Mass Transfer in Nonuniform Packing

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Many processes of interest to chemical engineers involve heat or mass transport from particles comprising a packed bed to a surrounding interstitial fluid. Among these may be found chromatography, coal gasification, combustion, ion exchange, drying, adsorption, and numerous fluid-solid catalytic reactions. In each of these operations, transfer from the fluid phase to the particulate phase becomes a possible rate determining step, and hence considerable effort has been expended toward developing reliable correlations for fluid-solid transport coefficients. A recent review by Karabelas et al. (1971) records some 28 such investigations toward this end. In spite of this abundance of work, there appears to have been little study directed toward ascertaining the possible effects, if any, of a disperse distribution of particle sizes upon the fluid-solid transfer coefficients. It appears that previous studies have been restricted to packings having an essentially uniform particle size distribution with no systematic variation in size distribution having been examined. The present research seeks to improve this situation by providing experimental measurements of mass transfer coefficients in packings having several well-defined, disperse particle size distributions. This particular study was motivated by the need to estimate mass transfer rates from the surface of granular refuse piles having in fact a wide range of particle sizes.

In contrast to the situation with respect to mass transfer, several investigations have been made concerning the effect of particle size distribution upon momentum transfer. Thus, Gauvin and Katta (1973) and Jacks and Merrill (1971) indicate that the Ergun equation, using a mean particle diameter based upon the hydraulic radius, satisfactorily predicts the pressure drop in packed beds having moderately disperse size distributions. In a mixture containing m discrete sizes of spheres with n_i spheres of diameter d_i in each size group, this hydraulic mean diameter is given by

$$D_p = \sum_{i=1}^{m} n_i d_i^3 \Big/ \sum_{i=1}^{m} n_i d_i^2 \qquad (1)$$

The research conducted here considers using this mean diameter for characterizing mass transfer coefficients in nonuniform packings.

EXPERIMENTAL METHOD

Benzoic acid-water mass transfer experiments were conducted using spherical packings having the four different particle size distributions shown in Table 1. Benzoic acid particles were produced using a special coating technique developed in this laboratory (Fuller et al., 1974). All runs were made in a 10-cm I.D. by 38-cm long plexiglass column. A 5-cm section of active packing was preceded and followed by 10 cm and 5 cm, respectively, of inert packing having the same size distribution. The packing was introduced by random pouring of groups containing small numbers of spheres, each group having the same size distribution as the total mixture. This method yields a loose random packing as defined by Haughey and Beveridge (1969). The bed porosity was determined by counting the number of spheres contained in a given volume. Additional experimental detail is given by Tan (1974).

RESULTS AND CONCLUSION

As shown in Figure 1, pressure drop measurements made using two mixtures yield reasonable agreement with the Ergun equation, as would be expected. The tendency for the data to fall below the asymptote of 1.75 at high N_{Re} was noted also by Jacks and Merrill (1971) who attributed the phenomenon to channeling caused by nonrandom packing, rather than a wall effect, or a failure of the mean hydraulic diameter to properly account for

TABLE 1. SIZE DISTRIBUTIONS USED AS MASS TRANSFER PACKING

	Relative number of spheres			D_p cm
Diameter, cm	1.02	1.42	2.30	
Mixture 1	3	2	1	1.70
Mixture 2	5	0	1	1.67
Mixture 3	0	1	0	1.42
Mixture 4	0	1	1	2.05

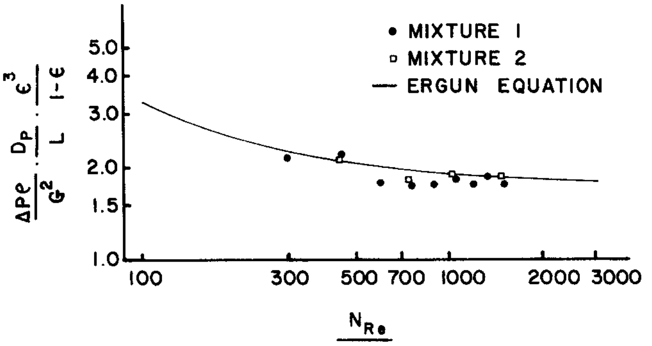

Fig. 1. Comparison of experimental pressure drop with prediction of Ergun equation.

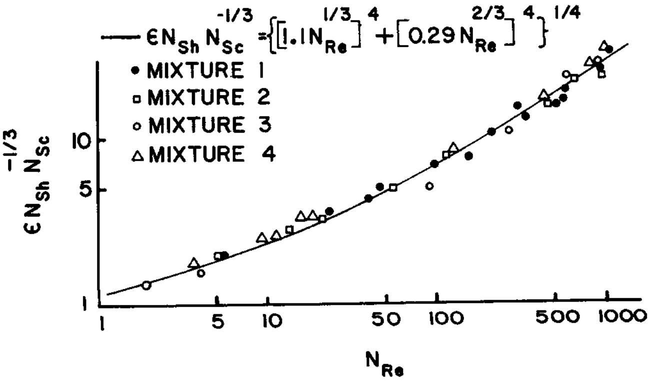

Fig. 2. Mass transfer data and correlation for nonuniform packing.

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the disperse size distribution.

Results of the 37 mass transfer runs made are presented in Figure 2. The nonuniform size distributions have been accounted for by the hydraulic mean diameter of Equation (1). From the figure, there appears to be no systematic deviation among the data for the different size distributions. Furthermore, the data have asymptotic forms corresponding to $N_{Sh} \rightarrow bN_{Pe}^{1/3}$ for small N_{Re} and $N_{Sh} \rightarrow cN_{Re}^{2/3}\ N_{Sc}^{1/3}$ for large N_{Re}. These asymptotic relations and the interpolation formula shown in Figure 2 were noted earlier by Karabelas et al. (1971) in the case of a uniform particle size distribution. Since the hydraulic mean diameter of Equation (1) remains valid in the limiting case of uniform particle size, one should expect the correlation shown in Figure 2 to agree with previous work. That this situation prevails may be seen upon comparison with results of Wilson and Geankoplis (1966), which are quite representative of earlier investigations:

$$\epsilon\, N_{Sh}\, N_{Sc}^{-1/3} = 1.09\, N_{Re}^{1/3}\ 0.0016 < N_{Re} < 55 \quad (2)$$

$$\epsilon\, N_{Sh}\, N_{Sc}^{-1/3} = 0.25\, N_{Re}^{0.69}\ 55 < N_{Re} < 1500 \quad (3)$$

Equations (2) and (3) are in essential agreement with the correlation in Figure 2. From the above, it is concluded that one can obtain reliable results by employing the hydraulic mean diameter when computing fluid-particle transfer coefficients in nonuniform packing.

ACKNOWLEDGMENT

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NOTATION

d_i = diameter of sphere in size group i, cm
D_p = mean particle diameter (equation 1), cm
D = molecular diffusivity, cm^2/s
G = superficial mass velocity, g/cm^2-s
k_L = mass transfer coefficient, cm/s
L = bed depth, cm
n_i = number of particles in size group i
N_{Re} = Reynolds number, UD_p/ν
N_{Pe} = Peclet number, UD_p/D
N_{Sh} = Sherwood number, D_pk_L/D
N_{Sc} = Schmidt number, ν/D
U = superficial velocity, cm/s
ϵ = porosity
ρ = density, g/cc
ν = kinematic viscosity, cm^2/s

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Generalized Equations of State for Compressed Liquids—Application of Pitzer's Correlation

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Volumetric properties of compressed liquids are often required in engineering calculations. The three-parameter generalized correlation of Pitzer et al. (1955) only covers the region for $0.8 \leq T_r \leq 1.0$ and $0 \leq P_r \leq 9$. Lu et al. (1973) recently extended the correlation to the $0.5 \leq T_r \leq 0.8$ and $0 \leq P_r \leq 9.0$ region.

These correlations are all in tabular forms. This makes it difficult for computer applications where large storage areas and iterative procedures would be necessary to use the correlation. The purpose of this investigation is to find a suitable analytic equation for the compressed liquid region.

DEFINITIONS

Pitzer (1955) introduced a third parameter called the *acentric factor* to extend the applicability of the theorem of corresponding state to normal fluids.

The acentric factor is defined as