Mass Transfer Efficiency of a Packed Bed Utilizing the Fractal Distributor

Report

Presented to:

Vadim Kochergin
Amalgamated Research, Inc.
P.O. Box 228
Twin Falls, Idaho 83303-0228
208/735-5400
208/733-8604 (fax)

by

A. Frank Seibert, J. Christopher Lewis and James R. Fair

Separations Research Program
Center for Energy and Environmental Resources
The University of Texas at Austin

December 18, 2002

CONTENTS

	Page
LIST OF TABLES	*iii*
LIST OF FIGURES	*iv*
LIST OF APPENDICES	*v*
BACKGROUND	1
EXPERIMENTAL EQUIPMENT	1
MASS TRANSFER RUN PROCEDURE	2
EXPERIMENTAL RESULTS	5
ANALYSIS OF RESULTS	13
CONCLUSIONS	20
APPENDIX	21

LIST OF TABLES

Page

Table 1. Liquid Distributor Capacity and Specifications 2

Table 2. Physical Properties of Air/Carbon Dioxide/Caustic System 6

LIST OF FIGURES

		Page
Figure 1.	Mass Transfer Column Configuration	4
Figure 2a.	Photograph of the Standard SRP Orifice Distributor (40 pts/ft^2)	6
Figure 2b.	Photograph of the High Capacity Trough Drip Tube Distributor (13.5 pts/ft^2)	6
Figure 2c.	Photograph of the Fractal I Distributor (10 pts/ft^2)	7
Figure 2d.	Photograph of the Fractal II Distributor (40 pts/ft^2)	7
Figure 3.	Mass Transfer Efficiency of the Standard SRP Orifice Distributor (40 pts/ft^2)	9
Figure 4.	Mass Transfer Efficiency of the High Capacity Trough Drip Tube Distributor (13.5 pts/ft^2)	10
Figure 5.	Mass Transfer Efficiency of the Fractal I Distributor (10 pts/ft^2)	11
Figure 6.	Mass Transfer Efficiency of the Fractal II Distributor (40 pts/ft^2)	12
Figure 7.	Comparison of Distributors at an f-factor = 0.52 ft/s $(lb/ft^3)^{0.5}$	14
Figure 8.	Comparison of Distributors at an f-factor = 0.86 ft/s $(lb/ft^3)^{0.5}$	15
Figure 9.	Comparison of Distributors at an f-factor = 1.29 ft/s $(lb/ft^3)^{0.5}$	16
Figure 10.	Comparison of Distributors at a Constant Pressure Drop = 0.75 in H_2O/ft	17
Figure 11.	Comparison of Distributors at a Liquid Rate of 5 gpm/ft^2	18
Figure 12.	Comparison of Distributors at a Liquid Rate of 10 gpm/ft^2	19

LIST OF APPENDICES

		Page
Appendix A.1.1	Mass Transfer Data for the Standard SRP Orifice Distributor (40 pts/ft^2), f-factor = 0.52 ft/s (lb/ft^3)$^{0.5}$	23
Appendix A.1.2	Mass Transfer Data for the Standard SRP Orifice Distributor (40 pts/ft^2), f-factor = 0.87 ft/s (lb/ft^3)$^{0.5}$	24
Appendix A.1.3	Mass Transfer Data for the Standard SRP Orifice Distributor (40 pts/ft^2), f-factor = 1.29 ft/s (lb/ft^3)$^{0.5}$	25
Appendix A.1.4	Mass Transfer Data for the Standard SRP Orifice Distributor (40 pts/ft^2), $\Delta P/Z_p$ = 0.75 in H_2O/ft	26
Appendix A.2.1	Mass Transfer Data for the High Capacity Trough Drip Tube Distributor (13.5 pts/ft^2), f-factor = 0.52 ft/s (lb/ft^3)$^{0.5}$	27
Appendix A.2.2	Mass Transfer Data for the High Capacity Trough Drip Tube Distributor (13.5 pts/ft^2), f-factor = 0.87 ft/s (lb/ft^3)$^{0.5}$	28
Appendix A.2.3	Mass Transfer Data for the High Capacity Trough Drip Tube Distributor (13.5 pts/ft^2), f-factor = 1.29 ft/s (lb/ft^3)$^{0.5}$	29
Appendix A.2.4	Mass Transfer Data for the High Capacity Trough Drip Tube Distributor (13.5 pts/ft^2), $\Delta P/Z_p$ = 0.75 in H_2O/ft	30
Appendix A.3.1	Mass Transfer Data for the Fractal I Distributor (10 pts/ft^2), f-factor = 0.52 ft/s (lb/ft^3)$^{0.5}$	31
Appendix A.3.2	Mass Transfer Data for the Fractal I Distributor (10 pts/ft^2), f-factor = 0.87 ft/s (lb/ft^3)$^{0.5}$	32
Appendix A.3.3	Mass Transfer Data for the Fractal I Distributor (10 pts/ft^2), f-factor = 1.29 ft/s (lb/ft^3)$^{0.5}$	33
Appendix A.3.4	Mass Transfer Data for the Fractal I Distributor (10 pts/ft^2), $\Delta P/Z_p$ = 0.75 in H_2O/ft	34

Appendix A.4.1 Mass Transfer Data for the Fractal II Distributor (40 pts/ft2), f-factor = 0.52 ft/s $(lb/ft^3)^{0.5}$ 35

Appendix A.4.2 Mass Transfer Data for the Fractal II Distributor (40 pts/ft2), f-factor = 0.87 ft/s $(lb/ft^3)^{0.5}$ 36

Appendix A.4.3 Mass Transfer Data for the Fractal II Distributor (40 pts/ft2), f-factor = 1.29 ft/s $(lb/ft^3)^{0.5}$ 37

Appendix A.4.4 Mass Transfer Data for the Fractal II Distributor (40 pts/ft2), $\Delta P/Z_p$ = 0.75 in H_2O/ft 38

Appendix A.5 Procedure for Calculating Mass Transfer Area 39

Mass Transfer Efficiency of a Packed Bed Utilizing the Fractal Distributor

December 18, 2002

A. Frank Seibert, J. Christopher Lewis and James R. Fair

BACKGROUND

The Separations Research Program (SRP) conducted a series of carbon dioxide/caustic absorption experiments tests to determine the mass transfer characteristics of a Montz B1-500 packed bed using four different liquid distributors:

1) Standard SRP Orifice Distributor (40 pts/ft^2)
2) High Capacity Trough Drip Tube Distributor (13.5 pts/ft^2)
3) Fractal I Distributor (10 pts/ft^2)
4) Fractal II Distributor (40 pts/ft^2)

Algamated Research, Inc. provided the Fractal distributors that were fabricated from plastic materials. The Separations Research Program provided the orifice and trough drip tube distributors. The primary objective of the study was to determine the effect of the liquid distributor type on packing mass transfer. The Montz B1-500 structured packing was selected because of its large available surface area which is thought to be difficult to wet completely with conventional liquid distributors. Also, the higher surface area should enable better discrimination among the effects of the different distributors. In these tests, only distributor was varied.

Experimental Equipment

The hydraulic and mass transfer performance of the packings was measured using a 16.8-in I.D. PVC air/water column connected to a 350 gallon capacity sump. The hydraulic system setup is shown in Figure 1. The packing elements were loaded into the column by lowering the elements onto a corrugated-type support plate for structured packing. The packed height was 118 inches. Inlet and outlet temperatures were measured with type-K thermocouples. The water flow rate was measured using an orifice plate and differential pressure transmitter. Water was supplied to the top of the column from the re-circulation tank via a centrifugal pump capable of discharging 150 gpm. Water flow was regulated with an automatic control valve. A 40 HP blower with variable speed motor drive supplied air to the column.

Pressure drop data were measured using a commercially available differential pressure cell (DPC) calibrated for 0-30 inches of water. Both legs of the cells were periodically purged of any entrained liquid, to insure accuracy.

Mass transfer data were calculated by comparing the carbon dioxide (CO_2) concentration in ambient air entering the column with the CO_2 concentration in the exit air, after scrubbing with a sodium hydroxide solution. The ambient CO_2 concentration generally ranged from 360 to 380 ppm. Carbon dioxide concentration levels were measured with a Horiba VIA-510 analyzer. The Horiba analyzer provided four calibration ranges:

- 0-100 ppm
- 0-200 ppm
- 0-500 ppm
- 0-1000 ppm.

The 0-500 ppm range was utilized in these experiments. The analyzer was calibrated before the start of each run. It was equipped to provide a 4-20 ma signal to our Fisher-Rosemount Delta-V process computer. This feature allowed for online CO_2 monitoring and calculation of the mass transfer efficiency. The diameter and length of the sample piping was optimized to minimize residence time.

Four liquid distributors are utilized, to ensure proper initial liquid distribution. See Table 1.

Table 1. Liquid Distributor Capacity and Specifications

Type	pts/ft^2	Drip Points	hole diameter, in	Min Liquid Flux, gpm/ft^2	Max Liquid Flux, gpm/ft^2
SRP Orifice	40.0	60	0.161	1	20
Trough Drip Tube	13.5	21	0.22	1	31.3
Fractal I	10	15	0.245	1	30
Fractal II	40	60	0.113	1	30

MASS TRANSFER RUN PROCEDURE

Approximately 300 gallons of 0.1 N NaOH solution are charged to the sump tank located below the packed column. The contents of the sump are then recycled through a pump bypass line. Care is taken to minimize contact with the stagnant air. During the mass transfer process, the CO_2 in air reacts with the sodium hydroxide to form sodium carbonate (Na_2CO_3):

$$2\,NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$$

A Horiba VIA-510 CO_2 analyzer monitors carbon dioxide concentration in the inlet and outlet air streams. This analyzer is checked at the start of each run with calibration gas (459 ppm CO_2) fed from a pressurized cylinder. The analyzer's baseline or "zero" is checked using pure nitrogen fed from a pressurized container.

After the instrument calibration, the initial concentration of CO_2 in ambient air is measured. Next, the sample piping is configured to analyze the effluent stream. The concentration of CO_2 is measured online.

For the present study, tests were performed at three air rates (180 ACFM, 300, and 450 ACFM) with liquid rates varying in sequence at 2.5, 5, 15, and 20 gpm/ft^2. We were unable to operate with higher rates because of the hydraulic limitations associated with the 500 m^2/m^3 packing. The air rate was fixed and the liquid rate was varied. In addition, runs were carried out at a constant pressure drop of 0.75 in H_2O/ft for the liquid rates 2.5, 5, 10, 15, and 20 gpm/ft^2. In the constant pressure drop runs, the liquid rate was fixed and the air rate was changed to provide a pressure drop of 0.75 in H_2O/ft. A process flow diagram is shown in Figure 1B.

A de-entraining device (Trutna Tray) was added to prevent accidental release of the sodium hydroxide solution. However, special care was taken to avoid a need for de-entraining. Also, the effluent gas sample was taken upstream of the Trutna tray: thus that device did not contribute to the mass transfer measurements. Steady state was achieved when the CO_2 concentration reached a constant value (stopped rising or falling). In general, steady state was achieved within 10-15 minutes of a set point change.

Figure 1. Mass Transfer Configuration

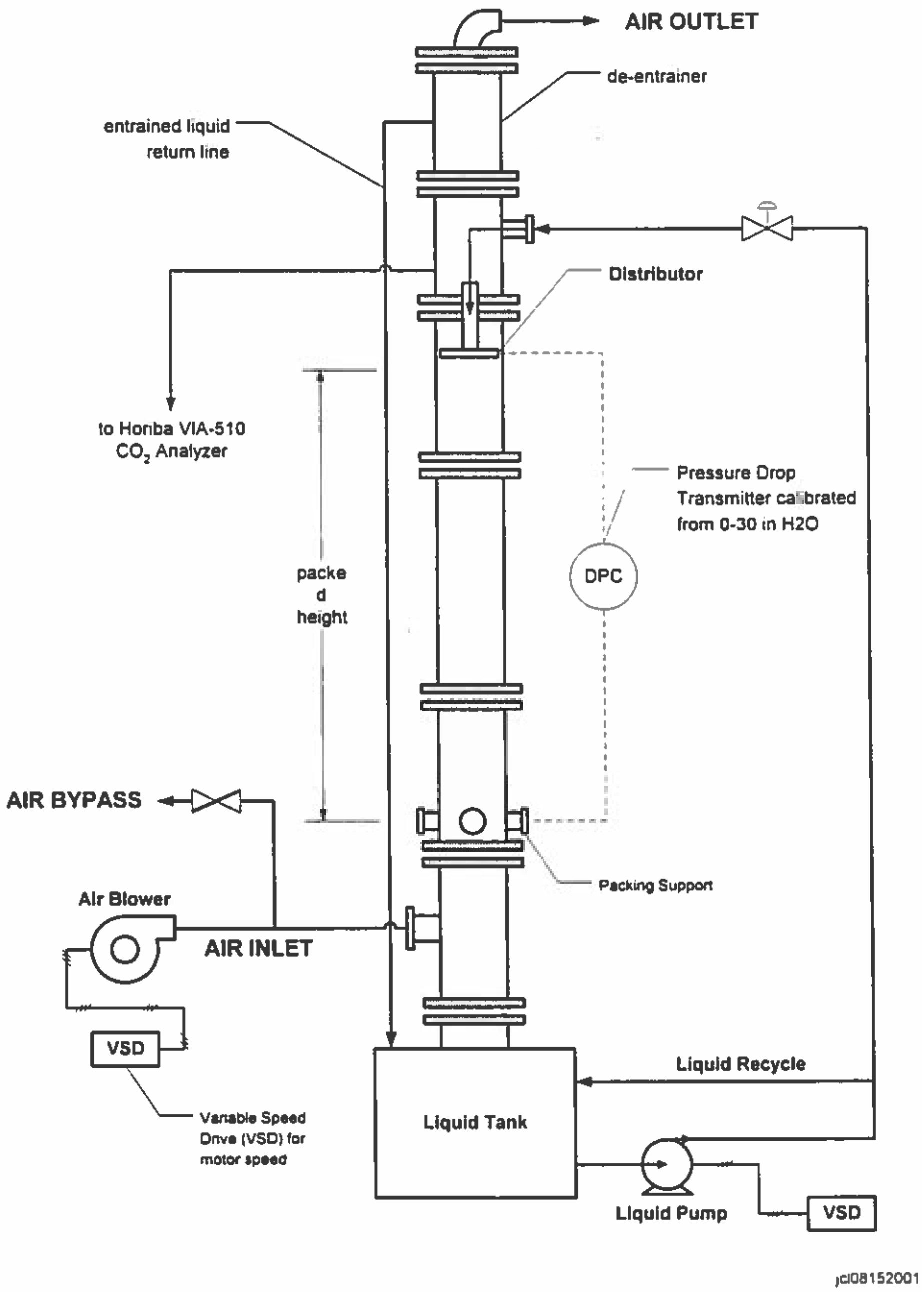


Figure 1. Mass Transfer Test Configuration

EXPERIMENTAL RESULTS

Tests were carried out at atmospheric pressure (14.7 psia) to evaluate the packed column mass transfer performance using four liquid distributors with the air/carbon dioxide/caustic test system. The mass transfer performance of each distributor is shown in Figures 3-6. The performance is shown to depend on the gas f-factor and liquid velocity (gpm/ft^2).

The gas f-factor is defined below.

$$f - \text{factor} = U_s \sqrt{\rho_v}$$

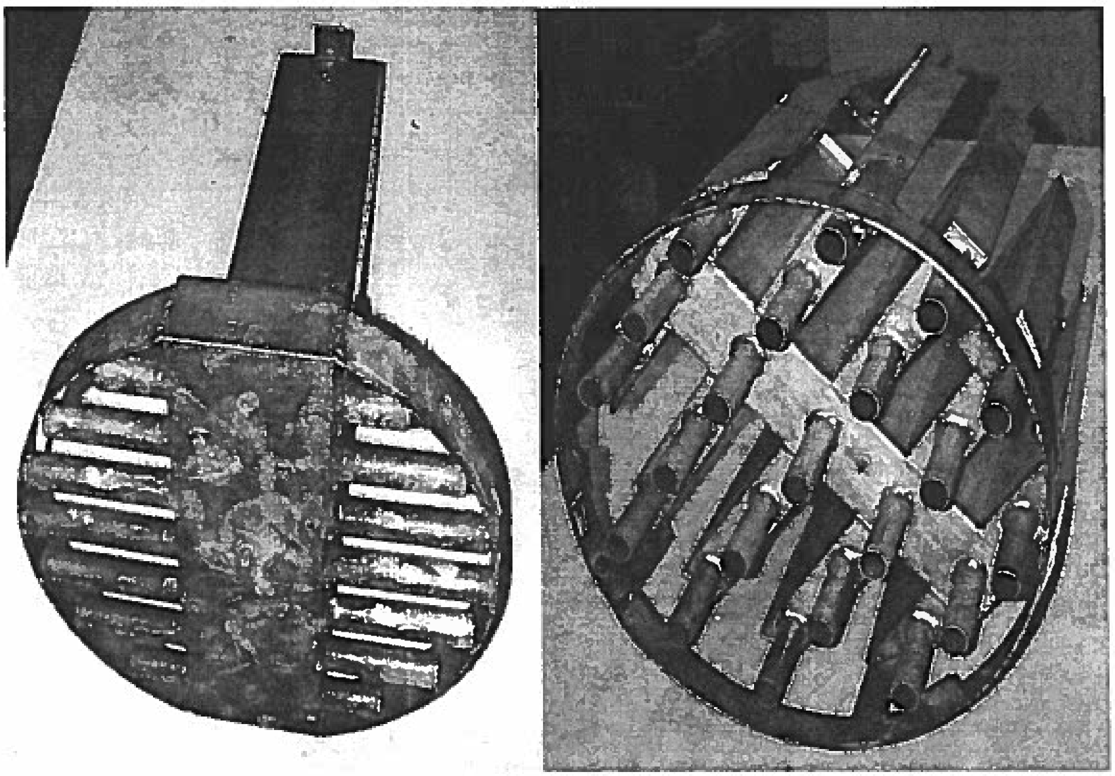
where U_s = superficial gas velocity, ft/sec
ρ_g = vapor density, lb/ft^3

The tests were generally carried out at a range of velocities (1 – 20 gpm/ft^2).

The physical properties of the air/carbon dioxide/caustic system are given in Table 1.

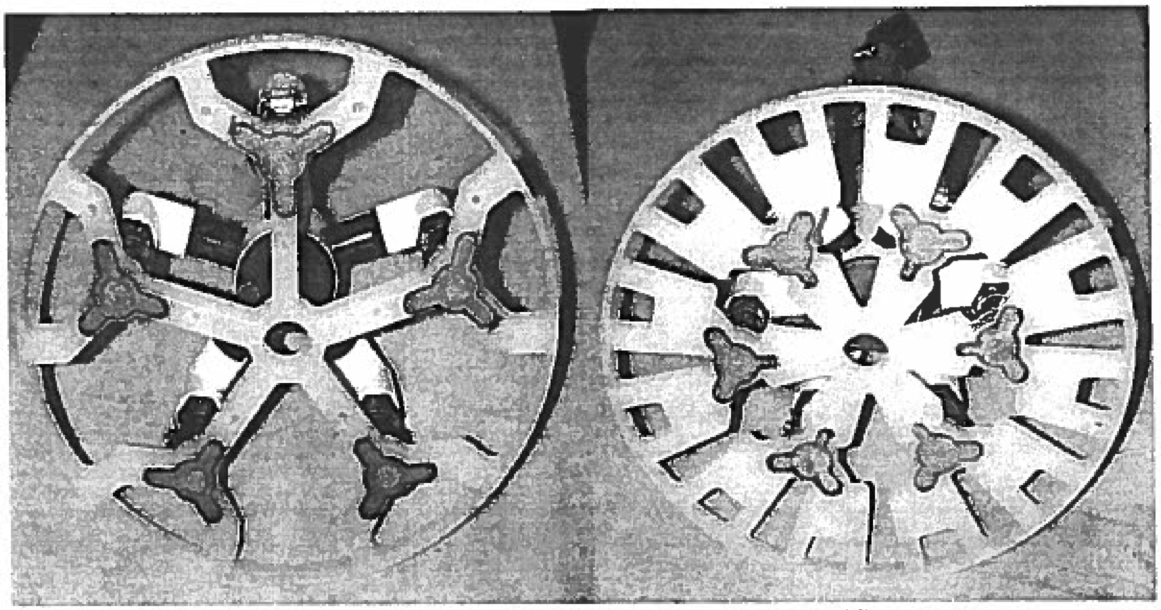
Table 2. Physical Properties of the Air/CO_2/Caustic System

Pressure (psia)	**14.7**
Liquid density, lb/ft^3	62.4
Liquid viscosity, cP	0.89
Vapor density, lb/ft^3	0.073
Vapor viscosity, cP	0.018
Surface tension, dynes/cm	72
Average Temperature, °F	85



(a) (b)

Figures 2a and b. Photographs of the Standard SRP Orifice Pipe Distributor with 40 pts/ft^2 (a) and the High Capacity Trough Drip Tube Distributor with 13.5 pts/ft^2 (b).



(c) (d)

Figures 2c and d. Photographs of the Fractal I 10 pts/ft^2 Distributor (c) and Fractal II 40 pts/ft^2 Distributor (d).

Mass transfer efficiencies were measured at a range of liquid rates (1 - 20 gpm/ft^2) and three air rates (180, 300 and 450 scfm). The upper range of the liquid rate was limited by the reduced capacity with the high surface area of the B1-500 packing. In addition, the mass transfer efficiencies at a range of liquid rates were measured at 0.75 in H_2O/ft of packing. The mass transfer efficiencies, shown as effective mass transfer area, are provided in Figures 3-6. The mass transfer efficiency was calculated from the following equations:

$$NTU_{og} = \ln\left(\frac{Y_{CO2,in}}{Y_{CO2,out}}\right)$$

where: $Y_{CO2,in}$ = carbon dioxide concentration in the inlet air, ppm
$Y_{CO2,out}$ = carbon dioxide concentration in the outlet air, ppm

$$HTU_{og} = \frac{Z_p}{NTU_{og}}$$

where: Z_p = packed height, ft

$$HTU_{og} = \frac{U_g}{\overline{K_{og}\,a}}$$

where $\overline{K_{og}\,a}$ lumps together chemical reaction, mass transfer coefficient, area and concentration.

U_g = Superficial velocity of the gas, ft/s

$$\overline{K_{og}\,a} = \frac{U_g}{HTU_{og}} = \frac{U_g}{\left(Z_p / NTU_{og}\right)}$$

The effective mass transfer area was estimated using the method given in Appendix A.5.

Figure 3. Mass Transfer Efficiency of the Standard SRP Orifice Distributor (40 pts/ft^2)

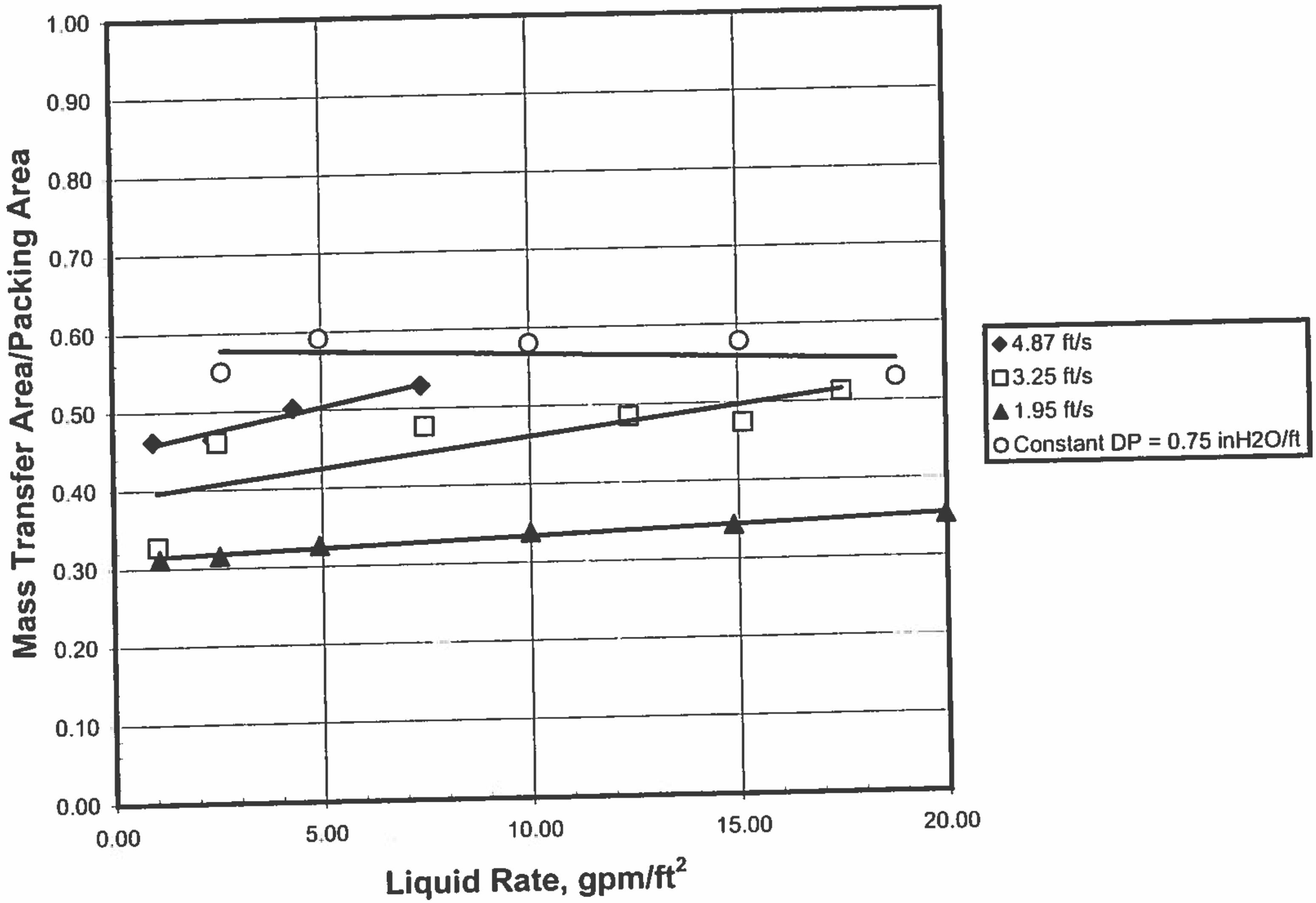


Figure 4. Mass Transfer Efficiency of the High Capacity Trough Drip Tube Distributor (13.5 pts/ft^2)

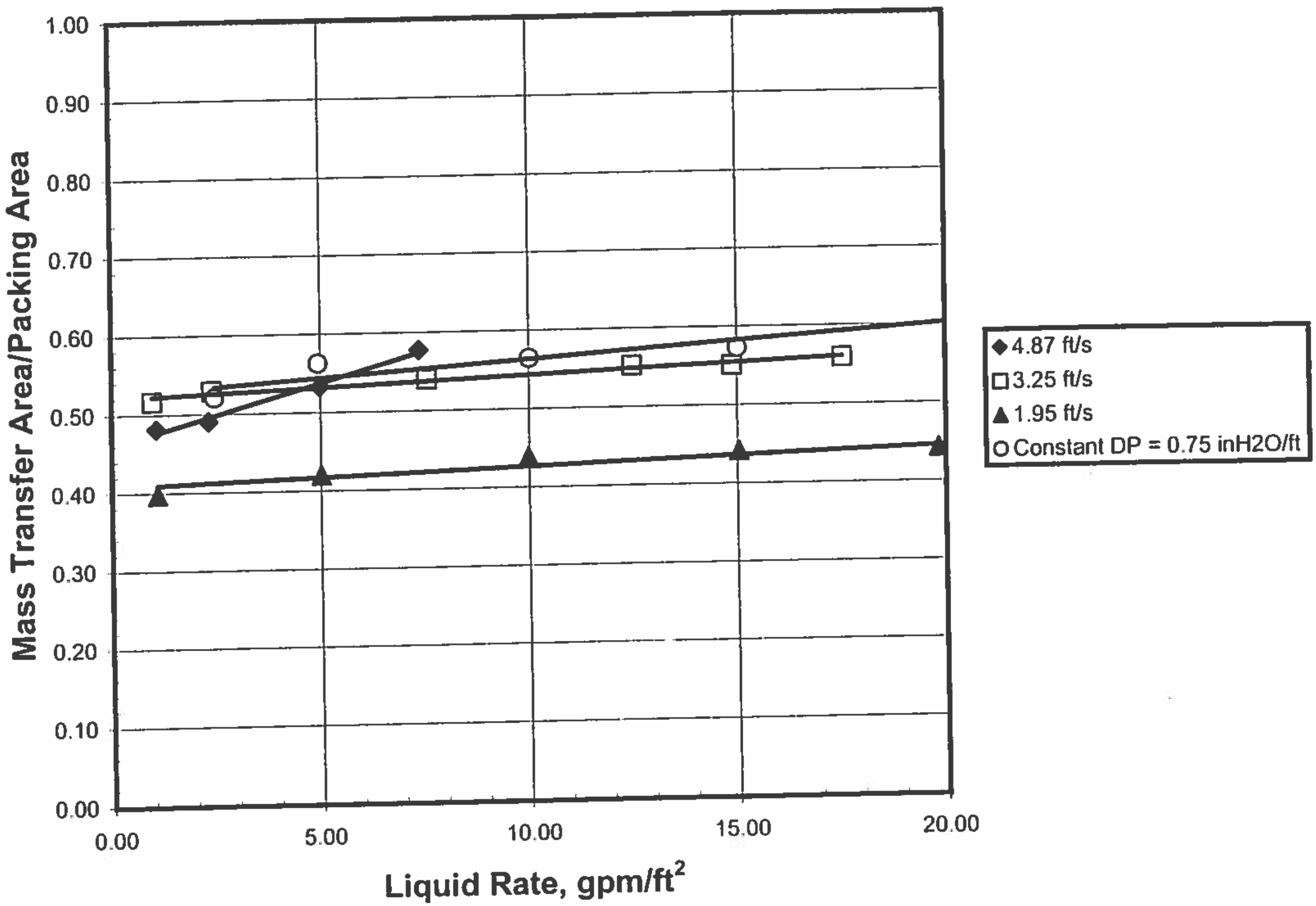


Figure 5. Mass Transfer Efficiency of the Fractal I Distributor (10 pts/ft^2)

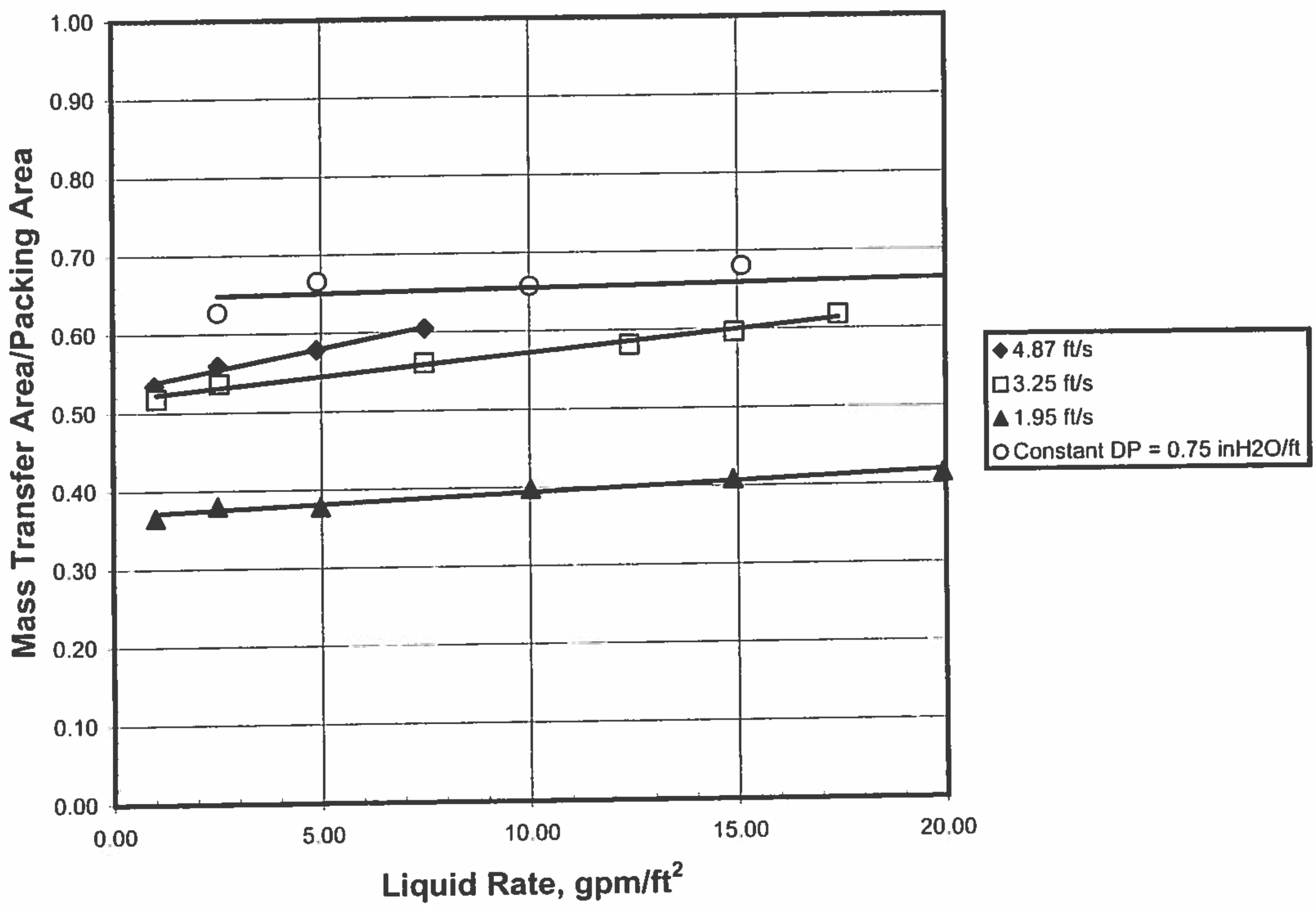
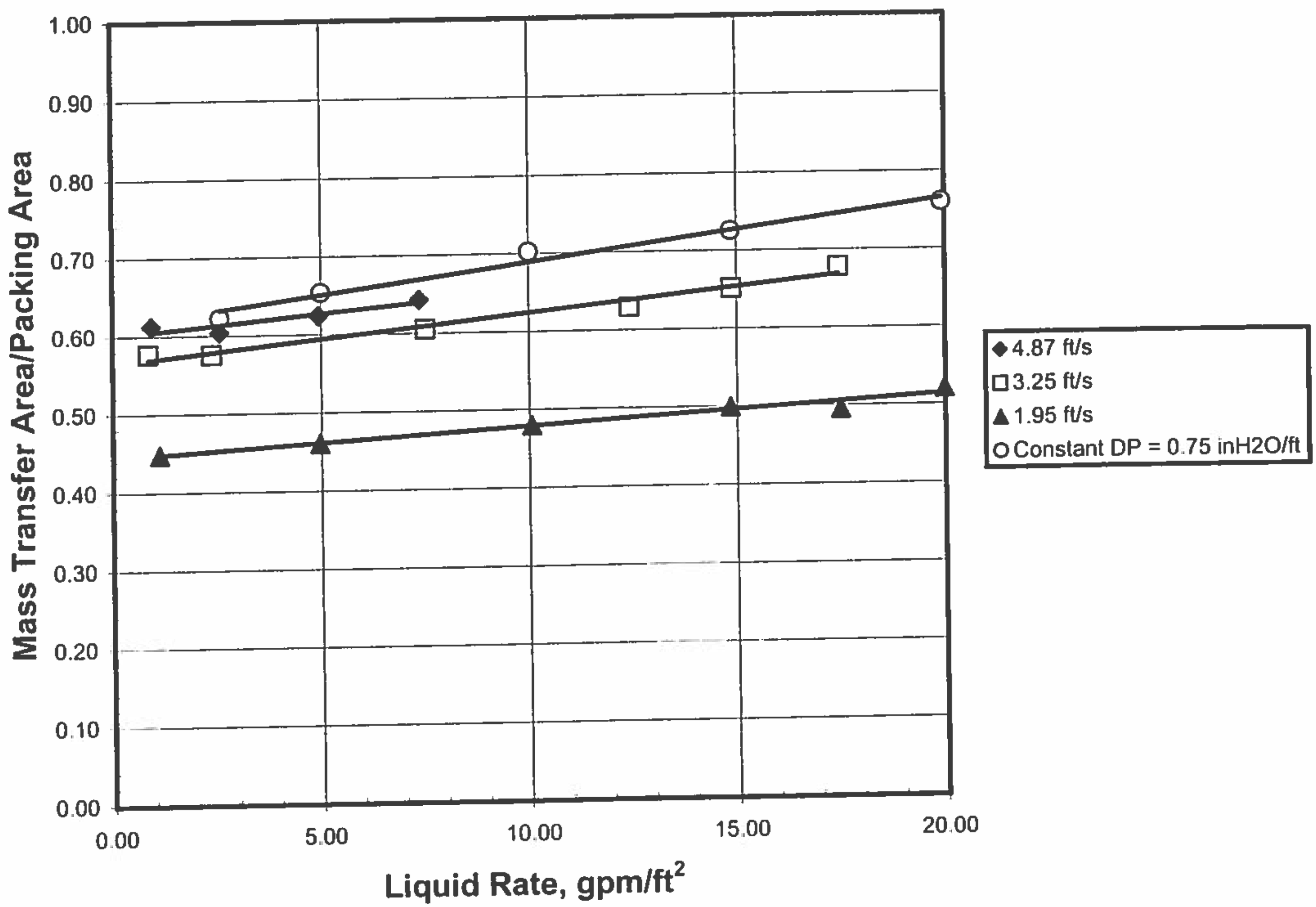


Figure 6. Mass Transfer Efficiency of the Fractal II Distributor (40 pts/ft^2)



ANALYSIS OF RESULTS

The mass transfer efficiency, expressed as the effective mass transfer area per available packing surface area, was observed to depend strongly on the gas f-factor. The increased gas velocity appears to assist in the liquid spreading and distribution. The efficiency was slightly dependent on liquid rate. In general for a given distribution point density, the Fractal distributors outperformed the orifice and trough drip tube distributors by approximately 20-30%. The performance of distributors are compared in Figures 7-12. The standard SRP orifice and high capacity trough drip tube distributors performed similarly.

The increasing slope of the fractional coverage with liquid rates indicates that additional improvements in distribution are possible.

Figure 7. Comparison of Distributors at an f-factor = 0.52 ft/s $(lb/ft^3)^{0.5}$

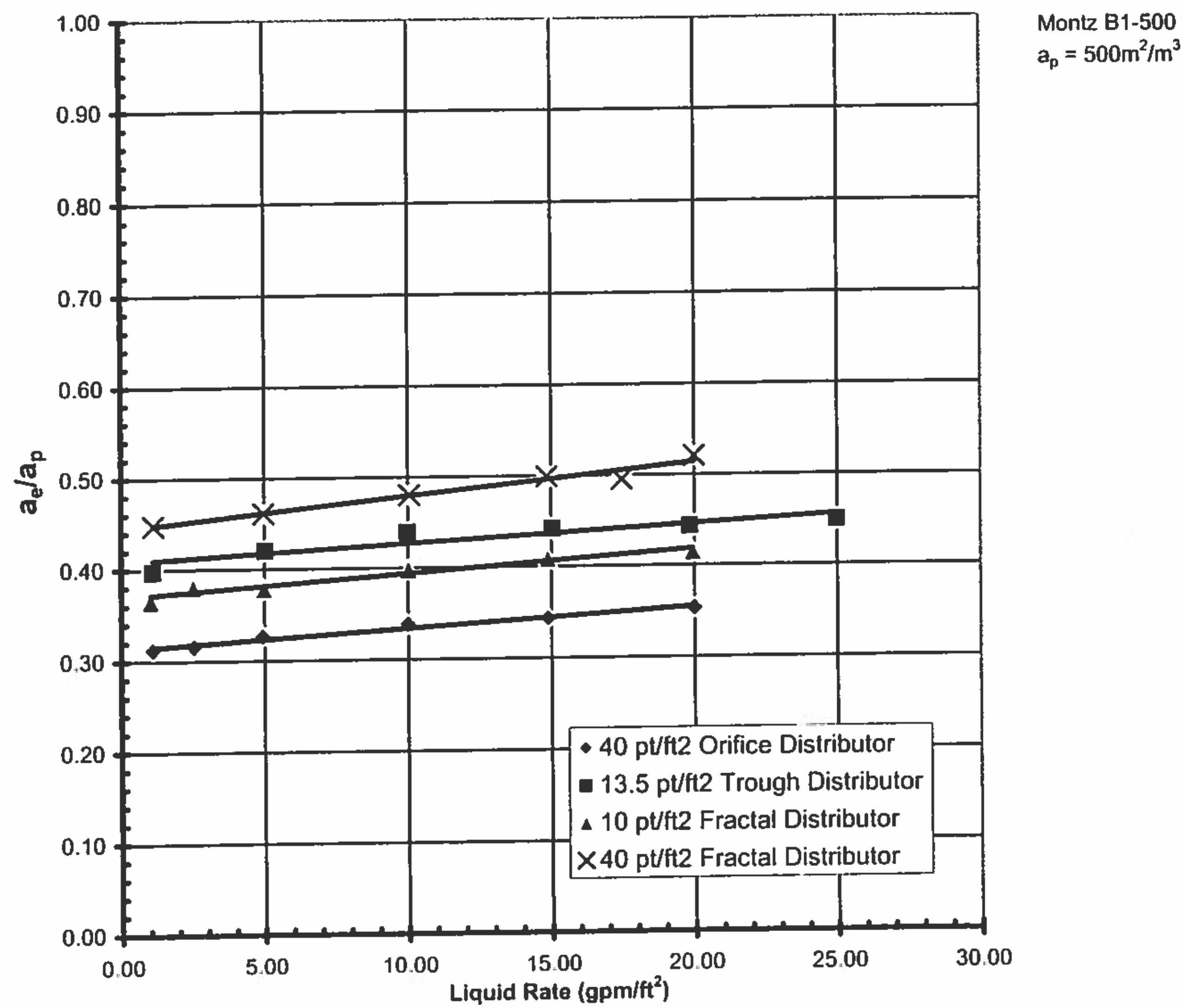


Figure 8. Comparison of Distributors at an f-factor = 0.86 ft/s $(lb/ft^3)^{0.5}$

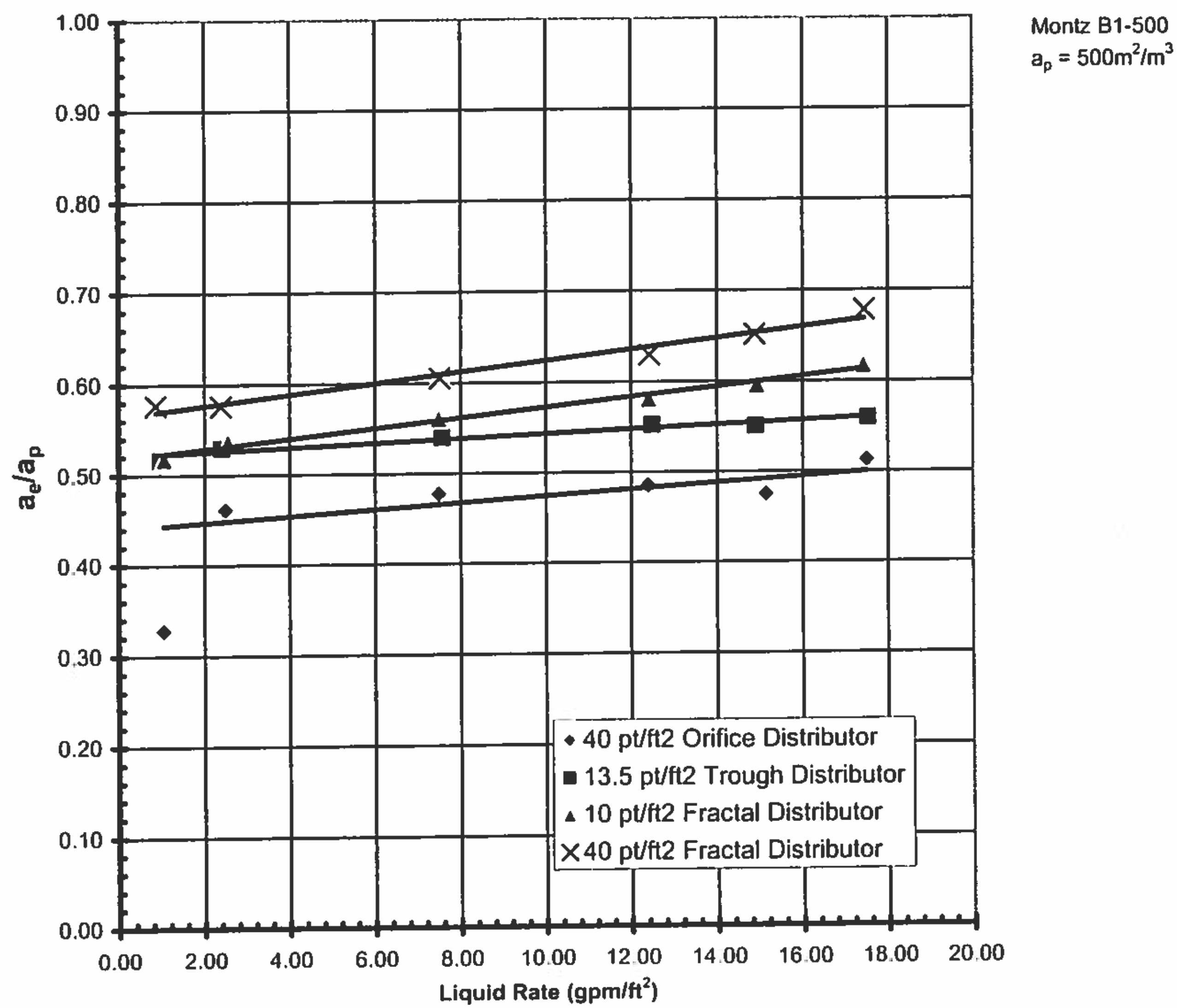


Figure 9. Comparison of Distributors at an f-factor = 1.29 ft/s $(lb/ft^3)^{0.5}$

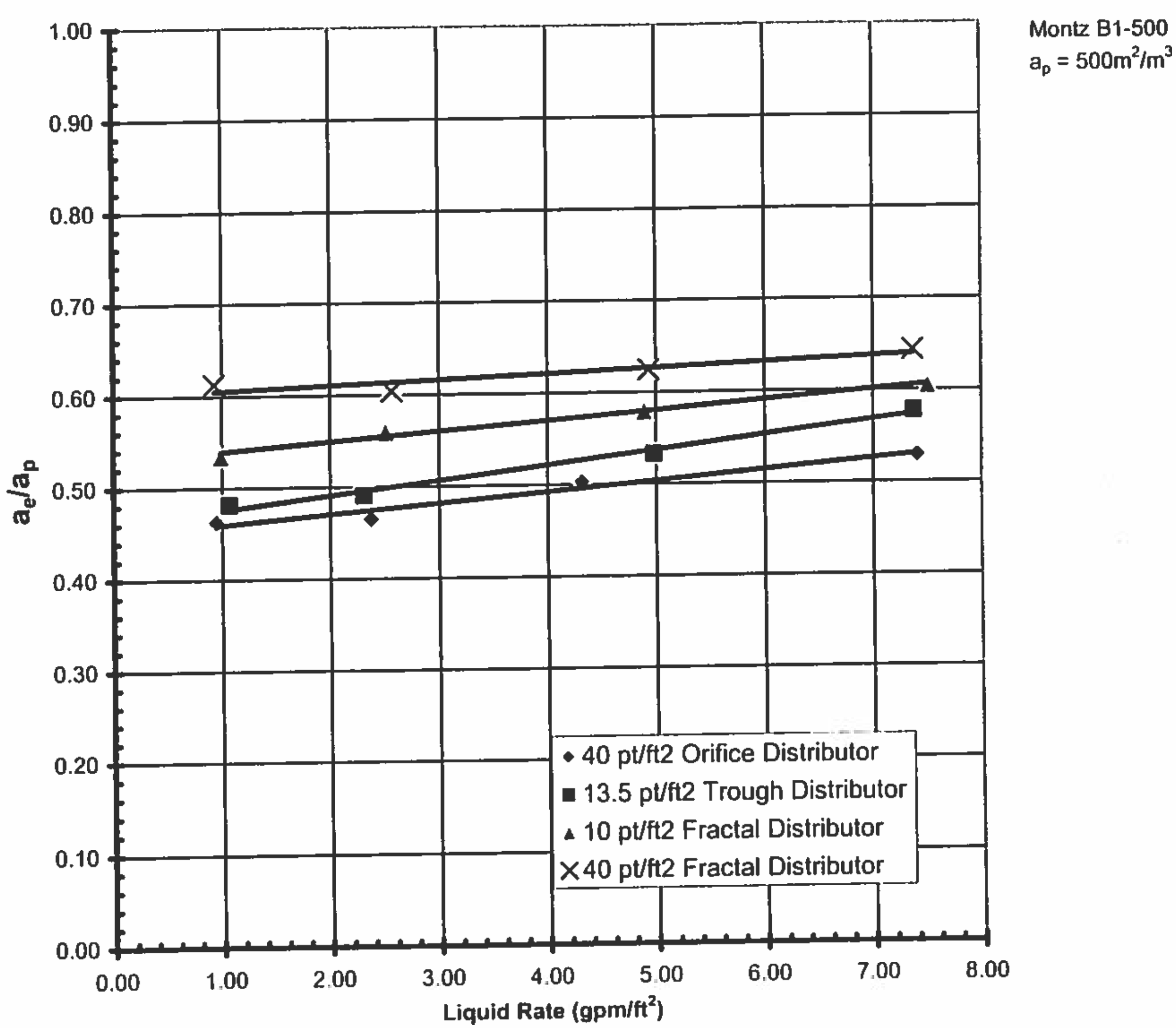
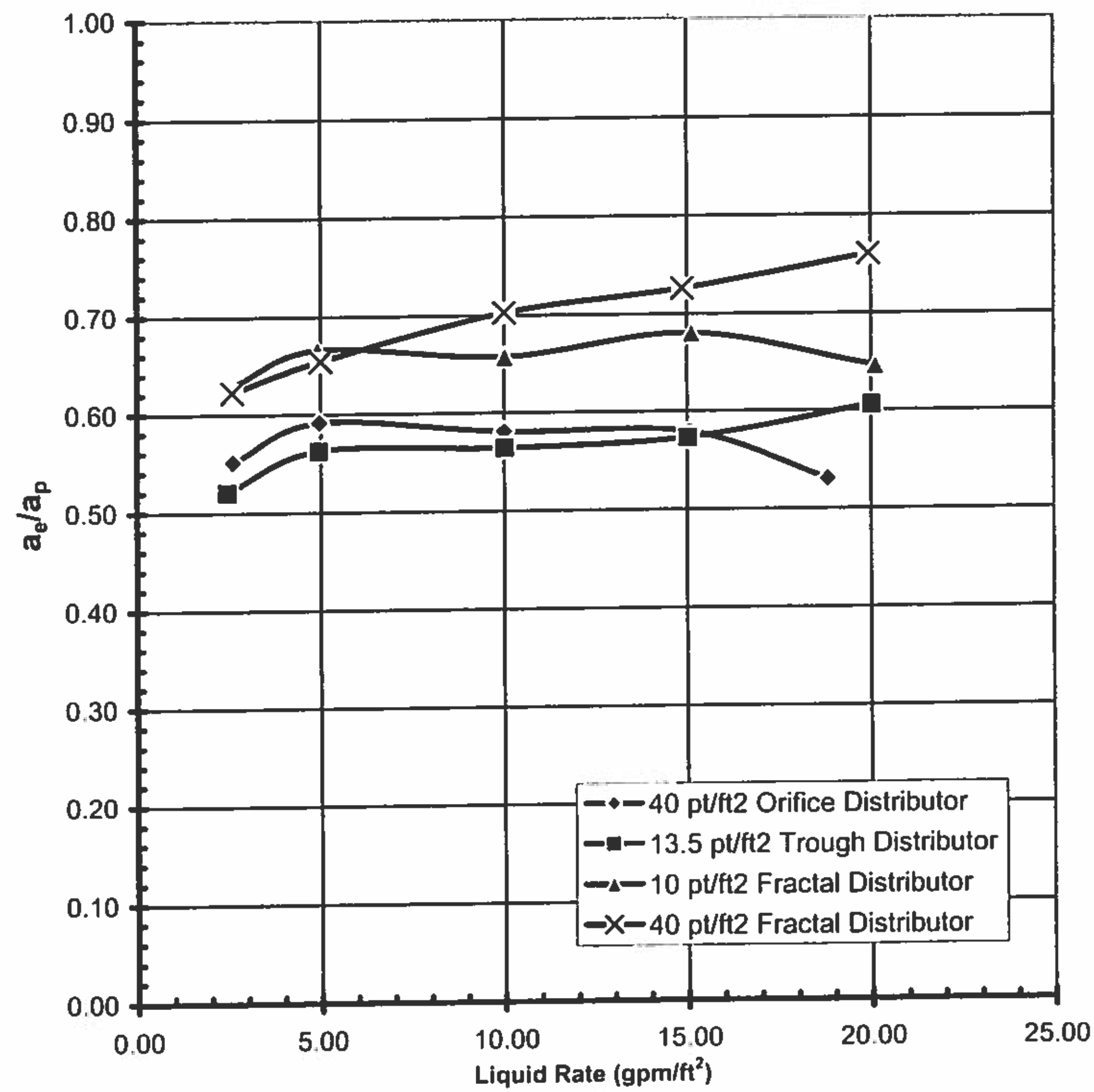
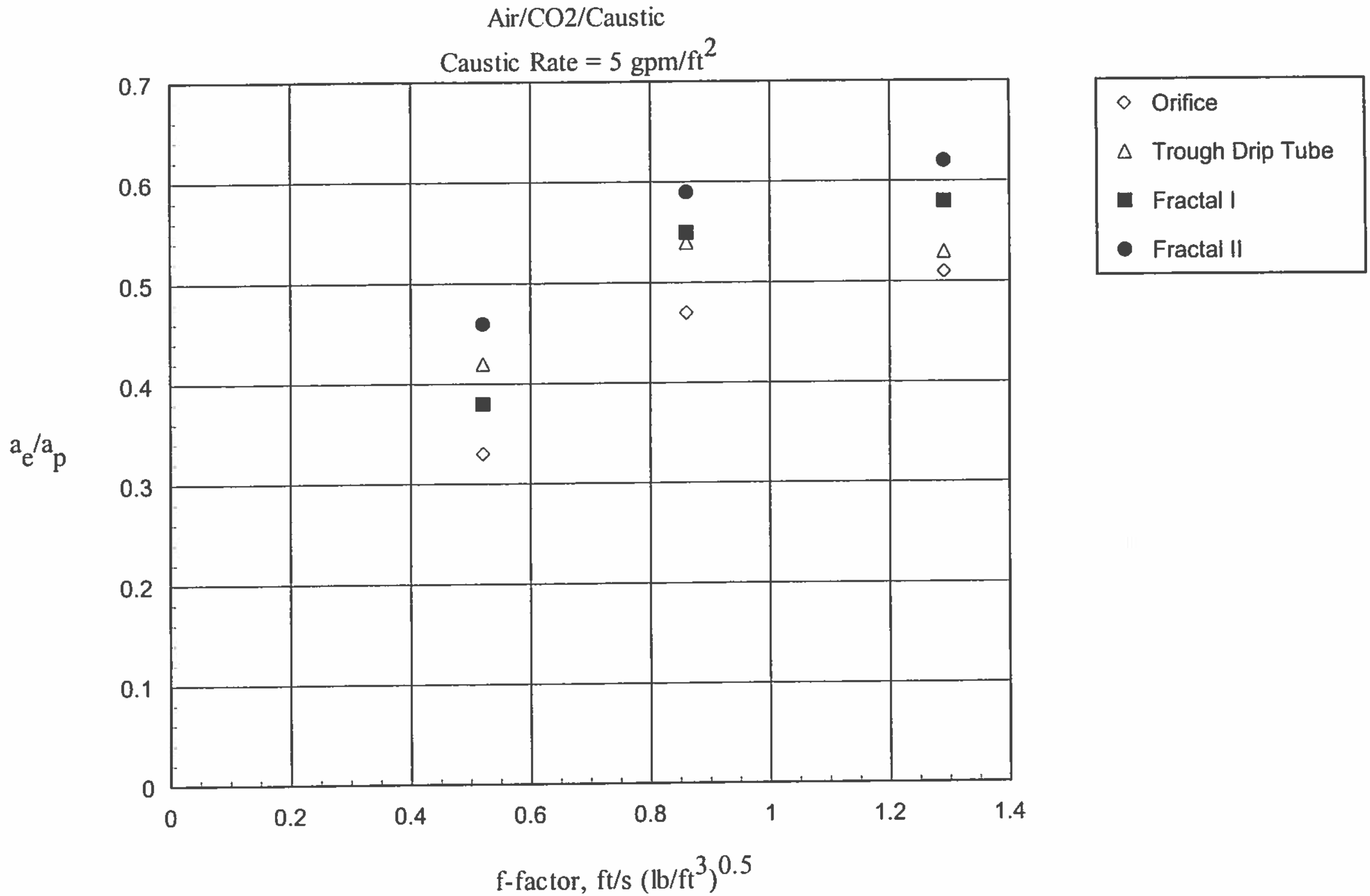


Figure 10. Comparison of Distributors at a Constant ΔP = 0.75 in H_2O/ft



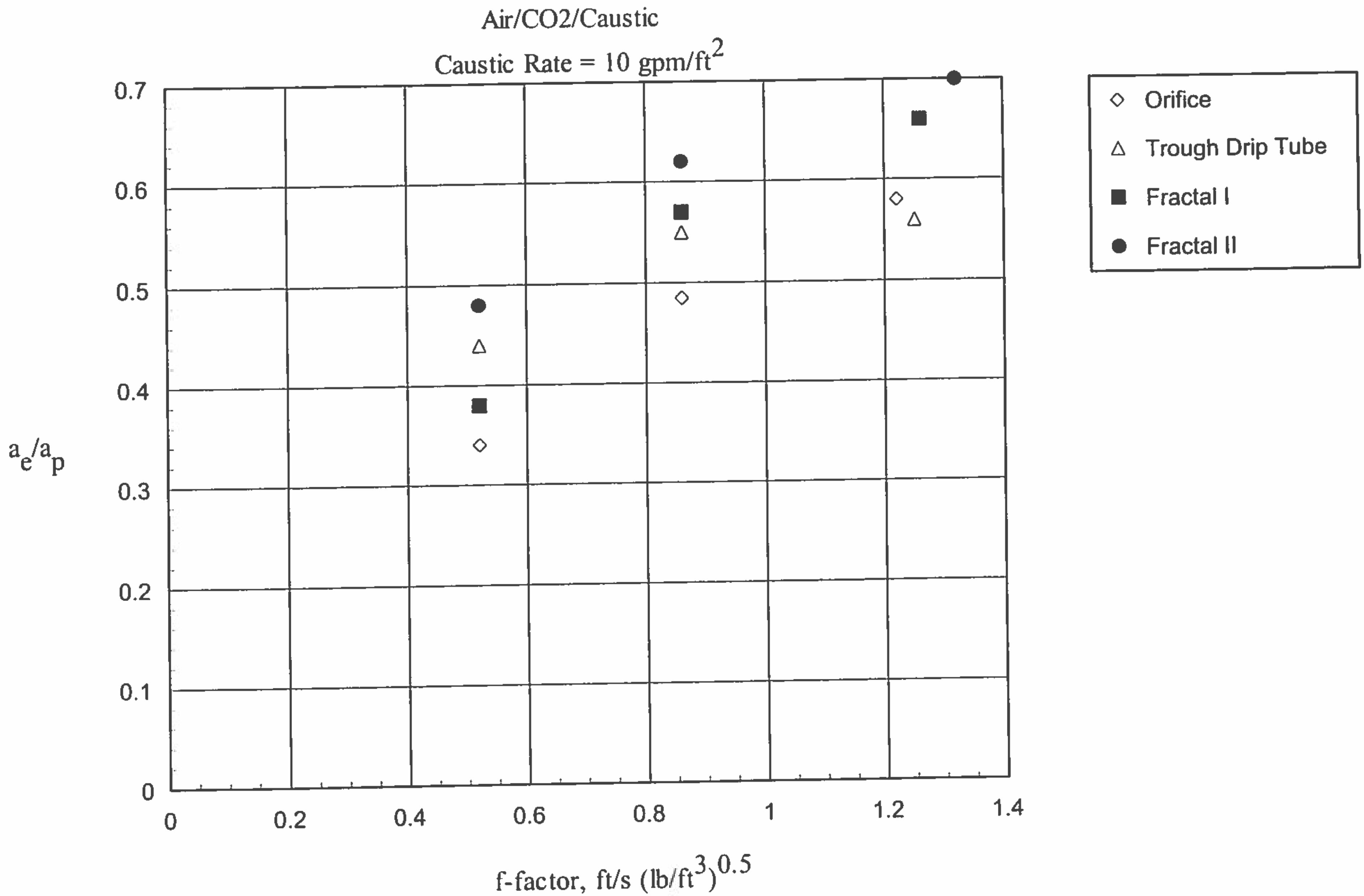
Constant Pressure Drop
ΔP = 0.75 inH_2O/ft Packing
f-factor = variable
Montz B1-500
a_p = 500m^2/m^3

Figure 11. Effect of Distributor Type and f-factor on the Mass Transfer Efficiency



* Some points are interpolated

Figure 12. Effect of Distributor Type and f-factor on the Mass Transfer Efficiency



* Some points are interpolated

CONCLUSIONS

For the tests described in this report, the mass transfer efficiency of the packings was found to depend on the type and geometry of the liquid distributor. The 40-point Fractal distributor was found to be superior to the others and was significantly better than the orifice distributor with the same (40) pour points. Notably , the 40-point Fractal distributor provided 6 to 20% greater effective surface than its 10-point counterpart, depending on gas and liquid flow rates.

The comparisons are given in terms of effective wetted surface. Since the same chemical system was being used for all tests, the enhancement of effective area should translate to an enhancement of the volumetric mass transfer coefficient ($K_{og}a$) and thus of the overall rate of mass transfer.

The data presented here are for unidirectional mass transfer, as in absorbers or strippers. Additional tests should be made under distillation conditions, where equimolar counter-diffusion prevails. It is quite possible that the same relative effects of the distributor will be observed.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge SRP technicians Steve Briggs and Robert Montgomery for their invaluable assistance during the study. The authors also acknowledge Ian Wilson, UT Chemical Engineering graduate student, for providing the detailed sodium hydroxide analysis for each run. We also acknowledge the assistance and consultation of Professor Gary Rochelle in establishing the techniques for the measurement of effective mass transfer area.

LIST OF APPENDICES

		Page
Appendix A.1.1	Mass Transfer Data for the Standard SRP Orifice Distributor (40 pts/ft^2), f-factor = 0.52 ft/s $(lb/ft^3)^{0.5}$	23
Appendix A.1.2	Mass Transfer Data for the Standard SRP Orifice Distributor (40 pts/ft^2), f-factor = 0.87 ft/s $(lb/ft^3)^{0.5}$	24
Appendix A.1.3	Mass Transfer Data for the Standard SRP Orifice Distributor (40 pts/ft^2), f-factor = 1.29 ft/s $(lb/ft^3)^{0.5}$	25
Appendix A.1.4	Mass Transfer Data for the Standard SRP Orifice Distributor (40 pts/ft^2), $\Delta P/Z_p$ = 0.75 in H_2O/ft	26
Appendix A.2.1	Mass Transfer Data for the High Capacity Trough Drip Tube Distributor (13.5 pts/ft^2), f-factor = 0.52 ft/s $(lb/ft^3)^{0.5}$	27
Appendix A.2.2	Mass Transfer Data for the High Capacity Trough Drip Tube Distributor (13.5 pts/ft^2), f-factor = 0.87 ft/s $(lb/ft^3)^{0.5}$	28
Appendix A.2.3	Mass Transfer Data for the High Capacity Trough Drip Tube Distributor (13.5 pts/ft^2), f-factor = 1.29 ft/s $(lb/ft^3)^{0.5}$	29
Appendix A.2.4	Mass Transfer Data for the High Capacity Trough Drip Tube Distributor (13.5 pts/ft^2), $\Delta P/Z_p$ = 0.75 in H_2O/ft	30
Appendix A.3.1	Mass Transfer Data for the Fractal I Distributor (10 pts/ft^2), f-factor = 0.52 ft/s $(lb/ft^3)^{0.5}$	31
Appendix A.3.2	Mass Transfer Data for the Fractal I Distributor (10 pts/ft^2), f-factor = 0.87 ft/s $(lb/ft^3)^{0.5}$	32
Appendix A.3.3	Mass Transfer Data for the Fractal I Distributor (10 pts/ft^2), f-factor = 1.29 ft/s $(lb/ft^3)^{0.5}$	33
Appendix A.3.4	Mass Transfer Data for the Fractal I Distributor (10 pts/ft^2), $\Delta P/Z_p$ = 0.75 in H_2O/ft	34
Appendix A.4.1	Mass Transfer Data for the Fractal II Distributor (40 pts/ft2), f-factor = 0.52 ft/s $(lb/ft^3)^{0.5}$	35

Appendix A.4.2 Mass Transfer Data for the Fractal II Distributor (40 pts/ft2), f-factor = 0.87 ft/s $(lb/ft^3)^{0.5}$ 36

Appendix A.4.3 Mass Transfer Data for the Fractal II Distributor (40 pts/ft2), f-factor = 1.29 ft/s $(lb/ft^3)^{0.5}$ 37

Appendix A.4.4 Mass Transfer Data for the Fractal II Distributor (40 pts/ft2), $\Delta P/Z_p$ = 0.75 in H_2O/ft 38

Appendix A.5 Procedure for Calculating Mass Transfer Area 39

APPENDIX A.1.1. Mass Transfer Data for the Standard SRP Orifice Distributor (40pts/ft^2). f-factor = 0.52 ft/s (lb/ft^3)$^{0.5}$

The Separations Research Program

packed height	118	inches	Packing:	Montz B1-500
f-factor	0.52	$(^{ft}/_{s})(^{lb}/_{ft^3})^{0.5}$		
$C_{initial}$	0.0900	N		
Tank Volume	300.00	gallons		
Hw	0.034	*gmole/L-atm*		
surface area/volume *	500	m^2/m^3		

* approximate

CONSTANTS Henry's Law Constant Calcs	h_i
Na^+	0.091
OH^-	0.066
HCO_3^- →	0.021
CO_3^{2-} →	
CO_2	-0.019

PROCESS DATA

run #	time	Water Flow FT901 (KPPH)	Air Flow FI900 (ACFM)	Pressure Drop PDT001 (in H_2O)	Air Press PT900 (PSIG)	Air In T900 (F)	Water In T901 (F)	Air Out T902 (F)	CO_2 In (ppm)	CO_2 Out (ppm)
1	10/30/02 13:40	15.40	179.7	2.01	0.03	97.08	94.92	100.42	386	84
2	10/30/02 13:47	11.47	180.1	1.31	0.02	96.82	94.51	100.11	386	86
3	10/30/02 13:54	7.70	180.0	1.08	0.02	96.31	94.14	100.71	386	89
4	10/30/02 14:06	3.80	179.5	0.88	0.02	95.60	93.48	102.36	386	97
5	10/30/02 14:22	1.94	180.9	0.70	0.01	94.70	92.65	101.55	386	107
6	10/30/02 14:38	0.84	180.0	0.65	0.01	93.47	91.78	100.82	386	113

RESULTS

run	$K_{OG}A$ (s^{-1})	NTU_{OG}	HTU_{OG} (ft)	K'_G	Effective Area (m^2/m^3)	Effective Area (ft^2/ft^3)	fractional area (ϕ)
1	0.302	1.527	6.438	6.62E-05	176.65	53.84	0.35
2	0.298	1.506	6.530	6.73E-05	171.70	52.33	0.34
3	0.290	1.463	6.722	6.63E-05	169.15	51.56	0.34
4	0.273	1.380	7.123	6.44E-05	163.26	49.76	0.33
5	0.256	1.284	7.658	6.26E-05	157.64	48.05	0.32
6	0.244	1.232	7.980	6.05E-05	155.98	47.54	0.31

HYDRAULIC CALCULATIONS

water velocity	f-factor $(^{ft}/_{s})(^{lb}/_{ft^3})^{0.5}$	Pressure Drop (inH_2O/ft packing)
19.98	0.52	0.205
14.88	0.52	0.133
9.99	0.52	0.110
4.93	0.52	0.089
2.52	0.52	0.071
1.08	0.52	0.066

MASS TRANSFER CALCULATIONS

Molar Concentration N	Ionic Concentration Na^+	OH^-	HCO_3^-	CO_3^{2-}	CO_2	Ionic Strength	Henry's Law Constant	Viscosity (cP)	Diffusivity (m^2/s)	Rate Constant	ρ_g
0.0900	0.09	0.0900	0.0000	0.0000	0.0000	0.0900	30.3970	0.9447	2.56E-09	17,558	0.03870
0.0890	0.09	0.0890		0.0010		0.0915	29.4118	0.9443	2.55E-09	17,279	0.03872
0.0880	0.09	0.0880		0.0020		0.0930	29.4118	0.9439	2.54E-09	17,031	0.03868
0.0860	0.09	0.0860		0.0040		0.0960	29.4118	0.9431	2.51E-09	16,599	0.03856
0.0850	0.09	0.0850		0.0050		0.0975	29.4118	0.9427	2.49E-09	16,062	0.03862
0.0830	0.09	0.0830		0.0070		0.1005	29.4118	0.9419	2.46E-09	15,528	0.03867

Values for molar concentration were measured before and after each gas rate by titration and TIC

APPENDIX A.1.2. Mass Transfer Data for the Standard SRP Orifice Distributor (40pts/ft^2). f-factor = 0.86 ft/s (lb/ft^3)$^{0.5}$

The Separations Research Program

packed height	118	inches	Packing:	Montz B1-500
f-factor	0.86	$(^{ft}/_{s})(^{lb}/_{ft^3})^{0.5}$		
$C_{initial}$	0.0800	N		
Tank Volume	300.00	gallons		
Hw	0.034	*gmole/L-atm*		
surface area/volume *	500	m^2/m^3		

* approximate

CONSTANTS	
Henry's Law Constant Calcs	
	h_i
Na^+	0.091
OH^-	0.066
HCO_3^- →	0.021
CO_3^{2-} →	(0.021)
CO_2	-0.019

PROCESS DATA

run #	time	Water Flow FT901 (KPPH)	Air Flow FI900 (ACFM)	Pressure Drp PDT901 (in H_2O)	Air Press PT900 (PSIG)	Air In T900 (F)	Water In T901 (F)	Air Out T902 (F)	CO_2 In (ppm)	CO_2 Out (ppm)
1	10/30/02 14:52	13.49	300.1	5.68	0.09	95.52	90.69	99.68	393	128
2	10/30/02 15:02	11.66	299.6	3.20	0.05	95.05	90.13	98.57	393	136
3	10/30/02 15:10	9.54	301.2	2.01	0.04	93.97	89.60	96.91	393	138
4	10/30/02 15:17	5.77	300.2	1.50	0.03	93.09	89.21	96.64	393	142
5	10/30/02 15:26	1.91	300.3	1.28	0.02	91.96	88.81	96.61	393	152
6	10/30/02 14.35	0.80	178.8	0.66	0.01	93.75	91.97	101.07	386	112

RESULTS

run	$K_{OG}A$ (s^{-1})	NTU_{OG}	HTU_{OG} (ft)	K'_G	Effective Area (m^2/m^3)	Effective Area (ft^2/ft^3)	fractional area (ϕ)
1	0.371	1.122	8.762	5.61E-05	256.24	78.10	0.51
2	0.350	1.062	9.258	5.72E-05	237.58	72.42	0.48
3	0.347	1.047	9.391	5.57E-05	242.55	73.93	0.49
4	0.336	1.016	9.680	5.48E-05	238.62	72.73	0.48
5	0.315	0.952	10.326	5.32E-05	230.69	70.31	0.46
6	0.243	1.237	7.948	5.74E-05	163.91	49.96	0.33

HYDRAULIC CALCULATIONS

water velocity ([illegible])	f-factor ([illegible])	Pressure Drop ([illegible] packing)
17.50	0.86	0.578
15.13	0.86	0.325
12.39	0.87	0.204
7.48	0.86	0.152
2.48	0.87	0.130
1.04	0.51	0.067

MASS TRANSFER CALCULATIONS

Molar Concentration N	Ionic Concentration Na^+	OH^-	HCO_3^-	CO_3^{2-}	CO_2	Ionic Strength	Henry's Law Constant	Viscosity (cP)	Diffusivity (m^2/s)	Rate Constant	ρ_g
0.0800	0.08	0.0800	0.0000	0.0000	0.0000	0.0800	30.2859	0.9406	2.42E-09	14,872	0.03875
0.0810	0.08	0.0810		-0.0010		0.0785	29.4118	0.9411	2.40E-09	14,547	0.03883
0.0790	0.08	0.0790		0.0010		0.0815	29.4118	0.9402	2.39E-09	14,241	0.03894
0.0780	0.08	0.0780		0.0020		0.0830	29.4118	0.9398	2.37E-09	14,024	0.03896
0.0750	0.08	0.0750		0.0050		0.0875	29.4118	0.9386	2.36E-09	13,799	0.03896
0.0740	0.08	0.0740		0.0060		0.0890	29.4118	0.9382	2.46E-09	15,639	0.03865

APPENDIX A.1.3. Mass Transfer Data for the Standard SRP Orifice Distributor (40 pts/ft^2). f-factor = 1.29 ft/s(lb/ft^3)$^{0.5}$

The Separations Research Program

packed height	118	inches	Packing:	Montz B1-500
f-factor	1.30	$(^{ft}/_{s})(^{lb}/_{ft^3})^{0.5}$		
$C_{initial}$	0.0720	N		
Tank Volume	300.00	gallons		
Hw	0.034	*gmole/L-atm*		
surface area/volume *	500	m^2/m^3		

CONSTANTS
Henry's Law Constant Calcs

	h_i
Na^+	0.091
OH^-	0.066
HCO_3^- →	0.021
CO_3^{2-} →	
CO_2	-0.019

PROCESS DATA

run #	time	Water Flow FT901	Air Flow FI900	Pressure Drp PDT901	Air Press PT900	Air In T900	Water In T901	Air Out T902	CO_2 In	CO_2 Out
		KPPH	(ACFM)	(in H_2O)	(PSIG)	(F)	(F)	(F)	ppm	ppm
1	10/30/02 15:52	5.70	448.3	5.71	0.10	96.29	86.81	94.03	393	203
2	10/30/02 16:00	3.33	450.9	3.85	0.07	94.98	86.28	92.31	393	212
3	10/30/02 16:09	1.83	451.8	3.18	0.06	91.92	85.66	91.29	393	225
4	10/30/02 16:15	0.73	447.8	2.97	0.06	89.84	85.19	87.40	393	228

RESULTS

run	$K_{OG}A$	NTU_{OG}	HTU_{OG}	K'_G	Effective Area	Effective Area	fractional area
	s^{-1}		ft		m^2/m^3	ft^2/ft^3	ϕ
1	0.325	0.658	14.934	4.81E-05	264.52	80.62	0.53
2	0.307	0.619	15.884	4.80E-05	251.34	76.61	0.50
3	0.277	0.557	17.666	4.68E-05	232.45	70.85	0.46
4	0.268	0.544	18.068	4.59E-05	231.42	70.54	0.46

HYDRAULIC CALCULATIONS

water velocity	f-factor	Pressure Drop
gpm/ft^2	$(^{ft}/_{s})(^{lb}/_{ft^3})^{0.5}$	$^{in H_2O}/_{ft}$ packing
7.40	1.29	0.581
4.32	1.30	0.392
2.37	1.30	0.323
0.95	1.29	0.302

MASS TRANSFER CALCULATIONS

Molar Concentration	Ionic Concentration					Ionic Strength	Henry's Law Constant	Viscosity	Diffusivity	Rate Constant	ρ_g
N	Na^+	OH^-	HCO_3^-	CO_3^{2-}	CO		$^{L\cdot atm}/_{gmol}$	cP	m^2/s	$^L/_{gmol\cdot s}$	$^{mol}/_{m^3}$
0.0720	0.07	0.0720	0.0000	0.0000	0.0000	0.0720	30.1974	0.9374	2.30E-09	12,739	0.03914
0.0700	0.07	0.0700		0.0020		0.0750	29.4118	0.9366	2.28E-09	12,474	0.03927
0.0690	0.07	0.0690		0.0030		0.0765	29.4118	0.9362	2.26E-09	12,163	0.03934
0.0680	0.07	0.0680		0.0040		0.0780	29.4118	0.9357	2.25E-09	11,936	0.03962

APPENDIX A.1.4. Mass Transfer Data for the Standard SRP Orifice Distributor (40 pts/ft2). $\Delta P/Z_p$ = 0.75 in H_2O/ft.

The Separations Research Program

RUN NUMBER 0

packed height	118	inches
f-factor	1.22	$(^{ft}/_s)(^{lb}/_{ft^3})^{0.5}$
$C_{initial}$	0.0650	N
Tank Volume	300.00	gallons
Hw	0.034	gmole/L-atm
surface area/volume *	500.000	m^2/m^3

* approximate

CONSTANTS	
Henry's Law Constant Calcs	
	h_i
Na^+	0.091
OH^-	0.066
HCO_3^-	0.021
CO_3^{2-}	(→ 0.021)
CO_2	-0.019

PROCESS DATA

run #	time	Water Flow FT901	Air Flow FI900	Pressure Drp PDT931	Air Press PT900	Air In T900	Water In T901	Air Out T902	CO_2 In	CO_2 Out
		KPPH	(ACFM)	(in H_2O)	(PSIG)	(F)	(F)	(F)	ppm	ppm
1	10/30/02 16:29	14.50	252.7	7.82	0.12	88.51	84.15	84.37	398	144
2	10/30/02 16:48	11.605	330.30	7.71	0.12	88.00	83.12	81.64	398	173
3	10/30/02 16:56	7.70	419.6	7.76	0.13	89.57	82.63	81.12	398	210
4	10/30/02 17:04	3.82	537.1	7.66	0.13	91.82	82.13	80.57	398	243
5	10/30/02 17:14	2.00	573.9	7.60	0.14	94.02	81.50	80.18	398	262

RESULTS

run	$K_{OG}A$	NTU_{OG}	HTU_{OG}	K'_G	Effective Area	Effective Area	fractional area
	s^{-1}		ft		m^2/m^3	ft^2/ft^3	ϕ
1	0.283	1.019	9.647	4.26E-05	264.97	80.76	0.53
2	0.302	0.830	11.840	4.18E-05	289.42	88.22	0.58
3	0.296	0.641	15.340	4.09E-05	290.20	88.45	0.58
4	0.292	0.495	19.875	3.97E-05	295.74	90.14	0.59
5	0.263	0.417	23.596	3.83E-05	275.69	84.03	0.55

HYDRAULIC CALCULATIONS

water velocity	f-factor	Pressure Drop
gpm/ft²	$(^{ft}/_s)(^{lb}/_{ft^3})^{0.5}$	in H₂O/ft packing
18.81	0.73	0.795
15.06	0.96	0.784
10.00	1.22	0.789
4.95	1.55	0.779
2.60	1.66	0.772

MASS TRANSFER CALCULATIONS

Molar Concentration	Ionic Concentration					Ionic Strength	Henry's Law Constant	Viscosity	Diffusivity	Rate Constant	ρ_g
N	Na^+	OH^-	HCO_3^-	CO_3^{2-}	CO_2			cP	m^2/s		
0.0650	0.07	0.0650	0.0000	0.0000	0.0000	0.0650	30.1201	0.9345	2.21E-09	11,445	0.03984
0.0630	0.07	0.0630		0.0020		0.0680	29.4118	0.9337	2.18E-09	10,974	0.04004
0.0620	0.07	0.0620		0.0030		0.0695	29.4118	0.9333	2.17E-09	10,758	0.04008
0.0600	0.07	0.0600		0.0050		0.0725	29.4118	0.9325	2.15E-09	10,543	0.04012
0.0580	0.07	0.0580		0.0070		0.0755	29.4118	0.9316	2.13E-09	10,273	0.04015

APPENDIX A.2.1. Mass Transfer Data for the High Capacity Trough Drip Tube Distributor (13.5 pts/ft^2). f-factor = 0.53 ft/s (lb/ft^3)$^{0.5}$

The Separations Research Program

packed height	118	inches	Packing:	Montz B1-500
f-factor	0.53	$(^{ft}/_{s})(^{lb}/_{ft^3})^{0.5}$		
$C_{initial}$	0.0890	N		
Tank Volume	300.00	gallons		
Hw	0.034	gmole/L-atm		
surface area/volume *	500	m^2/m^3		

* approximate

CONSTANTS Henry's Law Constant Calcs	h_i
Na^+	0.091
OH^-	0.066
HCO_3^- →	0.021
CO_3^{2-} →	
CO_2	-0.019

PROCESS DATA

run #	time	Water Flow FT901	Air Flow FI900	Pressure Drp PDT901	Air Press PT900	Air In T900	Water In T901	Air Out T902	CO_2 In	CO_2 Out
		KPPH	(ACFM)	(in H_2O)	(PSIG)	(F)	(F)	(F)	ppm	ppm
1	10/29/02 9:25	19.25	182.7	4.18	0.07	84.36	83.91	82.58	419	106
2	10/29/02 9:32	15.28	181.1	1.47	0.03	84.16	83.72	83.02	419	104
3	10/29/02 9:39	11.59	183.5	1.11	0.02	84.13	83.59	83.35	419	106
4	10/29/02 9:45	7.69	181.1	0.85	0.02	84.31	83.50	83.53	419	106
5	10/29/02 9:51	3.86	178.5	0.67	0.01	84.48	83.50	83.84	419	112
6	10/29/02 9:58	0.84	180.8	0.50	0.01	84.98	83.50	84.12	419	122

RESULTS

run	$K_{OG}A$	NTU_{OG}	HTU_{OG}	K'_G	Effective Area	Effective Area	fractional area
	s^{-1}		ft		m^2/m^3	ft^2/ft^3	Φ
1	0.276	1.373	7.162	4.91E-05	224.75	68.50	0.45
2	0.279	1.398	7.035	5.02E-05	221.69	67.57	0.44
3	0.277	1.370	7.176	5.00E-05	220.94	67.34	0.44
4	0.273	1.370	7.179	4.96E-05	219.64	66.95	0.44
5	0.260	1.323	7.432	4.93E-05	210.20	64.07	0.42
6	0.245	1.230	7.996	4.90E-05	198.88	60.62	0.40

HYDRAULIC CALCULATIONS

water velocity	f-factor	Pressure Drop
[illegible]	$(^{ft}/_{s})(^{lb}/_{ft^3})^{0.5}$	[illegible] packing
24.97	0.53	0.425
19.83	0.53	0.150
15.04	0.53	0.112
9.98	0.53	0.087
5.01	0.52	0.068
1.08	0.52	0.051

MASS TRANSFER CALCULATIONS

Molar Concentration	Ionic Concentration					Ionic Strength	Henry's Law Constant	Viscosity	Diffusivity	Rate Constant	ρ_g
N	Na^+	OH^-	HCO_3^-	CO_3^{2-}	CO_2		L-atm/gmole	cP	m^2/s	L/gmol·s	kg/m^3
0.0890	0.09	0.0890	0.0000	0.0000	0.0000	0.0890	30.3859	0.9443	2.21E-09	11,334	0.03997
0.0880	0.09	0.0880		0.0010		0.0905	29.4118	0.9439	2.20E-09	11,246	0.03994
0.0880	0.09	0.0880		0.0010		0.0905	29.4118	0.9439	2.20E-09	11,187	0.03991
0.0870	0.09	0.0870		0.0020		0.0920	29.4118	0.9435	2.19E-09	11,147	0.03990
0.0860	0.09	0.0860		0.0030		0.0935	29.4118	0.9431	2.19E-09	11,148	0.03988
0.0850	0.09	0.0850		0.0040		0.0950	29.4118	0.9427	2.19E-09	11,147	0.03986

Values for molar concentration were measured before and after each gas rate by titration and TIC

APPENDIX A.2.2. Mass Transfer Data for the High Capacity Trough Drip Tube Distributor. f-factor = 0.87 ft/s $(lb/ft^3)^{0.5}$

The Separations Research Program

packed height	118	inches	Packing:	Montz B1-500
f-factor	0.87	$(^{ft}/_{s})(^{lb}/_{ft^3})^{0.5}$		
$C_{initial}$	0.0810	N		
Tank Volume	300.00	gallons		
Hw	0.034	*gmole/L-atm*		
surface area/volume *	500	m^2/m^3		

* approximate

CONSTANTS Henry's Law Constant Calcs	h_i
Na^+	0.091
OH^-	0.066
HCO_3^- →	0.021
CO_3^{2-} →	
CO_2	-0.019

PROCESS DATA

run #	time	Water Flow FT001 KPPH	Air Flow FI000 (ACFM)	Pressure Drp PDT901 (in H_2O)	Air Press PT900 (PSIG)	Air In T900 (F)	Water In T901 (F)	Air Out T902 (F)	CO_2 In ppm	CO_2 Out ppm
1	10/29/02 10:29	13.50	299.5	3.42	0.06	88.59	82.77	83.57	396	150
2	10/29/02 10:35	11.48	303.4	2.09	0.04	88.35	82.72	83.94	396	151
3	10/29/02 10:41	9.62	302.7	1.57	0.03	87.90	82.64	84.38	396	151
4	10/29/02 10:47	5.83	298.5	1.21	0.03	87.96	82.68	84.38	396	153
5	10/29/02 10:54	1.84	301.3	0.97	0.02	87.93	82.69	85.28	396	158
6	10/29/02 11:01	0.74	300.1	0.93	0.02	88.06	82.63	85.43	396	162

RESULTS

run	$K_{OG}A$ (s^{-1})	NTU_{OG}	HTU_{OG} (ft)	K'_G	Effective Area (m^2/m^3)	Effective Area (ft^2/ft^2)	fractional area (ϕ)
1	0.319	0.968	10.154	4.55E-05	279.68	85.25	0.56
2	0.322	0.964	10.204	4.66E-05	275.53	83.98	0.55
3	0.320	0.961	10.228	4.62E-05	276.35	84.23	0.55
4	0.311	0.948	10.374	4.59E-05	270.18	82.35	0.54
5	0.304	0.917	10.726	4.56E-05	264.87	80.73	0.53
6	0.296	0.896	10.969	4.56E-05	258.38	78.75	0.52

HYDRAULIC CALCULATIONS

water velocity (gpm/ft²)	f-factor $(^{ft}/_{s})(^{lb}/_{ft^3})^{0.5}$	Pressure Drop in H_2O/ft packing
17.52	0.87	0.348
14.89	0.88	0.212
12.49	0.88	0.160
7.56	0.86	0.123
2.39	0.87	0.099
0.97	0.87	0.094

MASS TRANSFER CALCULATIONS

Molar Concentration N	Ionic Concentration Na^+	OH^-	HCO_3^-	CO_3^{2-}	CO_2	Ionic Strength	Henry's Law Constant (atm/(mol/L))	Viscosity cP	Diffusivity m^2/s	Rate Constant	k'_g
0.0810	0.08	0.0810	0.0000	0.0000	0.0000	0.0810	30.2970	0.9411	2.17E-09	10,820	0.03990
0.0800	0.08	0.0800		0.0010		0.0825	29.4118	0.9406	2.17E-09	10,800	0.03987
0.0790	0.08	0.0790		0.0020		0.0840	29.4118	0.9402	2.17E-09	10,762	0.03984
0.0780	0.08	0.0780		0.0030		0.0855	29.4118	0.9398	2.17E-09	10,781	0.03984
0.0770	0.08	0.0770		0.0040		0.0870	29.4118	0.9394	2.17E-09	10,786	0.03977
0.0770	0.08	0.0770		0.0040		0.0870	29.4118	0.9394	2.17E-09	10,757	0.03976

APPENDIX A.2.3. Mass Transfer Data for the High Capacity Trough Drip Tube Distributor. f-factor = 1.29 ft/s(lb/ft^3)$^{0.5}$

The Separations Research Program

packed height	118	inches	Packing:	Montz B1-500
f-factor	1.29	$(^{ft}/_s)(^{lb}/_{ft^3})^{0.5}$		
$C_{initial}$	0.0690	N		
Tank Volume	300.00	gallons		
Hw	0.034	gmole/L-atm		
surface area/volume *	500	m^2/m^3		

CONSTANTS Henry's Law Constant Calcs	h_i
Na^+	0.091
OH^-	0.066
HCO_3^- →	0.021
CO_3^{2-} →	
CO_2	-0.019

PROCESS DATA

run #	time	Water Flow FT901 KPPH	Air Flow FI900 (ACFM)	Pressure Drp PDT901 (in H_2O)	Air Press PT900 (PSIG)	Air In T900 (F)	Water In T901 (F)	Air Out T902 (F)	CO_2 In ppm	CO_2 Out ppm
1	10/29/02 11:37	5.68	450.9	4.50	0.08	96.63	82.52	84.26	391	212
2	10/29/02 11:46	3.84	448.5	3.35	0.07	95.18	82.57	85.21	391	219
3	10/29/02 12:14	1.78	449.2	2.91	0.06	95.62	82.56	88.32	391	230
4	10/29/02 12:08	0.82	450.4	2.65	0.06	94.97	82.60	87.74	391	233

RESULTS

run	$K_{OG}A$ (s^{-1})	NTU_{OG}	HTU_{OG} (ft)	K_G	Effective Area (m^2/m^3)	Effective Area (ft^2/ft^3)	fractional area (φ)
1	0.304	0.612	16.061	4.19E-05	288.73	88.00	0.58
2	0.286	0.580	16.952	4.27E-05	266.41	81.20	0.53
3	0.263	0.532	18.471	4.24E-05	245.41	74.80	0.49
4	0.256	0.517	19.005	4.22E-05	240.93	73.43	0.48

HYDRAULIC CALCULATIONS

water velocity ($^{gpm}/_{ft^2}$)	f-factor $(^{ft}/_s)(^{lb}/_{ft^3})^{0.5}$	Pressure Drop ($^{in H_2O}/_{ft}$ packing)
7.37	1.30	0.458
4.98	1.29	0.341
2.31	1.29	0.296
1.07	1.30	0.269

MASS TRANSFER CALCULATIONS

Molar Concentration N	Ionic Concentration Na^+	OH^-	HCO_3^-	CO_3^{2-}	CO_2	Ionic Strength	Henry's Law Constant	Viscosity cP	Diffusivity (m^2/s)	Rate Constant	ρ_g
0.0690	0.07	0.0690	0.0000	0.0000	0.0000	0.0690	30.1642	0.9362	2.16E-09	10,711	0.03985
0.0680	0.07	0.0680		0.0010		0.0705	29.4118	0.9357	2.17E-09	10,733	0.03978
0.0670	0.07	0.0670		0.0020		0.0720	29.4118	0.9353	2.17E-09	10,728	0.03955
0.0660	0.07	0.0660		0.0030		0.0735	29.4118	0.9349	2.17E-09	10,747	0.03959

APPENDIX A.2.4. Mass Transfer Data for the High Capacity Trough Drip Tube Distributor. $\Delta P/Z_p$ = 0.75 in H_2O/ft.

The Separations Research Program — RUN NUMBER 0

packed height	118	inches
f-factor	1.26	$(^{ft}/_s)(^{lb}/_{ft^3})^{0.5}$
$C_{initial}$	0.0580	N
Tank Volume	300.00	gallons
Hw	0.034	gmole/L-atm
surface area/volume *	500.000	m^2/m^3

* approximate

CONSTANTS Henry's Law Constant Calcs	h_i
Na^+	0.091
OH^-	0.066
HCO_3^-	0.021
CO_3^{2-}	
CO_2	-0.019

PROCESS DATA

run #	time	Water Flow FT901 KPPH	Air Flow FI900 (ACFM)	Pressure Drop PDT901 (in H_2O)	Air Press PT900 (PSIG)	Air In T900 (F)	Water In T901 (F)	Air Out T902 (F)	CO_2 In ppm	CO_2 Out ppm
1	10/29/02 12:56	15.42	294.4	7.77	0.12	99.08	83.75	90.36	386	150
2	10/29/02 13:25	11.573	348.72	7.60	0.12	100.89	84.43	92.35	386	180
3	10/29/02 13:42	7.72	437.0	7.85	0.13	102.42	84.64	92.78	386	214
4	10/29/02 14:00	3.81	535.4	7.66	0.14	105.67	84.63	95.46	386	243
5	10/29/02 14:11	1.89	583.0	7.97	0.15	108.39	84.77	96.38	386	260

RESULTS

run	$K_{OG}A$ (s^{-1})	NTU_{OG}	HTU_{OG} (ft)	K'_G	Effective Area (m^2/m^3)	Effective Area (ft^2/ft^3)	fractional area (ϕ)
1	0.307	0.947	10.380	3.99E-05	303.01	92.36	0.61
2	0.292	0.762	12.904	4.01E-05	286.48	87.32	0.57
3	0.284	0.591	16.625	3.96E-05	282.10	85.99	0.56
4	0.274	0.465	21.165	3.80E-05	281.28	85.73	0.56
5	0.255	0.397	24.775	3.81E-05	260.30	79.34	0.52

HYDRAULIC CALCULATIONS

water velocity	f-factor $(^{ft}/_s)(^{lb}/_{ft^3})^{0.5}$	Pressure Drop in H_2O/ft packing
20.01	0.85	0.790
15.02	1.00	0.773
10.01	1.25	0.798
4.95	1.53	0.779
2.45	1.66	0.810

MASS TRANSFER CALCULATIONS

Molar Concentration N	Ionic Concentration Na^+	OH^-	HCO_3^-	CO_3^{2-}	CO_2	Ionic Strength	Henry's Law Constant	Viscosity cP	Diffusivity m^2/s	Rate Constant	D_g
0.0580	0.06	0.0580	0.0000	0.0000	0.0000	0.0580	30.0430	0.9316	2.20E-09	11,259	0.03940
0.0540	0.06	0.0540		0.0040		0.0640	29.4118	0.9300	2.22E-09	11,575	0.03926
0.0520	0.06	0.0520		0.0060		0.0670	29.4118	0.9292	2.23E-09	11,674	0.03923
0.0480	0.06	0.0480		0.0100		0.0730	29.4118	0.9275	2.23E-09	11,670	0.03904
0.0480	0.06	0.0480		0.0100		0.0730	29.4118	0.9275	2.23E-09	11,733	0.03898

APPENDIX A.3.1. Mass Transfer Data for the Fractal I Distributor (10 pts/ft^2). f-factor = 0.52 ft/s (lb/ft^3)$^{0.5}$

The Separations Research Program

packed height	118	inches	Packing:	Montz B1-500
f-factor	0.53	$(^{ft}/_s)(^{lb}/_{ft^3})^{0.5}$		
$C_{initial}$	0.0910	N		
Tank Volume	300.00	gallons		
Hw	0.034	*gmole/L-atm*		
surface area/volume *	500	m^2/m^3		

* approximate

CONSTANTS	
Henry's Law Constant Calcs	
	f_i
Na^+	0.091
OH^-	0.066
HCO_3^- →	0.021
CO_3^{2-} →	(0.021)
CO_2	-0.019

PROCESS DATA

run #	time	Water Flow FT901	Air Flow FI900	Pressure Drp PDT901	Air Press PT900	Air In T900	Water In T901	Air Out T902	CO_2 In	CO_2 Out
		KPPH	(ACFM)	(in H_2O)	(PSIG)	(F)	(F)	(F)	ppm	ppm
1	10/31/02 16:47	15.36	179.7	3.02	0.05	76.67	85.18	78.93	400	105
2	10/31/02 16:53	11.47	179.6	1.55	0.02	75.60	84.65	78.74	400	105
3	10/31/02 17:01	7.72	179.8	1.29	0.02	74.72	84.00	78.12	400	112
4	10/31/02 17:12	3.84	179.1	1.06	0.02	73.97	83.18	77.33	400	123
5	10/31/02 17:19	1.93	183.3	0.92	0.01	73.63	82.65	76.85	400	129
6	10/31/02 17:28	0.78	182.1	0.89	0.01	73.28	82.06	76.59	400	137

RESULTS

run	$K_{OG}A$	NTU_{OG}	HTU_{OG}	K'_G	Effective Area	Effective Area	fractional area
	s^{-1}		ft		m^2/m^3	ft^2/ft^3	Φ
1	0.265	1.339	7.346	5.14E-05	207.43	63.23	0.41
2	0.264	1.336	7.358	5.21E-05	204.32	62.28	0.41
3	0.251	1.270	7.745	5.09E-05	199.11	60.69	0.40
4	0.232	1.177	8.357	4.95E-05	189.26	57.69	0.38
5	0.228	1.132	8.688	4.85E-05	190.30	58.00	0.38
6	0.215	1.071	9.184	4.74E-05	182.95	55.76	0.37

HYDRAULIC CALCULATIONS

water velocity	f-factor	Pressure Drop
[illegible]	$(^{ft}/_s)(^{lb}/_{ft^3})^{0.5}$	[illegible]/ft packing
19.94	0.53	0.307
14.88	0.53	0.157
10.02	0.53	0.131
4.98	0.52	0.108
2.50	0.54	0.093
1.01	0.53	0.090

MASS TRANSFER CALCULATIONS

Molar Concentration	Ionic Concentration					Ionic Strength	Henry's Law Constant	Viscosity	Diffusivity	Rate Constant	ρ_g
N	Na^+	OH^-	HCO_3^-	CO_3^{2-}	CO_2		[illegible]	cP	m^2/s	[illegible]	[illegible]
0.0910	0.09	0.0910	0.0000	0.0000	0.0000	0.0910	30.4082	0.9451	2.25E-09	11,932	0.04024
0.0900	0.09	0.0900		0.0010		0.0925	29.4118	0.9447	2.23E-09	11,676	0.04025
0.0890	0.09	0.0890		0.0020		0.0940	29.4118	0.9443	2.21E-09	11,376	0.04030
0.0880	0.09	0.0880		0.0030		0.0955	29.4118	0.9439	2.18E-09	11,003	0.04036
0.0870	0.09	0.0870		0.0040		0.0970	29.4118	0.9435	2.17E-09	10,769	0.04040
0.0860	0.09	0.0860		0.0050		0.0985	29.4118	0.9431	2.15E-09	10,514	0.04042

Values for molar concentration were measured before and after each gas rate by titration and TIC

APPENDIX A.3.2. Mass Transfer Data for the Fractal I Distributor (10 pts/ft^2). f-factor = 0.86 ft/s (lb/ft^3)$^{0.5}$

The Separations Research Program

packed height	118	inches	Packing:	Montz B1-500
f-factor	0.88	$(^{ft}/_s)(^{lb}/_{ft^3})^{0.5}$		
$C_{initial}$	0.0840	N		
Tank Volume	300.00	gallons		
Hw	0.034	gmole/L-atm		
surface area/volume *	500	m^2/m^3		

* approximate

CONSTANTS	
Henry's Law Constant Calcs	
	f_i
Na^+	0.091
OH^-	0.066
HCO_3^- →	0.021
CO_3^{2-} →	(0.021)
CO_2	-0.019

PROCESS DATA

run #	time	Water Flow FT001	Air Flow FI900	Pressure Drp PDT901	Air Press FT900	Air In T900	Water In T901	Air Out T902	CO_2 In	CO_2 Out
		KPPH	(ACFM)	(in H_2O)	(PSIG)	(F)	(F)	(F)	ppm	ppm
1	10/31/02 17:41	13.43	298.0	5.59	0.09	76.17	80.87	75.97	400	144
2	10/31/02 17:53	11.50	300.3	3.54	0.06	75.37	80.04	75.18	400	152
3	10/31/02 18:01	9.56	300.5	2.28	0.04	74.20	79.51	74.31	400	158
4	10/31/02 18:07	5.77	300.4	1.68	0.03	73.36	79.15	73.90	400	166
5	10/31/02 18:12	1.96	299.9	1.43	0.02	72.76	78.90	73.52	400	173
6	10/31/02 18:20	0.81	298.1	1.39	0.02	72.12	78.43	72.90	400	181

RESULTS

run	$K_{OG}A$	NTU_{OG}	HTU_{OG}	K'_G	Effective Area	Effective Area	fractional area
	s^{-1}		ft		m^2/m^3	ft^2/ft^3	φ
1	0.335	1.023	9.612	4.40E-05	308.76	94.11	0.62
2	0.320	0.969	10.153	4.35E-05	298.14	90.87	0.60
3	0.307	0.928	10.595	4.29E-05	290.58	88.57	0.58
4	0.291	0.881	11.158	4.22E-05	280.57	85.52	0.56
5	0.277	0.838	11.731	4.19E-05	268.56	81.86	0.54
6	0.260	0.793	12.405	4.08E-05	259.22	79.01	0.52

HYDRAULIC CALCULATIONS

water velocity	f-factor	Pressure Drop
$^{gpm}/_{ft^2}$	$(^{ft}/_s)(^{lb}/_{ft^3})^{0.5}$	$^{inH_2O}/_{ft}$ packing
17.42	0.87	0.568
14.92	0.88	0.360
12.41	0.88	0.231
7.49	0.88	0.171
2.55	0.88	0.146
1.05	0.87	0.141

MASS TRANSFER CALCULATIONS

Molar Concentration	Ionic Concentration					Ionic Strength	Henry's Law Constant	Viscosity	Diffusivity	Rate Constant	ρ_g
N	Na^+	OH^-	HCO_3^-	CO_3^{2-}	CO_2		$^{L \cdot atm}/_{gmol}$	cP	m^2/s	$^{L}/_{gmol \cdot s}$	$^{m^3}/_{m^3}$
0.0840	0.08	0.0840	0.0000	0.0000	0.0000	0.0840	30.3303	0.9423	2.11E-09	10,013	0.04046
0.0810	0.08	0.0810		0.0030		0.0885	29.4118	0.9411	2.09E-09	9,675	0.04052
0.0810	0.08	0.0810		0.0030		0.0885	29.4118	0.9411	2.07E-09	9,469	0.04059
0.0800	0.08	0.0800		0.0040		0.0900	29.4118	0.9406	2.06E-09	9,330	0.04062
0.0800	0.08	0.0800		0.0040		0.0900	29.4118	0.9406	2.05E-09	9,231	0.04065
0.0780	0.08	0.0780		0.0060		0.0930	29.4118	0.9398	2.04E-09	9,056	0.04070

APPENDIX A.3.3. Mass Transfer Data for the Fractal I Distributor (10 pts/ft^2). f-factor = 1.29 ft/s (lb/ft^3)$^{0.5}$

The Separations Research Program

packed height	118	inches	Packing	Montz B1-500
f-factor	1.31	$(^{ft}/_{s})(^{lb}/_{ft^3})^{0.5}$		
$C_{initial}$	0.0760	N		
Tank Volume	300.00	gallons		
Hw	0.034	gmole/L-atm		
surface area/volume *	500	m^2/m^3		

CONSTANTS	
Henry's Law Constant Calcs	
	h_i
Na^+	0.091
OH^-	0.066
HCO_3^- →	0.021
CO_3^{2-} →	
CO_2	-0.019

PROCESS DATA

		Water Flow FT901	Air Flow FI900	Pressure Drp PDT901	Air Press PT900	Air In T900	Water In T901	Air Out T902	CO_2 In	CO_2 Out
run #	time	KPPH	(ACFM)	(in H_2O)	(PSIG)	(F)	(F)	(F)	ppm	ppm
1	10/31/02 18:32	5.78	448.6	5.54	0.09	77.68	77.42	72.80	400	225
2	10/31/02 18:40	3.77	450.2	3.72	0.07	77.34	76.91	72.37	400	231
3	10/31/02 18:45	1.93	449.7	3.18	0.06	77.02	76.62	72.27	400	236
4	10/31/02 18:58	0.76	449.4	2.96	0.06	76.59	75.90	71.89	400	246

RESULTS

run	$K_{OG}A$	NTU_{OG}	HTU_{OG}	K'_G	Effective Area	Effective Area	fractional area
	s^{-1}		ft		m^2/m^3	ft^2/ft^3	ϕ
1	0.283	0.573	17.156	3.81E-05	302.40	92.17	0.60
2	0.273	0.550	17.868	3.84E-05	289.59	88.27	0.58
3	0.261	0.528	18.624	3.80E-05	279.94	85.32	0.56
4	0.240	0.485	20.295	3.65E-05	267.48	81.53	0.53

HYDRAULIC CALCULATIONS

water velocity	f-factor	Pressure Drop
	$(^{ft}/_{s})(^{lb}/_{ft^3})^{0.5}$	$^{inH_2O}/_{ft}$ packing
7.50	1.31	0.563
4.89	1.32	0.378
2.51	1.32	0.323
0.99	1.31	0.301

MASS TRANSFER CALCULATIONS

Molar Concentration	Ionic Concentration					Ionic Strength	Henry's Law Constant	Viscosity	Diffusivity	Rate Constant	ρ_g
N	Na^+	OH^-	HCO_3^-	CO_3^{2-}	CO_2			cP	m^2/s		
0.0760	0.08	0.0760	0.0000	0.0000	0.0000	0.0760	30.2416	0.9390	2.01E-09	8,683	0.04070
0.0750	0.08	0.0750		0.0010		0.0775	29.4118	0.9386	2.00E-09	8,501	0.04074
0.0750	0.08	0.0750		0.0010		0.0775	29.4118	0.9386	1.99E-09	8,398	0.04074
0.0720	0.08	0.0720		0.0040		0.0820	29.4118	0.9374	1.97E-09	8,151	0.04077

APPENDIX A.3.4. Mass Transfer Data for the Fractal I Distributor (10 pts/ft^2). $\Delta P/Z_p$ = 0.75 in H_2O/ft

The Separations Research Program

packed height	118	inches	Packing:	Montz B1-500
f-factor	1.26	$(^{ft}/_s)(^{lb}/_{ft^3})^{0.5}$		
$C_{initial}$	0.0700	N		
Tank Volume	300.00	gallons		
Hw	0.034	gmole/L-atm		
surface area/volume *	500.000	m^2/m^3		

* approximate

CONSTANTS Henry's Law Constant Calcs	h_i
Na^+	0.091
OH^-	0.066
HCO_3^-	→ 0.021
CO_3^{2-}	→ 0.021
CO_2	-0.019

PROCESS DATA

run #	time	Water Flow FT901 KPPH	Air Flow FI900 (ACFM)	Pressure Drp PDT901 (in H_2O)	Air Press PT900 (PSIG)	Air In T900 (F)	Water In T901 (F)	Air Out T902 (F)	CO_2 In ppm	CO_2 Out ppm
1	10/31/02 19:17	15.50	266.7	7.32	0.11	75.40	75.01	71.34	400	159
2	10/31/02 19:25	11.644	336.40	7.87	0.12	77.31	74.78	71.27	400	184
3	10/31/02 19:35	7.72	431.9	6.96	0.11	79.46	74.43	71.22	400	225
4	10/31/02 19:43	3.79	538.2	7.29	0.13	82.51	74.19	71.24	400	254
5	10/31/02 19:50	1.93	583.9	7.28	0.13	84.83	73.98	71.20	400	270

RESULTS

run	$K_{OG}A$ (s^{-1})	NTU_{OG}	HTU_{OG} (ft)	K'_G	Effective Area (m^2/m^3)	Effective Area (ft^2/ft^3)	fractional area (ϕ)
1	0.271	0.922	10.661	3.42E-05	322.82	98.40	0.65
2	0.287	0.774	12.705	3.44E-05	340.19	103.69	0.68
3	0.274	0.577	17.056	3.40E-05	328.62	100.16	0.66
4	0.270	0.455	21.604	3.31E-05	332.96	101.49	0.67
5	0.252	0.393	25.027	3.29E-05	313.72	95.62	0.63

HYDRAULIC CALCULATIONS

water velocity (gpm/ft^2)	f-factor $(^{ft}/_s)(^{lb}/_{ft^3})^{0.5}$	Pressure Drop (in H_2O/ft packing)
20.11	0.78	0.745
15.11	0.99	0.800
10.01	1.26	0.707
4.92	1.57	0.742
2.51	1.70	0.740

MASS TRANSFER CALCULATIONS

Molar Concentration N	Ionic Concentration Na^+	OH^-	HCO_3^-	CO_3^{2-}	CO_2	Ionic Strength	Henry's Law Constant (L atm/gmole)	Viscosity cP	Diffusivity m^2/s	Rate Constant (L/gmol s)	ρ_g (mol/m^3)
0.0700	0.07	0.0700	0.0000	0.0000	0.0000	0.0700	30.1753	0.9366	1.94E-09	7,853	0.04082
0.0680	0.07	0.0680		0.0020		0.0730	29.4118	0.9357	1.93E-09	7,778	0.04082
0.0680	0.07	0.0680		0.0020		0.0730	29.4118	0.9357	1.92E-09	7,665	0.04082
0.0650	0.07	0.0650		0.0050		0.0775	29.4118	0.9345	1.92E-09	7,587	0.04082
0.0650	0.07	0.0650		0.0050		0.0775	29.4118	0.9345	1.91E-09	7,520	0.04083

APPENDIX A.4.1. Mass Transfer Data for the Fractal II Distributor (40 pts/ft^2). f-factor = 0.52 ft/s (lb/ft^3)$^{0.5}$

The Separations Research Program

packed height	118	inches	Packing: Montz B1-500
f-factor	0.53	$(^{ft}/_s)(^{lb}/_{ft^3})^{0.5}$	
C_{total}	0.1000	N	
Tank Volume	300.00	gallons	
Hw	0.034	gmole/L-atm	
surface area/volume *	500	m^2/m^3	

* approximate

CONSTANTS	
Henry's Law Constant Calcs	
	l_i
Na^+	0.091
OH^-	0.066
HCO_3^- →	0.021
CO_3^{2-} →	
CO_2	-0.019

PROCESS DATA

run #	time	Water Flow FT901 KPPH	Air Flow FI900 (ACFM)	Pressure Drp PDT901 (in H_2O)	Air Press PT900 (PSIG)	Air In T900 (F)	Water In T901 (F)	Air Out T902 (F)	CO_2 In ppm	CO_2 Out ppm
1	11/4/02 15:36	15.40	179.2	1.90	0.03	62.04	71.49	65.02	390	131
2	11/4/02 15:42	13.47	177.7	1.59	0.02	61.95	71.25	64.97	390	135
3	11/4/02 15:48	11.44	179.4	1.44	0.02	61.90	70.98	64.85	390	137
4	11/4/02 15:54	7.75	180.4	1.26	0.02	61.70	70.70	64.78	390	144
5	11/4/02 16:00	3.83	180.9	1.10	0.02	61.44	70.48	64.63	390	152
6	11/4/02 16:05	0.86	181.3	0.95	0.01	61.28	70.15	64.47	390	158

RESULTS

run	$K_{OG}A$ (s^{-1})	NTU_{OG}	HTU_{OG} (ft)	K'_G	Effective Area (m^2/m^3)	Effective Area (ft^2/ft^3)	fractional area (ϕ)
1	0.215	1.089	9.029	3.41E-05	260.26	79.33	0.52
2	0.208	1.064	9.243	3.47E-05	247.50	75.44	0.49
3	0.207	1.048	9.382	3.43E-05	249.56	76.07	0.50
4	0.197	0.994	9.891	3.40E-05	239.92	73.13	0.48
5	0.187	0.940	10.458	3.36E-05	230.52	70.26	0.46
6	0.180	0.903	10.886	3.33E-05	224.12	68.31	0.45

HYDRAULIC CALCULATIONS

water velocity (gpm/ft^2)	f-factor $(^{ft}/_s)(^{lb}/_{ft^3})^{0.5}$	Pressure Drop ($in H_2O/ft$ packing)
19.98	0.53	0.193
17.48	0.53	0.161
14.84	0.53	0.146
10.06	0.53	0.128
4.97	0.54	0.112
1.12	0.54	0.097

MASS TRANSFER CALCULATIONS

Molar Concentration N	Ionic Concentration Na^+	OH^-	HCO_3^-	CO_3^{2-}	CO_2	Ionic Strength	Henry's Law Constant ($L \cdot atm/gmole$)	Viscosity cP	Diffusivity m^2/s	Rate Constant ($L/gmol \cdot s$)	ρ_g
0.0860	0.09	0.0860	0.0000	0.0000	0.0000	0.0860	30.3526	0.9431	1.84E-09	6,770	0.04131
0.0850	0.09	0.0850		0.0010		0.0875	29.4118	0.9427	1.83E-09	6,698	0.04131
0.0840	0.09	0.0840		0.0020		0.0890	29.4118	0.9423	1.83E-09	6,625	0.04132
0.0840	0.09	0.0840		0.0020		0.0890	29.4118	0.9423	1.82E-09	6,546	0.04133
0.0830	0.09	0.0830		0.0030		0.0905	29.4118	0.9419	1.81E-09	6,484	0.04134
0.0830	0.09	0.0830		0.0030		0.0905	29.4118	0.9419	1.80E-09	6,394	0.04135

Values for molar concentration were measured before and after each gas rate by titration and TIC

APPENDIX A.4.2. Mass Transfer Data for the Fractal II Distributor (40 pts/ft^2). f-factor = 0.86 ft/s (lb/ft^3)$^{0.5}$

The Separations Research Program

packed height	118	inches	Packing	Montz B1-500
f-factor	0.89	$(^{ft}/_s)(^{lb}/_{ft^3})^{0.5}$		
$C_{initial}$	0.0640	N		
Tank Volume	300.00	gallons		
Hw	0.034	*gmole/L-atm*		
surface area/volume *	500	m^2/m^3		

* approximate

CONSTANTS Henry's Law Constant Calcs	h_i
Na^+	0.091
OH^-	0.066
HCO_3^- →	0.021
CO_3^{2-} →	
CO_2	-0.019

PROCESS DATA

run #	time	Water Flow FT901 KPPH	Air Flow FI900 (ACFM)	Pressure Drp PDT901 (in H_2O)	Air Press PT900 (PSIG)	Air In T900 (F)	Water In T901 (F)	Air Out T902 (F)	CO_2 In ppm	CO_2 Out ppm
1	11/4/02 16:17	13.44	302.3	4.31	0.07	63.81	69.75	64.36	383	175
2	11/4/02 16:25	11.46	302.2	2.73	0.04	63.49	69.40	64.21	383	179
3	11/4/02 16:31	9.57	299.4	2.12	0.03	62.87	69.18	64.04	383	184
4	11/4/02 16:35	5.79	302.0	1.68	0.03	62.57	69.05	63.89	383	191
5	11/4/02 16:41	1.83	300.5	1.47	0.02	62.13	68.73	63.77	383	199
6	11/4/02 16:47	0.66	299.0	1.43	0.02	62.00	68.49	63.61	383	201

RESULTS

run	$K_{OG}A$ s^{-1}	NTU_{OG}	HTU_{OG} ft	K'_G	Effective Area m^2/m^3	Effective Area ft^2/ft^3	fractional area φ
1	0.261	0.786	12.515	3.19E-05	339.07	103.35	0.68
2	0.253	0.761	12.916	3.21E-05	325.96	99.35	0.65
3	0.241	0.732	13.428	3.17E-05	314.68	95.92	0.63
4	0.231	0.695	14.141	3.16E-05	302.71	92.27	0.61
5	0.216	0.654	15.028	3.11E-05	287.98	87.78	0.58
6	0.213	0.646	15.224	3.05E-05	288.51	87.94	0.58

HYDRAULIC CALCULATIONS

water velocity gpm/ft^2	f-factor $(^{ft}/_s)(^{lb}/_{ft^3})^{0.5}$	Pressure Drop inH_2O/ft packing
17.45	0.90	0.439
14.88	0.89	0.278
12.42	0.89	0.215
7.51	0.89	0.171
2.38	0.89	0.149
0.86	0.89	0.145

MASS TRANSFER CALCULATIONS

Molar Concentration N	Ionic Concentration Na^+	OH^-	HCO_3^-	CO_3^{2-}	CO_2	Ionic Strength	Henry's Law Constant	Viscosity cP	Diffusivity m^2/s	Rate Constant	ρ_g
0.0830	0.08	0.0830	0.0000	0.0000	0.0000	0.0830	30.3192	0.9419	1.79E-09	6,285	0.04136
0.0810	0.08	0.0810		0.0020		0.0860	29.4118	0.9411	1.78E-09	6,192	0.04137
0.0800	0.08	0.0800		0.0030		0.0875	29.4118	0.9406	1.78E-09	6,134	0.04138
0.0800	0.08	0.0800		0.0030		0.0875	29.4118	0.9406	1.77E-09	6,098	0.04140
0.0790	0.08	0.0790		0.0040		0.0890	29.4118	0.9402	1.76E-09	6,015	0.04141
0.0770	0.08	0.0770		0.0060		0.0920	29.4118	0.9394	1.76E-09	5,955	0.04142

APPENDIX A.4.3. Mass Transfer Data for the Fractal II Distributor (40 pts/ft^2). f-factor = 1.29 ft/s (lb/ft^3)$^{0.5}$

The Separations Research Program

packed height	118	inches	Packing:	Montz B1-500
f-factor	1.33	$(^{ft}/_s)(^{lb}/_{ft^3})^{0.5}$		
$C_{initial}$	0.0560	N		
Tank Volume	300.00	gallons		
Hw	0.034	gmole/L-atm		
surface area/volume *	500	m^2/m^3		

CONSTANTS	
Henry's Law Constant Calcs	
	h_i
Na^+	0.091
OH^-	0.066
HCO_3^- →	0.021
CO_3^{2-} →	
CO_2	-0.019

PROCESS DATA

run #	time	Water Flow FT901	Air Flow FI900	Pressure Drop PDT901	Air Press PT900	Air In T900	Water In T901	Air Out T902	CO_2 In	CO_2 Out
		KPPH	(ACFM)	(in H_2O)	(PSIG)	(F)	(F)	(F)	ppm	ppm
1	11/4/02 17:02	5.68	451.5	4.80	0.08	66.88	67.92	63.50	386	245
2	11/4/02 17:09	3.80	449.9	3.58	0.06	66.67	67.68	63.44	386	247
3	11/4/02 17:16	1.98	449.9	3.10	0.06	66.12	67.42	63.36	386	251
4	11/4/02 17:23	0.72	450.9	2.93	0.05	65.79	67.12	63.15	386	255

RESULTS

run	$K_{OG}A$	NTU_{OG}	HTU_{OG}	K'_G	Effective Area	Effective Area	fractional area
	s^{-1}		ft		m^2/m^3	ft^2/ft^3	ϕ
1	0.226	0.456	21.574	2.92E-05	321.63	98.03	0.64
2	0.222	0.447	21.982	2.94E-05	312.05	95.11	0.62
3	0.213	0.429	22.897	2.92E-05	301.96	92.04	0.60
4	0.206	0.416	23.630	2.79E-05	306.30	93.36	0.61

HYDRAULIC CALCULATIONS

water velocity	f-factor	Pressure Drop
[illegible]	$(^{ft}/_s)(^{lb}/_{ft^3})^{0.5}$	[illegible] packing
7.37	1.33	0.488
4.94	1.33	0.364
2.57	1.33	0.315
0.93	1.33	0.298

MASS TRANSFER CALCULATIONS

Molar Concentration	Ionic Concentration					Ionic Strength	Henry's Law Constant	Viscosity	Diffusivity	Rate Constant	ρ_g
N	Na^+	OH	HCO_3^-	CO_3^{2-}	CO_2		[illegible]	cP	m^2/s	[illegible]	[illegible]
0.0770	0.08	0.0770	0.0000	0.0000	0.0000	0.0770	30.2527	0.9394	1.74E-09	5,810	0.04143
0.0750	0.08	0.0750		0.0020		0.0800	29.4118	0.9386	1.73E-09	5,751	0.04143
0.0750	0.08	0.0750		0.0020		0.0800	29.4118	0.9386	1.73E-09	5,686	0.04144
0.0700	0.08	0.0700		0.0070		0.0875	29.4118	0.9366	1.72E-09	5,614	0.04145

APPENDIX A.4.4. Mass Transfer Data for the Fractal II Distributor (40 pts/ft^2). $\Delta P/Z_p$ = 0.75 in H_2O/ft.

The Separations Research Program

packed height	118	inches	Packing:	Montz B1-500
f-factor	1.31	$(^{ft}/_s)(^{lb}/_{ft^3})^{0.5}$		
$C_{initial}$	0.0480	N		
Tank Volume	300.00	gallons		
Hw	0.034	*gmole/L-atm*		
surface area/volume *	500.000	m^2/m^3		

* approximate

CONSTANTS	
Henry's Law Constant Calcs	
	f_i
Na^+	0.091
OH^-	0.066
HCO_3^-	0.021
CO_3^{2-}	0.021
CO_2	-0.019

PROCESS DATA

run #	time	Water Flow FT901 (KPPH)	Air Flow FI900 (ACFM)	Pressure Drp PDT901 (in H_2O)	Air Press PT900 (PSIG)	Air In T900 (F)	Water In T901 (F)	Air Out T902 (F)	CO_2 In (ppm)	CO_2 Out (ppm)
1	11/4/02 17:56	15.36	292.5	7.65	0.12	65.54	66.42	62.18	385	180
2	11/4/02 18:05	11.456	351.56	7.72	0.12	67.47	66.25	62.14	385	210
3	11/4/02 18:16	7.71	448.4	7.80	0.13	69.73	66.06	62.24	385	244
4	11/4/02 18:26	3.85	543.0	7.84	0.14	73.12	65.90	62.41	385	272
5	11/4/02 18:34	1.99	585.7	7.66	0.14	74.92	65.84	62.51	385	283

RESULTS

run	$K_{OG}A$ (s^{-1})	NTU_{OG}	HTU_{OG} (ft)	K'_G	Effective Area (m^2/m^3)	Effective Area (ft^2/ft^3)	fractional area (ϕ)
1	0.244	0.758	12.966	2.67E-05	380.08	115.85	0.76
2	0.235	0.606	16.223	2.68E-05	362.86	110.60	0.73
3	0.226	0.458	21.489	2.67E-05	351.28	107.07	0.70
4	0.208	0.348	28.281	2.64E-05	327.06	99.69	0.65
5	0.199	0.308	31.886	2.65E-05	311.14	94.84	0.62

HYDRAULIC CALCULATIONS

water velocity (gpm/ft^2)	f-factor $(^{ft}/_s)(^{lb}/_{ft^3})^{0.5}$	Pressure Drop (in H_2O/ft packing)
19.93	0.87	0.778
14.87	1.04	0.785
10.00	1.32	0.793
4.99	1.60	0.797
2.58	1.72	0.779

MASS TRANSFER CALCULATIONS

Molar Concentration N	Ionic Concentration Na^+	OH^-	HCO_3^-	CO_3^{2-}	CO_2	Ionic Strength	Henry's Law Constant (atm/gmole)	Viscosity (cP)	Diffusivity (m^2/s)	Rate Constant	ρ_g
0.0700	0.07	0.0700	0.0000	0.0000	0.0000	0.0700	30.1753	0.9366	1.70E-09	5,445	0.04153
0.0680	0.07	0.0680		0.0020		0.0730	29.4118	0.9357	1.70E-09	5,406	0.04153
0.0680	0.07	0.0680		0.0020		0.0730	29.4118	0.9357	1.69E-09	5,362	0.04153
0.0670	0.07	0.0670		0.0030		0.0745	29.4118	0.9353	1.69E-09	5,325	0.04151
0.0680	0.07	0.0680		0.0020		0.0730	29.4118	0.9357	1.68E-09	5,310	0.04150

Appendix A.15. Determination of Effective Mass Transfer Area

The effective mass transfer area of the packing may be estimated using a reactive absorption system such as air/CO_2/caustic. The method of calculation and example calculation are provided in this section.

The absorption system can be described using two-film theory:

$$\frac{1}{K_{og}\,a} = \frac{1}{k_g\,a} + \frac{H}{k_l\,a}$$

where the liquid phase mass transfer coefficient is corrected for the chemical reaction.

$$\frac{1}{K_{og}\,a} = \frac{1}{k_g\,a} + \frac{H}{\beta\,k_l^0\,a}$$

where:

- β = enhancement factor
- k_l^0 = physical mass transfer coefficient

The enhancement factor β depends on the Hatta number (Ha) and ϕ, where:

$$Ha = \sqrt{\frac{D_{AL}\,C_B^0\,k_r}{k_l^0}}$$

$$\phi = \sqrt{\frac{D_{AL}}{D_{BL}}} + \sqrt{\frac{D_{BL}}{D_{AL}}}\left(\frac{C_B}{b\,C_A^*}\right)$$

where:

- D_{AL} = diffusion coefficient of CO2 into the caustic phase
- D_{BL} = diffusion coefficient of NaOH ions into the caustic phase
- C_B = concentration of NaOH ions in caustic phase
- C_{A*} = equilibrium concentration of CO2 in the caustic phase
- k_r = rate constant

Assuming the liquid diffusion coefficients are equivalent ($D_{BL} \sim D_{AL}$), then ϕ may be rewritten:

$$\phi \cong 1 + \left(\frac{C_B}{b\,C_A^*}\right)$$

$C_A^* = P_{CO2}/H_{CO2}$

In general, ϕ is quite large and for large values of $\phi > 100$, the enhancement factor (β) is equivalent to the Ha number.

Therefore
$$\frac{k_l}{k_l^0} = \frac{\sqrt{D_{AL}\, C_B^0\, k_r}}{k_l^0}$$

or

$$k_l = \sqrt{D_{AB}\, C_B\, k_r}$$

Therefore the overall gas phase volumetric coefficient, $K_{og}a$, may be rewritten:

$$\frac{1}{K_{og}\, a} = \frac{1}{k_g\, a} + \frac{H}{\sqrt{D_{AB}\, C_B\, k_r}\quad a}$$

In general for low concentrations of sodium hydroxide (C_B), the gas phase resistance can be neglected. As a result,

$$K_{og}\, a = \frac{a\sqrt{D_{AB}\, C_B\, k_r}}{H}$$

Therefore, the mass transfer area can be deduced from the experimentally derived Koga and values of the diffusion coefficient (D_{AB}), sodium hydroxide concentration (C_B) and the reaction rate constant (k_r).

<u>CALCULATION STEPS:</u>

<u>Step 1: Solve for the NTU</u>

$$NTU_{og} = \ln\left(\frac{Y_{CO_2,in}}{Y_{CO_2,out}}\right)$$

Where NTU_{OG} is the number of transfer units in the gas phase.
$Y_{CO2,in}$ is the ambient CO_2 concentration (ppm) in the inlet stream and
$Y_{CO2,out}$ is the CO_2 concentration (ppm) in the scrubbed outlet stream.

<u>Step 2: Solve for the HTU</u>

$$HTU_{og} = \frac{Z_p}{NTU_{og}}$$

Where HTU_{OG} is the height of a transfer unit (ft)
Z_p is the height of the contacting bed

Step 3: Solve for the $K_{og}a$

$$\overline{K_{og}\,a} = \frac{U_s}{HTU_{og}} = \frac{U_s}{\left(Z_p / NTU_{og}\right)}$$

Where Us is the superficial vapor velocity (ft/s)
$K_{OG}a$ is the mass transfer/area combined term and it has units of s^{-1}.

Step 4: Calculate the Ionic Strength

$$I = \frac{1}{2}\sum z_i^2 C_i$$

Sherwood, Pigford, and Wilke, 1975, *Mass Transfer*, McGraw-Hill, New York (p. 362).

Where z_i is the number of positive or negative charges on an ion having molarity C_i. The number positive or negative charges in this case is determined by the ions in the solution, Na^+ and OH^-. The molarity has units of gmol/L.

Step 5. Calculate the Henry's Law Constant

$$\log_{10}\frac{H'}{H_w} = -h_i I$$

$$H = \frac{1}{H'}$$

Sherwood, Pigford, and Wilke, 1975, *Mass Transfer*, McGraw-Hill, New York (p. 365).

Where I is the ionic strength and $h = h_+ + h_- + h_g$ (these values come from Table 8.4 on page 365 in the above reference) and H_w is the Henry's law coefficient for water.

The Henry's law coefficient is related to the value in water by this empirical equation.

Step 6. Determine the Diffusivity:

$$D_{CO_2} = \frac{RT}{F^2}\cdot\frac{\frac{1}{n_+}+\frac{1}{n_-}}{\frac{1}{\lambda_+^0}+\frac{1}{\lambda_-^0}}$$

Sherwood, Pigford, and Wilke, 1975, *Mass Transfer*, McGraw-Hill, New York (p. 35).

Where R is the universal gas constant (8.315 J/K-gmol),
T is the absolute temperature (K),
F = Faraday = 96,488 C/g equiv
λ_+^0, λ_-^0 = limiting (zero concentration) ionic conductances at T, of cation and anion, respectively, (amp)/(cm^2)(V/cm)(g equiv/cm^3)
n_+, n_- = valences of cation and anion, respectively

Step 7. Calculate the Rate Constant:

$$\log_{10} k_r = 13.635 - \frac{2895}{T}$$

Sherwood, Pigford, and Wilke, 1975, *Mass Transfer*, McGraw-Hill, New York (p. 363).

Where k is the second order rate constant for the reaction of CO_2 with hydroxyl ion in aqueous solutions and has units of L/(gmol-sec)
T is the temperature in K

Step 8. Calculate the effective area:

$$K_{OG}a = \frac{a\sqrt{kD_{CO_2}C_{OH}}}{H}$$

Where a is the effective packing surface area
k is the rate constant, L/(gmol-sec). [step 7]
D_{CO2} is the Diffusivity of CO_2 [step 6]
C_{OH} is the concentration of OH^- ions remaining in the solution (after accounting for the amount consumed in the reaction), gmol/L
H is the Henry's law coefficient [step 5]

Example Calculation

Bases:

Packed height, z	120	inches
Column diameter (i.d.)	16.81	inches
Molar Concentration	0.1	N NaOH
Conversion	5	%
Liquid rate	15,000	lb/hr
Air rate	180	acfm
$CO_{2,\ ambient}$	360	ppm
$CO_{2,\ process\ out}$	160	ppm
Pressure drop, ΔP	3.0	inH_2O
$T_{air,\ in}$	100	□F
$T_{air,\ out}$	90	□F
T_{water}	80	□F
Henry's Law Constant (water), H_w	0.034	gmole/L•atm
h_{Na^+}	0.091	
h_{OH^-}	0.066	
$h_{(HCO_3^- \& CO_3^{2-})}$	0.021	
h_{CO_2}	-0.019	
reaction	$2NaOH + CO_2$ □ $Na_2CO_3 + H_2O$	

Solution:

Step 1: Solve for the NTU

$$NTU_{og} = \ln\left(\frac{360\,ppm}{160\,ppm}\right) = 0.811$$

Step 2: Solve for the HTU

$$HTU_{og} = \frac{120in\left(\frac{1ft}{12in}\right)}{0.811} = 12.33ft$$

Step 3: Solve for the $K_{og}a$

$$\overline{K_{og}\,a} = \frac{180\frac{ft^3}{\min}\left(\frac{1\min}{60s}\right)\left(\frac{1}{1.54ft^2}\right)}{12.33ft} = 0.157s^{-1}$$

Step 4: Calculate the Ionic Strength

$$I = \frac{1}{2}\left[\left(1^2\right)(0.100) + \left(1^2\right)(0.095) + \left(2^2\right)(0.005)\right] = 0.1075$$

The concentrations listed are for the ions: Na^+, OH^-, and CO_3^{2-}, respectively (see formula above). This is based on the assumption that the solution was initially 0.1 N NaOH and that 5% of the available OH^- have reacted to form Na_2CO_3).

Step 5. Calculate the Henry's Law Constant (with temperature correction)

$$\sum h_i = 0.91 + 0.66 + 0.21 - 0.19 = 1.59$$

$$\log_{10}\frac{H'}{0.034\frac{gmol-\sec}{L}} = -(1.59)(0.1075)$$

$$H = \frac{1}{H'} = \frac{1}{.0327\frac{gmol}{L\cdot atm}} = 30.6\frac{L\cdot atm}{gmol}$$

Step 6. Determine the Diffusivity:

$$D_{CO_2} = \frac{8.315\frac{J}{K\cdot gmol}\cdot 300K}{\left(96{,}488\frac{C}{g_{equiv}}\right)^2}\cdot\frac{\frac{1}{1}+\frac{1}{1}}{\frac{1}{50.1\frac{amp}{cm^2}\left(\frac{V}{cm}\right)\left(\frac{g_{equiv}}{cm^3}\right)}+\frac{1}{197.6\frac{amp}{cm^2}\left(\frac{V}{cm}\right)\left(\frac{g_{equiv}}{cm^3}\right)}}\cdot\frac{1m^2}{100^2cm^2} = 2.14\times10^{-9}\frac{m^2}{s}$$

Step 7. Calculate the Rate Constant:

$$\log_{10}k = 13.635 - \frac{2895}{T}$$

$$\log_{10}k = 13.635 - \frac{2895}{(460+80)/1.8}$$

$$k = 10^{13.635 - \left(\frac{2895}{300}\right)} = 9{,}660 \frac{L}{gmol \cdot s}$$

Step 8. Calculate the effective area:

$$K_{OG} = \frac{\sqrt{kD_{CO_2} C_{OH}}}{H}$$

Because the value for $K_{OG}a$ has been determined from empirical data, it is possible to calculate the effective area.

$$K_{OG} = \frac{\sqrt{9{,}660 \frac{L}{gmol \cdot s} \cdot 2.14E-9 \frac{m^2}{s} \cdot 0.095 \frac{gmolOH^-}{L}}}{30.6 \frac{L \cdot atm}{gmol}} = 4.57E-5 \frac{m}{s} \cdot \frac{gmol}{L \cdot atm}$$

$$a = \frac{\rho_g \cdot K_{OG}a}{K_{OG}} = \frac{0.04 \frac{gmol}{m^3} \cdot 0.157 s^{-1}}{4.57E-5 \frac{m}{s} \cdot \frac{gmol}{L \cdot atm}} = 137 \frac{m^2}{m^3}$$