GARY B. TATTERSON

FLUID MIXING AND GAS DISPERSION IN AGITATED TANKS

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Preface

Mixing in agitated tanks is part of the infrastructure of the chemical, petrochemical, and biochemical industries. Practically every plant will contain some sort of tank mixing process. Unfortunately, such mixing is based upon fluid mechanics that are not taught in undergraduate and graduate fluid mechanics courses, and, as such, a fundamental understanding of tank mixing by plant personnel is seldom obtained. The general topic of mixing in agitated tanks should be properly developed in some manner since the understanding of mixing will directly aid commercialization of processes and retrofitting of existing processes. A specific example of an important and successful commercialization of a tank mixing process is penicillin production during World War II in which deep tank fermentation was utilized.

Mixing consumes a considerable portion of the processing time as material moves through a plant. The key issues in such processing are processing times and capacities. The convenient cycle times of 8 or 24 hours are no longer adequate. There is no justification to hold material which has been processed. Equally, many processes are undermixed and many are overmixed. Neither situation is particularly important in the sense of mixing. However, economically, these situations lead directly to unnecessary waste in processing capacity, time, and material. Processing of material has become too important in the present marketplace for mixing to be ignored, especially in processing high-technology materials and value-added materials.

Chemical reactions cannot take place between species unless they are mixed. If the reactions are fast, then the reaction rates, selectivity, and production rates are determined by the mixing rate. In heterogeneous systems, other considerations force the need for effective mixing. Mass transfer controlled processes are most often mixing controlled, "mass transfer controlled" being an inaccurate statement in many cases. Mixing lies at the heart of chemical reactor engineering since mixing times are necessary to be able to size chemical reactors in a rational manner. Safety considerations are also present in mixing. Accounts of industrial accidents where mixing was not maintained include "The Physicochemical Origins of the Sevesco Accident," by T. G. Theofanous (*Chem. Eng. Sci.*, **38**, 10, 1615–1625, 1983).

Mixing is no longer a unit operation. Mixing is the contacting mechanics of chemical processing. Unfortunately, mixing is usually taught as a unit operation and is, only occasionally included in undergraduate curriculum courses. Most commonly, a mixing experiment is included as part of a unit operations course. In such a situation, mixing cannot be properly understood by students. Mixing has basic principles and has contributions from many sectors. A major portion of fluid mechanics in chemical engineering is mixing, whether the flow is a circulation pattern on a tray of a distillation column or in a high-temperature twin screw extruder. However, mixing cannot be presented as simply as distillation because of its complexity. Much depends upon data correlations and evolving theory.

Whereas there are many specialized textbooks on such areas as distillation, extraction, and fluidization, books on mixing are sparse and are usually monographs written with rather limited reference listings. Most only explain the state of the art. No textbook is available from which a course on the fundamental principles of mixing can be taught. Further, only a few mixing courses are taught per year across the United States.

This book is designed to serve students, faculty, researchers, and practitioners. This book is meant to be an in-depth review of the literature, to present the fundamentals of mixing, to show what is known, and to provide the supporting documentation, references, and the different methods used to study mixing. The book establishes a course in mixing in which the fundamentals of laminar and turbulent fluid mechanics and transport are given at the intermediate undergraduate and graduate levels. Areas in need of research are noted or are made obvious by the discussion. The book provides the practitioners and professional engineers with the background necessary to be reasonably assured about design calculations, the limits of the design, and to assert the appropriateness of the methods used. Hopefully, they will appreciate the implications of mixing on design and plant operations.

In my opinion, design equations require some validation before their use, and the use of design equations without a fundamental understanding can lead to poor designs and mistakes. However, serious validation is difficult. One method of validation is in comparison of technical results in the open literature and with data. This book provides considerable technical references as would be needed. However, mixing is also a subject where individual contributions are important. As a result, one should recognize that results from author to author will vary due to geometric differences, different definitions of quantities, and different measurement techniques and fluid properties. The search for agreement and absolutes and the critical evaluation of the literature are difficult. Evaluation of the available studies from the cited literature can be accomplished in private and in a critical manner.

The acceptance of mixing as a subject worthy of study and research is also obvious. Mixing has progressed to the point where it can be taken as a serious subject warranting a place in curriculum of chemical and mechanical engineering as a second fluids course, much like a course on rheology or two-phase flow. The text can also be used to show the evolution of research in mixing. The different approaches, the different experimental techniques and results, and the basic principles which guide the research are included. This information would be useful in developing a sense for research which can be useful.

The individual chapters are structured such that the background and fundamentals are given first followed by specific literature. The book is divided into six chapters. Chapter 1 treats the general geometries involved in mixing. Differences in laminar mixing equipment and turbulent mixing geometries are discussed. Chapter 2 discusses the turbulent power numbers for various agitators from which mixing equipment can be sized. Chapter 3 provides the basic methods used to establish power numbers for laminar mixing. Chapter 4 discusses turbulence theories and turbulent mixing. Chapter 5 treats laminar mixing, and Chapter 6 treats gas dispersion in aerated agitated tanks.

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Gary B. Tatterson is a professor of chemical engineering at North Carolina A&T State University. He has published a number of journal articles, given many presentations, and organized professional society meetings dealing with mixing in agitated tanks. He has taught at Texas A&M University and the University of South Carolina. Dr. Tatterson has worked for E. I. Du Pont de Nemours & Company, the National Bureau of Standards, and the Morgantown Energy Technology Center. He holds a B.S. in chemical engineering from the University of Pittsburgh and M.S. and Ph.D. degrees from Ohio State University. He is a member of the American Institute of Chemical Engineers and is a past chair of Mixing, 3A. He is also an active member of the American Society of Mechanical Engineers and the Instrument Society of America.

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Chapter

1

Mixing Geometries

Introduction

Mixing in tanks is an important area when one considers the number of processes which are accomplished in tanks. Essentially, any physical or transport process can occur during mixing in tanks. As a portion of these, this book focuses on liquid mixing and gas dispersion in agitated tanks and will cover the following topics: power consumption in laminar and turbulent flow, fluid mechanics and flow fields in agitated tanks under conditions of laminar and turbulent flow, turbulence theory as applied to agitated tanks, and gas-liquid dispersion.

Typically, human beings will use a pot, a tank, or a vessel for processing liquids before most anything else, and they will have the desire to stir the material while processing. In a great percentage of these cases, they will find the processing results satisfactory and will end further investigations into other geometries or configurations for their processing unit. Hence, there is a need for this book. Other sources for technical literature and texts concerning mixing are available. Some of these are noted in the reference list at the end of this chapter.

There are basic tools which can be employed in the understanding of mixing. One tool is the general property balance written in all its forms, i.e., continuity, scalar balance, equations of motion, higher-level equations of motion, turbulent equations of motions, energy balances, population balances, etc. Dimensional analysis, flow analogies, computational fluid mechanics, experimental observations and data are also utilized extensively. Equations of state, constitutive models for fluids, and kinetic rate expressions are sometimes used. Models for mixing processes using these tools can either be lumped or distributed, depending upon the complexity of the processes.

Quite often, the mixing process of interest is not well understood. In these cases, qualitative and quantitative observations, experimental data, and flow regime identification are needed and should be emphasized in any experimental pilot studies in mixing. Considerable literature on mixing is devoted to the development of experimental techniques to obtain such information. There is a tendency to model mixing without first understanding the physics of the process. This tendency should be avoided.

Above all else, however, fluid mechanics and geometry are key to understanding mixing. The fluid mechanics transport the material about the tank, whereas the geometry determines, in part, the fluid mechanics. In fact, the geometry is so important that processes can be considered geometry specific. Solid suspension is very much dependent upon the shape of the tank bottom; gas-liquid and liquid-liquid dispersion depend upon the geometry of the impeller; blending, upon the relative size of the tank to the impeller; and power draw, upon the impeller geometry.

The Mixing Tank

Mixing tanks and impellers have come in all shapes and sizes. However, it was not until the late 1940s to early 1960s that a more or less standard geometry, shown in Fig. 1.1 for two different impellers, was established for single-phase mixing for the turbulent flow regime. The figure shows the tank diameter T, the impeller diameter D, the impeller blade width W, the off-bottom clearance C of the impeller, liquid height H, and wall baffles of width B. The dimensions are scaled upon the tank diameter for easy reference. This standard configuration evolved from power studies and should be viewed as a reference geometry and as a point of departure for studies in turbulent flow. The gross flow patterns using the disk style and pitched blade turbine impellers are also shown in the figure.

Any geometric configuration can always be criticized in mixing as not being the best or optimum geometry. However, the determination of the best geometry is very much a function of the process which is being carried out. The determination of true optimum geometry for any process is very difficult indeed.

The standard geometries in Fig. 1.1 are not the optimum geometry for all types of processing which can occur in a tank. A standard geometry for viscous or laminar mixing has not been established as yet. The geometries in Fig. 1.1 are far from adequate. Given the sophistication in laminar mixing, there may not be a need for a standard geometry in laminar mixing and, likewise, in other areas. In many respects, the standardization to a specific geometry has limited research

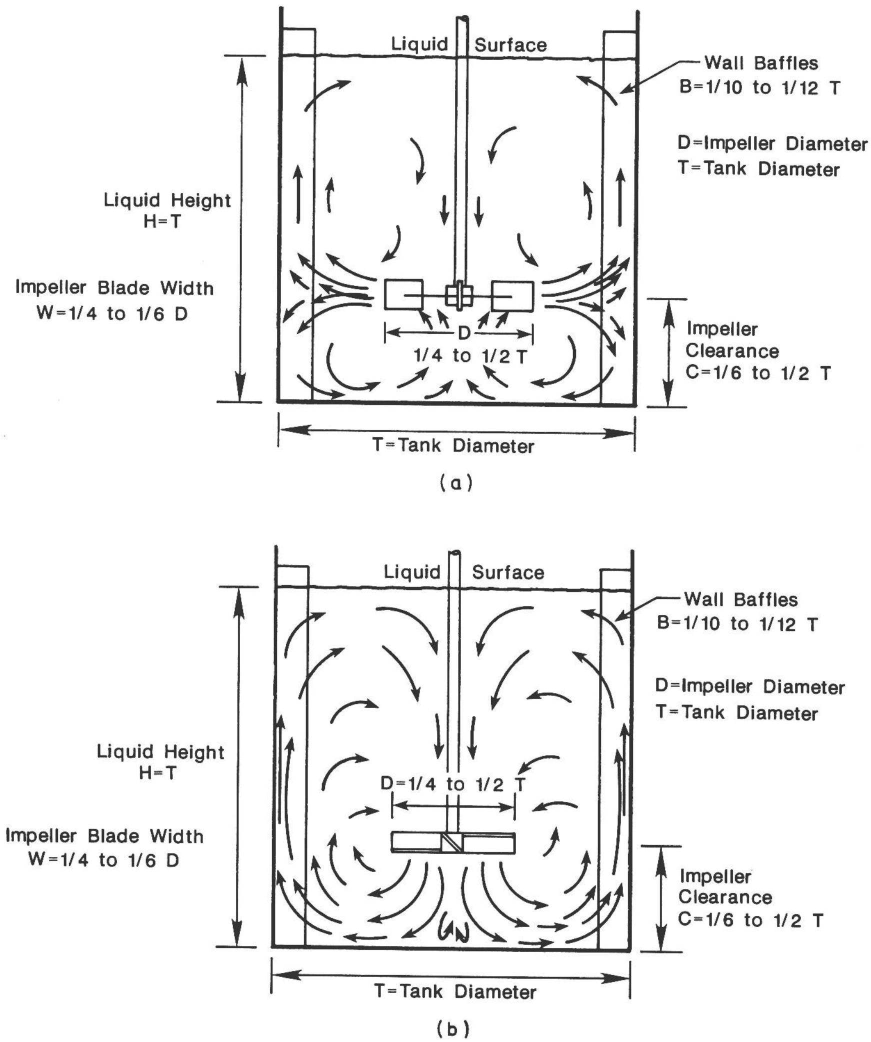

Figure 1.1 Turbulent mixing impellers. (*a*) Gross flow patterns for a radial flow impeller showing the standard tank geometry; (*b*) gross flow patterns for an axial flow impeller showing the standard tank geometry.

since it has been naturally assumed that the standard geometry is the optimum geometry.

The laminar to turbulent transition for an agitated tank occurs at an impeller Reynolds number $\rho ND^2/\mu$ from 1 to 10,000. The impeller Reynolds number is based upon the impeller tip speed πND, where N is the rotational speed in revolutions per time, not radians per time, and D is the impeller diameter. The thermodynamic viscosity μ used in the Reynolds number is the laminar viscosity for Newtonian fluids or the apparent viscosity μ_a for non-Newtonian fluids. Turbulent viscosities or eddy viscosities, μ_t or ν_t, are not used in defining the impeller Reynolds number.

Figure 1.1 shows tanks with standard wall baffles. Baffles are plates placed in the flow to disturb or redirect the flow. The most common types are wall baffles whose widths are usually expressed as a percentage, e.g., 10 percent, of tank diameter. There are also other baffle configurations: bottom baffles, surface baffles which float on the fluid surface, disk baffles placed on the impeller shaft, and baffles which are suspended from the surface at different radii. However, wall baffles have been well studied; they maximize power input to the fluid and minimize solid body rotation of the fluid in the tank, a situation which does not promote mixing.

In solid body rotation, Fig. 1.2, the fluid rotates as if it were a solid

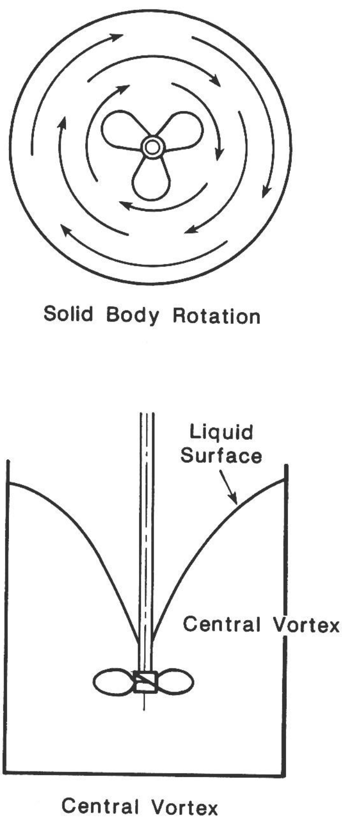

Figure 1.2 (*a*) Solid body rotation and (*b*) the central surface vortex.