P. A. Shamlou

Handling of Bulk Solids

Theory and Practice

Butterworths

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Preface

Of all the materials handled and produced by the process industries, the greatest bulk is in the solid state and almost always in particulate form. In the chemical industry alone the value of product formed as particles is greater than 30% of the whole. The handling of particles is big business often done wastefully from an energy point of view, and improvements in techniques could lead to considerable savings over a wide range of industries. Compared with our understanding of how to handle, move and store gases and liquids, our understanding of particles in bulk is rather primitive.

The subject is difficult and multi-faceted. Particles are rarely handled in a vacuum, and interaction between particles and intervening gas or liquid plays an important part in overall behaviour. Despite, or probably because of, the complex nature of particulate systems, there are relatively few books published covering the field. In particular, the few books that are currently available on the market are either highly specialized, appealing to only a limited group, or too superficial, forming a small section of a much more general book. What is needed is a book that covers the whole field of solids flow and handling in the process industries — a book which treats the subject in depth and is suitable for advanced undergraduate and postgraduate levels as well as for practitioners in industry.

This book is intended to fill this gap between experienced researchers and those new to the work. The subject matter presented is difficult to obtain elsewhere without referring to many sources of information, so the author has assumed a role of interpreter of the literature with those findings and equations being presented which can be of immediate utility to the reader.

Presentation of the subject follows classical lines of separate discussions for each topic, so each chapter is self-contained and can be read on its own. However, a background in mathematics at the first-degree level and an appreciation of the concept of Mohr circles is helpful for a proper understanding of the material, particularly in Chapters 2 and 3.

Worked-out examples are included at the end of each chapter to familiarize the reader with the numerical manipulations and orders of magnitude of various parameters which occur in the subject of bulk solids handling. Because of the complicated form of most of the design equations involved, the computer is an ideal vehicle for the solution of many design problems in bulk solids handling. Indeed computer-generated solutions have been utilized throughout this book, but the author has resisted the temptation to include specific computer programs because each computer installation is slightly different in its input-output capability and, in any case, such programs are not difficult to write and a number of these are readily available on the market.

The field of bulk solid handling is not static. New developments occur regularly, as depicted by the huge amount of information which is available in the open literature. For that reason, each chapter also includes a comprehensive and up-to-date list of references which can be used by the reader to build up further investigation.

I am grateful to Professor P. N. Rowe for suggesting that I should organize a course at University College London on the subject of bulk solids handling. This subsequently formed the foundation for many of the ensuing chapters.

I also wish to express my gratitude to Professor J. W. Mullin for first seeding the concept of this book in my mind and then helping me to materialize it by his useful comments and advice on the organization and layout of the chapters.

I am also indebted to many of my students and colleagues who contributed generously to the preparation of this book. Special thanks are due to Dr John G. Yates for so efficiently reading the final manuscript and for his useful suggestions. I should also like to thank Keyvan M. Djamarani for diligently checking the equations, computer programs and numerical examples.

My thanks are also due to Miss Mary P. Bell for so patiently and skilfully reading the whole manuscript and correcting my English.

P. A. Shamlou

Dedication

To my wife Monir and my children Naby and Nieki for their forbearance during the writing of this book

Contents

Chapter 1

Bulk solids flow and handling properties

Introduction

Enormous quantities of bulk solid materials are produced by the process industries each year; in the chemical industry alone the value of product formed as particles is greater than 30% of the whole. In any operation involving particulate solids, successful storage, flow and handling of the bulk material is a major and essential part of the overall plant design.

The proper design of bulk solid storage and handling equipment, in turn, requires knowledge of the individual and bulk properties of the particulate material under static and dynamic conditions. There are many such properties including the following (Anon., 1970):

- particle size, shape, size distribution and surface area;
- particle and bulk density;
- cohesive properties, flowability and fluidizability;
- hardness, compressibility;
- toxicity, flammability and explosibility;
- optical, thermal, magnetic and chemical characteristics;
- hygroscopicity (ability to attract moisture).

The relative importance of these properties depends largely upon the particular unit operation under consideration (Table 1.1). Many of the characteristics listed above, e.g. those relating to flammability, explosibility and toxicity, are secondary properties; consequently, their definitions and methods of measurement are often highly empirical, requiring considerable expertise to obtain and interpret meaningful data.

The aim of this chapter is to give an account of some of the more important solids properties that influence the behaviour of bulk materials during handling operations. The treatment is confined to those properties for which a fairly satisfactory basis exists for the interpretation of experimental results.

Table 1.1 Importance of particle and bulk properties to some solid handling operations

Unit operation	*Important bulk and particle properties*
Storage and gravity discharge from bins, silos and hoppers	Size, size distribution, shape, particle and bulk density, cohesive and frictional properties, fluidizability, flowability, explosibility, toxicity and compressibility
Pneumatic and mechanical conveying	Size, size distribution and shape, particle and bulk density, friability, toxicity and explosibility
Hydraulic conveying	Size, size distribution, particle density, friability and dispersibility

Particle and bulk properties

Particle size, shape and surface area

Particle size, shape and surface area are fundamental characteristics of bulk solids and are of paramount importance in most unit operations involving such materials; these properties are closely related and should be considered together. They determine to a very large extent the degree of interaction of particles with the surrounding fluid and with each other. These interactions, in turn, influence critically the behaviour of the bulk material, e.g. its flowability, fluidizability, compressibility, toxicity, flammability and explosibility. Unfortunately the relationships between these basic parameters and the practical behaviour of bulk materials are not yet fully understood.

Table 1.2 Classification of bulk solid materials according to size

Size range (μm)	*Standard term* *component*	*bulk*	*Characteristic*
30 000–3000 (but may be as low as 1000 μm)	grain and lump	broken solid	free-flowing, but could cause mechanical arching problems during discharge from bins and silos
1000–100	granule	granular solid	easy-flowing with cohesive effects if % of fines is high
< 100	particle	powder	
(i) 100–10	particle	granular powder	may show cohesive effects and some handling problems
(ii) 10–1	particle	superfine powder	highly cohesive; very difficult to handle
(iii) < 1	particle	ultrafine powder	extremely difficult (or impossible) to handle

In general, no universally accepted method has yet emerged to define and classify particles according to their grades. Table 1.2 lists some of the common terms relating to particle size. For a spherical particle, the size is defined uniquely by its diameter. However, with the exception of a few powders, the shapes of most industrial particles are irregular and the definition of particle size presents some difficulty. To overcome this, size is sometimes expressed in terms of the diameter of a sphere equivalent to some property of the particle. Table 1.3 lists some of the more common equivalent diameters and their definitions.

Particle size may also be expressed in terms of a statistical diameter; typical examples are Feret's diameter and Martin's diameter (Allen, 1981).

The more irregular the particle, the greater is the variation between the various equivalent diameters. Therefore, the shape of the particle is equally important and needs to be specified also. Particle shape may be defined in several ways. One approach is to define the sphericity, ψ, of the particle as:

$$\psi = \frac{\text{surface area of a sphere having the same volume as the particle}}{\text{surface area of the particle}}$$

that is

$$\psi = \left[\frac{d_v}{d_s}\right]^2 \tag{1.1}$$

where d_v is the diameter of a sphere with the same volume as the particle and d_s is the diameter of a sphere with the same surface as the particle.

Table 1.3 Equivalent diameters of irregular particles

Equivalent diameter	*Definition*
Projected area d_p	Diameter of a circle with the same projected area of the particle when viewed in a direction perpendicular to its most stable position ($A = \pi/4d_p^2$)
Volume d_v	Diameter of a sphere with the same volume as the particle ($V = \pi/6^3_v$)
Surface d_s	Diameter of a sphere having the same surface as the particle ($S = \pi d_s^2$)
Sieve d_a	The width of the minimum square opening through which the particle will pass
Specific surface d_{sv}	$d_{sv} = d_v^3/d_s^2$
Free-fall diameter d_f	Diameter of a sphere with the same terminal velocity and density of the particle
Drag d_d $\simeq d_s$	Diameter of a sphere with the same resistance to motion as the particle in a fluid of the same viscosity and having the same velocity
Stokes' d_{st}	$d_{st} = d_v^3/d_d$