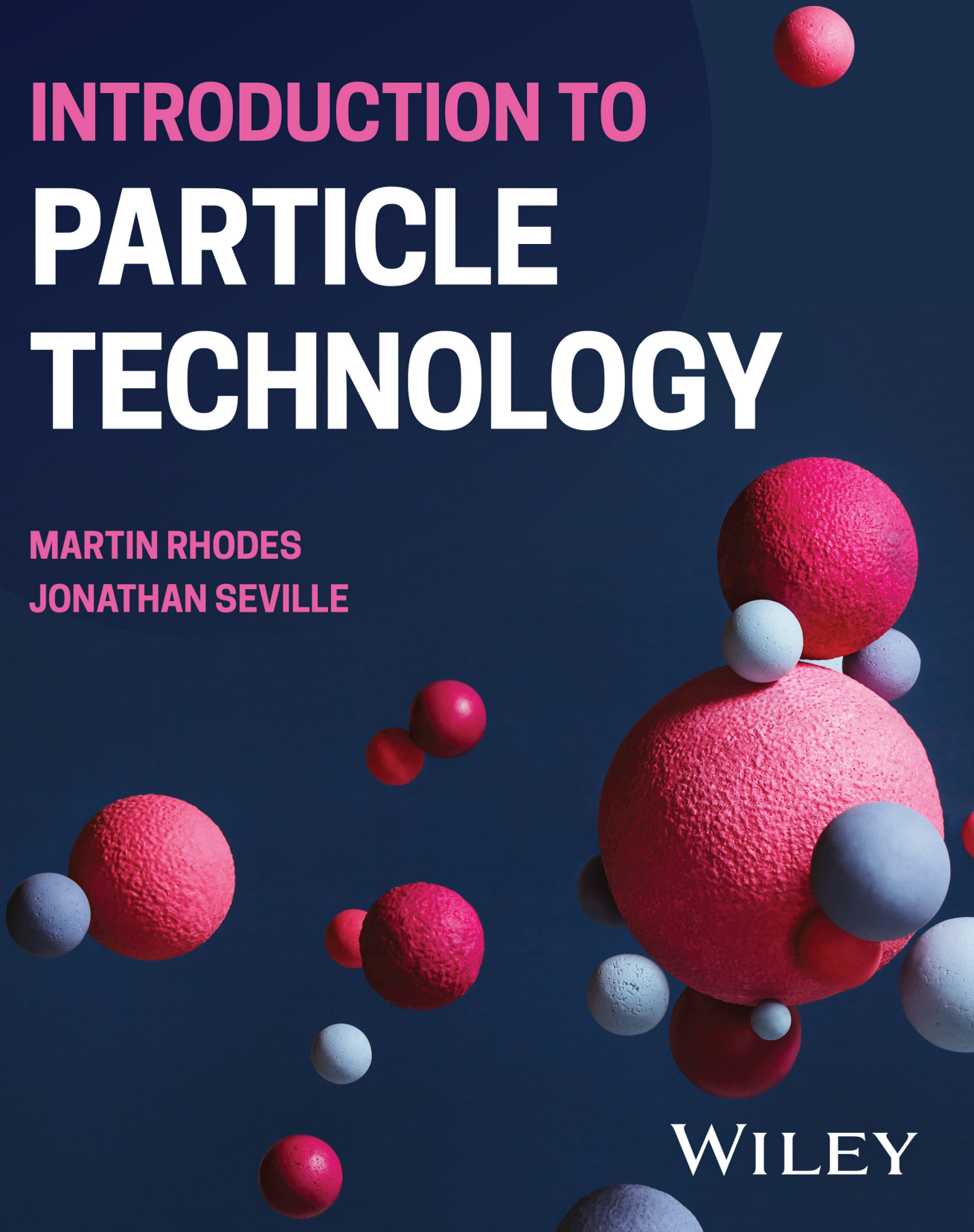


**THIRD EDITION**

**INTRODUCTION TO  
PARTICLE  
TECHNOLOGY**

**MARTIN RHODES  
JONATHAN SEVILLE**



**WILEY**



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# Introduction to Particle Technology

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# Introduction to Particle Technology

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*THIRD EDITION*

**Martin Rhodes**

*Monash University, Australia*

**Jonathan Seville**

*University of Birmingham, UK*

**WILEY**

This edition first published 2024  
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*Edition History*

John Wiley & Sons Ltd (1e,1998, 2e, 2017)

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*Library of Congress Cataloging-in-Publication Data*

Names: Rhodes, M. J. (Martin J.), author. | Seville, J. P. K. (Jonathan P. K.), author.

Title: Introduction to particle technology / Martin Rhodes, Monash University, Australia, Jonathan Seville, University of Birmingham, UK.

Description: Third edition. | Hoboken, NJ, USA : John Wiley & Sons, Inc., 2024. | Includes index.

Identifiers: LCCN 2024005304 (print) | LCCN 2024005305 (ebook) | ISBN 9781119931102 (paperback) | ISBN 9781119931157 (adobe pdf) | ISBN 9781119931164 (epub)

Subjects: LCSH: Particles.

Classification: LCC TP156.P3 R48 2024 (print) | LCC TP156.P3 (ebook) | DDC 620/.43-dc23/eng/20240304

LC record available at <https://lcn.loc.gov/2024005304>

LC ebook record available at <https://lcn.loc.gov/2024005305>

Cover Design: Wiley

Cover Image: © Eugene Mymrin/Getty Images

Set in 10/12pt Palatino by Straive, Pondicherry, India

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# About the Authors

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**Martin Rhodes** has a bachelor's degree in chemical engineering and a PhD in particle technology from Bradford University in the UK, industrial experience in chemical and combustion engineering and many years' experience as an academic at Bradford and Monash Universities. He has research interests in various aspects of gas fluidization and particle technology, areas in which he has many refereed publications in journals and international conference proceedings. Martin was co-founder of the Australasian Particle Technology Society. He is Emeritus Professor and former Head of the Department of Chemical and Biological Engineering at Monash University, Australia.

**Jonathan Seville** is Professor of Formulation Engineering in the School of Chemical Engineering at the University of Birmingham, UK, and a former Dean of Engineering and Physical Sciences at the University of Surrey. He was the editor-in-chief of the Elsevier journal *Powder Technology* for 20 years and is the author of several books and over 200 journal publications on particle technology. He has championed research into product-based particle technology and co-founded the Birmingham Positron Imaging Centre, which carries out radiation-based measurements on particulate systems. He is a Fellow of the Royal Academy of Engineering and was President of the Institution of Chemical Engineers (IChemE) in 2016–2017.

**Kit Windows-Yule** gained a PhD in Nuclear Physics from the University of Birmingham, UK, before working in the University of Twente's Thermal and Fluid Engineering department and the Friedrich-Alexander-Universität Erlangen-Nürnberg's Engineering of Advanced Materials Excellence Cluster, ultimately returning to Birmingham to take up a faculty position in the School of Chemical Engineering. He is a two-time Royal Academy of Engineering Industrial Fellow and a Turing Fellow and has applied his knowledge of particle technology and numerical modelling to diverse industrial problems spanning the aerospace, agriculture, chemical, defence, fast-moving consumer goods, food, green energy, and pharmaceutical sectors.

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# Preface to the Third Edition

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I was delighted when Jonathan Seville accepted my invitation to join me as co-author of the 3rd edition of Introduction to Particle Technology. This permitted us to broaden the scope of the text introducing a chapter on engineering of particles as products together with supporting chapters on aerosols and colloids and the mechanical properties of particles. Aware that discrete element modelling of particulate systems is increasingly important, we invited Kit Windows-Yule to contribute a chapter on the subject. Although pitched at an introductory level, the coverage is thorough and describes the state of the art as it stands today. We intend that this chapter should be a reference for people starting out in discrete element modelling and for practising engineers and scientists wishing to understand something that may at first seem inaccessible to many. Other chapters have been refined and updated. We have aimed to maintain the popular style of the first and second editions, with updated worked examples, test yourself questions and exercises for each chapter.

**Martin Rhodes**

*Cairns, October 2023*

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# Preface to the Second Edition

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It is 10 years since the publication of the first edition of Introduction to Particle Technology. During that time many colleagues from around the world have provided me with comments for improving the text. I have taken these comments into consideration in preparing the second edition. In addition, I have broadened the coverage of particle technology topics – in this endeavour, I am grateful to my co-authors Jennifer Sinclair Curtis and George Franks, who have enabled the inclusion of chapters on Slurry Transport and Colloids and Fine Particles, and Karen Hapgood, who permitted an improved chapter on size enlargement and granulation. I have also included a chapter on the Health Effects of Fine Powders – covering both beneficial and harmful effects. I am also indebted to colleagues Peter Wypych, Lyn Bates, Derek Geldart, Peter Arnold, John Sanderson and Seng Lim for contributing case studies for Chapter 16.

**Martin Rhodes**

*Balnarring, December 2007*

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# Preface to the First Edition

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## Particle Technology

Particle technology is a term used to refer to the science and technology related to the handling and processing of particles and powders. Particle technology is also often described as powder technology, particle science and powder science. Powders and particles are commonly referred to as bulk solids, particulate solids and granular solids. Today particle technology includes the study of liquid drops, emulsions and bubbles as well as solid particles. In this book only solid particles are covered and the terms particles, powder and particulate solids will be used interchangeably.

The discipline of particle technology now includes topics as diverse as the formation of aerosols and the design of bucket elevators, crystallization and pneumatics transport, slurry filtration and silo design. A knowledge of particle technology may be used in the oil industry to design the catalytic cracking reactor which produces gasoline from oil or it may be used in forensic science to link the accused with the scene of crime. Ignorance of particle technology may result in lost production, poor product quality, risk to health, dust explosion or storage silo collapse.

## Objective

The objective of this textbook is to introduce the subject of particle technology to students studying degree courses in disciplines requiring knowledge of the processing and handling of particles and powders. Although the primary target readership is amongst students of chemical engineering, the material included should form the basis of courses on particle technology for students studying other disciplines including mechanical engineering, civil engineering, applied chemistry, pharmaceuticals, metallurgy and minerals engineering.

A number of key topics in particle technology are studied giving the fundamental science involved and linking this, wherever possible, to industrial practice. The coverage of each topic is intended to be exemplary rather than exhaustive. This is not intended to be a text on unit operations in powder technology for chemical engineers. Readers wishing to know more about the industrial practice and equipment for handling and processing are referred to the various handbooks of powder technology which are available.

The topics included have been selected to give coverage of broad areas within easy particle technology: characterization (size analysis), processing (fluidized beds granulation), particle formation (granulation, size reduction), fluid-particle separation (filtration, settling, gas cyclones), safety (dust explosions), transport (pneumatic transport and



standpipes). The health hazards of fine particles or dusts are not covered. This is not to suggest in any way that this topic is less important than others. It is omitted because of a lack of space and because the health hazards associated with dusts are dealt with competently in the many texts on Industrial or Occupational Hygiene which are now available. Students need to be aware however, that even chemically inert dusts or 'nuisance dust' can be a major health hazard. Particularly where products contain a significant proportion of particles under 10  $\mu\text{m}$  and where there is a possibility of the material becoming airborne during handling and processing. The engineering approach to the health hazard of fine powders should be strategic wherever possible, aiming to reduce dustiness by agglomeration, to design equipment for containment of material and to minimize exposure of workers.

The topics included demonstrate how the behaviour of powders is often quite different from the behaviour of liquids and gases. Behaviour of particulate solids may be surprising and often counter-intuitive when intuition is based on our experience with fluids. The following are examples of this kind of behaviour:

When a steel ball is placed at the bottom of a container of sand and the container is vibrated in a vertical plane, the steel ball will rise to the surface.

A steel ball resting on the surface of a bed of sand will sink swiftly if air is passed upward through the sand causing it to become fluidized.

Stirring a mixture of two free-flowing powders of different sizes may result in segregation rather than improved mixture quality.

Engineers and scientists are used to dealing with liquids and gases whose properties can be readily measured, tabulated and even calculated. The boiling point of pure benzene at one atmosphere pressure can be safely relied upon to remain at 80.1 °C. The viscosity of water at 20 °C can be confidently predicted to be 0.001 Pa s. The thermal conductivity of copper at 100 °C is 377W/m K. With particulate solids, the picture is quite different. The flow properties of sodium bicarbonate powder, for example, depend not only on the particle size distribution, the particle shape and surface properties, but also on the humidity of atmosphere and the state of the compaction of the powder. These variables are not easy to characterize and so their influence on the flow properties is difficult to predict with any confidence.

In the case of particulate solids it is almost always necessary to rely on performing appropriate measurements on the actual powder in question rather than relying on tabulated data. The measurements made are generally measurements of bulk properties, such as shear stress, bulk density, rather than measurements of fundamental properties such as particle size, shape and density. Although this is the present situation, in the not too distant future, we will be able to rely on sophisticated computer models for simulation of particulate systems. Mathematical modelling of particulate solids behaviour is a rapidly developing area of research around the world, and with increased computing power and better visualization software, we will soon be able to link fundamental particle properties directly to bulk powder behaviour. It will even be possible to predict, from first principles, the influence of the presence of gases and liquids within the powder or to incorporate chemical reaction.

Particle technology is a fertile area for research. Many phenomena are still unexplained and design procedures rely heavily on past experience rather than on fundamental

understanding. This situation presents exciting challenges to researchers from a wide range of scientific and engineering disciplines around the world. Many research groups have websites which are interesting and informative at levels ranging from primary schools to serious researchers. Students are encouraged to visit these sites to find out more about particle technology.

**Martin Rhodes**

*Mount Eliza, May 1998*

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# Acknowledgements

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The authors are indebted to a large number of people who have helped them in various ways to prepare this edition, by advising, reading, commenting and in some cases supplying material which we have included. In particular, we would like to thank the following:

Professor Karen Hapgood, now of Swinburne University, Melbourne, Australia, who prepared the chapter on Size Enlargement for the 2nd edition, upon which the 3rd edition chapter on this subject is based.

Professor George V. Franks of the University of Melbourne, Australia, who prepared the chapter on Colloids and Fine Particles for the 2nd edition, upon which the 3rd edition chapter on Colloids and Aerosols is based.

Professors Mike Adams, Bettina Wolf and Zhibing Zhang and Dr. Andy Ingram at the University of Birmingham, UK.

Professor Peter Knight, formerly of Unilever Research.

Professor Chuan-yu Wu at the University of Surrey, UK.

Professor Mojtaba Ghadiri at the University of Leeds, UK.

Dr. Ted Knowlton of Particulate Solids Research Inc., USA.

Professor Mark Jones at Newcastle University, Australia.

Dominik Werner, Andrei Leonard Niçusan, Ben Jenkins, PhD candidates at the University of Birmingham, UK.

Allen Forbes of the Collaborative Teaching Laboratory at the University of Birmingham, UK, for help with microphotography.

Professor Hsiu-Po Kuo of National Taiwan University.

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Winkworth Machinery for permission to use Figure 10.7.

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# About the Website

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This book is accompanied by the website:

[www.wiley.com/go/rhodes/particle3e](http://www.wiley.com/go/rhodes/particle3e)



A website with laboratory demonstrations in particle technology and interactive code examples, designed to accompany this text, is available. This easily navigated resource incorporates many video clips of particle and powder phenomena with accompanying explanatory text. The videos bring to life many of the phenomena that we have tried to describe here in words and diagrams. For example, you will see: fluidized beds (bubbling, non-bubbling, spouted) in action; core flow and mass flow in hoppers, size segregation during pouring, vibration and rolling; agglomeration of fine powders, a coal dust explosion; a cyclone separator in action; dilute and dense phase pneumatic conveying. The interactive online notebooks will provide the reader with a deeper understanding of the techniques used to model particulate and multiphase systems. As a whole, the website will aid the reader in understanding particle technology and is recommended as a useful adjunct to this text.

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# Introduction

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Particulate materials, powders or bulk solids are used widely in all areas of the process industries, for example in the food processing, pharmaceutical, biotechnology, energy, chemical, mineral processing, metallurgical, detergent, paint, plastics and cosmetics industries. These industries involve many different types of professional scientists and engineers, such as chemical engineers, chemists, biologists, physicists, pharmacists, mineral engineers, food technologists, metallurgists, material scientists/engineers, environmental scientists/engineers, mechanical engineers, combustion engineers and civil engineers. Numerous surveys have suggested the importance of particle-based products to the world's economy and new products and applications are emerging every day.

Some examples of the processing steps involving particles and powder include particle formation processes (such as crystallization, precipitation, granulation, spray drying, tableting, extrusion and grinding), transportation processes (such as pneumatic and hydraulic transport, mechanical conveying and screw feeding) and mixing, drying and coating processes. In addition, processes involving particulates require reliable storage facilities and give rise to health and safety issues, which must be satisfactorily handled. Design and operation of these many processes across this wide range of industries require a knowledge of the behaviour of powders and particles. This behaviour is often counterintuitive, when intuition is based on our knowledge of liquids and gases. For example, actions such as stirring, shaking or vibrating, which would result in mixing of two liquids, are more likely to produce size segregation in a mixture of free-flowing powders of different sizes. A storage hopper holding 500 tonnes of powder may not deliver even 1 kg when the outlet valve is opened unless the hopper has been correctly designed. When a steel ball is placed at the bottom of a container of sand and the container is vibrated in the vertical plane, the steel ball will rise to the surface. This steel ball will then sink swiftly to the bottom again if air is passed upwards through the sand causing it to be fluidized.

Engineers and scientists are used to dealing with gases and liquids, whose properties can be readily measured, tabulated or even calculated. The boiling point of pure benzene at atmospheric pressure can be safely assumed to remain at 80.1 °C. The thermal conductivity of copper can always be relied upon to be 377 W/mK at 100 °C. The viscosity of water at 20 °C can be confidently expected to be 0.001 Pa s. With particulate solids, however, the situation is quite different. The flow properties of sodium bicarbonate powder, for example, depend not only on the particle size distribution, but also on particle shape and surface properties, the humidity of the surrounding atmosphere and the state of compaction of the powder. These variables are not easy to characterize and so their influence on the flow properties of the powder is difficult to predict or control with any confidence. Intriguingly, powders appear to have some of the behavioural characteristics of all three phases: solids, liquids and gases. For example, like gases, powders can be compressed;

like liquids, they can be made to flow; and like solids, they can withstand some deformation.

The importance of knowledge of the science of particulate materials (often called particle or powder technology) to the process industries cannot be overemphasized. Very often, difficulties in the handling or processing of powders are ignored or overlooked at the design stage, with the result that powder-related problems are the cause of an inordinate number of production stoppages. However, it has been demonstrated that the application of even a basic understanding of the ways in which powders behave can minimize these processing problems, resulting in less downtime, improvements in quality control and reduced environmental emissions.

This text is intended as an introduction to particle technology. The topics included have been selected to give coverage of the broad areas of particle technology: characterization (size analysis, surface area), processing (granulation, fluidization), particle formation (granulation, crystallisation, tableting, size reduction), storage and transport (hopper design, pneumatic conveying, standpipes), separation (filtration, settling, cyclones), safety (fire and explosion hazards, health hazards), engineering the properties of particulate systems to achieve desired product performance, discrete element modelling. For each of the topics studied, the fundamental science involved is introduced and this is linked, where possible, to industrial practice. In each chapter there are worked examples and exercises to enable the reader to practice the relevant calculations and a 'Test Yourself' section, intended to highlight the main concepts covered.

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Jonathan Seville

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# 1

## Particle Analysis

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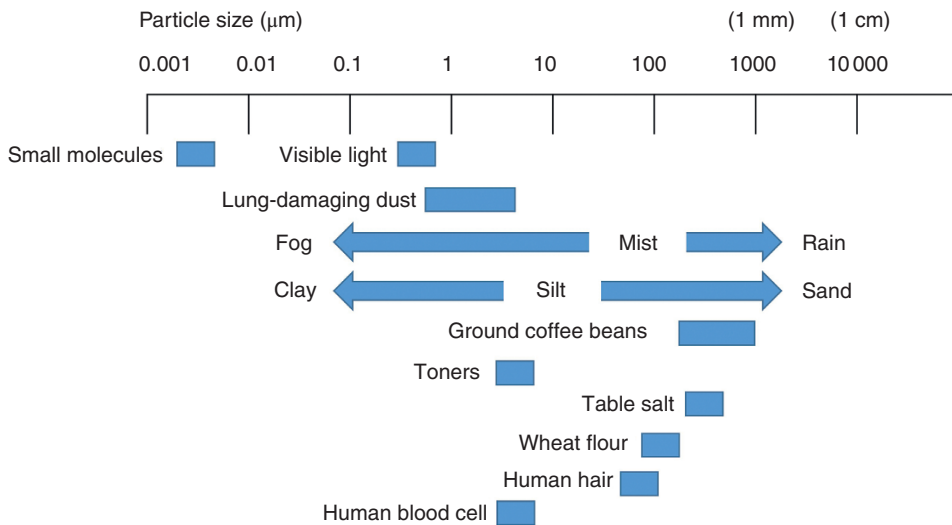
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Particle size and size distribution are fundamentally important in determining how a powder will behave in its bulk form. Measuring the particle size distribution, describing it in graphical and mathematical form and comparing it with other distributions are therefore important tasks for the particle technologist and are introduced in this chapter. Particle “size” can be described unambiguously by a single number only for a distribution of monosized spheres, but real particles are neither spherical nor monosized. We therefore need to understand how to describe particle shape and what effects this has on measurement and calculation. In many industrial applications it is common to represent an entire distribution by some sort of averaged single number. Calculation methods and choices for this are shown. Finally, we also introduce methods for measurement of the surface area of particle distributions.

### 1.1 PARTICLE SIZE

Size is the most fundamental of particle properties. We will see throughout this book that the size of a particle affects all of its properties. For example, larger particles usually flow freely whereas smaller particles do not. Larger particles dissolve slowly and smaller ones more quickly, resulting in different pharmaceutical effectiveness. Light is scattered strongly from small particles but much less so from larger ones, resulting in different atmospheric effects and a different appearance of painted surfaces, for example.

The objects we describe as particles can cover a wide range of sizes, as shown in Figure 1.1, from large molecules (of order  $0.01\ \mu\text{m}$  or  $10^{-8}\ \text{m}$ ) to bricks (of order  $10\ \text{cm}$  or  $10^{-1}\ \text{m}$ ). Particles almost always come in large numbers (there are hundreds of millions of salt particles on your dinner table right now!) and as a *distribution* of sizes. Mono-sized distributions, containing only one particle size or a very narrow distribution of sizes, are very rare (pollen is an example in nature). Distributions can be wide, often very wide. For example, your container of salt will include not only salt crystals of around  $0.3\ \text{mm}$  or  $300\ \mu\text{m}$  but also broken salt dust particles down to  $1\ \mu\text{m}$  in size. In many processes

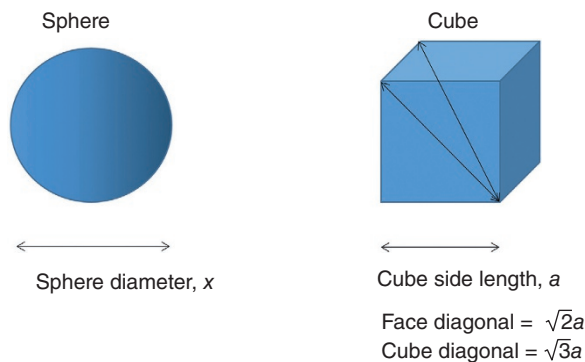


**Figure 1.1** Ranges of particle size

and products the entire distribution is important; those very fine particles can have a big effect on how the whole distribution behaves.

What do we mean by *particle size*? This might seem like a simple question but in general it is not. If the particle is a sphere, the obvious answer is that its size is the same as its diameter. What if the particle is a cube? (Crystalline particles usually have an angular shape and crystals of common salt – sodium chloride – are roughly cubic.) In this case, it might seem logical to choose the side length of the cube to represent its size but as shown in Figure 1.2, there are other choices and the maximum dimension is actually  $\sqrt{3}$  times the side length  $a$ .

Another way of looking at the problem of selection of a representative or equivalent diameter is to calculate the size of a sphere which has the same property as the non-spherical particle we are interested in. Two widely used possibilities are:



**Figure 1.2** Sizes of spheres and cubes



the diameter of a sphere of equivalent projected area  $A$

$$x_A = \sqrt{\frac{4A}{\pi}} \quad (1.1)$$

or the diameter of a sphere of equivalent volume  $V$

$$x_V = \sqrt[3]{\frac{6V}{\pi}} \quad (1.2)$$

For the cube considered earlier, Figure 1.3 shows how the projected area may take the value  $a^2$  or  $\sqrt{2}a^2$  or  $\sqrt{3}a^2$  according to the orientation of the particle, or, of course, values in between these for other orientations. The equivalent projected area diameter will then depend upon the orientation and in these three cases will take values of  $a\sqrt{4/\pi}$ ,  $2a\sqrt{1.414/\pi}$  and  $2a\sqrt{1.732/\pi}$ .

Note that the equivalent volume diameter  $x_V$ , does not depend on the orientation.

The example of a cube is relatively easy to deal with. Real particles seldom have a regular shape but approximation to a spheroid, plate or rod may sometimes be useful.

For irregular particles, the projected image can be used to obtain a number of types of *shape factors*, as illustrated in Figure 1.4.

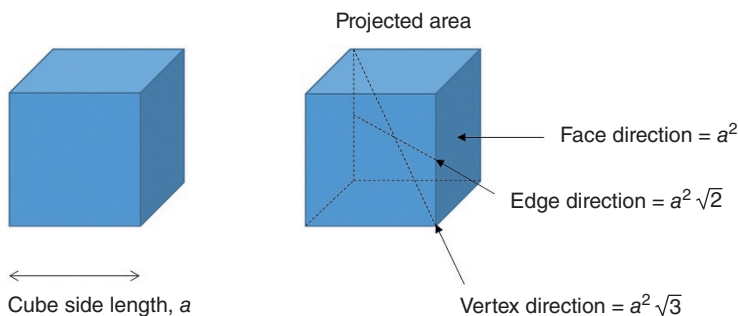
Roundness  $S_R$ , is a measure of how closely the particle outline resembles a circle:

$$S_R = \frac{4\pi A}{P^2} \quad (1.3)$$

where  $P$  is the perimeter length and  $A$  is the area. Roundness is defined such that the value for a circle is 1. The roundness of other particles is then less than 1.

The Feret diameter is obtained by taking the distance between two parallel lines on either side of the particle perimeter, as shown. By varying the angle  $\varphi$  it is possible to find the minimum and maximum Feret diameters; a shape factor can be simply obtained from the ratio between them.

Many other measures of shape can be defined.



**Figure 1.3** Equivalent areas for a cube

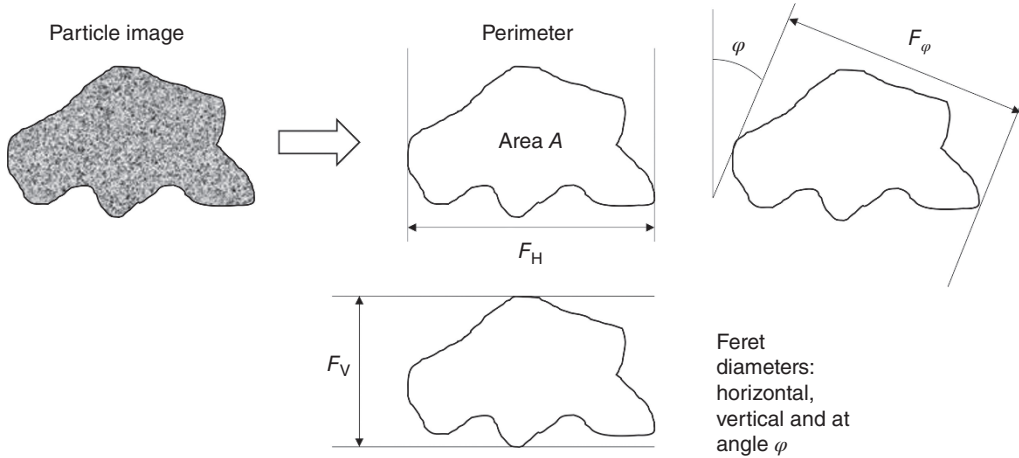


Figure 1.4 Shape and the Feret diameter

## 1.2 DESCRIPTION OF POPULATIONS OF PARTICLES

A population of particles is described by a particle size distribution. Particle size distributions may be expressed as frequency distributions or cumulative distributions. These are illustrated in Figure 1.5. The two are related mathematically in that the cumulative distribution is the integral of the frequency distribution; i.e. if the cumulative distribution is denoted as  $F$ , then the frequency distribution is  $dF/dx$ . For simplicity,  $dF/dx$  is often written as  $f(x)$ . The distributions can be by number, surface, mass or volume (where particle density does not vary with size, the mass distribution is the same as the volume distribution). Incorporating this information into the notation,  $f_N(x)$  is the frequency distribution by number,  $f_S(x)$  is the frequency distribution by surface,  $F_S$  is the cumulative distribution by surface and  $F_M$  is the cumulative distribution by mass. In reality, for many particles these distributions are smooth continuous curves. However, size measurement methods usually divide the size spectrum into size ranges or classes and the size distribution becomes a histogram.

For a given population of particles, the distributions by mass, number and surface can differ dramatically, as can be seen in Figure 1.6.

## 1.3 CONVERSION BETWEEN DISTRIBUTIONS

Many modern size analysis instruments measure particles individually and therefore produce a number distribution, which is rarely the one which is of most practical use. These instruments include software to convert the measured distribution into more practical distributions by mass, surface, etc.

Relating the size distributions by number  $f_N(x)$ , and by surface  $f_S(x)$  for a population of particles having the same geometric shape but different size:

$$\text{Fraction of particles in the size range } x \text{ to } x + dx = f_N(x)dx$$

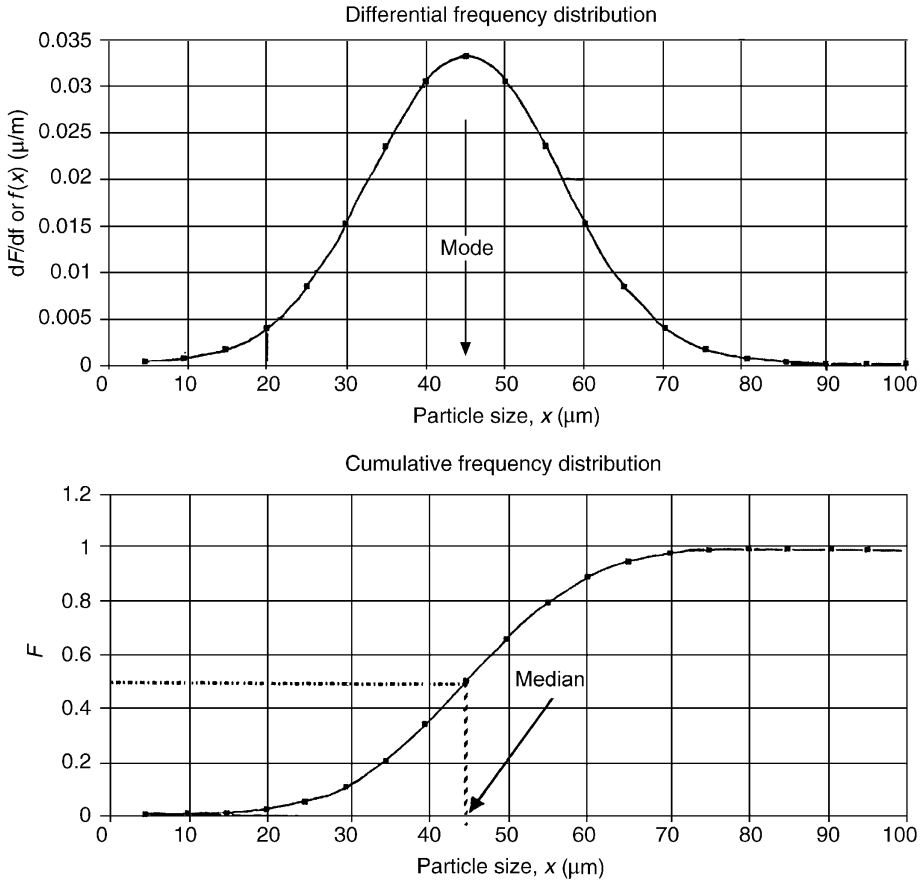


Figure 1.5 Typical differential and cumulative frequency distributions

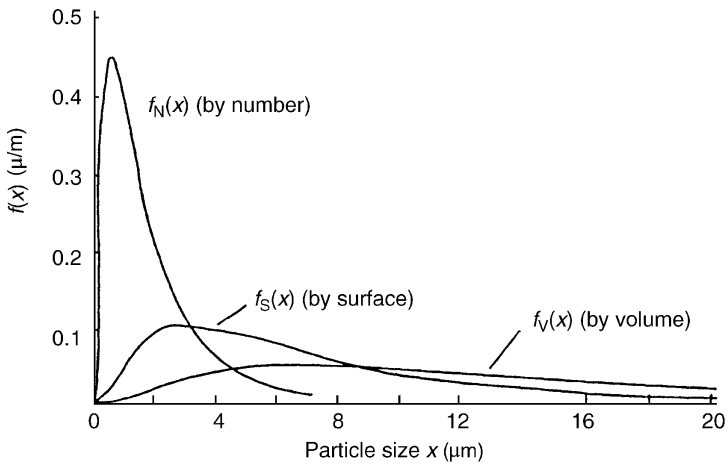


Figure 1.6 Comparison between distributions

Fraction of the total surface of particles in the size range  $x$  to  $x + dx = f_S(x)dx$

If  $N$  is the total number of particles in the population, the number of particles in the size range  $x$  to  $x + dx = Nf_N(x)dx$  and the surface area of these particles  $= (x^2\alpha_S)Nf_N(x)dx$ , where  $\alpha_S$  is the factor relating the linear dimension of the particle to its surface area.

Therefore, the fraction of the total surface area contributed by these particles  $[f_S(x)dx]$  is:

$$\frac{(x^2\alpha_S)Nf_N(x)dx}{S}$$

where  $S$  is the total surface area of the population of particles.

For a given population, the total number of particles,  $N$ , and the total surface area,  $S$  are constant. Also, assuming particle shape is independent of size, i.e. all particles have the same shape,  $\alpha_S$  is constant, and so

$$f_S(x) \propto x^2f_N(x) \quad \text{or} \quad f_S(x) = k_Sx^2f_N(x) \quad (1.4)$$

where

$$k_S = \frac{\alpha_S N}{S}$$

Similarly, for the distribution by volume

$$f_V(x) = k_Vx^3f_N(x) \quad (1.5)$$

where

$$k_V = \frac{\alpha_V N}{V}$$

where  $V$  is the total volume of the population of particles and  $\alpha_V$  is the factor relating the linear dimension of the particle to its volume.

And for the distribution by mass

$$f_m(x) = k_mx^3f_N(x) \quad (1.6)$$

where

$$k_m = \frac{\alpha_V \rho_p N}{V}$$

assuming particle density  $\rho_p$  is independent of size, i.e. all the particles have the same density.

The constants  $k_S$ ,  $k_V$  and  $k_m$  may be found by using the fact that

$$\int_0^{\infty} f(x)dx = 1 \quad (1.7)$$

Thus, when we convert between distributions it is necessary to make assumptions about the constancy of shape and density with size. If these assumptions are not valid, the conversions are likely to be in error. For example, this approach would not be valid in the case where the population consists of whole spheres and broken pieces of spheres, because shape will then vary with size. Also, calculation errors are introduced into the conversions. For example, imagine that we used an electron microscope to produce a number distribution of size with a measurement error of  $\pm 2\%$ . Converting the number distribution to a mass distribution we triple the error involved (i.e. the error becomes  $\pm 6\%$ ). For these reasons, conversions between distributions are to be avoided wherever possible. This can be done by choosing the measurement method which gives the required distribution directly.

#### 1.4 DESCRIBING THE POPULATION BY A SINGLE NUMBER

In most practical applications, we require to describe the particle size of a population of particles (millions of them) by a single number. There are many options available: the mode, the median, and several different means including arithmetic, geometric, quadratic, harmonic, etc. Whichever expression of central tendency of the particle size of the population we use needs to reflect the property or properties of the population of importance to us. We are, in fact, modelling the real population with an artificial population of mono-sized particles. This section deals with calculation of the different expressions of central tendency and selection of the appropriate expression for a particular application.

The *mode* is the most frequently occurring size in the sample (Figure 1.5). We note, however, that for the same sample, different modes would be obtained for distributions by number, surface and volume. The mode has no practical significance as a measure of central tendency and so is rarely used in practice.

The *median* is easily read from the cumulative distribution as the 50% size (Figure 1.5): the size which splits the distribution into two equal parts. In a mass distribution, for example, half of the particles by mass are smaller than the median size. Since the median is easily determined, it is often used. However, it has no special significance as a measure of central tendency of particle size.

Various *means* can be defined for a given size distribution. However, they can all be described by:

$$g(\bar{x}) = \frac{\int_0^1 g(x) dF}{\int_0^1 dF} \quad \text{but} \quad \int_0^1 dF = 1 \quad \text{and so} \quad g(\bar{x}) = \int_0^1 g(x) dF \quad (1.8)$$

where  $\bar{x}$  is the mean and  $g$  is the weighting function, which is different for each mean definition. Examples are given in Table 1.1.

Equation (1.8) tells us that the mean is the area between the curve and the  $F(x)$  axis in a plot of  $F(x)$  versus the weighting function  $g(x)$  (Figure 1.7).

Each mean can be shown to retain two properties of the original population of particles. For example, the arithmetic mean of the surface distribution retains the surface and volume of the original population. This is demonstrated in Worked Example 1.3. This mean

**Table 1.1** Definitions of means

$g(x)$	Mean and notation
$x$	Arithmetic mean $\bar{x}_a$
$x^2$	Quadratic mean $\bar{x}_q$
$x^3$	Cubic mean $\bar{x}_c$
$\log x$	Geometric mean $\bar{x}_g$
$1/x$	Harmonic mean $\bar{x}_h$

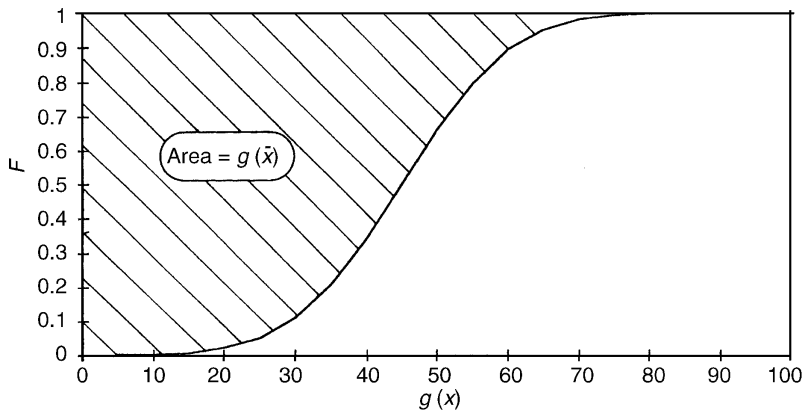
is commonly referred to as the *surface-volume mean* or the *Sauter mean*. The arithmetic mean of the number distribution  $\bar{x}_{aN}$  retains the number and length of the original population and is known as the number-length mean  $\bar{x}_{NL}$ :

$$\text{Number-length mean } \bar{x}_{NL} = \bar{x}_{aN} = \frac{\int_0^1 x dF_N}{\int_0^1 dF_N} \quad (1.9)$$

As another example, the quadratic mean of the number distribution  $\bar{x}_{qN}$  conserves the number and surface of the original population and is known as the number-surface mean  $\bar{x}_{NS}$ :

$$\text{Number-surface mean } \bar{x}_{NS}^2 = \bar{x}_{qN}^2 = \frac{\int_0^1 x^2 dF_N}{\int_0^1 dF_N} \quad (1.10)$$

A comparison of the values of the different means and the mode and median for a given particle size distribution is given in Figure 1.8. This figure highlights two points: (a) that



**Figure 1.7** Plot of cumulative frequency against weighting function  $g(x)$ . Shaded area is  $g(\bar{x}) = \int_0^1 g(x) dF$