

**Harriott P.** Mass transfer to particles: Part I. Suspended in agitated tanks. Part II. Suspended in a pipeline. *AIChE J.* 8:93-102, 1962. [American Cyanamid Company, Stamford, CT]

Mass transfer coefficients were measured for particles suspended in liquids in agitated tanks and in a pipeline. The effects of particle size, diffusivity, viscosity, density difference, and agitation variables were determined, and the effects of these variables were explained using a slip-velocity theory combined with a modified penetration theory. [The SCI® indicates that this paper has been cited in over 100 publications since 1962.]

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"I did this work while on sabbatical leave from Cornell University. I was interested in the design of chemical reactors for multiphase systems and saw the need for fundamental studies of mass transfer to drops, bubbles, or suspended particles. Hugh Hulbert offered me a position in his fundamental research group at American Cyanamid Company, and the cooperation I received from everyone in the group made it possible to carry out an extensive study in one year.

"My first idea was to study a chemical reaction such as hydrogenation in a slurry reactor and to separate the resistances involved in mass transfer from the bubbles and mass transfer to the solid catalyst from the overall resistance. However, possible problems of catalyst poisoning, pore diffusion, and bubble size determination made me seek a simpler system which involved only mass transfer to solids. Early studies of mass transfer to suspended solids used soluble particles such as salt crystals or organic

acids, but the change in size and shape during a test and crystal breakage introduce significant errors. For most of my experiments I used ion-exchange beads, which are nearly perfect spheres and can be reused many times. By choosing a dilute solution of NaOH to react with an acid-form resin, the external diffusion resistance becomes controlling, and the reaction can be followed by changes in pH or conductivity. Thus, I ended up using a chemical reaction to get mass transfer data, but a much simpler one than catalytic hydrogenation.

"The effects of agitation variables were quickly explored, since a charge of resin could be used for several consecutive runs, each at a different stirrer speed or position. Only a small fraction of the exchange capacity of the resin was used in one run, and check runs showed no effect of internal diffusion as the resin became nearly converted to the sodium form.

"One of the most satisfying experiments was to demonstrate that molecular diffusion was the predominant mass transfer mechanism, since some previous correlations for turbulent suspensions included the viscosity but not the diffusivity. To check this, I varied the viscosity ( $\mu$ ) by changing the temperature, which also changes the diffusivity ( $D$ ), and using a water-soluble polymer, which has hardly any effect on  $D$ . For the two series, the coefficient varied with about  $\mu^{-1.1}$  and  $\mu^{-0.3}$  respectively, indicating a dependence on about  $D^{0.7}$ . Tests with other solids such as benzoic acid, boric acid, and metal spheres confirmed the dependence on diffusivity and showed the slight effect of density difference.

"This paper has been frequently cited because it was the first to treat the problem of transfer to suspended solids from a fundamental standpoint, and it provided accurate data over a much wider range of properties than any previous study. The complete data for ion-exchange beads have been used by many authors of recent studies<sup>1,2</sup> to test or extend their correlations."

1. Levins D M & Glastonbury J R. Particle-liquid hydrodynamics and mass transfer in a stirred vessel. Part II—mass transfer. *Trans. Inst. Chem. Eng. London* 50:132-46, 1972.
2. Batchelor G K. Mass transfer from small particles suspended in turbulent fluid. *J. Fluid Mech.* 98:609-23, 1980.