MIXING

THEORY AND PRACTICE

Volume I

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MIXING

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WILMINGTON, DELAWARE

VOLUME I

1966

ACADEMIC PRESS New York and London

ACADEMIC PRESS INC.
111 Fifth Avenue, New York, New York 10003

United Kingdom Edition published by
ACADEMIC PRESS INC. (LONDON) LTD.
Berkeley Square House, London W.1

LIBRARY OF CONGRESS CATALOG CARD NUMBER: 65-26039

PRINTED IN THE UNITED STATES OF AMERICA

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Preface

Mixing is a widely practiced operation; it occurs whenever fluids are moved in the conduits and vessels of laboratory and industrial-processing equipment. Mixing is of interest not only when it results in the dispersion of one component in another but also when it is an agency for the promotion of heat transfer, mass transfer, solid suspension, and reaction.

Although much has been published on the theory and practice of mixing, these writings are spread throughout the literature. This situation calls for a work devoted to organizing, summarizing, and interpreting this substantial mine of source material. A book which provides a complete and practical summary of mixing knowledge should save hours of literature searching and review by research workers and students. Such a book should also markedly improve the application of mixing knowledge by development, design, and operating engineers.

A dozen authors have cooperated in the writing of this treatise to meet these needs. Their interests cover most of the theoretical and practical aspects of various mixing operations, which range from the statistical theory of turbulence to construction details of various types of equipment. Each chapter has its special flavor and emphasis which reflect the kinds of problems involved in the various mixing operations and the viewpoints and insights of the authors. The extent to which a fundamental approach is used to relate the process variables differs among the mixing operations discussed. The theoretical relationships are inherently more complex in some cases than others. For example, the mathematics of tensors is required for understanding the turbulent behavior of fluids, while mathematically simple rate equations are adequate for some heat and mass transfer operations. In most cases, correlations of dimensionless groups provide practical relationships among the process variables.

The subject matter of this book has been divided into two volumes because a single volume would be too bulky and awkward for the reader to handle. In the first volume, the chapters deal with mixing in turbulent flow, the power consumption of rotating impellers, the mixing process in vessels, and mechanically aided heat transfer. In the second volume, the subject areas for the chapters are mass transfer in two-phase systems, the effects of mixing on chemical reactions, the mixing of highly viscous materials, the suspension of particles in liquids, the mixing of dry solid particles, and the mechanical design of impeller-type mixers.

The editors wish to acknowledge the efforts of those people who have contributed to the successful completion of this book—foremost, of course, are the authors of the many chapters and their patient, understanding wives. The assistance of others who helped shape the work by their comments, criticisms, and suggestions is also acknowledged. Those who helped especially in this way are L. C. Eagleton, S. I. Atallah, E. D. Grossmann, and H. E. Grethlein.

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April, 1966

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CHAPTER 1

Introduction

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I. What Is Mixing?

The term *mixing* is applied to operations which tend to reduce nonuniformities or gradients in composition, properties, or temperature of material in bulk. Such mixing is accomplished by movement of material between various parts of the whole mass. For fluids the movement occurs by a combination of these mechanisms: bulk flow in both laminar and turbulent regimes and both eddy and molecular diffusion. Stirring a colored pigment in a bucket of paint is an example of laminar mixing. Here layers of pigment are thinned, lumps flattened, and threads elongated by laminar bulk flow. Stirring of cream in a cup of coffee is an example of turbulent mixing in which the mechanisms of turbulent bulk flow, then eddy diffusion, and finally molecular diffusion predominate. The basis for all mixing is fluid and particle mechanics.

The mixture ultimately produced by extensive use of the physical motions noted above is not an ordered homogeneity; it is a completely random distribution. This randomness is apparent in dry solids mixing and in suspensions of solids in fluids because of the relatively few particles in a sample. However, in fluid blends the random character of the mixture cannot be discerned because the particles are molecules, and therefore the number of particles in any perceivable sample are several orders of magnitude greater than mixtures which include solid particles.

For commingled fluids, the quality of the mixture can be described by two characteristics: scale and intensity (D1). Scale can be defined as the average distance between centers of maximum difference in properties. In turbulent mixing, scale corresponds to the size of the eddies and is reduced by the breakup of eddies. In laminar mixing, scale is diminished by thinning layers, flattening lumps, and stretching threads of the discontinuous components. Intensity can be defined in terms of the variance or range of properties existing in a mixture. When two fluids of different composition are first intermingled, the difference in properties or spread is at a maximum. Intensity does not decrease until the scale of the nonuniformity becomes smaller than the sample size or until molecular diffusion reduces the spread in properties. The fundamental nature of mixing and mixtures is treated in detail in Chapter 2 (this volume) and Chapters 8 and 10 (Vol. II).

II. Applications of Mixing

Mixing action is not only promoted to produce more uniform mixtures of components. In some cases, an important part of the mixing operation is movement or transfer of materials to or from surfaces of particles or phases (see Chapter 6, Vol. II). Examples of such operations are dissolution, leaching, gas absorption, crystallization, and liquid-liquid extraction. In these cases, fluid motion reduces the thickness of the resisting "film," or expressed differently, it effectively increases the concentration gradient immediately adjacent to the particle or phase surfaces of the transferring components in the fluid. The performance of equipment for such interfacial mass-transfer operations can be characterized by an interfacial mass-transfer coefficient.

A few mixing operations involve transfer of a component to or from an equipment boundary or surface. An example is electroplating.

A very common and important mixing operation is bringing different molecular species together to obtain a chemical reaction [Chapters 2 (this volume) and 7 (Vol. II)]. The components may be (*a*) miscible liquids, (*b*) immiscible liquids, (*c*) solid particles and a liquid, (*d*) a gas and a liquid, (*e*) a gas and solid particles, or (*f*) two gases. Equipment performance when chemical reactions are involved can be expressed in terms of extent of reaction (conversion) or yields and the chemical species of the products obtained.

In many cases, temperature differences exist in bulk fluid, between an equipment surface and the fluid, or between suspended particles and the continuous phase fluid. Essentially the same mechanisms that accomplish mass transfer by reduction of the film thickness are used to promote heat transfer by increasing the temperature gradient in the film. These mechanisms are bulk flow, eddy diffusion, and molecular diffusion. In addition, heat transfer by molecular vibration or thermal conductivity occurs. The performance of equipment in which heat transfer takes place can be expressed in terms of heat transfer coefficients. Heat transfer in mixing equipment is discussed in Chapter 5.

The movements of fluids or particles which are required to carry out the types of mixing operations described above require that external forces be imposed to overcome resisting forces in the fluid. The inertia of a fluid exerts a resisting force when there is a change in direction or velocity of motion. Viscous drag or fluid shear forces provide another type of resistance to fluid motion. For low viscosity fluids like water in which turbulence is readily induced, the inertia of the fluid provides not only the major resistance to stirring the fluid but also the major method by which fluid movement is transmitted to parts of the fluid which are remote from the stirrer or from an entering jet of fluid. For viscous materials like polymers and polymer solutions, shear forces are not only the major resistance to moving a stirrer, but also provide the mechanism for moving the fluid in a desired flow pattern. In cases involving two phases, such as for immiscible liquids, or gases and liquids, interfacial forces may provide a significant resistance to motion. Some high molecular weight polymers have an elastic as well as viscous resistance to motion. Frictional forces between dry particulate solids provide a resistance to particle motion. When there is a difference in specific gravity between immiscible fluids, gravitational and buoyant forces become significant. Since the energy or power required for various mixing operations arises in the resistance of materials to be moved or accelerated, it is an important performance criterion. The practical aspects of power consumption of mixers are discussed in Chapter 3.

The existence of inertia and shear forces when mixing two-phase systems is responsible for the reduction of the dispersed-phase particle size and the accompanying increase in interfacial area. Higher fluid velocities increase inertia and shear forces and produce smaller particles. Gases can be dispersed in liquids; immiscible liquids can be interdispersed; and particle agglomerates suspended in a liquid can be broken up by these inertia and shear forces. The major purpose of many operations which produce and maintain dispersions is not dispersions per se but mass transfer. This is the case for gas absorption and liquid-liquid extraction. For cases in which the result of the operation is the production of a dispersed phase, such dispersion operations are generally considered *mixing* operations because the equipment is that commonly used for other types of mixing operations. The particle size distribution and interfacial area produced in dispersion operations is in large part a measure of dispersion equipment performance. Mixing operations involving dispersion of one phase in another are discussed in Chapter 6 (Vol. II).

The basic types of equipment which are used for the mixing operations discussed above are not many. With a few exceptions, all types are modifications of vessels or pipes. In vessel-type equipment, there is a circulation or backflow that moves fluid into all parts of the vessel or chamber. In pipe-type equipment, flow is predominantly in one direction, but there is a cross-flow pattern which moves fluids radially or perpendicular to the axial or direction of flow. Examples of vessels are cylindrical tanks stirred by rotating turbines or propellers, by jets of liquid, or by gas bubbles. In some cases, the stirring device may completely fill the mixing chamber or vessel. A helical ribbon stirrer is an example. In other cases, the vessel rotates and tumbles the material to be mixed. Examples of pipe or tubular mixers are coaxial jets with turbulent flow in the pipe downstream of the jets, and modified helical screws in a tube. Information on the types of equipment suited for mixing is found in nearly all of the chapters which follow. The major emphasis is not on detailed description of the variety of equipment but rather on the performance characteristics of mixing equipment.

III. Theoretical Relationships

The basic relationships among the variables affecting uniformity of composition and rates of interfacial mass transfer are transient, partial-differential, material balance equations. When chemical changes are involved, reaction rate terms are included in the mass conservation equations for each molecular species involved. Similar energy balance equations provide the basic relationships among variables which influence heat transfer. Variables affecting fluid stresses, equipment stresses, and fluid velocities are related by analogous equations for the conservation of momentum of fluids. Detailed presentations of these basic equations for transport phenomena are presented by Bird *et al.* (B1).

Because the complex shapes of mixing vessels and the flow patterns of contained fluids lead to differential equations which are impossible to solve, the empirical approach employing dimensionless groups is most frequently used for correlation of the process performance variables in mixing equipment. The basic principles involved in this method are developed by Johnstone and Thring (J1).

IV. Prediction of Equipment Performance

The kinds of problems that arise in the design and use of mixing equipment are selecting the type, size, and operating conditions, which will perform a desired service or obtain a desired production rate of material with the desired properties. Keeping the combination of capital and operating costs low is an important aspect of these problems. Methods of predicting the process performance characteristics of mixing equipment generally depend upon empirical methods involving correlations of dimensionless groups and model relationships. Empirical methods are often involved in predicting the forces acting on equipment parts. The theoretical and "code" relations for the mechanics of structures and materials can then be used to obtain a mechanically sound piece of equipment.

In the following chapters, the authors also present the theoretical and empirical methods that provide a basis for predicting the process and mechanical performance characteristics of equipment used in various types of mixing operations. The details of the subject matter in this book and its arrangement have been determined largely by the interests and background of the chapter authors. With the exception of Chapter 2, an empirical approach has been used in relating the variables affecting process performance. The general objective of all chapters has been to provide a summary of information available on mixing equipment and mixing operations for the use of engineers in solving research, development, design, and operating problems.

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CHAPTER 2

Fluid Motion and Mixing

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I. Introduction

The terms "diffusion" and "mixing" have been used to describe a multitude of physical processes, some of which occur and can be studied separately and others which exist only as groups of simultaneous processes. Before one can attempt to relate any of these processes to the fluid dynamics of a system, a visualization, upon which a mathematical model will be based, is necessary. For this reason, the first section of this chapter will dwell upon a description of diffusion and mixing processes. Here, the terms will be defined, the processes described, and the basic relations derived. It is hoped that the reader will find that the required background material provided is adequate, but references are included to facilitate further study. Once the definitions of the various diffusion and mixing processes have been established, criteria for mixing can be presented. These criteria will be the starting point for the actual theories of mixing. Both laminar and turbulent conditions will be considered.