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DEHUMIDIFICATION OF MOIST AIR WITH SIMULTANEOUS REMOVAL OF SELECTED INDOOR POLLUTANTS BY TRIETHYLENE GLYCOL SOLUTIONS IN A PACKED-BED ABSORBER

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ABSTRACT

A packed bed absorber-stripper system was used to remove selected indoor pollutants during the dehumidification of air by triethylene glycol solutions. Triethylene glycol concentrations of 90% and 95% by weight in water were used. Both random and structured packings were employed to provide the contact surface between the liquid and gas phases. A six-inch I. D. absorption column was operated between 50% and 80% of flooding conditions. The heights of a transfer unit for mass transfer for randomly packed 5/8-inch polypropylene Flexi rings and 1/2-inch ceramic Intalox saddles varied from 0.12 m to 0.17 m when dehumidifying air only. However, the height of a transfer unit was in the range of 0.31 m to 0.40 m for the cross corrugated cellulose and PVC structured packings. Heat and mass transfer coefficients were also calculated from the experimental data and were correlated with various process variables. The values predicted by these correlations were within ±10% of the experimental data.

Pollutants used in the study included formaldehyde, toluene, 1,1,1-trichloroethane and carbon dioxide, and their concentrations in the air were controlled to 0.02 ± 0.005 ppm, 3 ± 0.02 ppm, 24 ± 0.1 ppm, and 1000 ± 5 ppm, respectively. Although nearly 100% of the toluene and 1,1,1-trichloroethane were removed by the 95% triethylene glycol solution, only 56% of the carbon dioxide and 30% of the formaldehyde could be removed from the air stream under similar conditions. As expected, the removal of these pollutants by the triethylene glycol solution was not affected by varying the relative humidity of the air.

INTRODUCTION

Aqueous triethylene glycol solutions are frequently used to dehumidify air. Although packed, spray, and tray columns can be used to provide the contact between the gas and liquid phases, spray columns are most common for dehumidification applications. Kean et al. (1) reported that structured packings (Flexipac II from Koch Engineering Co.) used in the dehydration of natural gas provided approximately twice the capacity and up to 50% greater efficiency than bubble-cup trayed columns. However, no attempt has been made to dehumidify air using a packed column.

The size and efficiency of an absorption system depend on the effectiveness of the gas and liquid contact, as this determines the mass transfer process. While Intalox saddles and Raschig rings made of ceramic are most frequently used, recently a number of new packing materials, including polypropylene, polyethylene, and kynar have become available commercially. These packings are not only lighter in weight, but are also less expensive. They are specially designed to provide a large surface area and free gas space. A number of structured packings have been developed as alternatives to random packings since they improve the mass transfer rate by taking advantage of the fixed orientation of the mass transfer surfaces. Consequently, the size and cost of the liquid desiccant unit may be reduced.

Poor indoor air quality is considered to be responsible for a number of health problems, which has resulted in increased absentees from work and rising medical costs (2). Conceptually, absorption processes have the potential to remove a number of chemicals, such as combustion by-products, inorganic gases, volatile organic compounds, and biological pollutants such as bacteria, fungi, and viruses. Chung et al. (3) found that a significant amount of formaldehyde, carbon dioxide, toluene, and 1,1,1-trichloroethane could be removed from air by a 95% aqueous solution of triethylene glycol in a packed bed arrangement when the relative humidity of the air was about 20%. Ghosh and Hines (4) noted that more than 92% of the airborne microorganisms were killed by a 90% triethylene glycol solution during dehumidification of air in a packed bed.

The focus of this work was to dehumidify air using triethylene glycol solutions in a column packed either randomly or with structured packings. Polypropylene Flexi rings (5/8 - inch) and ceramic Intalox saddles (1/2-inch)

were used to pack the column randomly, whereas structured cross corrugated cellulose and PVC were employed as structured packings. Column efficiencies and heat and mass transfer coefficients for these packings were calculated from the experimental dehumidification data. The column efficiencies were compared with these for dehumidification systems that employed similar packings and utilized an aqueous 40% lithium chloride solution. Heat and mass transfer correlations for water vapor absorption by triethylene glycol were developed by using nondimensional groups.

After conducting studies with the humid air, selected indoor air pollutants that included formaldehyde, toluene, 1,1,1-trichloroethane, and carbon dioxide were introduced into the system, first individually and then together as a mixture with the moist air. The percent removal of each pollutant was determined by analyzing the mixture concentration in the inlet and outlet streams.

EXPERIMENTAL SECTION

A detailed description of the absorption–regeneration system that was used in this study is given by Chung et al. (5). Both the absorber and the regenerator were glass columns, 15.24-cm (6-in) in I.D. Both columns were packed up to a depth of 42 cm with either a random or structured packing. The air entered at the bottom of the column and the liquid desiccant was sprayed counter-currently from the top of the column over the packing. Air and triethylene glycol solution flow rates up to 60 CFM (7207 kg/m^2 h or 24.7 lb/ft2 min) and 3 GPM (41782 kg/m^2h or 142.9 lb/ft2 min), respectively, were required to operate the absorption column between 50% and 80% of the flooding velocities. The concentrations of the two triethylene glycol solutions were 90% and 95% by weight in water. The relative humidity and temperature of the inlet and outlet air streams were measured simultaneously by using a probe obtained from Vaisala, Inc. The concentrations of toluene, 1,1,1-trichloroethane, and carbon dioxide were determined by using a gas chromatograph, whereas a formaldehyde monitor (Model TGM-555 obtained from CEA Instruments Inc.) was used for continuous measurement of the formaldehyde concentration.

Since outdoor air was used in all experiments, and the conditions of the inlet air stream had to be constant from one test to another, the air was first

cleaned and washed in a separate column (pre-dehumidifier)by using triethylene glycol. It was then re-humidified to a predetermined level in a Plexiglas chamber with a water spray. The humidity and temperature of the air stream were controlled by varying the temperature of the water and the amount that was sprayed into the air. With this arrangement, the temperature and relative humidity of the test air could be reproduced. The spent triethylene glycol solution was regenerated by heating it at 135°F in a heat exchanger and contacting it with air in the regenerator column. The regenerated glycol solution was cooled and returned to the absorber for further use.

DEVELOPMENT OF CORRELATIONS FOR MASS AND HEAT TRANSFER COEFFICIENTS

The gas phase mass and heat transfer coefficients were calculated from the experimental data following a procedure given by Hines and Maddox (6). It was assumed that the water from air was transferred into the bulk liquid through a stagnant film of liquid desiccant. The overall gas side mass transfer coefficient was calculated from the following equation.

$$K_{GA}\,a = \left(\frac{G}{Z}\right)_{avg} \int_{y_{A,a}}^{y_{A,b}} \frac{(1-y_A)_{*M}}{1-y_A} \frac{dy_A}{y_A - y_A^*} \tag{1}$$

The integration of Equation (1) was carried out numerically by using Simpson's integration method. The height of a transfer unit, which is usually less dependent on liquid and gas flow rates, is given as

$$H_{OG} = \frac{G}{K_{GA}\,a} \tag{2}$$

The gas side heat transfer coefficient was calculated by assuming that the column was operated adiabatically and can be expressed as

$$h_{GA}\,a = \frac{G(c_{p_{air}} + y_A\, c_{pw})}{Z} \ln \frac{t_{G_{in}} - t_i}{t_{G_{out}} - t_i} \tag{3}$$

where the interface temperature, t_i, is assumed to be the average of the inlet and outlet liquid temperatures. A detailed derivation of Equations (1) and (3) is given by Chung et al. (7).

The mass and heat transfer coefficients calculated from Equations (1) and (3) were correlated in terms of the process variables by employing a dimensional analysis. Variables that affect the gas phase mass transfer coefficient include air and liquid flow rates, physical properties of both air and the liquid, packing volume and size, molecular weight of the vapor phase, diffusion coefficient of water in air, and the mass fraction of the triethylene glycol in the liquid solution. In functional form mass transfer can be expressed as

$$f(K_{GA}, a, M_t, d_p, D_v, \rho_v, G', L', X, \mu_v) = 0 \tag{4}$$

The above variables are arranged into pertinent dimensionless groups by using the Buckingham pi theorem. The same variables were considered for a structured packing, but the packing diameter was replaced by an equivalent diameter that was calculated following a procedure given by Bravo et al. (8). The mass transfer correlation obtained from the dimensional analysis is given below as

$$K_G a\left(\frac{M_t d_p^2}{D_v \rho_v}\right) = \alpha (1 - X)^{\beta} \left(\frac{L'}{G'}\right)^{\gamma} (Sc_v)^{\omega} (Re_v)^{\delta} \tag{5}$$

where α, β, γ, ω, δ are constants and are obtained by nonlinear regression of the experimental data for only one type of packing. The experimental data for 5/8-inch polypropylene Flexi rings were used to evaluate the constants for random packings, whereas the data for cross corrugated cellulose packing were employed to obtain the correlation constants for the structured packings. Correlations for two packings are given below.

Mass transfer correlation for random packing:

$$K_G a\left(\frac{M_t d_p^2}{D_v \rho_v}\right) = 6.33 \times 10^{-5} (1 - X)^{-0.09} \left(\frac{L'}{G'}\right)^{0.27} (Sc_v)^{0.333} (Re_v)^{1.38} \tag{6}$$

Mass transfer correlation for structured packing:

$$K_G a\left(\frac{M_t d_{eq}^2}{D_v \rho_v}\right) = 9.03 \times 10^{-6} (1 - X)^{-0.05} \left(\frac{L'}{G'}\right)^{0.26} (Sc_v)^{0.333} (Re_v)^{1.34} \tag{7}$$

The following variables were used to develop correlations for the heat transfer coefficients: air and liquid mass flow rates, physical properties of the air and liquid, and packing volume and size. Therefore, the functional form of the heat transfer equation is

$$f(h_{GA}, a, d_p, k_v, G', L', X, c_{pv}, \rho_v, \mu_v) = 0 \quad (8)$$

Values of the exponents of the dimensionless groups were also obtained from nonlinear regression of the experimental data. Exponents for the heat transfer correlations for random and structured packings were obtained by using experimental data for 5/8-inch polypropylene Flexi rings and cross corrugated cellulose packings, respectively. Correlations for the two packings are given below.

Heat transfer correlation for random packing:

$$h_{GA}\, a \left(\frac{d_p^2}{k_v}\right) = 8.16 \times 10^{-4} (1 - X)^{1.23} \left(\frac{L'}{G'}\right)^{0.47} (Pr_v)^{0.333} (Re_v)^{1.12} \quad (9)$$

Heat transfer correlation for structured packing:

$$h_{GA}\, a \left(\frac{d_{eq}^2}{k_v}\right) = 1.76 \times 10^{-6} (1 - X)^{0.07} \left(\frac{L'}{G'}\right)^{0.49} (Pr_v)^{0.333} (Re_v)^{1.52} \quad (10)$$

RESULTS AND DISCUSSION

The minimum liquid flow rate, if calculated from the equilibrium data, was found to be too small to wet the packing surfaces uniformly. Therefore, the flow rate necessary to wet the packing completely (minimum wetting flow rate) was determined from an equation given by Strigle (9).

Since aqueous solutions of lithium chloride and triethylene glycol are most frequently used as liquid desiccants, the data for triethylene glycol were compared with data for lithium chloride. Operating conditions for a column packed with different types of packings and employing triethylene glycol are given in Table 1. Similar data for lithium chloride solutions are given by Chung et al (5). The pressure drop in the six-inch column when packed with 5/8-inch Flexi rings was approximately 0.25 cm of water per cm of the packing height. As shown in Figure 1, these values are in the same range as when lithium chloride was used as the desiccant. Grosso et al. (10) noted that with the current liquid distributors and packings, the pressure drop in a large diameter packed absorber can be limited to a few psi. When using triethylene glycol, the column reached flooding conditions at a lower air flow rate than when using lithium chloride, since the viscosity of a

TABLE 1. EXPERIMENTAL DATA FOR TRIETHYLENE GLYCOL-AIR-WATER SYSTEM IN A COLUMN PACKED WITH DIFFERENT TYPES OF PACKINGS

Percent of flooding (%)	Air flow rate (ft^3/min)	Liquid flow rate (gal/min)	Air inlet temp (°F)	Air outlet temp (°F)	Air inlet humidity (lb H_2O/lb dry air)	Air outlet humidity (lb H_2O/lb dry air)	Liquid inlet temp (°F)	Liquid outlet temp (°F)	TEG (% wt)	Equilibrium humidity (lb H_2O/lb dry air)	Packing height (cm)	Efficiency (%)	Mass transfer coefficient (kmol/m^3s)	Heat transfer coefficient (kw/m^3K)	Height of transfer unit (m)
Polypropylene Flexi Ring (5/8-inch)															
80	40	2.0	74.4	69.8	0.0112	0.0029	67.4	69.0	95	0.0022	42	92.2	0.28	4.49	0.17
70	35	2.0	75.3	69.8	0.0110	0.0028	67.6	68.2	95	0.0022	42	93.2	0.27	3.94	0.16
60	30	2.0	73.9	69.4	0.0108	0.0027	67.4	68.0	95	0.0022	42	94.2	0.24	3.22	0.15
50	25	2.0	73.4	69.2	0.0102	0.0026	67.4	67.8	95	0.0022	42	95.0	0.21	2.67	0.14
80	32	2.8	70.7	63.3	0.0103	0.0025	61.5	61.8	95	0.0020	42	94.0	0.25	4.51	0.15
71	32	2.5	70.5	63.5	0.0096	0.0025	61.3	61.5	95	0.0020	42	93.4	0.24	3.89	0.15
64	32	2.0	70.1	64.4	0.0102	0.0026	61.7	62.4	95	0.0020	42	92.7	0.23	3.27	0.16
58	32	2.5	70.1	65.1	0.0096	0.0026	61.7	62.7	95	0.0020	42	92.1	0.22	2.66	0.17
82	40	2.0	72.5	68.0	0.0111	0.0050	65.8	67.4	90	0.0044	42	91.0	0.27	4.77	0.18
72	35	2.0	72.9	68.1	0.0108	0.0049	65.8	67.5	90	0.0044	42	92.2	0.25	4.23	0.17
62	30	2.0	73.7	68.1	0.0117	0.0049	65.8	66.9	90	0.0044	42	93.2	0.22	3.57	0.16
52	25	2.0	74.2	68.3	0.0115	0.0048	65.8	67.1	90	0.0044	42	94.4	0.20	2.97	0.15
82	32	2.8	77.3	71.6	0.0123	0.0055	69.6	71.2	90	0.0050	42	93.2	0.24	4.64	0.16
73	32	2.5	77.0	72.0	0.0117	0.0055	69.8	71.4	90	0.0050	42	92.5	0.23	4.03	0.16
66	32	2.0	77.5	72.3	0.0121	0.0056	69.2	71.6	90	0.0050	42	91.6	0.22	3.50	0.17
60	32	1.5	77.3	73.5	0.0116	0.0056	69.8	73.2	90	0.0050	42	90.8	0.21	2.82	0.18
Intalox Saddle (1/2-inch)															
80	22.5	1.5	73.5	64.0	0.0110	0.0050	61.7	64.8	90	0.0046	42	93.7	0.17	4.99	0.15
70	20	1.5	76.1	66.6	0.0123	0.0054	63.5	67.6	90	0.0050	42	94.5	0.16	4.32	0.14
60	17.5	1.5	78.8	66.7	0.0112	0.0054	64.4	66.9	90	0.0051	42	95.0	0.15	3.76	0.14
50	15	1.5	78.9	66.7	0.0115	0.0053	64.0	66.5	90	0.0050	42	95.4	0.13	2.86	0.12
72.5	17.5	1.7	75.3	65.5	0.0120	0.0052	62.9	66.7	90	0.0050	42	95.7	0.17	4.02	0.12
70	17.5	1.5	76.1	69.4	0.0113	0.0034	66.7	70.8	95	0.0032	42	96.3	0.15	3.60	0.13

(continued)

TABLE I (CONTINUED)

Structured Cross Corrugated Cellulose Packings (size 7060 from Munters)

Percent of flooding (%)	Air flow rate (ft^3/min)	Liquid flow rate (gal/min)	Air inlet temp (°F)	Air outlet temp (°F)	Air inlet humidity (lb H_2O/lb dry air)	Air outlet humidity (lb H_2O/lb dry air)	Liquid inlet temp (°F)	Liquid outlet temp (°F)	LiCl conc (% wt)	Equilibrium humidity (lb H_2O/lb dry air)	Packing height (cm)	Efficiency (%)	Mass transfer coefficient (kmol/m^3s)	Heat transfer coefficient (kw/m^3K)	Height of transfer unit (m)
80	41	2.0	81.6	78.8	0.0178	0.0088	73.4	76.1	95	0.0037	40	63.8	0.12	1.83	0.39
70	36	2.0	83.3	79.0	0.0180	0.0086	70.8	72.5	95	0.0036	40	65.2	0.11	1.41	0.38
60	31	2.0	83.2	78.9	0.0180	0.0085	68.5	70.8	95	0.0036	40	66.2	0.10	1.15	0.37
50	25	2.0	82.9	78.0	0.0178	0.0082	68.0	69.8	95	0.0036	40	67.9	0.08	0.91	0.36
82	31	2.8	85.8	77.1	0.0171	0.0080	69.4	70.8	95	0.0036	40	67.4	0.10	2.13	0.36
76	31	2.5	85.6	77.6	0.0172	0.0082	68.3	69.9	95	0.0036	40	66.2	0.10	1.75	0.37
60	31	2.0	85.0	78.2	0.0174	0.0084	67.4	69.4	95	0.0036	40	65.2	0.09	1.39	0.38
55	31	1.5	85.4	79.4	0.0174	0.0086	66.2	69.0	95	0.0036	40	63.8	0.09	1.08	0.40
83	41	2.0	79.8	73.2	0.0139	0.0083	63.8	65.3	90	0.0051	40	63.2	0.12	1.97	0.40
73	36	2.0	79.8	73.2	0.0138	0.0082	63.1	64.5	90	0.0051	40	64.8	0.11	1.63	0.39
63	31	2.0	79.0	73.5	0.0133	0.0080	65.1	66.9	90	0.0052	40	65.4	0.09	1.45	0.38
53	25	2.0	79.0	73.7	0.0140	0.0081	65.3	68.9	90	0.0052	40	67.0	0.08	1.25	0.36
85	31	2.8	75.0	68.8	0.0138	0.0081	62.9	64.9	90	0.0051	40	65.6	0.09	2.15	0.38
79	31	2.5	77.4	70.2	0.0140	0.0082	62.2	63.5	90	0.0051	40	65.1	0.09	1.80	0.38
63	31	2.0	79.3	72.2	0.0137	0.0082	62.2	63.5	90	0.0051	40	64.0	0.09	1.49	0.40
58	31	1.5	80.7	74.1	0.0139	0.0083	62.2	64.4	90	0.0051	40	63.6	0.09	1.25	0.40

80	60	2.75	82.5	72.0	0.0100	0.0052	66.6	70.1	95	0.0032	41	70.5	0.21	6.90	0.34
70	52.5	2.75	82.5	72.5	0.0101	0.0052	66.5	69.2	95	0.0032	41	71.0	0.18	5.11	0.33
60	45	2.75	81.5	72.8	0.0100	0.0051	66.2	68.2	95	0.0032	41	72.0	0.16	3.58	0.32
50	37.5	2.75	80.4	72.3	0.0098	0.0050	66.0	67.2	95	0.0032	41	72.7	0.14	2.82	0.32
78	55	3.0	73.0	70.3	0.0128	0.0058	67.8	71.0	95	0.0033	41	73.6	0.21	6.47	0.31
70	55	2.5	73.2	70.6	0.0126	0.0060	67.4	70.8	95	0.0033	41	71.0	0.19	4.69	0.33
62	55	2.0	73.2	71.2	0.0126	0.0062	67.8	70.7	95	0.0033	41	68.8	0.18	3.30	0.35
51	55	1.5	73.3	71.2	0.0127	0.0063	66.5	69.8	95	0.0033	41	67.4	0.18	2.45	0.36
83	60	2.75	71.2	67.6	0.0132	0.0076	65.4	67.4	90	0.0052	41	70.0	0.20	7.06	0.34
73	52.5	2.75	71.2	67.4	0.0119	0.0071	64.9	67.2	90	0.0051	41	70.6	0.18	5.97	0.34
63	45	2.75	71.0	66.9	0.0120	0.0070	64.0	65.6	90	0.0050	41	71.4	0.16	4.17	0.33
53	37.5	2.75	70.8	66.5	0.0118	0.0069	63.5	64.5	90	0.0050	41	72.1	0.13	3.19	0.32
75	55	3.0	71.4	67.5	0.0135	0.0076	65.4	67.4	90	0.0052	41	71.1	0.19	6.88	0.33
67	55	2.5	71.0	67.6	0.0133	0.0077	65.3	67.0	90	0.0052	41	69.1	0.18	5.64	0.35
59	55	2.0	71.0	67.7	0.0133	0.0078	64.4	66.4	90	0.0051	41	67.1	0.17	4.16	0.37
48	55	1.5	70.8	67.8	0.0133	0.0079	63.5	66.0	90	0.0050	41	65.1	0.16	3.20	0.39

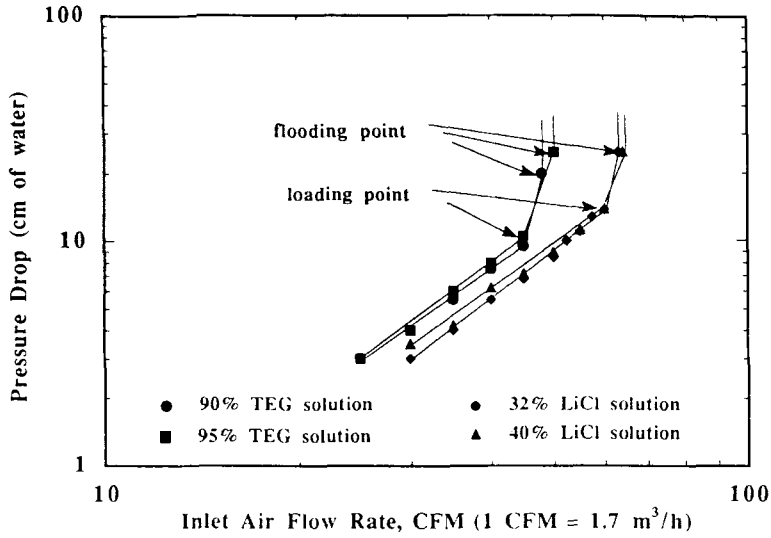


FIGURE 1. Pressure drop in a column packed with 5/8-inch polypropylene Flexi rings for triethylene glycol and lithium chloride solutions.

95% triethylene glycol solution is about 8 times greater than that of a 40% lithium chloride solution.

The performance of the absorption column was determined by evaluating its efficiency as well as the gas side heat and mass transfer coefficients and the heights of a mass transfer unit. The column efficiency was defined as the ratio of the actual change in moisture content of the air leaving the absorber to the maximum possible change in moisture content under a given set of operating conditions. Therefore, the column efficiency, ε, can be expressed as

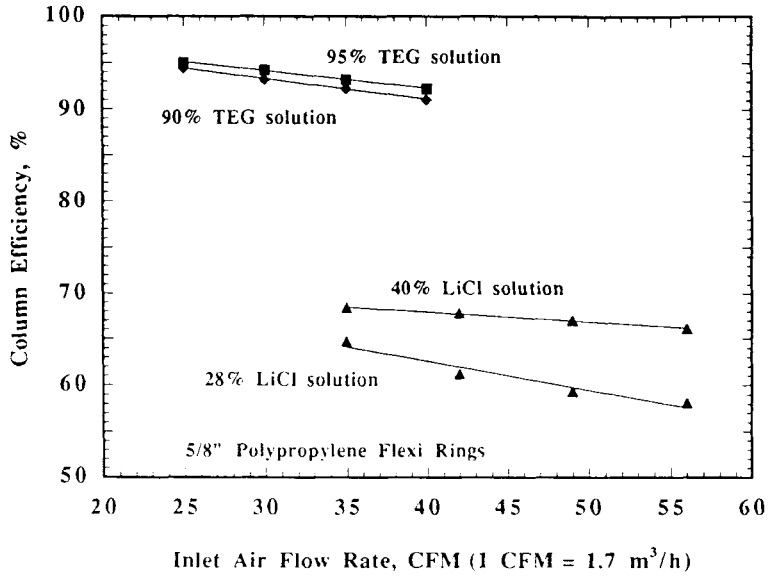
$$\varepsilon = \frac{W_{in} - W_{out}}{W_{in} - W_{equ}} \tag{11}$$

Although the dew point depression capability of triethylene glycol and lithium chloride solutions at a particular temperature is almost the same, the amount of triethylene glycol solution required to dehumidify a specific amount of air was only one half of the amount of the 40% lithium chloride solution. However, about 25 to 42 ft^3/min of air was required to maintain the column between 50 and 80% of the flooding velocity when using triethylene glycol. The air flow rate required

to maintain the same flooding conditions in the same column using 40% lithium chloride was in the range of 28 to 56 ft^3/min. At these conditions, the column efficiency of the triethylene glycol system varied from 90% to 95%. The efficiency dropped by only 3% when the inlet air flow rate was increased from 25 to 40 ft^3/min. The increase in the efficiency with the liquid flow rate was also marginal. The efficiencies are shown in Figure 2 as a function of air and liquid rates along with the data for the lithium chloride-air-water system. As can be seen from these figures, a 95% triethylene glycol solution was found to be more effective than a 40% lithium chloride solution in dehumidifying air when polypropylene Flexi rings was used as the packing. The efficiency of the triethylene glycol system was almost 20% higher than the lithium chloride system. However, the column efficiencies were in the same range for both desiccants when PVC structured packings were used. The column efficiencies for different packings are compared in Table 2.

When using triethylene glycol, the column that was packed randomly with either Flexi rings or Intalox saddles had a higher efficiency than when packed with structured packings. It should be noted, however, that the air flow rates through the structured packings were greater than those through the random packings. It appears that triethylene glycol wetted the Flexi rings and Intalox saddles more effectively than it did the structured packings. The face velocity through the column packed with structured packings was in the range of 122 to 305 ft/min, whereas it varied from 76 to 203 ft/min for random packings.

The gas side mass transfer coefficient for the triethylene glycol-air-water system was significantly higher than for the LiCl-air-water system in a Flexi ring-column. These data are plotted in Figure 3 as a function of air and liquid flow rates, respectively. In general, the coefficients exhibited a linear relationship with respect to both the air and liquid flow rates. An increase in the heat transfer coefficients with the increase of air and liquid flow rates was also observed for these systems (see Figure 4). Values for the heat transfer coefficients varied from 2.5 to 4.5 $kw/m^3 \cdot s$ when the liquid flow was changed from 1.4 to 2.8 gal/min. Although these values were in the same range as those for the lithium chloride systems, the flow rate of the lithium chloride solution was almost twice that of the triethylene glycol solution. The difference in the heat transfer coefficients between the two systems was greater when the air flow rates were varied than when liquid flow rates were changed. This suggests that heat can be transferred



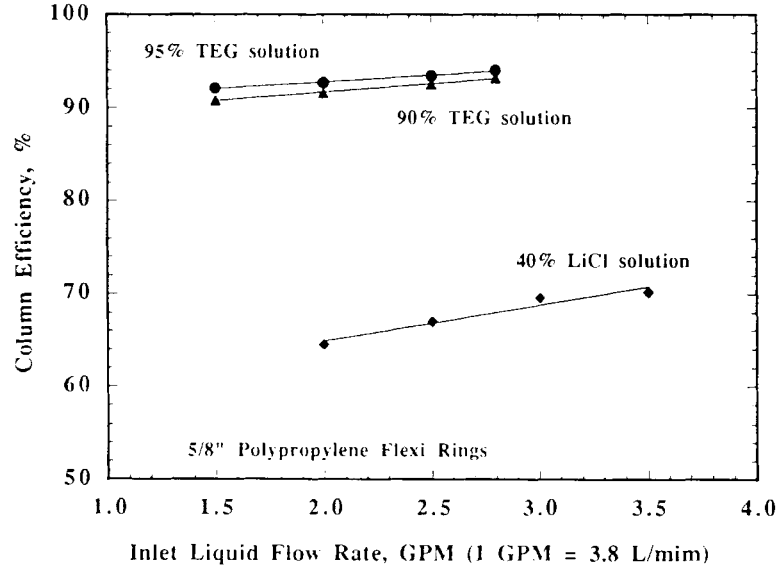


FIGURE 2. Effect of inlet air and liquid flow rates on column efficiency for triethylene glycol and lithium chloride solutions in a column packed with 5/8-inch polypropylene Flexi rings.

TABLE 2. COMPARISON OF THE PERFORMANCE OF TRIETHYLENE GLYCOL AND LITHIUM CHLORIDE SOLUTIONS FOR DEHUMIDIFICATION OF AIR IN A PACKED COLUMN ARRANGEMENT

Liquid desiccants	Packings	Air flow rate (ft^3/min)	Liquid flow rate (gal/min)	Column efficiency (%)	Mass transfer coefficients (kmol/m^3s mole fraction)	Heat Transfer coefficients (kw/m^3K)	Height of a transfer unit (m)
95% TEG Solution	5/8"-Polypropylene Flexi Rings	25 - 40	1.5 - 2.8	92.1 - 95.0	0.207 - 0.282	2.66 - 4.49	0.14 - 0.17
	1/2"-Ceramic Intalox Saddles	15 - 22.5	1.5 - 1.7	93.7 - 96.3	0.127 - 0.172	2.86 - 5.00	0.12 - 0.15
	0.28"-Structured Cellulose	25 - 41	1.5 - 2.8	63.8 - 67.9	0.081 - 0.121	0.91 - 1.83	0.36 - 0.40
	0.28"-Structured PVC	37.5 - 60	1.5 - 3.0	67.4 - 73.6	0.137 - 0.207	2.45 - 6.90	0.31 - 0.36
40% LiCl solution*	5/8"-Polypropylene Flexi Rings	28 - 56	2.0 - 3.5	64.5 - 70.2	0.091 - 0.166	3.16 - 11.56	0.35 - 0.41
	1/2"-Ceramic Berl Saddles	22.5 - 36	1.0 - 2.5	73.7 - 78.1	0.092 - 0.142	4.17 - 8.03	0.28 - 0.32
	0.28"-Structured Cellulose	27.5 - 44	2.0 - 3.5	62.0 - 67.1	0.081 - 0.121	2.66 - 4.45	0.36 - 0.42
	0.28"-Structured PVC	40 - 55	2.5 - 4.0	66.7 - 71.6	0.138 - 0.196	4.48 - 7.16	0.33 - 0.37

* Chung et al. (5,7)

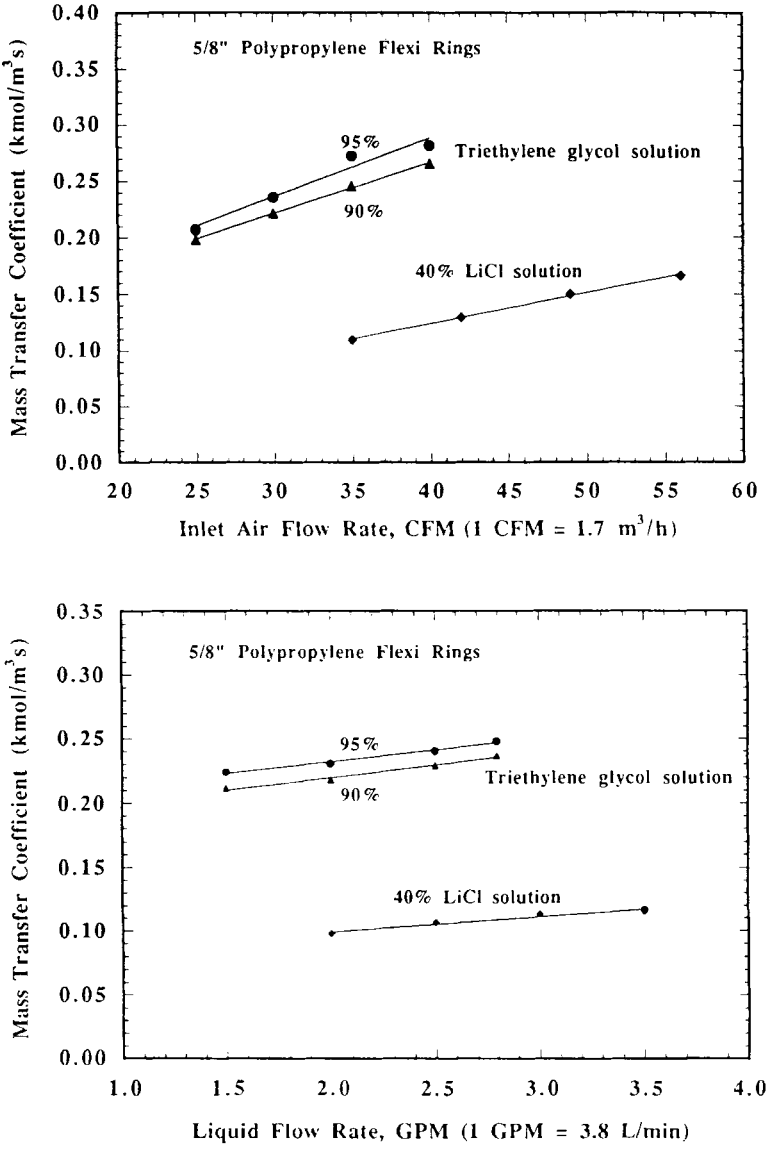


FIGURE 3. Effect in inlet air and liquid flow rates on the mass transfer coefficient for triethylene glycol and lithium chloride solutions in a column packed with 5/8-inch polypropylene Flexi rings.

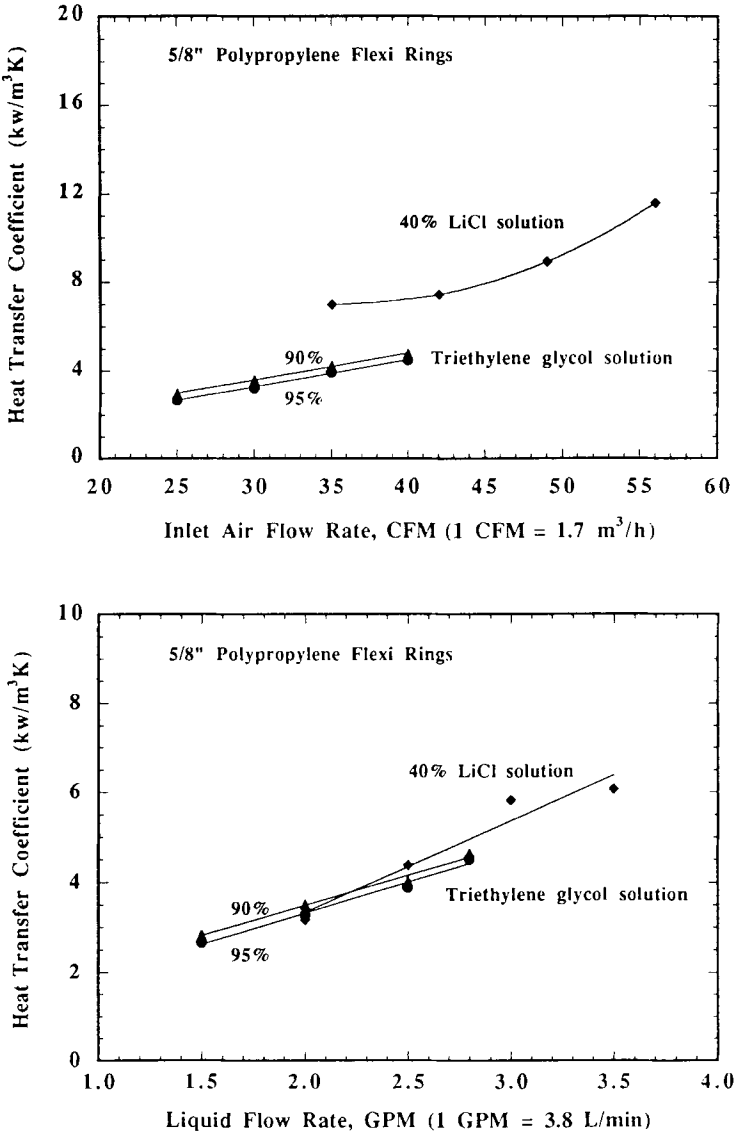


FIGURE 4. Effect of inlet air and liquid flow rates on the heat transfer coefficient for triethylene glycol and lithium chloride solutions in a column packed with 5/8-inch polypropylene Flexi rings.

more effectively between air and the lithium chloride solution than between air and the triethylene glycol solution. Therefore, the exit air temperature in a lithium chloride column was closer to the inlet liquid temperature. As expected, the heights of the transfer unit were also lower for the triethylene glycol systems, varying from 0.14 to 0.18 m. They varied from 0.28 to 0.34 m for the lithium chloride system. Since the same packing and column height were used for both systems, the lower height of the transfer unit was due to the better wetting of the packing surfaces by triethylene glycol. The heights of the transfer units for the two desiccants are compared in Figure 5.

When using triethylene glycol, the mass transfer coefficients were greater for the random packings than for the structured packings (see Figure 6). A similar result was observed for the height of a mass transfer unit. The size of a mass transfer unit for random packings ranged from 0.12 m to 0.17 m, whereas it was in the range of 0.31 m to 0.40 m for structured packings. Heat was transferred more effectively from the air to the triethylene glycol solution when using the structured PVC packing than when using either Flexi rings or cross corrugated cellulose packing. These results are shown in Figure 7. Neither the column efficiency nor the heat and mass transfer coefficients changed significantly when the glycol concentration was decreased from 95% to 90%. The liquid flow rates used in this study were based on the flooding conditions required to wet the packing surface uniformly, and they were several times higher than the flow rates obtained from equilibrium calculations.

The heat and mass transfer coefficients calculated from the experimental data by using Equations (1) and (3) for 5/8-inch polypropylene Flexi rings were employed to obtain the values of exponents for the random packing correlations. The correlation for the mass transfer coefficient predicted the data within ±10%. Errors in the predicted values for the heat transfer coefficient were in the range of 0.1% to 10%. Later the same heat and mass transfer correlations were used (without any modification of exponent values) to correlate the data obtained with 1/2" ceramic Intalox saddles. The results are shown in Figure 8. As can be seen from the figure, errors in the predicted values were within ± 10% for both correlations. The mass transfer correlations developed by Onada et al. (11) and Bolles and Fair (12) for an absorption-stripping system gave a large error when used to correlate the present data. However, it should be noted that their correlations were intended for use when employing a pure solvent. Chung et al.

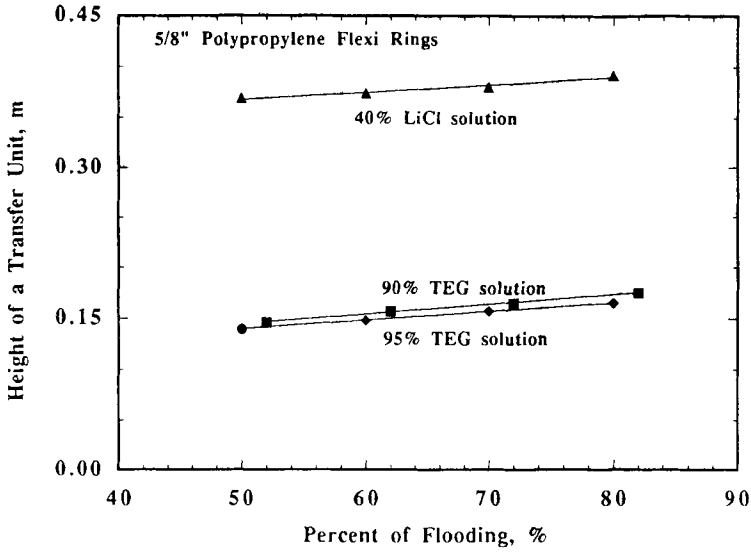


FIGURE 5. Change in height of a transfer unit as a function of percent of flooding for triethylene glycol and lithium chloride solutions in a column packed with 5/8-inch polypropylene Flexi rings.

(7) also reported a large error when correlating the mass transfer data for lithium chloride-water dehumidification systems. The proposed correlations gave a better result because the change in the driving force due to the change in the solution concentration was taken into consideration in these equations.

The data obtained with cross corrugated cellulose and PVC based packings were used to test the correlations for structured packings. Predicted values were within ±10% of the experimental data. The results are shown in Figure 9.

REMOVAL OF INDOOR POLLUTANTS

Pollutants were introduced into the system individually, as binary mixtures with formaldehyde, and together as a multicomponent mixture. The pollutants and

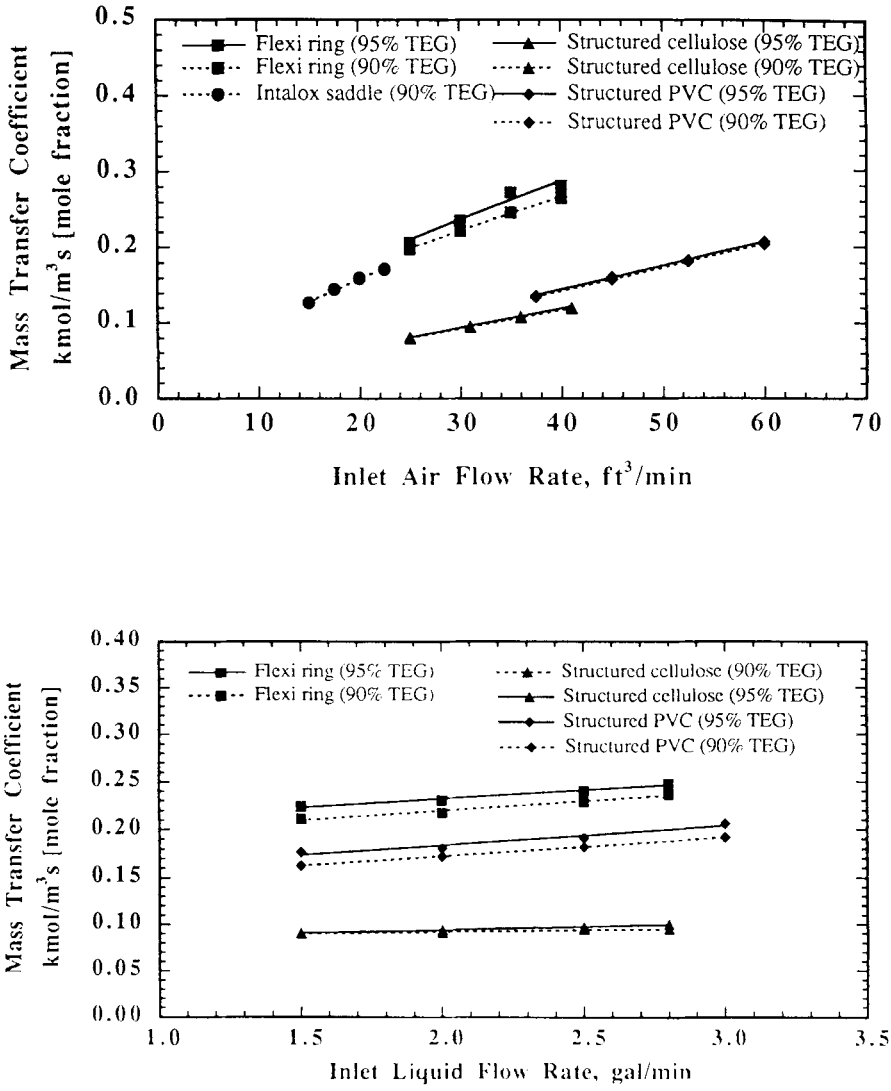


FIGURE 6. Effect in inlet air and liquid flow rates on mass transfer coefficient for triethylene glycol solutions in a packed column.

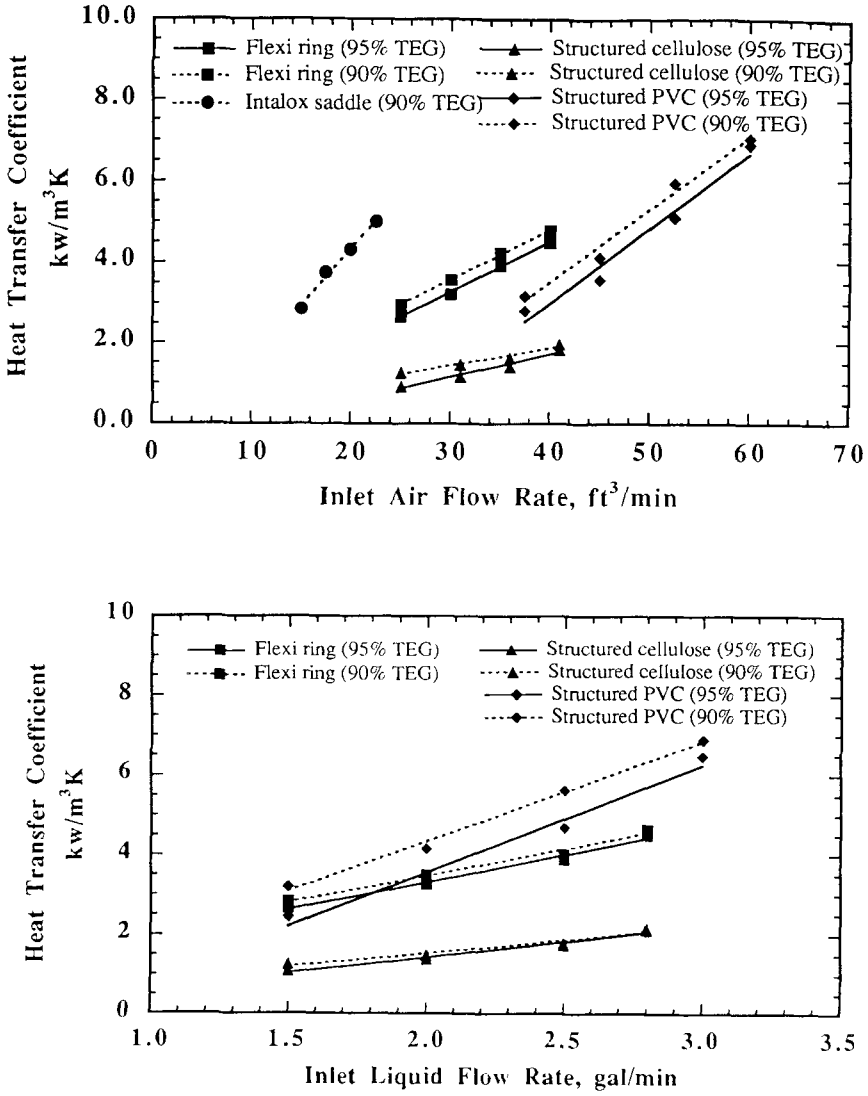


FIGURE 7. Effect of inlet air and liquid flow rates on the heat transfer coefficient for triethylene glycol solutions in a packed column.

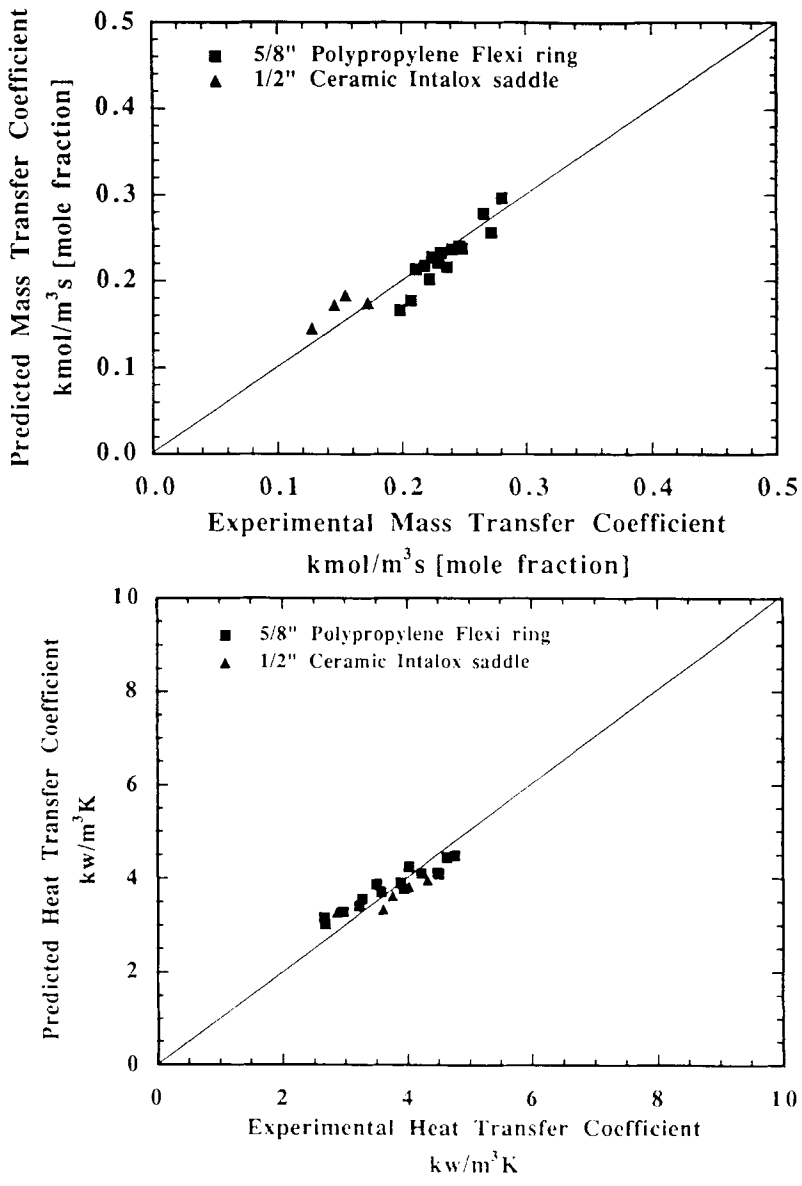


FIGURE 8. Comparison between predicted values and experimental data for mass and heat transfer coefficient for random packings when using triethylene glycol solutions for dehumidification of air.

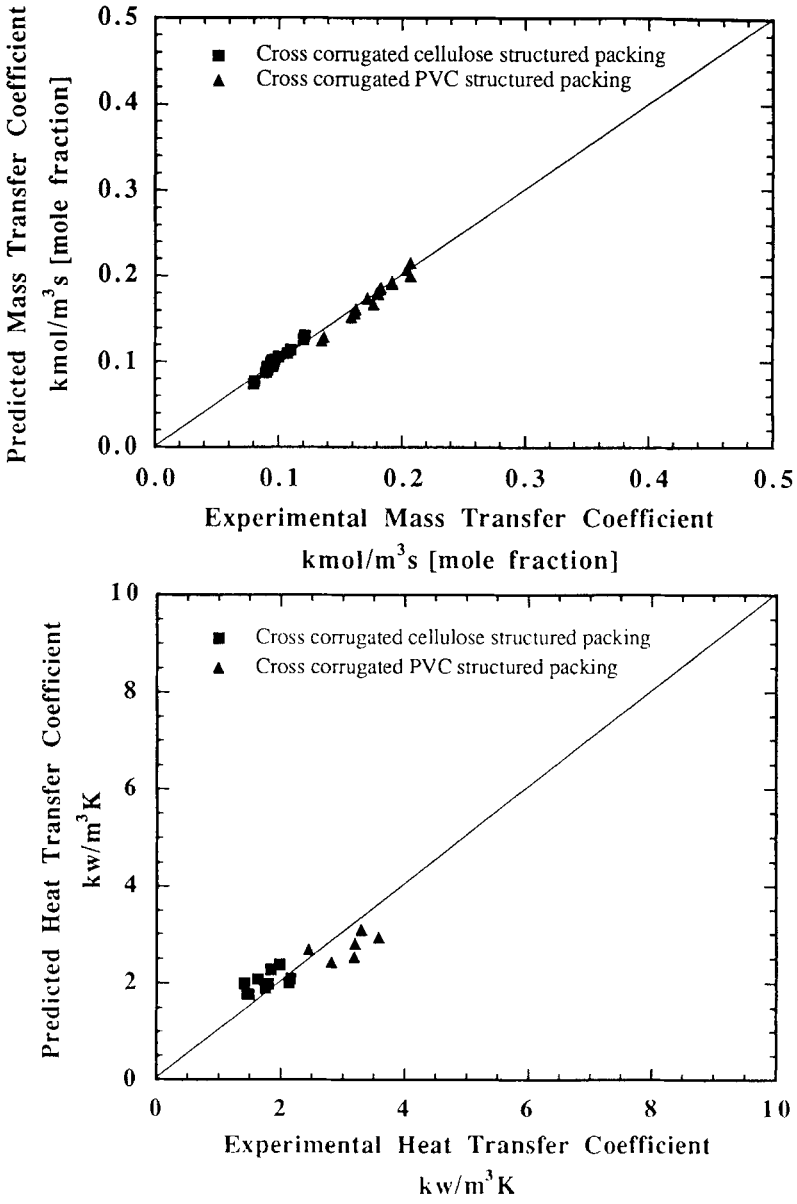


FIGURE 9. Comparison between predicted values and experimental data for mass and heat transfer coefficients for structured packings when using triethylene glycol for dehumidification of air.

their concentrations are as follows: carbon dioxide – 1000 ± 10 ppm, formaldehyde – 20 ± 5 ppb, toluene – 3 ± 0.1 ppm, and trichloroethane – 24 ± 1 ppm. For this work the column was packed with 5/8-inch polypropylene Flexi rings. The humidity of the air-pollutant mixture was varied from about 20% to 80%. The percent removal of each pollutant is given in Table 3. Approximately 100% removal was achieved for both toluene and trichloroethane, whereas only about 50% carbon dioxide and 25% formaldehyde were removed. The same level of removal efficiency was noted when all pollutants were present in the air mixture. The data provided in Table 3 were obtained after the system reached steady state, which required about 15 minutes. However, the experiments were continued for 7 to 8 hours, during which time the outlet concentration of the pollutants remained constant. The relative humidity of air had little or no effect on the removal of the pollutants since the removal depends on the gas phase concentration of pollutants and their solubility in the solvent, which contained from 90% to 95% triethylene glycol.

Solubilities of these pollutants in triethylene glycol and water are given in Table 4. Toluene, 1,1,1-trichloroethane, and carbon dioxide have a higher solubilities in triethylene glycol than in water, which may be due partly to the stronger dipole moment of triethylene glycol.

Although carbon dioxide has a very weak dipole moment, it has a rather strong quadrupole moment, which results in a stronger interaction with hydroxyl groups of triethylene glycol. Triethylene glycol has four hydroxyl groups compared to only one for water. Takahasi et al. (13) noted from their experimental study that the solubility of CO_2 in triethylene glycol decreased as its water content increased. Chang and Rousseau (14) also observed a similar phenomenon while studying solubilities of CO_2 in methanol-water mixtures.

Interestingly, only 50% of the formaldehyde, which has a stronger dipole moment than 1,1,1-trichloroethane, could be removed by the triethylene glycol solution from air compared to a about 100% removal of 1,1,1-trichloroethane. This may be due to strong self-association of triethylene glycol molecules. The chloride group can withdraw electrons from neighboring atoms, which increases its electron density, making it more electronegative. Therefore, 1,1,1-trichloroethane was able to form a strong bond with triethylene glycol molecules.

Concentrations of pollutants (solutes) in this study were in the parts per million range. Although Henry's Law is expected to be applicable for these

TABLE 3. INDOOR POLLUTANTS REMOVAL CAPABILITY OF 95% TRIETHYLENE GLYCOL SOLUTION

Pollutants	Relative Humidity %	Inlet Air Temperature °F	Liquid Temperature °F	Efficiency of removal* by 95% Triethylene Glycol Solution, %			
				Formaldehyde (20 ppb)	Carbon dioxide (1000 ppm)	Toluene (3 ppm)	1,1,1-Trichloroethane (24 ppm)
Formaldehyde	19.5	82.9	62.6	30			
	68.4	76.2	67.5	27			
Carbon dioxide	21.1	80.0	63.6		56		
	64.2	75.2	68.1		48		
Toluene	20.0	81.5	63.6			~ 100	
	79.0	81.0	67.1			~ 100	
1,1,1-Trichloroethane	19.5	82.5	64.7				~ 100
	78.7	75.9	66.7				~ 100
Formaldehyde + Carbon dioxide	17.2	87.9	68.0	23	51		
	68.0	76.2	67.5	20	48		
Formaldehyde + Toluene	24.1	76.2	60.4	29		~ 100	
	65.0	76.0	60.0	26		~ 100	
Formaldehyde + 1,1,1-Trichloroethane	21.3	80.0	69.2	26			~ 100
	78.7	79.0	69.0	25			~ 100
Formaldehyde + Carbon dioxide+ Toluene+ 1,1,1-Trichloroethane	23.5	77.1	61.2	26	54	~ 100	~ 100
	78.0	77.0	61.0	24	50	~ 100	~ 100

*Efficiency of removal = $\frac{\text{Inlet Conc. - Outlet Conc.}}{\text{Inlet Conc.}}$

TABLE 4. SOLUBILITY OF SELECTED POLLUTANTS IN WATER AND TRIETHYLENE GLYCOL AT 25°C

	Solubility (mole of solute/g of solvent)	
Solute (Polluatnt)	Water	Triethylene glycol
Carbon dioxide	2.86×10^{-5}	5.45×10^{-5}
Formaldehyde	1.23×10^{-2}	—
Toluene	3.01×10^{-6}	2.40×10^{-3}
1,1,1-Trichloroethane	7.5×10^{-6}	8.73×10^{-3}

systems, a deviation from Henry's Law may result even at very low solute concentrations due to the chemical reactions or dissociation of the solute molecules in the solvent. No attempt was made to study the chemical effect in these systems, but it can be seen from Table 3 that a synergistic effect was not observed when binary or quaternary mixtures of solute gases were studied. In the absence of a chemical reaction, it may be assumed that the solubility of each gas is independent of the other and the solubility of the individual species is determined by its own partial pressure. This phenomenon has been observed in this study. The percent removal of each pollutant remained about the same when they were present together in a mixture and as a single component.

NOMENCLATURE

a	Specific interfacial surface area of a packing, m^2/m^3
c_{pw}	Heat capacity of water vapor, kJ/kg.K
c_{pair}	Heat capacity of dry air, kJ/kg.K
c_{pv}	Heat capacity of the gas phase, kJ/kg.K
D_c	Column diameter, m
d_{eq}	Equivalent diameter for structured packings, m
d_p	Diameter or nominal size of random packings, m
D_v	Diffusion coefficient for key component, m^2/s

G	Superficial molar velocity of air, kmol/s·m^2
G'	Gas mass velocity, kg/m^2·s
h_{GA}	Heat transfer coefficient, kw/m^2·K
H_{OG}	Height of a transfer unit, m
k_v	Gas thermal conductivity, w/m·K
K_{GA}	Overall gas phase mass transfer coefficient, kmol/s·m^2·[mole fraction]
L'	Liquid mass velocity, kg/m^2·s
M_t	Molecular weight of the solute, kg/kmol
Pr_v	Prandtl number ($c_{pv}/\rho_v D_v$)
Re_v	Reynolds number ($d_c V \rho_v/\mu_v$)
Sc_v	Schmidt number ($\mu_v/\rho_v D_v$)
t_i	Temperature at the gas-liquid interface, K
$t_{G_{in}}$	Temperature of air at the inlet, K
$t_{G_{out}}$	Temperature of air at the outlet, K
V	Velocity of air through the column, m/s
W_{in}	Water content of inlet air stream, g/kg of dry air
W_{out}	Water content of outlet air stream, g/kg of dry air
W_{equ}	Water content of the air at equilibrium with the desiccant solution at a particular concentration and temperature, g/kg of dry air
X	Mass fraction of the solute in liquid solution, kg/kg
y_A	Mole fraction of water vapor in the bulk phase, kmol/kmol of gas mixture
$y_{A,a}$	Mole fraction of water vapor at the top of the column, kmol/kmol of gas mixture
$y_{A,b}$	Mole fraction of water vapor at the bottom of the column, kmol/kmol of gas mixture
y_A^*	Equilibrium mole fraction of water vapor in the air, kmol/kmol of gas mixture
Z	Height of packing, m
ρ_v	Density of gas, kg/m^3
μ_v	Viscosity of the gas phase, kg · m/s

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