HANDBOOK OF INDUSTRIAL MIXING

SCIENCE AND PRACTICE

Edited by

Edward L. Paul
Merck & Co., Inc.
Rahway, New Jersey

Victor A. Atiemo-Obeng
The Dow Chemical Company
Midland, Michigan

Suzanne M. Kresta
University of Alberta
Edmonton, Canada

Sponsored by the North American Mixing Forum

WILEY-INTERSCIENCE

A JOHN WILEY & SONS, INC., PUBLICATION

Cover: The jet image is courtesy of Chiharu Fukushima and Jerry Westerweel, of the Laboratory for Aero and Hydrodynamics, Delft University of Technology, The Netherlands.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

Library of Congress Cataloging-in-Publication Data:

Paul, Edward L.
Handbook of industrial mixing : science and practice / Edward L. Paul, Victor A. Atiemo-Obeng, Suzanne M. Kresta
p. cm.
"Sponsored by the North American Mixing Forum."
Includes bibliographical references and index.
ISBN 0-471-26919-0 (cloth : alk. paper)
1. Mixing—Handbooks, manuals, etc. I. Atiemo-Obeng, Victor A. II. Kresta, Suzanne M. III. Title.

TP156,M5K74 2003
660'.284292—dc21
2003007731

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

- *What happens to the suspension when agitation is increased?* Most solid–liquid mixing operations operate above the minimum speed for suspension. A higher agitation speed improves the degree of suspension and enhances mass transfer rates. The higher speed also translates into higher turbulence as well as local and average shear rates, which for some processes may cause undesirable particle attrition. Obviously, there is also a practical economic limit on the maximum speed of agitation.
- *What effect does vessel geometry have on the process?* The geometry of the vessel, in particular the shape of the vessel base, affects the location of dead zones or regions where solids tend to congregate. It also influences the minimum agitation speed required to suspend all particles from the bottom of the vessel. In flat-bottomed vessels, dead zones and thus "fillet formation" tend to occur in the corner between the tank base and the tank wall, whereas in dished heads the solids tend to settle beneath the impeller or midway between the center and the periphery of the base. The minimum agitation speed is typically 10 to 20% higher in a flat-bottomed vessel than in one with a dished head. Both the minimum agitation speed and the extent of fillet formation are also a function of impeller type, ratio of impeller diameter to tank diameter, and location of the impeller from the vessel bottom. In general, a dished-head vessel is preferred to a flat-bottomed vessel for solid–liquid mixing operations. There is little or no difference between ASME dished, elliptical, or even hemispherical dished heads as far as solid–liquid mixing is concerned. However, elliptical heads are preferred for higher-pressure applications.
- *What is the appropriate material of construction for the process vessel?* The main issue here is that, for steel or alloy vessels, the standard four wall-mounted baffles provide a better environment for solid–liquid mixing. The standard glass-lined vessels are usually underbaffled because of a deficiency of nozzles from which to mount baffles.

10-2 HYDRODYNAMICS OF SOLID SUSPENSION AND DISTRIBUTION

Solid suspension requires the input of mechanical energy into the fluid–solid system by some mode of agitation. The input energy creates a turbulent flow field in which solid particles are lifted from the vessel base and subsequently dispersed and distributed throughout the liquid. Nienow (1985) discusses in some detail the complex hydrodynamic interactions between solid particles and the fluid in mechanically agitated vessels. Recent measurements (Guiraud et al., 1997; Pettersson and Rasmuson, 1998) of the 3D velocity of both the fluid and the suspension confirm the complexity.

Solids pickup from the vessel base is achieved by a combination of the drag and lift forces of the moving fluid on the solid particles and the bursts of turbulent eddies originating from the bulk flow in the vessel. This is clearly evident in

Figure 10-1 Sudden pickup of solids by turbulent burst (Cleaver and Yates, 1973).

visual observations of agitated solid suspensions as in the video clip included on the accompanying CD ROM. Solids settled at the vessel base mostly swirl and roll around there, but occasionally, particles are suddenly and intermittently lifted up as a tornado might lift an object from the ground. An illustration of sudden pickup by turbulent bursts is shown in Figure 10-1.

The distribution and magnitude of the mean fluid velocities and large anisotropic turbulent eddies generated by a given agitator determine to what degree solid suspension may be achieved. Thus, different agitator designs achieve different degrees of suspensions at similar energy input. Also for any given impeller the degree of suspension will vary with D/T as well as C/T at constant power input. One of the video clips on the accompanying CD ROM shows the effect of D/T on solid suspension for a pitched blade impeller at constant power input.

For small solid particles whose density is approximately equal to that of the liquid, once suspended they continue to move with the liquid. The suspension behaves like a single-phase liquid at low solid concentrations; the mixing operation is more like blending than solid suspension. For heavier solid particles, their velocities will be different from that of the liquid. The drag force on the particles caused by the liquid motion must be sufficient and directed upward to counteract the tendency of the particles to settle by the action of gravity.

The properties of both the liquid and the solid particles influence the fluid–particle hydrodynamics and thus the suspension. Also important are vessel geometry and agitation parameters. The important fluid and solid properties and operational parameters include:

1. Physical properties of the liquid, such as:
   a. Liquid density, ρ_l (lb/ft^3 or kg/m^3)
   b. Density difference, $\rho_s - \rho_l$ (lb/ft^3 or kg/m^3)
   c. Liquid viscosity, μ_l (cP or Pa · s)
2. Physical properties of the solid, such as:
   a. Solid density, ρ_s (lb/ft^3 or kg/m^3)
   b. Particle size, d_p (ft or m)

   c. Particle shape or sphericity, ψ (dimensionless factor defined by the ratio of surface area of a spherical particle of the same volume to that of a nonspherical particle)
   d. Wetting characteristics of the solid
   e. Tendency to entrap air or headspace gas
   f. Agglomerating tendencies of the solid
   g. Hardness and friability characteristics of the solid
3. Process operating conditions, such as:
   a. Liquid depth in vessel, Z (ft or m)
   b. Solids concentration, X (lb solid/lb liquid or kg solid/kg liquid)
   c. Volume fraction of solid, ϕ
   d. Presence or absence of gas bubbles
4. Geometric parameters, such as:
   a. Vessel diameter, T (ft or m)
   b. Bottom head geometry: flat, dished, or cone-shaped
   c. Impeller type and geometry
   d. Impeller diameter, D (ft or m)
   e. Impeller clearance from the bottom of the vessel, C (ft or m)
   f. Liquid coverage above the impeller, CV (ft or m)
   g. Baffle type and geometry and number of baffles
5 Agitation conditions, such as:
   a. Impeller speed, N (rps)
   b. Impeller power, P (hp or W)
   c. Impeller tip speed (ft/s or m/s)
   d. Level of suspension achieved
   e. Liquid flow pattern
   f. Distribution of turbulence intensity in the vessel

10-2.1 Settling Velocity and Drag Coefficient

A dense solid particle placed in a quiescent fluid will accelerate to a steady-state settling velocity. This velocity, often called the *free* or *still-fluid settling velocity*, occurs when the drag force balances the buoyancy and gravitational force of the fluid on the particle. In an agitated solid suspension, because of the complex turbulent hydrodynamic field, including solid–solid interactions, it is difficult to clearly define and/or measure a particle settling velocity. However, the particle settling velocity in an agitated solid suspension is a function of the free settling velocity and is always less than the free settling velocity (Guiraud et al., 1997).

The magnitude of the free settling velocity has proven useful in characterizing solid suspension problems into easy, moderate, or difficult categories (see Table 10-2). It is also used in solid–liquid mixing correlations, as described below.