Dynamics of Multiphase Flows

Understand multiphase flows using multidisciplinary knowledge in physical principles, modeling theories, and engineering practices. This essential text methodically introduces the important concepts, governing mechanisms, and state-of-art theories, using numerous real-world applications, examples, and problems. It covers all major types of multiphase flows, including gas–solid, gas–liquid (sprays or bubbling), liquid–solid, and gas–solid–liquid flows. It introduces the volume–time-averaged transport theorems and associated Lagrangian-trajectory modeling and Eulerian–Eulerian multifluid modeling. It explains typical computational techniques, measurement methods, and four representative subjects of multiphase flow systems. Suitable as a reference for engineering students, researchers, and practitioners, this text explores and applies fundamental theories to the analysis of system performance using a case-based approach.

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Dedicated to

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and

Li An Bao and Ning Liu

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Chao Zhu , Liang-Shih Fan , Zhao Yu
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Preface

Multiphase flows refer to the flows with distinctively different dynamic responses of each phase in the transport and phase interactions that impact the transport phenomena. Knowledge of multiphase flows is important for researchers, scientists, and engineers in various disciplines. Our motivation for writing this book was propelled by the rapidly expanding interest in the optimized design, operation, and applications in the field of multiphase flows and the ever-increasing needs of higher education in this field. Understanding multiphase flows requires both the multidisciplinary knowledge in inherent flow concepts and theories, and their associated engineering practices. There is indeed a considerable literature that is already available for students, researchers, and other readers who are interested in multiphase flows. This literature includes research articles on fundamental concepts or problems of an applied nature, edited books on the progress of specific topics of interest, monographs on focused subjects, special collections of an individual researcher's publications, and handbooks contributed by various topic experts that outline basic principles and design criteria or formulae. However, these monographs and edited books on multiphase flows tend to have a more narrowly focused scope of subject matter and are often concerned with advanced topics, making them a desirable reference source for researchers rather than a foundational, comprehensive, and systematic introductory guide to the fundamental theories of the field, particularly for beginners. While there are a number of books that do address some fundamental theories, they either lack exercise examples and homework problems that are essential to deep learning for students, or they are not accompanied by solution manuals for homework problems. Their pedagogical effectiveness is therefore limited as they cannot be conveniently adapted by instructors as textbooks for use in the classroom.

A unified textbook in the field that can methodically encompass a broad range of the important elements of knowledge in the multiphase flow field, along with sufficient theoretical and applied details in a manner suitable to both introductory and advanced level learning in an instructional setting would be a welcome addition. This book is conceived for just this purpose, serving as an educational, learning-oriented text that introduces multiphase flows to engineering students, advanced researchers, and other readers. This book may also be regarded, to some degree, as an expanded sequel to an earlier book published in 1998 by two of the current co-authors (Fan and

Zhu), titled *Principles of Gas–Solids Flows* (Cambridge University Press). This earlier book was limited only to the gas–solid flows and did not include the other topics of multiphase flows such as gas–liquid flows (sprays or bubbling flows), liquid–solid flows (slurry flows), and gas–solid–liquid flows (sprays in gas–catalysts flows or catalysts in bubbly liquid reactors). Thus, this book seeks to more fully articulate the coherent linkages among, for example, hydrodynamics, phase changes (reactions, mass, and heat transfer), and electrostatic charges in multiphase flow applications, as well as provide an introduction to computational multiphase flow theories and basic measurement methods.

The book contains twelve chapters. The first eight chapters cover fundamentals, and the last four chapters are dedicated to the introduction of representative applications. Specifically, this book has the following characteristics:

– It provides a systematic introduction and review of multidisciplinary fundamentals critical to understanding multiphase flows (Part I, Chapters 2–6). Specifically, Chapter 2 offers a summarized review of various single-phase flows, including the turbulent modeling of Newtonian fluid flows, viscous flow through porous media, and inertia-dominated granular flows. Chapter 3 focuses on the introduction of phase transfer between an isolated object and a surrounding fluid flow, including various physical mechanisms and their representative formulations for momentum, heat, and mass transfer across the interface between the object and fluid with a relative motion. Chapter 4 discusses the impact of neighboring objects and their dynamic behaviors on the phase transfer mechanisms between the object of concern and its surrounding fluid flow. Such an impact can be affected by the noncontact interobject interactions via the intervening common fluid, by the direct contact (collisions) of the interacting objects, by the noncontact field interactions (such as electrostatic or electromagnetic fields), or by all three of the aforementioned scenarios. Chapter 5 and Chapter 6 introduce the two most popular methods in the modeling of multiphase flows. Chapter 5 is primarily focused on Eulerian–Lagrangian modeling where the Lagrangian equations are used to account for motions or trajectory tracking of individual objects and the Eulerian equations are used to describe the Eulerian field behavior of the fluid flow surrounding those objects. Chapter 6 presents Eulerian–Eulerian modeling (also known as continuum modeling) to yield field descriptions of individual component phases that constitute a multiphase flow. The key conceptual elements in continuum modeling include the constitution of each continuum phase that co-occupies a physical space, the continuum description of phase interactions or coupling, and the in-phase transport due to phase nonuniformity (hence the definition or formulation of transport coefficients).

– Part II of the book is concerned with the characteristics of four selected subjects of multiphase flow systems. They are introduced in the last four chapters. This part of the book is designed not only for readers who wish to explore important engineering applications involving multiphase flows, but also for those readers who wish to apply the fundamental knowledge gained from Part I in an integrated manner to the analysis of the performance of the systems with practical engineering relevance. It should be noted that the real multiphase flow systems can be complicated by such factors as irregular vessel geometry, varied flow regimes with complex interphase transport and phase change properties, and polydispersity of the size of the discrete phases. Such complexity is well beyond what the theoretical modeling based on the multiphase flow principles described in Part I can fully account for. However, it is expected that by following the flow principles presented in Part I while, over time, augmenting them with additional knowledge on model formulation and closure relationship, and the computing capabilities, the gap of the comparison between the model prediction and experimental data can significantly narrow down. Specifically, Chapter 9 introduces typical multiphase flow systems of phase separation, with highlighted fundamentals of separations by inertia, filtration, and electrostatic precipitation. Chapter 10 describes the basic principles of fluidization and typical fluidization systems including dense-phase fluidized beds and circulating fluidized beds. Fluidization is a major industrial practice applied not only for phase mixing and reactions but also for phase transport. Fluidization in vertical columns or pipes is also discussed in this chapter. Chapter 11 focuses on phase transport by multiphase flows through horizontal pipes. Chapter 12 explores some complex multiphase flow systems with strong coupling to physical phase changes and chemical reactions.

- The book also contains two chapters dedicated to the numerical methods and experimental techniques of multiphase flows. These chapters can be found between Part I and Part II. Chapter 7 provides a brief introduction to common numerical methods that can be used for solving coupled differential equations with boundary conditions in various types of multiphase flow models. Highlights include the methods for numerical treatments of interfacial phase transfer, the algorithm coupling equations of individual phases, and the multiscale behavior among various phases or transport properties. Chapter 8 summarizes some common measurement technologies in the experimental studies of multiphase flows. The sections in this chapter are organized according to the specific purposes of the measurements such as particle size or volumetric concentrations.

- Most established theories of multiphase flow are based on simple multiphase flows characterized by, for example, dispersed monosized rigid spheres of solids being transported in the laminar flows of Newtonian fluids. It is natural, therefore, that the core of the book is oriented toward the introduction of basic theories that are formulated for such idealized multiphase flows. Nevertheless, in order for the theories to be more applicable to practical situations, this book also aims to include more complex flows to which a simple theoretical treatment can be reasonably extended. Such treatments and situations can be exemplified by the mechanistic modifications associated with deformable particles (such as droplets and bubbles), porous or permeable particles, phase changes (such as vaporization and reactions), complex interfacial transfers (such as collision-induced phase transfers), turbulence, non-Newtonian fluid flow, and coupling with external fields (such as electric, electromagnetic, or acoustic fields).

- Throughout the book, the structure of each chapter is organized based on the following framework: (1) basic concept and formulation, and (2) examples or case studies with detailed explanation and analysis.

- Homework problems are included in each chapter. These problems are designed to provide practice opportunities for readers to gauge and assess their progress. The companion solution manual for the end-of-chapter problems is available upon request for instructors from the publisher at cambridge.org/9781108473743. Some problems are open ended and are posed only with necessary conditions rather than the usual “sufficient and necessary conditions,” which yield unique answers to the problems. Thus, for these open-ended problems, various possible solutions can result from the reasonable assumptions of additional conditions required to ensure problem closure or the uniqueness of the solution. Some homework problems are also designed to further explore relevant theories or applications, with the aid of references cited in the problems.

- References for each chapter are given at the end of each chapter. Throughout the book, most of the references adapted are classical in the field, which have endured years of validation. Some more recent publications are also referenced. They are associated more with case studies and advanced homework problems, typically in modeling and simulations, for readers who wish to keep pace with related advances, understandings, and emerging subjects.

This book should by no means be used to the exclusion of other published books devoted to multiphase flows. Rather, readers are encouraged to adopt an integrative approach, as a number of these books complement each other. Thus, using this book in conjunction with others will likely maximize the development of the reader's knowledge and understanding. Such books include, but are not limited to, the following:

- *Bubbles, Drops and Particles*, R. Clift, J. R. Grace, and M. E. Weber, Dover Publications, 1978.
- *Multiphase Flow in Porous Media: Mechanics, Mathematics, and Numerics*, M. B. Allen III, G. A. Behie, and J. A. Trangenstein, Springer, 1988.
- *Particulate and Continuum-Multiphase Fluid Dynamics*, S. L. Soo, CRC Press, 1989.
- *Multiphase Fluid Dynamics*, S. L. Soo, Science Press, 1990.
- *Boiling Heat Transfer and Two-Phase Flow*, L. S. Tong and Y. S. Tang, 2nd edition, CRC Press, 1997.
- *Principles of Gas-Solid Flows* , L.-S. Fan and C. Zhu, Cambridge University Press, 1998.
- *Dynamics of Bubbles, Droplets and Rigid Particles*, Z. Zapryanov and S. Tabakova, Springer, 1998.
- *Fluid Dynamics and Transport of Droplets and Sprays*, W. A. Sirignano, Cambridge University Press, 1999.
- *The Dynamics of Fluidized Particles*, R. Jackson, Cambridge University Press, 2000.
- *Two-Phase Flow: Theory and Application*, C. Kleinstruer, CRC Press, 2003.
- *Computational Models for Turbulent Reacting Flows*, R. O. Fox, Cambridge University Press, 2003.

- *Fundamentals of Multiphase Flow*, C. E. Brennen, Cambridge University Press, 2005.
- *Multiphase Flows with Droplets and Particles*, C. T. Crowe, J. D. Schwarzkopf, M. Sommerfeld, and Y. Tsuji, 2nd edition, CRC Press, 2011.
- *Theory and Modeling of Dispersed Multiphase Turbulent Reacting Flows*, L. Zhou, Butterworth-Heinemann, 2018.
- *Essentials of Fluidization Technology*, Ed. J. R. Grace, X. T. Bi, and N. Ellis, Wiley-VCH, 2020.

Like our 1998 book, *Principles of Gas–Solid Flows*, this book can be used at the advanced undergraduate and graduate levels in courses related to mechanical and power engineering, chemical reaction engineering, pharmaceutical engineering, environmental engineering, and process system engineering. The pre-requisite subject knowledge for this book includes basic thermodynamics, fluid mechanics, and heat and mass transfer. To use this book in its entirety for teaching, a two-semester course sequence is ideal. For a 14-week or one-semester tech-elective course offered to undergraduate students, the following selective subjects taken from this book can be covered:

1. Introduction to Multiphase Flows (Chapter 1)
   - Basic concepts and definitions
   - Examples of multiphase flows in engineering applications
2. Single-Phase Flows (laminar flow of Newtonian fluids) (Chapter 2)
   - Flow over a sphere
   - Pipe flow
   - Jet flow
3. Phase Interaction with a Sphere (Chapters 3 and 4)
   - Drag force and other particle-fluid forces
   - Modification in presence of neighboring spheres
   - Momentum transfer by collisions
   - Heat and mass transfer
4. Lagrangian Trajectory Modeling (Chapter 5)
   - BBO equation
   - Deterministic Lagrangian trajectory modeling
   - Stochastic Lagrangian trajectory modeling
   - Collision-dominated trajectory modeling
5. Eulerian Continuum Modeling (Chapter 6)
   - Phase averages and averaging theorems
   - Volume-fraction-based equations
   - Time-fraction-based equations
6. Systems for Phase Separation (Chapter 9)
   - Sedimentation chamber
   - Cyclone
   - Impactor and scrubber
   - Granular and fibrous filters
   - Electrostatic precipitator

7. Systems for Phase Mixing (Chapter 10)
   - Fluidized beds
   - Jet mixer
   - Rotational blenders
8. Systems for Phase Transport (Chapter 11)
   - Pneumatic conveyers
   - Risers
   - Sprayers

For a 14-week or one-semester course offered to graduate students, the following selective subjects taken from this book can be covered:

1. Introduction to Multiphase Flows (Chapter 1)
   - Basic concepts and definitions
   - Examples of multiphase flows in engineering applications
2. Modeling of single-phase flows (Chapter 2)
   - Classification of viscous fluids
   - Laminar flows of Newtonian fluids
   - Turbulent flows of Newtonian fluids: RANS and turbulence modeling
   - Flow through porous media
   - Granular flows: kinetic theory modeling
3. Particle–Fluid Interactions (Chapters 3 and 4)
   - Momentum transfer: drag and other particle–fluid interaction forces
   - Heat transfer by conduction and convection
   - Mass transfer by diffusion and phase change
4. Collision of Solid Particles (Chapters 4 and 5)
   - Hard-sphere model
   - Normal collision characteristics of elastic objects
   - Oblique collision with tangential friction and torsional traction
   - Inelastic collisions and plastic deformation
   - Soft-sphere model
5. Formation and Interactions of Fluid Particles (Chapters 4, 6, 10, and 12)
   - Bubble formation and bubble column
   - Droplet formation and spray atomization
   - Breakup and coalescence of fluid particles
   - Population balance model
6. Continuum-Discrete Tracking Modeling of Multiphase Flows (Chapter 5)
   - Lagrangian Trajectory Modeling
   - Transport Coupling in Eulerian–Lagrangian Modeling
7. Continuum Modeling of Multiphase Flows (Chapter 6)
   - Phase averages and averaging theorems
   - Volume-averaged equations
   - Volume–time-averaged equations
   - Turbulence modulation

8. Multiphase Flow Applications with Modeling Analysis (Chapters 9–12)
   - Cascade impactors
   - Cyclone separation
   - Electrostatic precipitation
   - Fibrous filtration
   - Pneumatic pipeline transport
   - Fluidization and fluidized beds
   - Spray drying
   - Bubble columns
   - FCC riser reactor
9. Projects: Presentation of a Research Paper (from published references)
   - CFD modeling and simulation of a multiphase flow (Chapter 7); or
   - Experimental method or system of a multiphase flow, with data analysis (Chapter 8)

Such coverage could naturally be supplemented with material from the reference books given above and some state-of-the-art publications. The projects indicated above, preferably presented and discussed in class, can be extraordinarily beneficial to the students since they represent the more recent advances and practical applications of modeling, simulation, and/or measurements of multiphase flows. The draft of this book had been used effectively in one- and/or two-semester formats for mechanical engineering and chemical engineering students, respectively, at the New Jersey Institute of Technology (NJIT) and the Ohio State University (OSU).

The feedback provided by students who took the multiphase flow course or related courses such as particle technology, particulates flows, and multiphase reaction engineering from both NJIT and OSU for the past two decades has been extraordinarily helpful in shaping the contents and the structure of the book in its present form. The authors are deeply thankful for this constructive feedback and the valuable insights of the students. Several colleagues, Professor Alissa Park, Dr. Teh C. Ho, Dr. Chao-Hsin Lin, and Professor Jonathan Fan have been very generous with their time in reading the book manuscript in full or in part during its preparation. They have provided invaluable comments that have been incorporated in this book, and the authors are very appreciative of their engagement. A final stage in the revision of part of the book manuscript was undertaken by Dr. Liang-Shih Fan during the spring semester 2019 when he took a sabbatical leave at ETH, Switzerland hosted by Professor Sotiris Pratsinis. Professor Pratsinis's thoughtful and supportive facilitation of LSF's work at this stage was invaluable, and the authors are indebted to him for his assistance. Gratitude is also extended to Dr. Dawei Wang, Dr. Pengfei He, Dr. Bo Zhang, and Mr. Soohwan Hwang for dedicated help on solution manual preparation; to Mr. Guangyu Guo and Ms. Hongling Deng for excellent figure drawings; and to Ms. Phoebe Del Boccio and Mr. Nicholas Almerini for outstanding editorial assistance. The financial support provided by the C. John Easton Professorship funds of the Ohio State University is gratefully acknowledged.

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