MULTIPHASE FLOWS *with* DROPLETS *and* PARTICLES

SECOND EDITION

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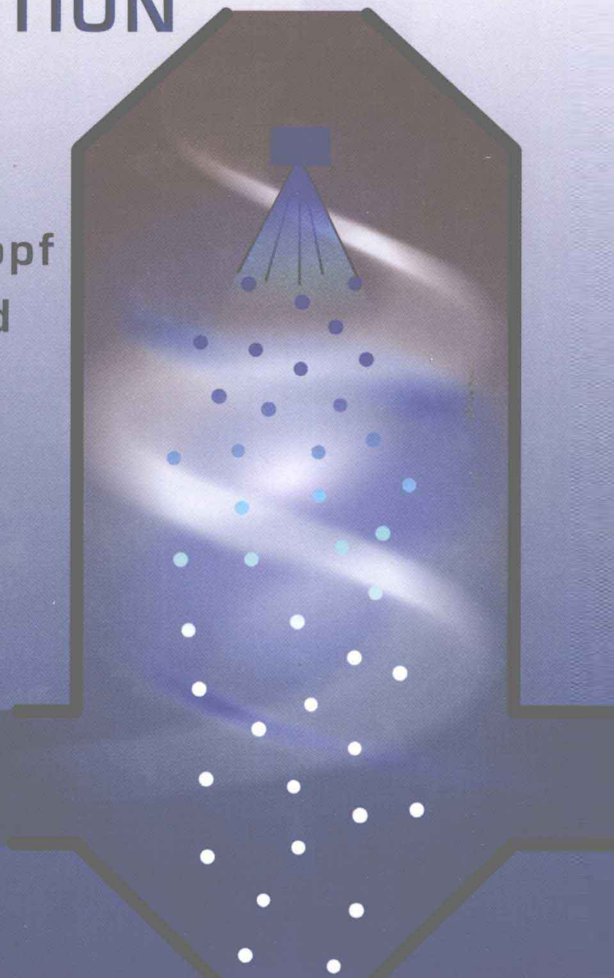

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Preface

Since the publication of the first edition of *Multiphase Flow with Droplets and Particles* in 1998 there have been important advances in the science and technology of dispersed phase flows. The intent of the second edition is to include these advances while retaining the organized, pedagogical approach of the first edition. The primary change is the introduction of a new chapter, Chapter 7, on the effect of the dispersed phase particles on the turbulence of the carrier phase. The other chapters have been modified and revised to reflect the new material. Chapter 4 has been updated to include the new information on particle drag and heat transfer. In Chapter 6, a reassessment of the volume-averaged conservation equations has been made with respect to the general applicability of the "two-fluid" concept. Chapter 8, on the equations for the dispersed phase, has been completely rewritten to include the current techniques for modeling dilute and dense flows. Chapter 9, on numerical modeling, has also been rewritten to include DNS and LES as well as volume-averaged equations for the $k - \varepsilon$ and Reynolds stress models. The exercises have been expanded and a solution manual is available to support the use of the book in an instructional environment.

The first edition of *Multiphase Flow with Droplets and Particles* included a FORTRAN computer program for the multiphase flow of particles in a quasi-one-dimensional duct based on the conservative variable approach. This has not been included in the second edition. Should anyone want the description of the model and the program, they can contact the senior author (CTC) directly.

Several books on or relating to dispersed phase flows have appeared since 1998. In 2006 Michaelides published *Particles, Bubbles, and Drops: Their Motion, Heat and Mass Transfer,* which is an extension of the classic work, *Bubbles, Drops and Particles* (Clift, Grace and Weber, 1978). Michaelides' book provides an excellent resource on particle-fluid interactions. Also, in 2006, the *Multiphase Flow Handbook* appeared, which has several chapters devoted to dispersed phase flows. In 2007, *Computational Methods for Multiphase Flows* was published by Prosperetti and Tryggvason. This book reviews various numerical techniquess such as immersed-boundary, lattice-Boltzmann and boundary-integral methods for detailed analysis of fluid-particle flow systems. Finally in 2009, Brennen published *Fundamentals of Multiphase Flow,* which gives an excellent background on fundamentals and focuses primarily on bubbly flows.

Authors

Clayton T. Crowe is Professor Emeritus at Washington State University (WSU) in Pullman, WA, retiring from the university in 2001. He received his Ph.D. from the University of Michigan in Ann Arbor, MI, in 1962. For seven years he worked in the rocket industry, before joining the Department of Mechanical Engineering of WSU in 1969. He is the primary author of *Engineering Fluid Mechanics* currently in its 9th edition, coauthor of *Multiphase Flow of Droplets and Particles* (1998), and editor of the *Multiphase Flow Handbook* (2006). He received the ASME Fluids Engineering Award in 1995 and the International Prize for Multiphase Flows in 2001. In 2009 ASME recognized Professor Crowe for his contributions to the Society, and in 2010 he received the WSU Emeritus Society Award for Excellence.

John D. Schwarzkopf is currently a staff scientist in the X-Theoretical Design (XTD) Division of the Los Alamos National Laboratory in Los Alamos, NM. He received his Ph.D. in mechanical engineering from Washington State University in 2008. His graduate work addressed turbulence modulation in particle-laden flows. Prior to receiving his Ph.D., he worked in the electronics cooling industry for seven years; he is the coauthor on a patent in this area. Currently he is involved with code development and validation.

Martin Sommerfeld is currently Professor of Mechanical Process Engineering at the Martin-Luther University of Halle-Wittenberg in Germany. He received his Dipl.-Ing. degree in 1981 and his Dr.-Ing. degree in 1984 from the University of Aachen, Germany. Before his promotion to professor at Martin-Luther University he led a research group on two-phase flow at the University of Erlangen in Germany. He has performed detailed experimental studies of multiphase flows utilizing advanced digital image analyses and phase-Doppler anemometry. In 1997 he received the DECHEMA Award for his contributions to multiphase flow measurements, modeling, and numerical predictions. His current activities include development of models for flow around agglomerates, experimental analysis with modern optical instrumentation, and direct numerical simulation.

Yutaka Tsuji retired from Osaka University, Japan, in 2007. After receiving his DE from Osaka University in 1974, he directed his attention to numerical analysis and measurements of fluid-solid flows. He has been the recipient of several prestigious awards, such as the JSME Metal in 1992 and the AIChE Thomas Baron Award in 1999, honoring his contributions to the field. Since retirement he has become the managing director of the Hosokawa Powder Technology Foundation promoting powder and particle technology. He is also the editor-in-chief for the *KONA Powder and Particle Journal.*

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Contents

Chapter 1

Introduction

The flow of particles and droplets in fluids is a subcategory of multicomponent, multiphase flows. The flow of multicomponent, multiphase mixtures covers a wide spectrum of flow conditions and applications. A *component* is a chemical species such as nitrogen, oxygen, water or Freon. A *phase* refers to the solid, liquid or vapor state of the matter. Examples of single and multicomponent, multiphase flows are provided in Table 1.1.

	Single component	Multicomponent
Single-phase	Water flow Nitrogen flow	Air flow Flow of emulsions
Multiphase	Steam-water flow Freon-Freon vapor flow	Air-water flow Slurry flow

Table 1.1. Examples of single and multicomponent, multiphase flows.

The flow of air, which is composed of a mixture of gases (nitrogen, oxygen, etc.), is the best example of a single-phase multicomponent flow. It is common practice to treat these types of flows as the flow of a single component with a viscosity and thermal conductivity which represents the mixture. Such an approach is practical unless the major constituents of the component gases have significantly different molecular weights. In this case the momentum associated with the diffusional velocities may be important. Also, the multicomponent nature of air will be important at high temperatures where dissociation occurs, or at very low temperatures where some species may condense out.

The flow of mixtures of liquids is also an important industrial application. For example, water is sometimes used to flush oil from a well which gives rise to a multicomponent single-phase flow. If the two liquids are miscible, then the mixture will be treated as a single-phase with modified properties. If the liquids are immiscible, then the liquid cannot be regarded as homogeneous and treatment of the flow problem becomes much more complex. In this situation one may have "globs" of oil in the water or for high oil content, globs of water carried by the oil. The mixtures of two liquids are generally referred to as emulsions.

Single-component, multiphase flows are typically the flow of a liquid with its vapor. The most common example is steam-water flows which are found in a wide variety of industries. Another example of single-component, multiphase flows are refrigerants in a refrigeration system.

The flow of fluids of a single phase has occupied the attention of scientists and engineers for many years. The equations for the motion and thermal properties of single-phase fluids are well accepted (Navier-Stokes equations) and closed-form solutions for specific cases are well documented. The major difficulty is the modeling and quantification of turbulence and its influence on mass, momentum and energy transfer. The state-of-the art for multiphase flows is considerably more primitive in that the correct formulation of the governing equations is still subject to debate. For this reason, the study of multiphase flows represents a challenging and potentially fruitful area of endeavor for the scientist or engineer.

Gas-liquid flows	Bubbly flows Separated flows Gas-droplet flows
Gas-solid flows	Gas-particle flows Pneumatic transport Fluidized beds
Liquid-solid flows	Slurry flows Hydrotransport Sediment transport
Three-phase flows	Bubbles in a slurry flow Droplets/particles in gaseous flows

Table 1.2. Categories and examples of multiphase flows.

Multiphase flows can be subdivided into four categories: gas-liquid, gas-solid, liquid-solid and three-phase flows. Examples of these four categories are shown in Table 1.2. A gas-liquid flow can assume several different configurations. For example, the motion of bubbles in a liquid in which the liquid is the continuous phase is a gas-liquid flow. On the other hand, the motion of liquid droplets in a gas is also a gas-liquid flow. In this case, the gas is the continuous phase. Also, a separated flow in which the liquid moves along the bottom of a pipe and the gas along the top is also a gas-liquid flow. In this situation both phases are continuous. The first two examples, bubbles in a liquid and droplets in a gas, are known as dispersed phase flows since one phase is dispersed and the other is continuous. By definition, one can pass from one point to another in the continuous phase while remaining in the same medium. One cannot pass from one droplet to another without going through the gas.

Gas-solid flows are usually considered to be a gas with suspended solid particles. This category includes pneumatic transport as well as fluidized beds. Another example of a gas-solid flow would be the motion of particles down a chute or inclined plane. These are known as granular flows. Particle-particle and particle-wall interactions are much more important than the forces due to the interstitial gas. If the particles become motionless, the problem reduces to flow through a porous medium in which the viscous force on the particle surfaces is the primary mechanism affecting the gas flow. An example is a pebble-bed heat exchanger. It is not appropriate to refer to flow in a porous medium as a gas-solid flow since the solid phase is not in motion. Gas-solid flow is another example of a dispersed phase flow since the particles constitute the dispersed phase and the gas is the continuous phase.

Liquid-solid flows consist of flows in which solid particles are carried by the liquid and are referred to as slurry flows. Slurry flows cover a wide spectrum of applications from the transport of coals and ores to the flow of mud. These flows can also be classified as dispersed phase flows and are the focus of considerable interest in engineering research. Once again it is not appropriate to refer to the motion of liquid through a porous medium as a liquid-solid flow since the solid phase is not in motion.

Three-phase flows are also encountered in engineering problems. For example, bubbles in a slurry flow gives rise to the presence of three phases flowing together. There is little work reported in the literature on three-phase flows.

The subject of this book is the flow of particles or droplets in a fluid, specifically the flow of particles and/or droplets in a conveying gas as well as particles in a conveying liquid. The other area of dispersed phase flows, namely, bubbly flows, will not be addressed here.

The flow of particles and droplets in fluids has a wide application in industrial processes. The removal of particulate material from exhaust gases is essential to the control of pollutants generated by power plants fired by fossil fuels. The efficient combustion of droplets and coal particles in a furnace depends on the interaction of particles or droplets with air. The generation of many food products depends on the drying of liquid droplets to powders in high temperature gas streams. The transport of powders in pipes is common to many chemical and processing industries.

For many years, the design of systems with particle/droplet flows was based primarily on empiricism. However, more sophisticated measurement techniques have led to improved process control and evaluation of fundamental parameters. Increased computational capability has enabled the development of numerical models that can be used to complement engineering system design. The improved understanding of this is a rapidly growing field of technology which will have far-reaching benefits in upgrading the operation and efficiency of current processes and in supporting the development of new and innovative approaches.

A current status of multiphase flow technology in industrial applications can be found in the *Multiphase Flow Handbook* (Crowe, 2006).

1.1 Industrial applications

The objective of this book is to provide a background in this important area of fluid mechanics to assist those new to the field and to provide a resource to those actively involved in the design and development of multiphase systems. In this chapter, examples of multiphase flows in industrial and energy conversion processes are outlined to illustrate the wide application of this technology.

1.1.1 Spray drying

Many products such as foods, detergents and pharmaceuticals are produced through spray drying (Masters, 1972). This is a process in which a liquid material is atomized, subjected to hot gases and dried into the form of a powder. The general configuration of a counter current flow spray dryer is shown in Figure 1.1. A slurry or concentrated mixture is introduced at the top of the dryer and atomized into droplets. Hot gases are fed into the bottom with a swirl component and move upward through the dryer. The droplets are dried as they fall through the hot rising gases to form a powder which is collected at the bottom and removed as the final product.

Accumulation of the dried product on the wall is to be avoided because of uncontrolled drying and the possibility of fire. Also, in the case of food production, the product cannot become too hot to avoid altering the taste.

The gas-droplet (particle) flow within the dryer is very complex. The swirling motion of the gases transports the particles toward the wall which may lead to impingement and accumulation. The temperature distribution in the dryer will depend on the local concentration of the droplets as they fall through the dryer. High local concentrations will depress the local gas temperature and lead to less effective drying. The result may be a non-uniformly dried product reducing product quality.

Even though spray drying technology has been continuously improved through the years, it is still difficult to scale up models to prototype operation. It is also difficult to determine, without actual testing, how modifying the design of a conventional dryer will affect performance. There have been significant progress (Verdurmen et al., 2004) in the development of numerical and analytic tools that adequately simulate the gas-droplet flow field in the dryer. Such models or analyses could be effectively used to improve the efficiency of current designs, predict off-design performance and serve as a tool for scale-up of promising bench-scale designs to prototype operation.

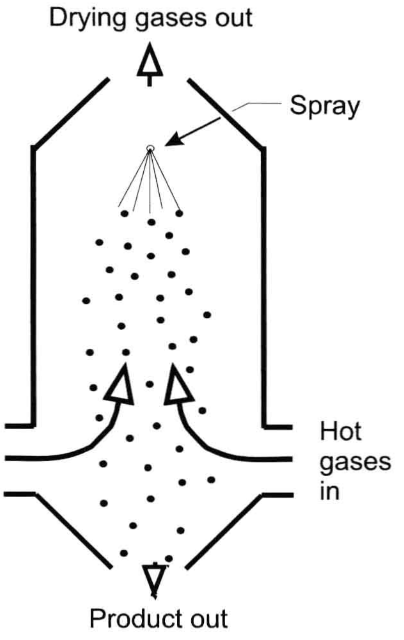

Figure 1.1: Counter-current flow spray dryer.

1.1.2 Pollution control

The removal of particles and droplets from industrial effluents is a very important application of gas-particle and droplet flows (Jorgensen and Johnsen, 1981). Several devices are used to separate particles or droplets from gases. If the particles are sufficiently large (greater than 50 microns), a settling chamber can be used in which the condensed phase simply drops out of the flowing gas and is collected. For smaller particles ($\sim$ 5 microns), the cyclone separator shown in Figure 1.2 is used. The gas-particle flow enters the device in a tangential direction as shown. The resulting vortex motion in the separator causes the particles to migrate toward the wall due to centrifugal acceleration and then fall toward the bottom where they are removed. The gases converge toward the center and form a vortex flow which exits through the top. The performance of the cyclone is quantified by the "cut size" which is the particle diameter above which all the particles are collected. Years of experience in cyclone design have resulted in "standard" designs that, under normal operating conditions, have predictable performance. Numerical modeling or other approaches are needed to design cyclones for special applications such as hot-gas clean up.

The particles issuing from power plants operating with fossil fuels are on the order of a micron in diameter. In these applications, the electrostatic

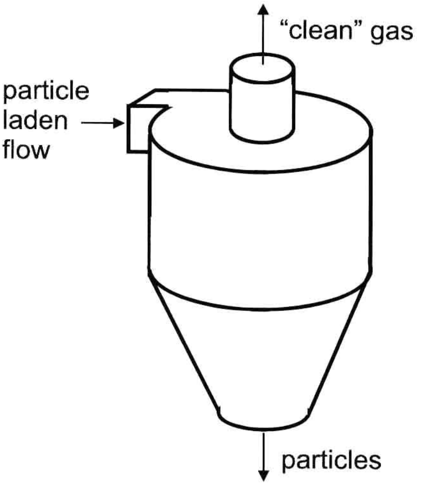

Figure 1.2: Cyclone separator.

precipitator is generally used. The top view of a conventional electrostatic precipitator is shown in Figure 1.3. The high voltage applied to the wires creates a corona with charged ions. These ions travel along the electric lines of force to the particles and accumulate on the particles. The resulting charged particles are moved toward the wall by Coulomb forces and deposited on the wall. Periodically the plates are vibrated (rapped) and the particles fall into a collection bin. The fluid mechanics of the electrostatic precipitator is quite complex. The particle-fluid interaction obviously influences the particle concentration and the charge density. These, in turn, affect the electric field. Flow turbulence is also introduced by the structural ribs in the system. Electrostatic precipitators are still designed using empirical formulas because of the complexity of the fluid-particle-electrical field interactions.

Another pollution control device is the wet gas scrubber which is designed to remove particulate as well as gaseous pollutants. Scrubbers come in many configurations but the venturi scrubber shown in Figure 1.4 represents a simple design. Droplets are introduced upstream of the venturi and the particles are collected on the droplets. The droplets, being much larger than the particles, can be more easily separated from the flow. Sulfur dioxide can also be removed by using droplets mixed with lime. The sulfur dioxide is absorbed on the surface of the droplets. These droplets are collected, the sulfur products are removed and the droplets are reused in the scrubber.

1.1.3 Transport systems

Materials can be transported by either gases or liquids, depending on the specific application. The transport of materials by air is known as pneumatic