

Table 1 Physical properties of liquids investigated

Liquid	Temp. [°C]	Density $\rho_L \times 10^{-3}$ [kg/m ³]	Viscosity $\mu_L \times 10^3$ [kg/m·sec]	Surface tension $\sigma \times 10^3$ [kg/sec ²]	$\mu_L^4 g / \rho_L \sigma^3$ [—]
Water	20.0	1.00	1.00	72.0	2.63×10^{-11}
8 wt % aq. methanol sol.	18.1	0.985	1.33	59.5	1.48×10^{-10}
15 wt % aq. methanol sol.	16.0	0.974	1.71	51.0	6.49×10^{-10}
53 wt % aq. methanol sol.	12.5	0.911	2.02	38.2	3.21×10^{-9}
35 wt % aq. cane sugar sol.	14.0	1.156	5.18	73.6	3.80×10^{-9}
50 wt % aq. cane sugar sol.	16.4	1.233	19.20	75.5	2.51×10^{-6}

vertical difference among the lines in Fig. 2 may be due to the difference in the value of the dimensionless group $\mu_L^4 g / \rho_L \sigma^3$. The values of $\mu_L^4 g / \rho_L \sigma^3$ for the liquids investigated are given in Table 1. In Fig. 3, the values of $E_L / \sqrt{D_T^3 g}$ read from Fig. 2 at a constant $u_G / \sqrt{D_T g}$ value of 0.10 are plotted against $\mu_L^4 g / \rho_L \sigma^3$ on logarithmic coordinates. Data points fall on a straight line with a slope of -0.03 , indicating that $E_L / \sqrt{D_T^3 g}$ should be proportional to $(\mu_L^4 g / \rho_L \sigma^3)^{-0.03}$.

From the results described above, the following equation correlating the experimental data was obtained:

$$\left(\frac{E_L}{\sqrt{D_T^3 g}}\right) \left(\frac{\mu_L^4 g}{\rho_L \sigma^3}\right) = 0.037 + 0.188 \left(\frac{u_G}{\sqrt{D_T g}}\right)^{0.72} \quad (4)$$

Figure 4 shows the comparison of the observed values of E_L presented in Figs. 1 and 2 with the values of E_L calculated from Eq. (4). The observed values are in good agreement with the calculated values, with an average deviation of 3.2%.

Nomenclature

D_T	= column diameter	[m]
d_0	= diameter of gas inlet nozzle	[cm]
E_L	= liquid-phase longitudinal dispersion coefficient	[m ² /sec]

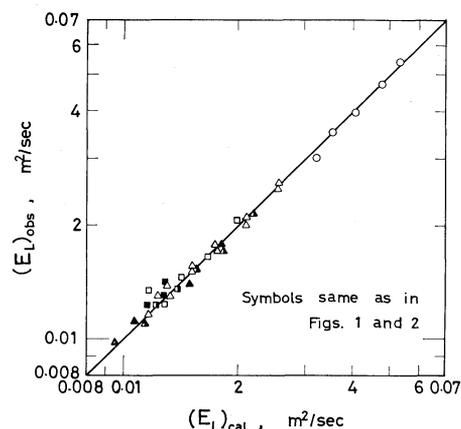


Fig. 4 Comparison of observed and calculated values of liquid-phase dispersion coefficient

g	= gravitational acceleration	[m/sec ²]
u_G	= superficial gas velocity	[m/sec]
Z_F	= aerated liquid height	[m]
ρ_L	= density of liquid	[kg/m ³]
μ_L	= viscosity of liquid	[kg/m·sec] or [cP]
σ	= surface tension of liquid	[kg/sec ²]

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ON THE LOW REYNOLDS NUMBER MASS TRANSFER IN PACKED BEDS

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Considerable experimental information is available in the literature on the particle-fluid heat and mass transfer in packed beds^{1,10}. For the most part, these efforts are confined to the measurement of transfer rates to gases and liquids flowing at moderate

and high flow rates. Low rate data, especially for solid-liquid systems, are scanty and are mainly for spherical particles. In the present work new mass transfer rate data are obtained by measuring the rate of dissolution of compressed benzoic acid pellets into water and 60% aqueous propylene glycol solutions.

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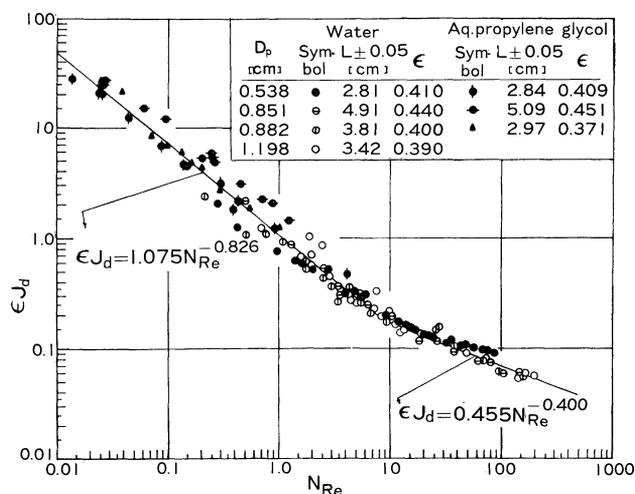
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Table 1 Pellet characteristics

Thickness [cm]	Diameter [cm]	D_p [cm]
0.488	1.276	1.198
0.275	0.960	0.851
0.449	0.876	0.882
0.246	0.554	0.538

Table 2 Range of the parameters covered

Column dia. [cm]	4.268
Particle density [g/cm ³]	1.252—1.290
Active bed height [cm]	(2.81—5.09)±0.05
Void fraction	0.371—0.451
N_{Re}	0.01—150
N_{Sc}	767—42400

**Fig. 1** ϵJ_d vs. N_{Re} plot

Experimental

The experimental set-up and procedure employed were very similar to those used by others^{8,9,11}. Distilled water or 60% aqueous propylene glycol flowed upward through a packed bed of known weight of benzoic acid pellets (weighed to the nearest 0.05 mg) sandwiched between two inert layers of 6 mm glass beads. The test column was a Pyrex glass tube of 4.27 cm inside diameter and 50 cm length. The glass bead layers were used to minimise end effects. The flow rate during a run was determined by collecting the exit stream for a known interval of time. Inlet and outlet temperatures were also recorded. The mass transfer rate was determined by finding the weight loss of the bed pellets after drying them to a constant weight in a desiccator at the end of the run. Each run lasted for a period of 20 ± 1 minutes which was accurately timed. For runs using aqueous propylene glycol solutions, the bed pellets were washed with saturated aqueous benzoic acid solution before drying in the desiccator.

In a separate set of blank runs, the loss in weight, during charging of the pellets to the test column and

their removal from the same and during their washing with saturated aqueous benzoic acid solution (only for runs using aqueous propylene glycol), was determined. At least ten such measurements were made for each pellet size and the mean of these in each case was used as the correction factor. The correction factor increased with decreasing pellet size and ranged from 2.3 to 20% of the total weight loss during a run. Those runs where the correction factor was more than 20% of the total weight loss were rejected. The loss in weight by sublimation during drying in the the desiccator was not appreciable, hence no correction was considered necessary. The measured weight losses during the runs were corrected by subtracting the appropriate correction factors.

Measurements were made with four cylindrical pellets of benzoic acid. The pellet characteristics are listed in **Table 1**. The pellet diameter and thickness for a particular size are the mean of respective measurements made on fifty randomly chosen samples. Fresh pellets were used for each run. Void fraction of the bed was determined from the weight of the pellets in the active bed and its mean height. The measured mass transfer rates were converted to the mass transfer coefficient and then to the mass transfer factor. Superficial flow velocities were used in calculating the Reynolds number and mass transfer factor. Diffusivity and solubility data for benzoic acid in water were those used by other^{6,8,9}. For 60% aqueous propylene glycol these were taken from Steinberger and Treybal⁷. The range of the major variables covered is given in **Table 2**, and complete data is given elsewhere⁵.

Discussion

As reported by previous investigators^{8,9}, mass transfer coefficients decrease with increasing pellet size. At very low flow rates ($u \leq 0.02$ cm/sec), the k_c values for various pellet sizes are nearly the same. This is probably due to the increased predominance of natural convection over forced convection at very low flow rates.

Various alternative correlations⁹ were tried for correlating the data and the regression analysis results indicated that

$$\epsilon J_d = 1.075 N_{Re}^{-0.826}, \text{ for } N_{Re} < 10 \quad (1)$$

and

$$\epsilon J_d = 0.455 N_{Re}^{-0.400}, \text{ for } N_{Re} > 10 \quad (2)$$

correlate the data with least deviations. The respective average deviations are ± 19.3 and 9.4%. Equations (1) and (2) are compared with the experimental data in **Fig. 1**. The above equations corroborate the conclusions of Gupta *et al.*², Sengupta and Thodos⁴ and Wilson and Geankoplis¹², on the

inverse proportionality between transfer factor and void fraction.

Acknowledgment

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Nomenclature

A_p	= particle surface area	[cm ²]
D	= molecular diffusivity	[cm ² /sec]
D_p	= particle diameter, $\sqrt{A_p/\pi}$	[cm]
J_d	= mass transfer factor; $(k_c/u)(N_{Sc})^{2/3}$	[—]
k_c	= mass transfer coefficient	[cm/sec]
L	= active bed height	[cm]
G	= superficial mass flow rate	[g/cm ² ·sec]
N_{Re}	= Reynolds number; $D_p u \rho / \mu$ or $D_p G / \mu$	[—]
N_{Sc}	= Schmidt number; $(\mu / \rho D)$	[—]
ϵ	= void fraction	[—]
μ	= viscosity	[cm·sec]
ρ	= density	[g/cm ³]

EXPERIMENTAL STUDIES ON MASS TRANSFER RATE AROUND SINGLE OSCILLATING DROPS IN LIQUID-LIQUID SYSTEMS

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In a previous paper⁷⁾, we presented experimental results on mass transfer rate in the dispersed phase and moving behavior for single liquid drops falling or rising with oscillation mode of oblate-prolate type.

This work is an extension of the previous study, aimed at obtaining mass transfer rates in the continuous phase around single liquid drops moving with oscillation through stationary liquid fields.

Experimental

The experimental apparatus and procedure were essentially the same as described in the previous paper⁷⁾.

Experimental systems and their physical properties measured at each experimental temperature are shown in **Table 1**. The solute as the third component of the systems was iodine, which was transferred from the continuous aqueous phase to the organic drops. The distribution coefficients of iodine as reported in the

previous paper are so large in favour of the organic solvent phase that the resistance to mass transfer can be considered to be exclusively in the aqueous phase. The water used as the continuous phase was deionized water distilled in an all-glass flask. The organic liquids benzene, carbon tetrachloride and glycerine were special-grade chemicals and were used without further purification.

Experimental Results and Discussion

The experimental values of $N/\{(C_0 - C^*)A\}$ were plotted against the residence times of the drops moving through the continuous phase in Cartesian coordinates. The relations were given by good straight lines for all series of the runs. Consequently, the mass transfer coefficients (k_c) in the continuous phase around a single drop moving with oscillation were obtained from the slopes of the straight lines. In **Fig. 1** the results of the mass transfer coefficients are plotted against the equivalent drop diameters for the system of benzene drops in water.

The terminal velocity decreased with increase in drop diameter. This tendency is in agreement with

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