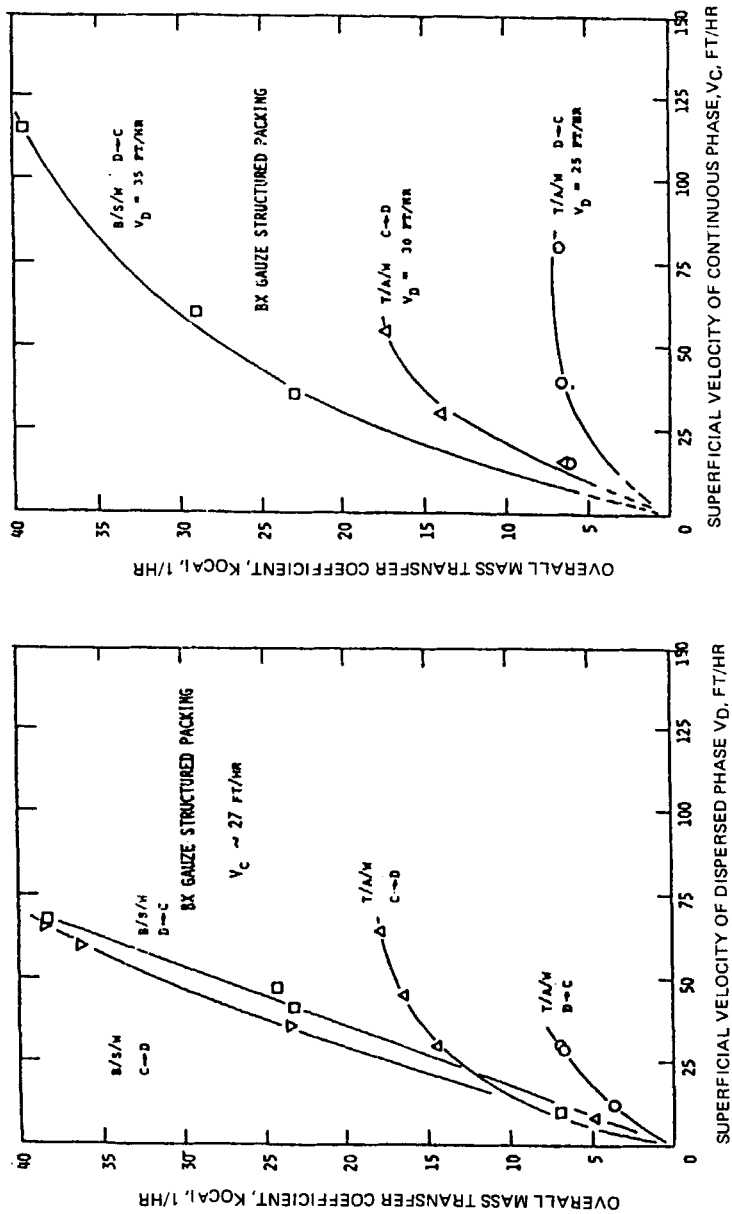


Figure 7. Mass transfer coefficients for BX gauze structured packing.

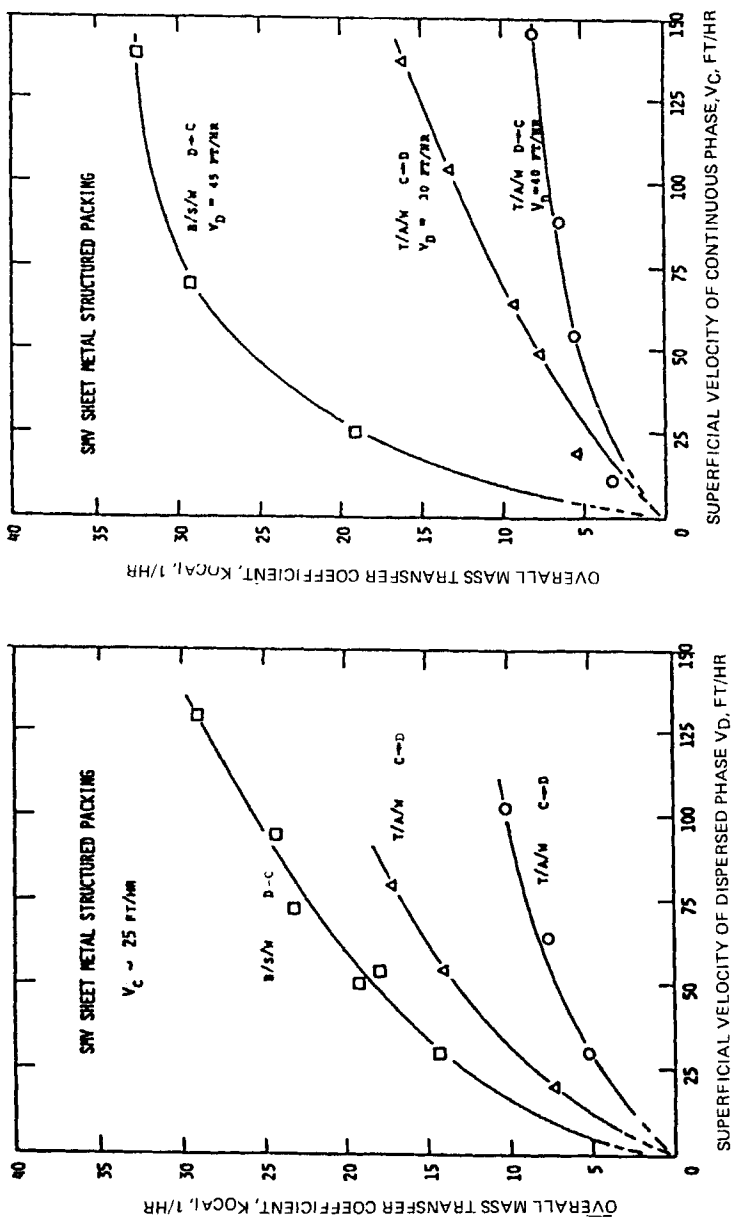


Figure 8. Mass transfer coefficients for SMV sheet metal structured packing.

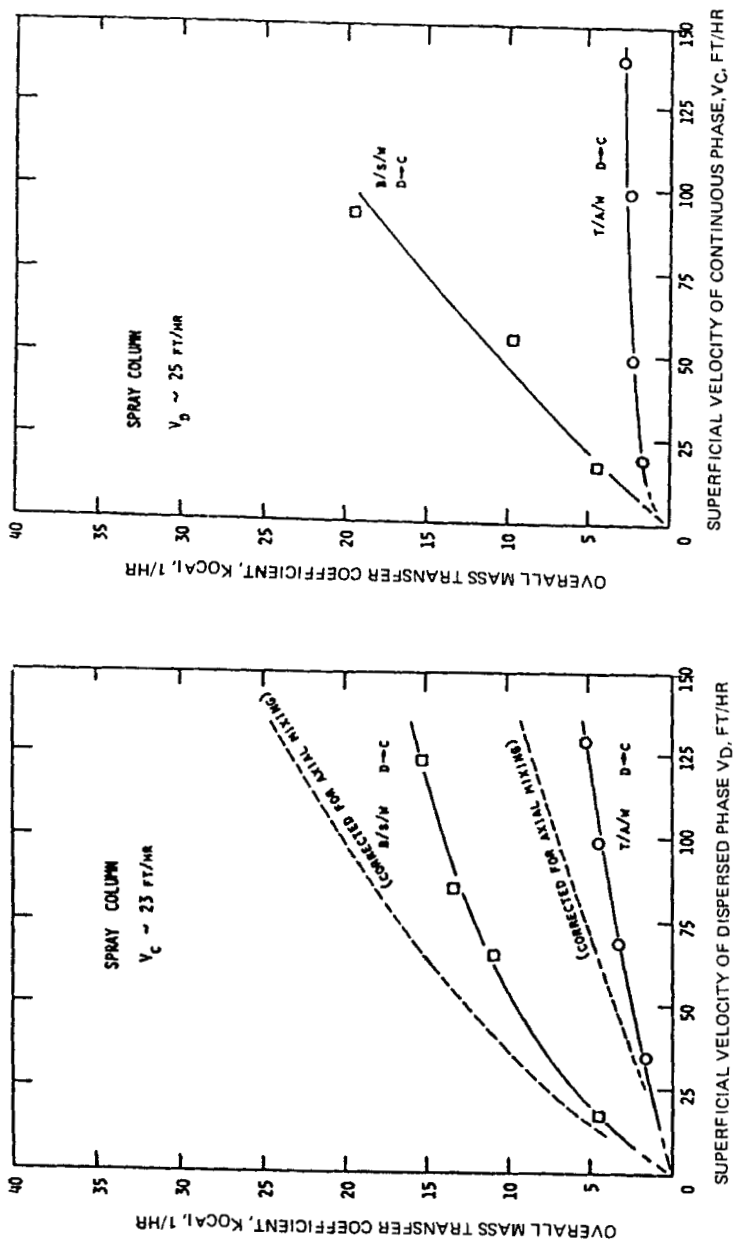


Figure 9. Mass transfer in empty (spray) column.

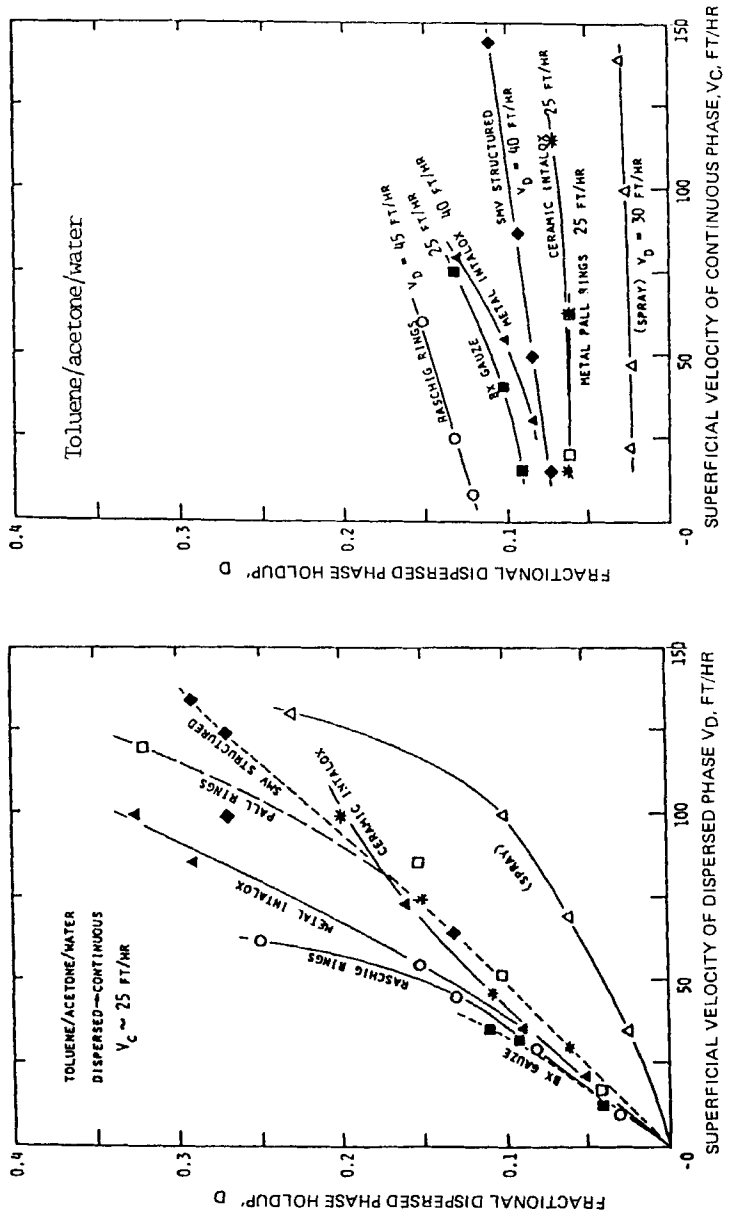


Figure 10. Dispersed phase holdup for packings tested

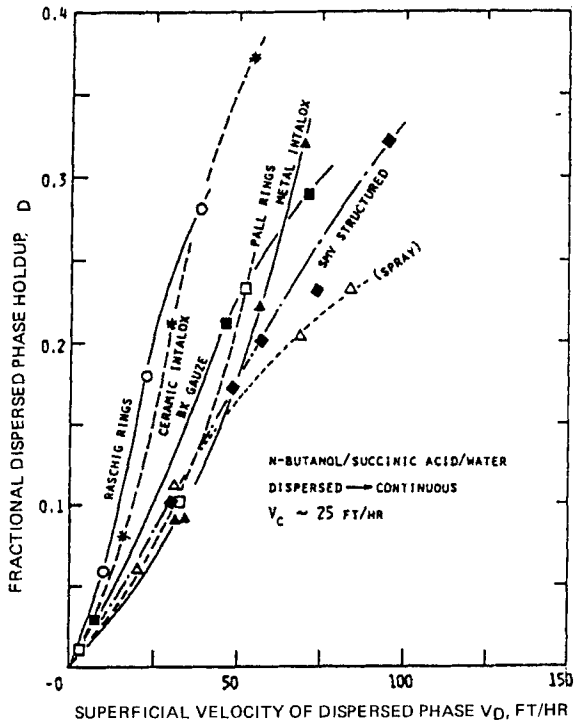


Figure 10 (Continued)

An effect of packing wetting appeared to be present, but data are not sufficient to permit firm conclusions. As an example, for BX gauze, the aqueous phase was observed to wet the packing preferentially. When that phase was dispersed, the drops moved along the packing surface, losing about half of their available interfacial area for mass transfer. Accordingly, the rate of mass transfer was about cut in half.

Correlation of Results

The packed extraction column was considered to be a variant of the basic spray extraction column. The presence of the packing is expected to decrease axial mixing, increase dispersed phase holdup, and decrease effective drop size through a modest amount of coalescence and re-formation. Accordingly, the experimental spray column data were corrected to an idealized, non-backmixed case and were modeled through the use of the Handlos and Baron correlation for mass transfer outside the drops. Each of the packings was then treated in the

Table 8

Effective drop diameters for packings tested

(Diameters in centimeters)

	Toluene/acetone/water		n-Butanol/Succinic acid/water	
	d → c	c → d	d → c	c → d
Ceramic Raschig rings, 1/2-inch . . .	0.71	0.74	0.31	-
Ceramic Intalox saddles, 1/2-inch. . .	0.86	1.00	0.39	
Metal Pall rings, 5/8-inch	0.73	0.87	0.33	0.24
Metal Intalox saddles, No. 15	0.72	0.72	0.33	-
BX Gauze packing	0.59	0.43	0.21	0.23
SMV Structured packing	0.79	0.51	0.31	-
(Spray column)	1.05	-	0.44	-

d → c = solute transfer from dispersed to continuous phase

c → d = solute transfer from continuous to dispersed phase

following way. The measured values of volumetric coefficient $K_{oc}a_i$ and holdup ε were used to find an effective drop diameter that would also satisfy the Handlos/Baron and Ruby/Elgin mass transfer relationships. This was an iterative procedure. The resulting effective diameter provides a relative measure of the packing effectiveness, but is not necessarily a general term that is independent of packing size. Table 8 shows values of the effective drop diameters of the packings tested, and Figure 11 is a parity plot comparing measured coefficients and those calculated using the effective diameters from Table 8. It is clear that much more work will be required in order to determine the extent to which larger packing sizes influence the value of the effective diameter.

Summary and Conclusions

Mass transfer efficiencies have been studied for a variety of packing materials under liquid-liquid extraction conditions. Extraction data for several of the packings have not previously been reported.

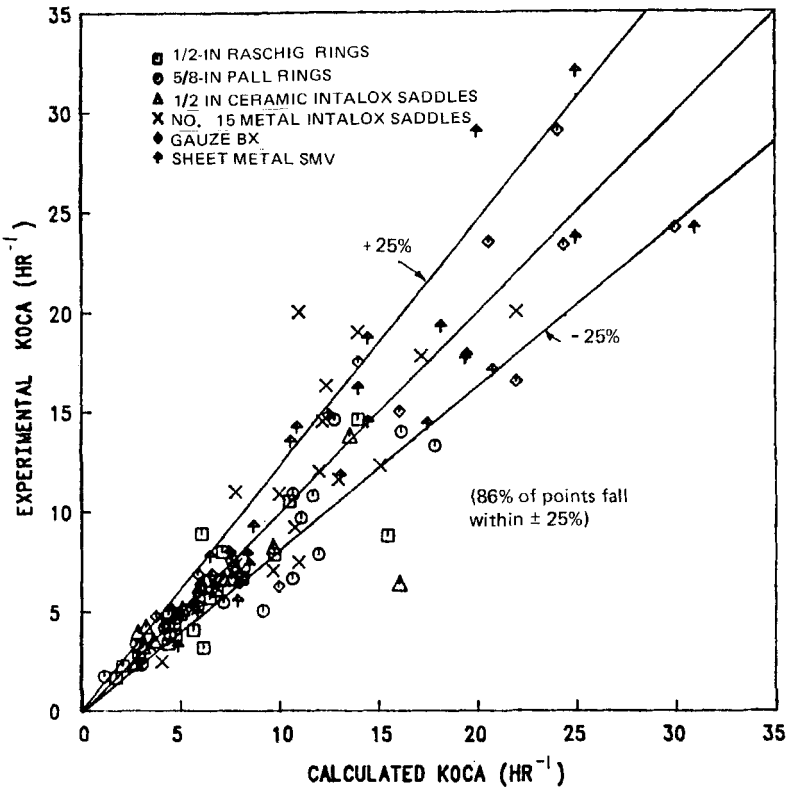


Figure 11. Parity plot for overall mass transfer coefficient

It has been found that the packed column can be treated as a variant of the spray column, so long as the effects of axial mixing are taken into account. A mass transfer model was developed on this basis, with the primary correlating variable being an effective drop diameter. While there is some indication that the model will serve for larger packing sizes than could be tested in the experimental column, confirmatory work at larger scales will be necessary.

Acknowledgments

The packings used in this study were donated by Norton Company (Raschig rings, Ceramic Intalox saddles, Pall rings and metal Intalox saddles) and Koch Engineering Company (BX gauze and SMV sheet metal). The n-butanol was donated by Shell Development Company. Stipends for the senior author were provided by the Separations Research Program of The University of Texas at Austin. The authors are grateful for these very significant generosities.

SYMBOLS

a_i	Interfacial area, defined by Equation 6, L^2/L^3
C	Concentration of solute, M/L^3
d	Drop diameter, L
d_{vs}	Sauter mean drop diameter, L
D	Molecular diffusion coefficient, L^2/t
$(HTU)_{oc}$	Height of an overall transfer unit, based on continuous phase concentration, L
K_{oc}	Overall mass transfer coefficient, based on continuous phase concentration, L/t
k_c	Individual film mass transfer coefficient outside the drop, L/t
k_d	Individual film mass transfer coefficient inside the drop, L/t
m_{dc}	Distribution coefficient, of slope of the equilibrium curve plotted on a concentration basis and with the dispersed phase as the ordinate scale
$(NTU)_{oc}$	Number of overall transfer units based on the continuous phase
Re_c	Reynolds number based on the continuous phase (Equation 10)
Sc_c	Schmidt number based on the continous phase (Equation 11)
V_c	Superficial velocity of the continuous phase, L/t
V_d	Superficial velocity of the dispersed phase, L/t
V_s	Slip velocity, defined by Equation 8, L/t
Z	Contacting height, L

Greek letters

ε	Void fraction of packing
λ	Extraction factor, $\rho_d V_d m_{dc}/(\rho_c V_c)$
μ	Liquid viscosity, M/Lt
ρ	Liquid density, M/L^3
σ	Interfacial tension, F/L
ϕ_d	Fraction of dispersed phase holdup in packed section

Subscripts

c	Continuous phase
d	Dispersed phase

REFERENCES

1. F.J. Appel and J.C. Elgin, Ind. Eng. Chem. 29, 451 (1937).

2. T.K. Sherwood, J.E. Evans and J.V.A. Longcor, Ind. Eng. Chem. 31, 1144 (1939).

3. R.R. Nemunaitis, J.S. Eckert, E.H. Foote, and L.H. Rollison, Chem. Eng. Progr. 67 (11) 60 (1971).

4. J.S. Eckert, Hydrocarbon Processing 55 (3) 117 (1976).

5. L. Steiner and S. Hartland, "Hydrodynamics of Liquid-Liquid Spray Columns", Chapter 40 in Handbook of Fluids in Motion, N.P. Cheremisinoff and R. Gupta, Eds., Ann Arbor: Ann Arbor Science Publishers, 1983.

6. A. Kumar and S. Hartland, Chem. Eng. Commun. 31, 1983 (1984).

7. R.E. Treybal, Liquid Extraction, Second ed., New York: McGraw-Hill Book Co., 1963.

8. A.E. Handlos and T. Baron, AIChE J. 3, 127 (1957).

9. C.L. Ruby and J.C. Elgin, Chem. Eng. Progr. Symp. Ser. 51 (16) 17 (1955).

10. J.A. Rocha, J.L. Humphrey and J.R. Fair, "Mass Transfer Efficiency for Sieve Tray Extractors", to be published in Ind. Eng. Chem., Proc. Des. Devel.

11. J.A. Rocha, "Mass Transfer Efficiency of Sieve Tray Liquid-Liquid Extraction Columns", Ph.D. Dissertation, The University of Texas at Austin, 1985.

12. T. Miyauchi and T. Vermeulen, Ind. Eng. Chem. Fundam. 2, 113 (1963).

13. T. Vermeulen, J.S. Moon, A. Hennico and T. Miyauchi, Chem. Eng. Progr. 62 (9) 95 (1966).

14. J.S. Watson and L.E. McNeese, Ind. Eng. Chem., Proc. Des. Devel. 11, 120 (1972).

15. F.R. Dell and H.R.C. Pratt, Trans. Instn. Chem. Engrs. 29, 89 (1951).

16. E.H. Hoffing and F.J. Lockhart, Chem. Eng. Progr. 50, (2) 94 (1954).

17. J.W. Crawford and C.R. Wilke, Chem. Eng. Progr. 47 (8) 423 (1951).

18. T. Misek (Ed.), "Recommended Systems for Liquid Extraction Studies", Instn. Chem. Engrs., Rugby, England, 1978.

19. R. Gayler and H.R.C. Pratt, Trans. Instn. Chem. Engrs. 31, 78 (1953).

20. J.B. Allerton, B.D. Satrom and R.E. Treybal, Trans. AIChE 39, 361 (1943).

21. R. Billet and J. Kackowiak, Chem.-Ing.-Tech. 52 (2) 170 (1980).

22. J.C. Chu, C.C. Taylor and D.J. Levy, Ind. Eng. Chem. 42, 1157 (1950).

23. J.B. Claffey, C.O. Badger, J.J. Skalemara and G.W.M. Phillips, Ind. Eng. Chem. 44, 274 (1952).

24. J.W. Clegg and A.E. Bearse, Ind. Eng. Chem. 42, 1222 (1950).

25. E.W. Comings and S.W. Briggs, Trans. AIChE 38, 143 (1942).

26. T.E. Degaleesan and G.S. Laddha, Indian Jour. Technol. 3, 137 (1965).

27. P. Eaglesfield, B.K. Kelly and J.E. Short, Ind. Chemist 29, 243 (1953).

28. L. Garwin and E.C. Barber, Petrol. Refiner 32 (1) 144 (1953).

29. O.S. Knight Trans. AIChE 39, 439 (1943).

30. I. Leibson and R.B. Beckmann, Chem. Eng. Progr. 49 (8) 405 (1953).

31. H.P. Meissner, C.A. Stokes, C.M. Hunter and G.M. Morrow, Ind. Eng. Chem. 36, 917 (1944).

32. H.R.C. Pratt and S.T. Glover, Trans. Instn. Chem. Engrs. 24, 54 (1946).

33. R.M. Rao and C.V. Rao, J. Chem. Eng. Data 6, 201 (1961).

34. S.B. Row, J.H. Koffolt and J.R. Withrow, Trans. AIChE 37, 559 (1941).

35. T. Sitaramayya and G.S. Laddha, Chem. Eng. Sci. 13, 263 (1961).

36. F.A. Streiff and S.J. Jancic, Ger. Chem. Eng. 7, 178 (1984).

37. R. Gayler and H.R.C. Pratt, Trans. Instn. Chem. Engrs. 31, 69 (1953).

38. J.A. Hamilton and H.R.C. Pratt, AIChE J. 30, 442 (1984).

39. I. Komasawa and J. Ingham, Chem. Eng. Sci. 33, 341 (1978).

40. J.B. Lewis, I. Jones and H.R.C. Pratt, Trans. Instn. Chem. Engrs. 29, 126 (1951).

41. R. Gayler and H.R.C. Pratt, Trans. Instn. Chem. Engrs. 29, 109 (1951).

42. R. Gayler, N.W. Roberts and H.R.C. Pratt, Trans. Instn. Chem. Engrs. 31, 57 (1953).

43. G. Venkataraman and G.S. Laddha, AIChE J. 6, 355 (1960).

44. D.C. Sakiadis and A.I. Johnson, Ind. Eng. Chem. 46, 1229 (1954).