Handbook of Industrial Mixing

INCLUDES CD-ROM

Science and Practice

Edited by

Edward L. Paul
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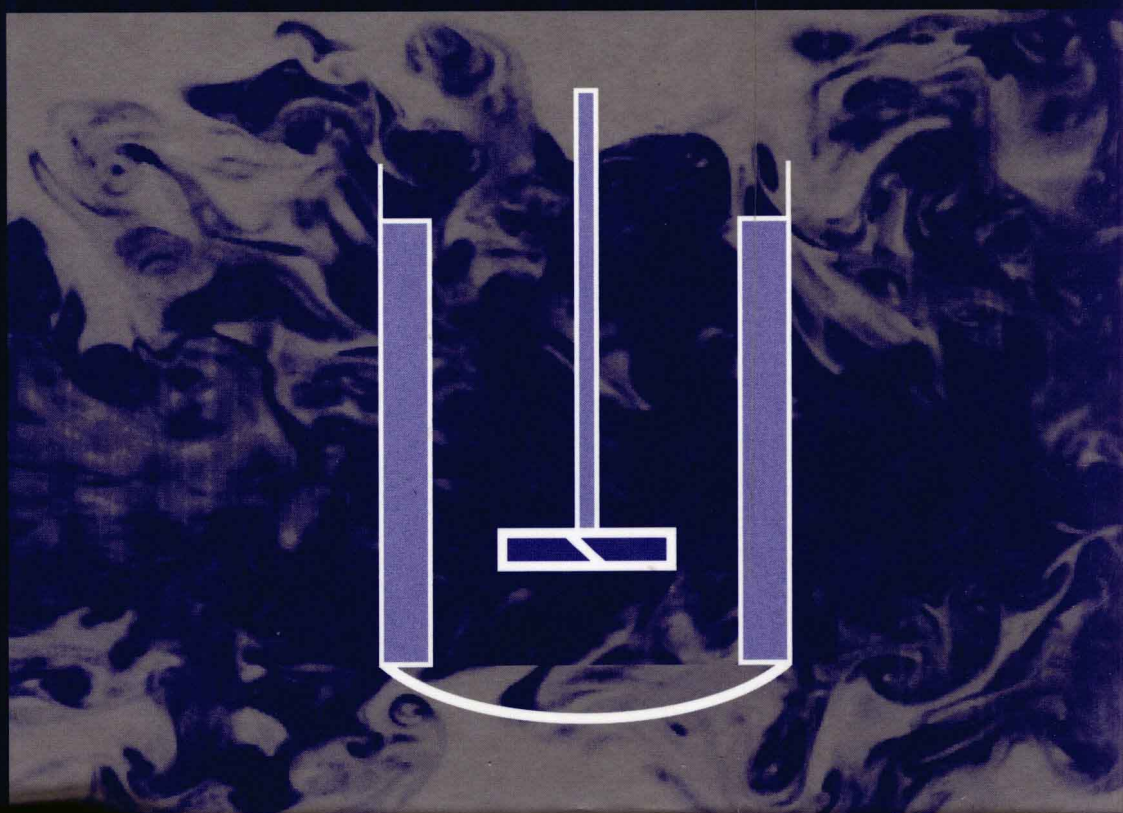

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INTRODUCTION

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Mixing as a discipline has evolved from foundations that were laid in the 1950s, culminating in the publication of works by Uhl and Gray (1966) and Nagata (1975). Over the last 30 years, many engineering design principles have been developed, and design of mixing equipment for a desired process objective has become possible. This handbook is a compilation of the experience and findings of those who have been most active in these developments. Together, the authors' experience extends over more than 1000 years of research, development, and consulting work.

This book is written for the practicing engineer who needs to both identify and solve mixing problems. In addition to a focus on industrial design and operation of mixing equipment, it contains summaries of the foundations on which these applications are based. To accomplish this, most chapters have paired an industrialist and an academic as coauthors. Discussions of theoretical background are necessarily concise, and applications contain many illustrative examples. To complement the discussions, a CD ROM is included which contains over 50 video clips and animations of mixing processes. These clips are accompanied by explanatory text. Internal cross-referencing and external references are used extensively to provide the reader with a comprehensive presentation of the core topics that constitute current mixing practice.

The core mixing design topics are:

- Homogeneous blending in tanks and in-line mixers
- Dispersion of gases in liquids with subsequent mass transfer
- Suspension and distribution of solids in liquids

- Liquid–liquid dispersions
- Heat transfer
- Reactions: both homogeneous and heterogeneous

Underlying principles are presented in chapters on:

- Residence time distribution
- Turbulence
- Laminar blending and flow

Additional information is provided on ways of investigating mixing performance:

- Experimental measurement techniques
- Computational fluid dynamics

These topics are augmented by chapters on specific industrial mixing topics:

- Solid–solid blending
- Polymer processing
- Fine chemical and pharmaceutical processes
- Fermentation and cell culture
- Petroleum
- Pulp and paper
- Mixing equipment: vessels, rotor–stators, and pipeline mixers
- Mechanical aspects of mixing equipment
- The vendor's role

At the end of this introduction, a set of charts is provided for the initial assessment of mixing related problems. These charts are designed to assist the reader who is meeting a mixing problem for the first time, and is unsure of where to start. They are not meant to replace the senior engineer or mixing specialist, who will typically be able to quickly evaluate the key issues in mixing-sensitive processes.

MIXING IN PERSPECTIVE

What is mixing? We define *mixing* as the reduction of inhomogeneity in order to achieve a desired process result. The inhomogeneity can be one of concentration, phase, or temperature. Secondary effects, such as mass transfer, reaction, and product properties are usually the critical objectives.

What constitutes a mixing problem? Process objectives are critical to the successful manufacturing of a product. If the mixing scale-up fails to produce the

required product yield, quality, or physical attributes, the costs of manufacturing may be increased significantly, and perhaps more important, marketing of the product may be delayed or even canceled in view of the cost and time required to correct the mixing problem.

Although there are many industrial operations in which mixing requirements are readily scaled-up from established correlations, many operations require more thorough evaluation. In addition to presenting the state of the art on the traditional topics, this book presents methods for recognition of more complex problems and alternative mixing designs for critical applications.

Failure to provide the necessary mixing may result in severe manufacturing problems on scale-up, ranging from costly corrections in the plant to complete failure of a process. The costs associated with these problems are far greater than the cost of adequately evaluating and solving the mixing issues during process development. Conversely, the economic potential of improved mixing performance is substantial. Consider the following numbers:

- *Chemical industry.* In 1989, the cost of poor mixing was estimated at $1 billion to $10 billion in the U.S. chemical industry alone. In one large multinational chemical company, lost value due to poor mixing was estimated at $100 million per year in 1993. Yield losses of 5% due to poor mixing are typical.
- *Pharmaceutical industry.* Three categories should be considered: costs due to lower yield (on the order of $100 million); costs due to problems in scale-up and process development (on the order of $500 million); and costs due to lost opportunity, where mixing problems prevent new products from ever reaching the market (a very large number).
- *Pulp and paper industry.* Following the introduction of medium consistency mixer technology in the 1980s, a CPPA survey documented chemical savings averaging 10 to 15% (Berry, 1990). Mills that took advantage of the improved mixing technology saw their capital investment returned in as little as three months.

From these numbers, the motivation for this handbook and for the research efforts that it documents becomes clear. The reader will almost certainly profit from the time invested in improved understanding of the design of mixing equipment. *Mixing equipment design must go beyond mechanical and costing considerations, with the primary consideration being how best to achieve the key mixing process objectives. Mixing solutions focus on critical issues in process performance.*

How much mixing is enough, and when could overmixing be damaging to yield or quality? These critical issues depend on the process and the sensitivity of selectivity, physical attributes, separations, and/or product stability to mixing intensity and time. The nonideality of residence time distribution effects combined with local mixing issues can have a profound effect on continuous processes.

Useful methods for mixing process development effort have been evolving in academic and industrial laboratories over the past several decades. They include improvements to traditional correlations as well as increasingly effective methods both for experiments and for simulation and modeling of complex operations. The combination of these approaches is providing industry with greatly improved tools for development of scalable operations. This handbook provides the reader with all the information required to evaluate and use these technologies effectively in process development and scale-up.

How should new mixing problems be solved? Solutions for new mixing problems require answers to the question "Why?" as well as the very pressing question "How?" This question is best addressed with a good understanding of both the process and the underlying fundamentals. This requires discussion with both operations and developmental chemists. It is often well served by reposing the question "How can we scale this up?" as "How can we scale down the process equipment to closely replicate plant conditions in the lab?" The importance of this question should never be underestimated, as it often opens the door for discussions of geometric similarity and matching of mixing conditions. Good experimental design based on an understanding of mixing mechanisms is critical to obtaining useful data and robust solutions. Engineers who ignore the fundamentals always do so at their own peril. It is our hope in writing this book that mixing fundamentals will become accessible to a much wider audience of engineers, chemists, and operators whose processes are affected by mixing issues.

Scope of Mixing Operations

Mixing plays a key role in a wide range of industries:

- Fine chemicals, agrichemicals, and pharmaceuticals
- Petrochemicals
- Biotechnology
- Polymer processing
- Paints and automotive finishes
- Cosmetics and consumer products
- Food
- Drinking water and wastewater treatment
- Pulp and paper
- Mineral processing

In all of these industries, the components of mixing problems can be reduced to some fundamental concepts and tools. The key variables to identify in any mixing problem are the time available to accomplish mixing (the time scale) and

the required scale of homogeneity (the length scale of mixing). In the remainder of this section we briefly summarize the key mixing issues, the time and length scales of interest, from the perspective of key mixing objectives. We begin with residence time distributions, since this is typically the only area of mixing covered in the undergraduate curriculum.

Residence Time Distributions: Chapter 1

Classical reactor analysis and design usually assume one of two idealized flow patterns: plug flow or completely backmixed flow. Real reactors may approach one of these; however, it is often the nonidealities and their interaction with chemical kinetics that lead to poor reactor design and performance (Levenspiel, 1998). Nonidealities include channeling, bypassing, and dead zones, among others.

A well-known method for assessing the nonideality of continuous process equipment is the determination of fluid residence time distributions. Residence time distribution (RTD) is a concept first developed by Danckwerts is his classic 1953 paper. In RTD analysis, a tracer is injected into the flow and the concentration of tracer in the outlet line is recorded over time (see Chapter 4). From the concentration history, the distribution of fluid residence times in the vessel can be extracted.

The limits of RTD analysis are the ideal plug flow of a pulse of tracer and a perfectly mixed pulse of tracer. In plug flow a pulse that is completely isolated from the rest of the reactor volume travels through the vessel in exactly the mean residence time. In a perfectly mixed stirred tank, the pulse of tracer is immediately mixed with the full volume of the reactor, leaving the vessel with an exponential decay of concentration as the volume is diluted with fresh feed. These two ideal limits provide us with a great deal of information about the bulk flow pattern or macromixing. When the mixing is ideal or close to ideal and the reaction kinetics are known, the RTD can be used to obtain explicit solutions for the reactor yield [see Levenspiel's classic introductory discussion (1972), Baldyga and Bourne's summary of the key cases (1999, Chap. 2), and Nauman's comprehensive treatment (2002)]. For many industrially important applications, the ideal and close-to-ideal models work very well.

The chief weakness of RTD analysis is that from the diagnostic perspective, an RTD study can identify whether the mixing is ideal or nonideal, but it is not able to uniquely determine the nature of the nonideality. Many different nonideal flow models can lead to exactly the same tracer response or RTD. The sequence in which a reacting fluid interacts with the nonideal zones in a reactor affects the conversion and yield for all reactions with other than first-order kinetics. This is one limitation of RTD analysis. Another limitation is that RTD analysis is based on the injection of a single tracer feed, whereas real reactors often employ the injection of multiple feed streams. In real reactors the mixing of separate feed streams can have a profound influence on the reaction. A third limitation is that RTD analysis is incapable of providing insight into the nature

of micromixing. RTD studies and analyses deal primarily with bulk flow or macroscopic mixing phenomena.

Where do the ideal models fail? For flow in a pipe, the ideal model is plug flow. This is a good assumption for fully turbulent flow with a uniform distribution of feed. There are two important cases where nonideal mixing must be addressed. If the second component is added from a small feed pipe rather than as a slug, radial dispersion of the feed must be considered. This case is discussed in Chapter 7. If the flow is laminar rather than turbulent, the velocity profile is parabolic (not flat), so the fluid in the center of the pipe will exit much sooner than the fluid close to the walls. This is the laminar axial dispersion problem which has been studied very extensively. The animation of flow in a Kenics mixer (CD ROM) illustrates this concept, showing axial dispersion of tracer particles for laminar flow in a static mixer. Ways to avoid this problem are also discussed in Chapter 7. For turbulent flow the problem of axial dispersion is less severe. A third practical consideration is partial plugging or fouling of a line. In this case the apparent residence time will be much shorter than expected because the effective volume of the vessel is less than the design volume.

For well-designed stirred tanks with simple reaction schemes and kinetics which are slow relative to the mixing time, the perfectly backmixed CSTR model works well. The most critical factor for design of a CSTR is placement of the feed and outlet locations. If a line drawn from the feed pipe to the outlet passes through the impeller, short circuiting is not likely to be a problem. If, however, the feed and the outlet are both located near the top of the vessel, short circuiting will almost certainly occur. Baffles may be used to reduce or eliminate this problem. The second characteristic of a well-designed CSTR is that the volume and mixing must be balanced with the feed rate. The volume must be big enough to allow 10 batch blend times to occur over the mean residence time (see Chapter 6). Alternatively, the primary impeller pumping capacity (see Chapter 6) should be 10 to 16 times the volumetric feed rate $q/Q = 10$ to 16 (Nauman, 2002, Chap. 8). These numbers are very conservative but are the best design standards currently available.

Residence time distributions, discussed in Chapter 1, represent the first generation of mixing models. The ideal cases of plug flow and perfectly mixed tanks provide solutions for most standard problems. Where the kinetics are more complex, are faster than the mixing time, or require a segregated feed strategy, the local mixing concepts discussed in this book and the zone-based models developed over the last 20 years have proved invaluable. The third generation of modeling will see coupling of computational fluid dynamics (Chapter 5) with reaction kinetics and heat transfer to obtain explicit and localized models for the most difficult mixing problems. Early reports of successes in this area include the production of adipic acid in the laminar flow regime in a stirred tank, modeling of crystallization reactions, and evaluation of the disinfection capabilities of ultraviolet treatment reactors in the water and wastewater treatment industries.

Residence time distributions are the first characteristic of mixing, but because they treat the vessel as a black box, they cannot address local mixing issues, which are the focus of much of this book. The characteristic time scale for a residence time distribution is the mean residence time of the vessel. The characteristic length scale is the vessel diameter, or volume. Many of the key process objectives of interest require more local information.

Mixing Fundamentals: Chapters 1–5

There is a set of fundamental topics which, while not leading directly to design of mixing equipment, must be understood to address difficult mixing problems. Residence time distribution theory and modeling constitute the classical approach to mixing and were discussed earlier. Turbulent and laminar mixing theory is covered in Chapters 2 and 3. Laminar mixing theory springs from dynamical systems theory, or chaos theory. A number of topics are addressed, but perhaps most useful is the idea that well-designed laminar mixing devices repeat the stretching and folding patterns in the flow, thus producing repeating structures of mixing on ever smaller scales. Turbulent mixing theory is concerned primarily with two questions: "What is the range of time and length scales in the flow?" and the analog to this question, "Where is the energy dissipated?" The points of highest energy dissipation are the points of most intense mixing, or of the smallest time and length scales. Chapters 4 and 5 discuss the two principal tools used to investigate mixing phenomena and evaluate mixing equipment: laboratory experiments and computational fluid dynamics. There is a wide range of experimental and computational tools available with a wide range of experimental or computational difficulty and a wide range of detail in the results. Perhaps the most difficult question for the engineer is to understand the problem well enough to define a well-posed question. Once the question is defined, an appropriate tool can be selected relatively easily, and useful results can usually be obtained. These five fundamental topics provide the key tools needed to tackle new problems and to understand much of the theory underlying mixing design.

Mixing Equipment: Chapters 6, 7, 8, and 21

A wide range of mixing equipment is now available, with the current generation of equipment typically designed for a specific process result. Chapter 6 covers traditional stirred tanks, baffling, the full range of impellers, and other tank internals and configurations. Chapter 7 provides information on equipment and design for pipeline mixing. Chapter 8 focuses on rotor–stators, which have been used for many years but have been investigated on a more fundamental level only in the last decade. Chapter 21 covers the mechanical aspects of mixing equipment design, providing a welcome primer on the vocabulary of mechanical engineering as well as important design information. Chapter 22 focuses on the vendor: what expertise can be offered and what information is needed for accurate specification of mixing equipment. Additional specialized equipment is discussed in

Chapters 15 (powder blending), 16 (high viscosity), 19 (petroleum), and 20 (pulp and paper industry). Key design concepts for equipment selection are:

- Selection of tanks versus in-line mixers and use of backmixed flow versus plug flow
- Selection of residence times are required: long residence times are well served by tanks, short residence times can be accomplished in pipes
- Design requirements: robust and flexible (typically stirred tanks) versus tight and specific (pipeline mixers and other specialized equipment)
- Mechanical design considerations: seals, dynamic loads, rotating shafts, and critical speed
- Classical and modern impeller design; the function and importance of baffles
- Characteristics of in-line mixing equipment, including static mixers and rotor–stators

Miscible Liquid Blending: Chapters 3, 7, 9, and 16

Miscible liquid blending is the easiest mixing task. The reader is cautioned that miscible blending requires two things: The streams must be mutually soluble, and there must be no resistance to dissolution at the fluid interface. Chapters 7 and 9 present well-developed correlations for prediction of mixing time in this simplest case, and corrections for density and viscosity differences. Although laminar and non-Newtonian fluids are more difficult to handle, the current recommendations on these issues are also included in Chapters 7 and 9.

Chapter 3 provides a careful discussion of how we characterize and measure mixing scales. These concepts are combined with dynamical systems, or chaos theory, to identify similarities of scale in laminar mixing applications. This is a key theoretical concept that will allow rigorous advances in mixing design in the future. In Chapter 16, current polymer and high viscosity blending equipment is discussed. In these cases the blending objective must be combined with the heat transfer and high pressures required to produce polymer melts. For pastes, the fluids are typically non-Newtonian, so further specialized equipment is required.

Solid–Liquid Suspension: Chapters 10, 17, and 18

Design methods for solid–liquid suspension were some of the first to be established (Zwietering, 1958), and this early work has withstood the test of time virtually unchanged. Solid–liquid mixing is discussed in Chapter 10, with design guidelines for:

- Mixing requirements for achieving and maintaining off-bottom suspension of solids (the just suspended speed, N_{js})

- Requirements for achieving and maintaining uniform solids concentration throughout the tank—of interest particularly for slurry catalyst reactors and for feeding downstream equipment (e.g., centrifuges, continuous stirred tank reactors, fluid bed coaters)
- Mass transfer correlations for solids dissolution
- Maintaining the required slurry composition on discharge
- Tank draining with solids present: avoiding plugged nozzles

Difficult design problems that have not yet been resolved involve nonwetting, clumping, or floating solids. The key qualitative aspects of these problems can be identified and useful heuristic solutions are provided. Other mixing effects involving solids in suspension include clumping, agglomeration, fouling, and scaling. These problems can be reduced with good mixing designs, but a full discussion lies outside the scope of this book.

Reactions involving solids are discussed extensively in Chapters 13 and 17. Where solids are involved in reactions, there are two steps in the kinetics. The first, solids dissolution, is dominated by the particle size and the mixing conditions. The apparent reaction kinetics and even the reaction products can change depending on the mixing conditions. Key solids reaction topics include:

- Solids dissolution with reaction (Chapters 13 and 17)
- Potential for impeller damage to solids in suspension, including crystals (Chapter 17), cells (Chapter 18), and resin beads
- Mixing effects on nucleation and growth in crystallization (Chapter 17)

Gas–Liquid Contacting: Chapter 11

Gas–liquid mixing has one key objective: the dispersion of gas in liquid with the maximum surface area for mass transfer. As with many multiphase systems, this objective is complicated by the difficulties of multiphase flow. The gas can flood the impeller, dramatically reducing its effectiveness; surface properties determine whether the system is coalescing or noncoalescing, and thus whether the surface area created is stable; boiling systems require completely different treatment; and gas–liquid reactions require consideration of local concentrations of gas. Chapter 11 includes the traditional topics:

- Correlations for prediction of k_L a, including fermentation applications (also discussed in Chapter 18)
- Discussion of operating regimes: interaction of power and gassing rate to produce stable operation or flooding of the impeller
- Recommendations for sparger design and placement
- Design for sufficient gas phase residence time
- Gas–liquid reactions (also discussed in Chapter 13)

New discussions are provided on:

- The new generation of impellers designed for efficient gas dispersion
- Boiling systems

The reader should beware of conditions in the headspace, particularly for high viscosity and/or foaming systems. This is potentially detrimental for several types of operations. Excessive foaming can lead to interference with mass transfer. Gas entrained into high viscosity systems can be difficult to remove and severely affect product quality.

Liquid–Liquid Mixing: Chapter 12

Liquid–liquid mixing is one of the most difficult and least understood mixing problems, despite extensive literature on both the mechanical agitation side of the problem and the surface science side of the problem. In spite of this, a number of important lessons emerge from the discussion in Chapter 12:

- Impurities, surface-active agents, and small changes in chemical composition can be critical in determining drop size distribution. Performance can change dramatically due to small changes in composition, even at the parts per million level, particularly for reactions, separations, and preparation of stable emulsions.
- Both the mixing system and duration of mixing can have an important effect on drop size distribution, drop breakup, and coalescence.
- Addition strategy can determine which phase is continuous.
- Phase inversion can play an important role in extraction and reaction.
- Overmixing can result in a stable emulsion or an overreacted product.
- Inadequate mixing can result in incomplete phase transfer or slow reaction.

Mixing and Chemical Reactions/Reactor Design: Chapters 13 and 17

When mixing rates and chemical reaction rates occur on similar time scales, or when mixing is slower than chemical reaction, mixing effects can be very important. On the small scale, blend times and mixing time scales are typically very short and mixing effects may not be apparent. When reactions are scaled up, however, the chemical kinetics stay the same while mixing times get longer. Mixing effects are always worse on scale-up. These issues are discussed in some detail in Chapters 13 and 17. The key points are:

- How and when mixing effects can influence the yield and selectivity of complex homogeneous and heterogeneous chemical reactions.