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Principles of Gas-Solid Flows

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Principles of Gas–Solid Flows

Gas–solid flows are involved in numerous industrial processes and occur in various natural phenomena. This authoritative book addresses the fundamental principles that govern gas–solid flows and the application of these principles to various gas–solid flow systems.

The book is arranged in two parts: Part I deals with basic relationships and phenomena, including particle size and properties, collision mechanics of solids, momentum transfer and charge transfer, heat and mass transfer, basic equations, and intrinsic phenomena in gas–solid flows. Part II discusses the characteristics of selected gas–solid flow systems such as gas–solid separators, hopper and standpipe flows, dense-phase fluidized beds, circulating fluidized beds, pneumatic conveying systems, and heat and mass transfer in fluidization systems.

As a comprehensive information source on gas–solid flows, this text will be useful to a broad range of engineers and applied scientists – chemical, mechanical, agricultural, civil, environmental, aeronautical, and materials engineers, as well as atmospheric and meteorological scientists.

Cambridge Series in Chemical Engineering

To

Lois Liang-Yen, Liang-Fu, and Jeannine Liang-Chi

and

Zhichi Zhu, Zhu Ruan, Baolan Shi, and Victor

Preface

Gas–solid flows are involved in numerous industrial processes and occur in various natural phenomena. For example, in solid fuel combustion, gas–solid flows are involved in pulverized coal combustion, solid waste incineration, and rocket propellant combustion. Gas–solid flows are encountered in pneumatic conveying of particulates commonly used in pharmaceutical, food, coal, and mineral powder processing. Fluidization is a common gas–solid flow operation with numerous important applications such as catalytic cracking of intermediate hydrocarbons, and Fischer–Tropsch synthesis for chemicals and liquid fuel production. Gas–solid flows occur in gas–particle separations, as exemplified by cyclones, electrostatic precipitators, gravity settling, and filtration operations. Fine powder–gas flows are closely associated with material processing, as in chemical vapor deposition for ceramics and silicon production, plasma coating, and xerography. In heat transfer applications, gas–solid flows are involved in nuclear reactor cooling and solar energy transport using graphite suspension flows. Solid dispersion flows are common in pigment sprays, dust explosions and settlement, and nozzle flows. The natural phenomena accompanied by gas–solid flows are typified by sand storms, moving sand dunes, aerodynamic ablation, and cosmic dusts. The optimum design of the industrial processes and accurate account of the natural phenomena that involve gas–solid flows as exemplified previously require a thorough knowledge of the principles governing these flows.

This book is intended to address basic principles and fundamental phenomena associated with gas–solid flows, as well as characteristics of selected gas–solid flow systems. It covers the typical range of particle sizes of interest to gas–solid flows, *i.e.*, 1 μm–10 cm, recognizing that flow characteristics for submicrometer particles are also of great industrial importance. The book features a systematic account of important theories or models concerning particle mechanics as well as fluid dynamics from their origins of the development. The physical interpretation and limitations in application of these theories or models are emphasized. Various intrinsic phenomena underlying the gas–solid flow systems are also illustrated. The book is aimed as a textbook for seniors and graduate students who are interested in general or specific topics of gas–solid flows. In addition, it can be used as a reference for researchers and practitioners who are interested in the general field of multiphase flow. It is written with multidisciplinary engineering readers in mind. Specifically, it will be of benefit to chemical and mechanical engineering readers as well as readers in other engineering disciplines, including agricultural, civil, environmental, pharmaceutical, aeronautical, mining, and atmospheric and meteorological sciences.

The book contains two parts; each part comprises six chapters. Part I deals with basic relationships and phenomena of gas–solid flows while Part II is concerned with the characteristics of selected gas–solid flow systems. Specifically, the geometric features (size and size distributions) and material properties of particles are presented in Chapter 1. Basic particle sizing techniques associated with various definitions of equivalent diameters of particles are also included in the chapter. In Chapter 2, the collisional mechanics of solids, based primarily on elastic deformation theories, is introduced. The contact time, area, and force of colliding particles are discussed using theories of elastic collision, which are important to the formulation of the momentum, heat, and charge transfer processes involving collisions of solids. Chapter 3 is devoted to the momentum and charge transfer of gas–solid flows. Various forces in gas–solid flows due to gas–particle interactions, particle–particle interactions, and external fields are delineated. Equations for single-particle motion, based on a force balance analysis, are derived. Basic mechanisms of charge generation in gas–solid flows are also introduced in the chapter, along with a detailed discussion of charge transfer mechanism by particle collisions. Chapter 4 deals with fundamental concepts and theories of heat and mass transfer in gas–solid flows. Highlights include thermal radiation of the particulate phase and heat conduction in collisions of elastic particles. Chapter 5 presents four basic modeling approaches of gas–solid flows, namely, continuum modeling of multiphase flows or multifluid modeling, trajectory modeling, kinetic theory modeling for collision-dominated dense suspensions, and the Ergun equation for flow through a packed bed of particles. In this chapter, the hydrodynamic equations of single-phase flows are first discussed. Here, basic concepts of kinetic theory of gas and turbulence models are introduced as a preamble to discussion of these basic modeling approaches. In contrast to the k–ϵ turbulence model for single-phase flows, the k–ϵ–k_p model is introduced with the continuum approach of gas–solid flows to account for gas–solid turbulence interactions. Chapter 6 focuses on the discussion of intrinsic phenomena in gas–solid flows, such as erosion and attrition, acoustic wave and shock wave propagation through a gas–solid suspension flow, thermodynamic properties of a gas–solid mixture, flow instability, and gas–solid turbulence interactions.

Chapter 7 is concerned with gas–solid separations. The basic separation methods introduced in this chapter include cyclone, filtration, electrostatic precipitation, gravity settling, and wet scrubbing. Chapter 8 deals with hopper flows and standpipe flows, which are commonly encountered in the bulk solids handling and transport processes. In order to understand the fundamental hopper and standpipe flow characteristics, some basic concepts of powder mechanics are illustrated. Chapter 9 introduces the general concept of gas fluidization. Specifically, the chapter addresses dense-phase fluidization, which represents a gas–particle operation of enormous industrial importance. Various operating regimes including particulate fluidization, bubbling/slugging fluidization, and turbulent fluidization are discussed along with spouting. The fundamental properties of bubble, cloud, and wake and the intrinsic bubble coalescence and breakup and particle entrainment phenomena are illustrated. Chapter 10 continues the discussion of fluidization under higher-velocity conditions which are characterized by fast fluidization. Fast fluidization is conducted in a riser of a circulating fluidized bed system where solid particles are circulating in a loop. This chapter illustrates the interactive relationship of gas–solid flows in a loop situation by considering the flow behavior of the individual loop components and their effects on the overall gas–solid flow characteristics. Chapter 11 is concerned mainly with the dilute transport or pipe flow of gas–solid suspensions. Some pertinent phenomena such as drag reduction are discussed. Fully developed pipe flow and gas–solid flow in a bend are also illustrated. Chapter 12 describes transport phenomena underlying heat and mass transfer in fluidized systems. Transport models and empirical correlations are introduced to allow heat and mass transfer properties in various fluidized systems to be quantified. An appendix which summarizes the scalar, vector, and tensor notations presented in the text is provided. Throughout the text, unless otherwise noted, the correlation equations presented are given in SI units. Common notations used across the chapters such as superficial gas velocity and particle Reynolds number are unified. The solution manual for homework problems is available. Interested instructors are urged to contact the publisher about it.

The book is intended to be used in various ways depending on the specific information that the readers desire. While the material is described in a logical sequence chapter by chapter, each chapter is presented with extensive cross-references and maintains reasonable independence. Thus, readers who wish to have a quick grasp of a specific subject may go directly to the relevant chapters. It is important to note that gas–solid flow is a rapidly developing field of research, and that the physical phenomena of gas–solid flows are so complex that a comprehensive understanding of the phenomena is far from complete. Therefore, the present text is also intended to provide readers with ample fundamental concepts to allow them to follow through new developments in the field.

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PART I

Basic Relationships