CHEMICAL ENGINEERING SERIES

Chemical Engineering Essentials 2

Advanced Processes, Materials, and Sustainability

Edited by
Raj Kumar Arya
George D. Verros and J. Paulo Davim

ISTE WILEY

Chemical Engineering Essentials 2

Chemical Engineering Essentials 2

Advanced Processes, Materials, and Sustainability

Edited by
Raj Kumar Arya
George D. Verros
J. Paulo Davim

ISTE
WILEY

First published 2025 in Great Britain and the United States by ISTE Ltd and John Wiley & Sons, Inc.

ISTE Ltd
27-37 St George's Road
London SW19 4EU
UK

www.iste.co.uk

John Wiley & Sons, Inc.
111 River Street
Hoboken, NJ 07030
USA

www.wiley.com

Library of Congress Control Number: 2024951537

British Library Cataloguing-in-Publication Data
A CIP record for this book is available from the British Library
ISBN 978-1-83669-017-7

Contents

Preface

The field of chemical engineering has evolved significantly over the decades, expanding its horizons to encompass a range of interdisciplinary applications and cutting-edge advancements. *Chemical Engineering Essentials 2* is designed as a comprehensive resource for both students and professionals, providing fundamental insights along with in-depth discussions on advanced topics. With the rapid advancements in technology and growing concerns over sustainability and safety, chemical engineering is at a transformative juncture, poised to offer sustainable and innovative solutions across industries. This handbook seeks to serve as a definitive guide for the current generation of engineers, providing both foundational knowledge and modern approaches required to navigate and excel in this dynamic field.

Volume 2 is organized into three sections, as is Volume 1, each addressing critical aspects of chemical engineering.

Part 1 of Volume 1: Fundamental Principles lays the groundwork, beginning with an overview of the field and covering essential topics like material and energy balances, thermodynamics and phase equilibrium. These fundamental principles form the bedrock upon which more specialized knowledge is built, equipping readers with a strong theoretical base.

Part 2 of Volume 1: Fluid Mechanics and Transport Phenomena delves into the physics and behavior of fluid systems and heat transfer. Chapters on fluid flow, heat conduction, convection, radiation and mass transfer provide essential understanding for designing and analyzing chemical processes.

Part 3 of Volume 1: Separation Processes covers the vital area of chemical separations, with discussions on extraction, distillation, filtration and emerging membrane processes such as pervaporation. Mathematical modeling techniques for

binary and multicomponent distillation are also covered to provide a deeper insight into process design and optimization.

Part 1 of this volume: Reaction Engineering introduces readers to various reaction mechanisms and reactor designs, with a special focus on applications within the pharmaceutical industry and the concept of reactive chromatography. The section concludes with the mathematical modeling of batch reactors and non-isothermal continuous stirred-tank reactors (CSTRs), complemented by simulation studies using MATLAB and ASPEN PLUS.

Part 2 of this volume: Material Properties and Advanced Applications focuses on the diverse materials used in chemical engineering, alongside advanced applications like hydrogen production, vinyl chloride production, process intensification and the integration of nanotechnology in the field. These topics underscore the importance of selecting the right materials and processes to achieve efficiency and innovation in chemical engineering applications.

Part 3 of this volume: Sustainability and Safety highlights the importance of green chemistry and sustainable practices in chemical engineering. This section also covers waste minimization, resource recovery and safety management, including hazard identification and risk assessment, which are critical components of responsible engineering practice in today's world.

This handbook represents the collective effort of numerous contributors, whose expertise and dedication have shaped this comprehensive guide. We extend our deepest gratitude to each author who has contributed invaluable insights and research to make this work possible. Our heartfelt thanks also go to our families, whose unwavering support, love and encouragement made this journey possible.

Special acknowledgment goes to the team at ISTE. Their efforts and guidance were instrumental in bringing this book to completion.

It is our sincere hope that *Chemical Engineering Essentials 1 and 2* will serve as valuable resources, offering knowledge, inspiration and practical tools for all of those engaged in the field of chemical engineering.

Raj Kumar ARYA
George D. VERROS
J. Paulo DAVIM
January 2025

PART 1

Reaction Engineering

1

Compaction, Compression and Consolidation in Pharmaceutical Industries

Compressibility and compactability are the defining features of medicinal powder's compaction characteristics. The capacity to create mechanically robust compacts is known as compactability, whereas compressibility refers to the powder's deformability under pressure. Compaction, in the context of pharmaceutical powders, involves the combined processes of compression and consolidation between the solid particles and gaseous phase, caused by an external force. This is relevant to pharmaceutical powders, particularly processes such as the handling of powdered pharmaceuticals, hard shell gelatin capsule filling, tablet and granule manufacturing, and other processes in the field of pharmaceuticals which are especially vulnerable to the impacts of such forces. Studying the possibilities that occur during the compaction of pharmacological materials is the crucial aspect of designing solid dosage forms, whereas universal testing machines or compaction simulators make systematic investigations of pharmaceuticals easier (Nguyen et al. 2020). Various parameters are measured during compaction among various researchers. Several pharmaceutical powders and formulations have had their compaction behavior evaluated using data collected from various measurements, including punch forces, die wall friction, ejection forces, change in temperature during compaction and other random variables. Among all other mathematical models, Heckel and Kawakita models show a better mathematical representation of compaction for the pharmaceutical systems within the appropriate pressure range.

1.1. Introduction to compression, compaction and consolidation

The matter or the substances present in the form of powdered solids are heterogeneous. They consist of various individual particles with different shapes and sizes in the presence of air voids. This is why it is difficult to analyze and

Chapter written by Neha DHIMAN and Girish GUPTA.

characterize the fundamental properties of this complex powdered solid system (Lachman et al. 1986). However, with the considerable advancements in qualitative and quantitative measurements, it is possible to determine some fundamental properties of individual particles as well as bulk powdered solids from an industrial point of view. In pharmaceutical industries, the study of the physical and mechanical properties of powdered solids is necessary for the compression, compaction and consolidation of tablets.

1.2. Definition and importance in pharmaceutical manufacturing

1.2.1. *Compression*

Compression is the mechanical process of reduction of bulk powdered solid under applied pressure resulting in the removal of air spaces or voids. In pharmaceutical industries, compression is used for the tableting process of a particular volume of granules in a die cavity under pressure to convert it into an intact tablet. An appropriate volume of powdered solid is taken in a die cavity/mold that is compressed under pressure using an upper and a lower punch to convert it into a single matrix by removing air/gas voids, then ejected from the die/mold in the form of a tablet (Dudhat 2022).

The assessment of the compression behavior of a powdered solid is mainly dependent upon the macroscopic properties, i.e. density of solid bed and porosity. Furthermore, these properties are also affected by the punching velocity of compression, stress–strain indices and elasticity of the material after compression (Vanhoorne and Vervaet 2020).

1.2.2. *Compaction*

Compaction of a powdered solid is defined as the ability of powdered solid compressed to form a coherent compact solid tablet having high mechanical strength under increasing stress (Stranzinger et al. 2021; Dudhat 2022).

Compaction is considered to be one of the most important pharmaceutical unit operations. For good compaction of tablets, powdered solids must have excellent flowability and a lesser tendency of segregation. The mechanical strength of a compact solid depends upon the physical, chemical and mechanical properties of the constituent solid such as hardness, flowability, particle–particle interaction, etc., whereas lubricants and moisture content also affect the compactability of the material (Bellini 2018).

Compaction = Compression + Consolidation of two phases (solid + gas) on applying force

1.2.3. *Consolidation*

Consolidation is the state of powdered solid having mechanical strength due to particle–particle interactions (Mohan 2012).

There are mainly three types of mechanisms involved in the consolidation of powder solids:

– cold welding;

– fusion welding;

– recrystallization.

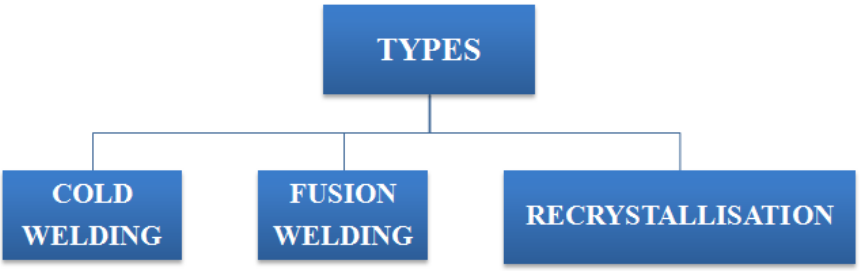

Figure 1.1. *Different types of mechanisms involved in consolidation (prepared for this work)*

1.2.3.1. *Cold welding*

Cold welding is one of the most widely used mechanisms for consolidation when the surface of two particles lies close enough to each other (i.e. less than 50 nm distance) having a strong attractive force, leading to strong particle–particle interaction. For this reason, cold welding increases the mechanical strength of powdered solid bed, when high compressive forces are applied.

1.2.3.2. *Fusion welding*

Generally, pharmaceutical powdered solids have irregular shapes and sizes, which provide a large surface area of contact (Mori et al. 2020). Therefore, a small compression force is sufficient to increase the particle–particle area of contact (Mohan 2012). If a high compression force is applied through the powdered solid

bed, a considerable amount of frictional heat is produced. This heat is dissipated through the contact surfaces of solid, which causes melting of the contact area of solid particles (Sampat et al. 2022). Fusion occurs at the contact surface after the melting of irregular shapes or corners of solid particles. Melt solidifies on the removal of compressive load, which leads to a further increase in the mechanical strength of the solid bed, known as fusion bonding. There must be a possibility of deformation of the solid surface, causing the breaking and formation of new bonds, which in turn increases the consolidation effect (Wahlich 2021).

1.2.3.3. *Recrystallization*

The solubility of a powdered solid is directly proportional to the applied compression load. If a high compression load is applied at the point of contact of moisture and solid surface, the solubility of the solid in solution also increases.

1.2.4. *Factors affecting consolidation process*

1.2.4.1. *Chemical properties of solids*

The lattice structure and nature of the crystallinity of the powdered solid affected the solidity of the material under high compression loads (Fonteyne et al. 2015). For example, those particles having cubic lattice structures are more suitable for the tableting process than those having rhombohedral lattices.

1.2.4.2. *Extent of availability of surface*

The consolidation of a powdered solid is also dependent upon the extent of availability of specific surface area. When compressive force is increased to an appreciable extent, particle surfaces become fractured, which leads to an increase in surface area. Further increase in compressive force causes particles to rebond. Hence, at very high compressive force, the surface area decreases to form a solid bed of powdered solid called tablet lamination.

1.2.4.3. *Effect of the presence of contamination on the surface of the particle*

The consolidation process is also affected due to the presence of surface contaminants. Surface contamination plays a vital role in the initial bond formation between powdered solid particles. For example, the presence of diluents, and lubricants on the surface of pharmaceutical powder aims to create a weak bond between them. This causes continuous coating on the tableting mass. Therefore, if contamination occurs at a larger extent on the surface of particles, it results in the formation of weaker tablets (Arshad et al. 2021).

1.2.4.4. *Interparticle attractive forces*

The interparticle attractive forces have a direct influence on the consolidation of the powdered solid bed. When a small compressive load is applied, molecular or electrostatic forces exist between individual particles. Van der Waals forces become predominant at an intersurface distance of 100 nm, which tends to form agglomerates. This agglomeration leads to an increase in the air spaces of the solid bed. The tablet then formed has low mechanical strength and is not stabilized. This may lead to cracking in the internal structure.

Therefore, the consolidation behavior of powdered solid can be controlled by internal (Van der Waals) as well as external forces (i.e. elasticity and plasticity). Consolidation gives rise to a decrease in air space, hence preventing the breakdown of a tablet (Kengar et al. 2019).

1.3. Powder properties and their characterization

1.3.1. *Characteristics of pharmaceutical powders, flowability, particle size and distribution*

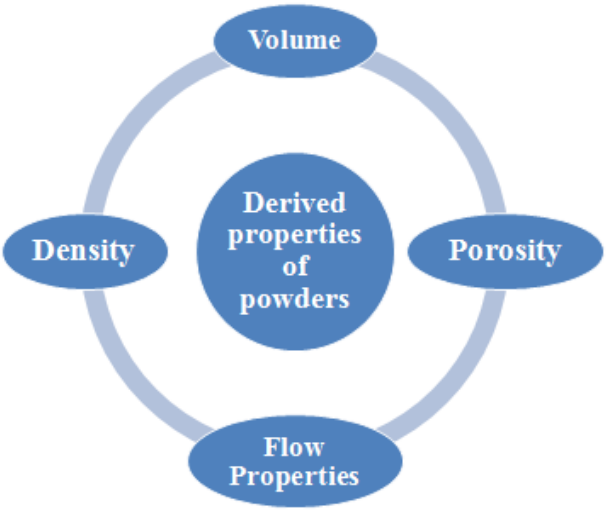

Figure 1.2. *Derived properties of powder (prepared for this work)*

While considering the tableting process of the pharmaceutical powdered solid, some physical and mechanical properties of solid particles play a key role, which

further affects the compressibility, compactability and consolidation behaviors of powder (Awad et al. 2021).

Some of the most important physical properties are density, porosity, particle size, shape and distribution, and moisture content. These physical properties help us to understand the flow behavior of the powdered solid, and a change in one such property may affect the other, resulting in a change in the compression and consolidation behavior of tablets. Physical properties are also related to the study of dosage form as well as the bioavailability of the tablet.

On the other hand, the mechanical properties of powder deal with the compression–decompression behavior or stress–strain behavior.

1.3.1.1. *Volume*

The mass of the bulk powdered solid can be measured easily as compared to the measurement of the volume of powder. When a powdered solid is poured into a container under gravity, the air spaces or voids must be present there. That is why more complications arise while measuring the actual volume of the powdered solid. These air voids are mainly of three types and are explained using mass–volume relationships:

– *Open intraparticulate voids*: these voids are present within a single particle of powdered solid but are open to the external environment.

– *Closed intraparticulate voids*: the voids lie within the single particle but are closed to the external environment.

– *Interparticulate voids*: the air voids that exist between the individual particles of powdered solid.

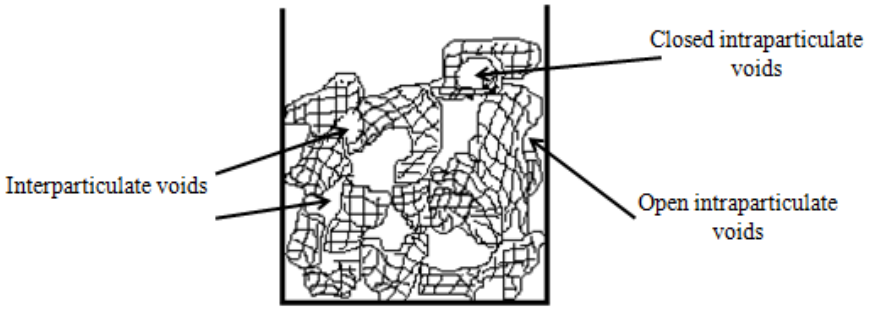

Figure 1.3. *Types of voids (prepared for this work)*

In keeping these air voids under consideration, the powdered volume can be classified as follows:

– *True volume (V_T)*: true volume of powdered solid can be defined as the total volume of the solid particulate itself except the volume occupied by the inter- and intraparticulate voids.

– *Granular volume (V_G)*: the granular volume of powdered solid is the sum of the volume occupied by the solid particulate itself and the volume occupied by all intraparticulate voids (except interparticulate voids)

$$V_G = V_T + \textit{volume occupied by intraparticulate voids}$$

– *Bulk volume (V_B)*: the bulk volume of powdered solid is equal to the sum of the volume occupied by the solid particulate itself, intraparticulate voids as well as interparticulate voids

$$V_B = V_T + \textit{volume occupied by (intraparticulate + interparticulate) voids}$$

or

$$V_B = V_G + \textit{volume occupied by interparticulate voids}$$

– *Relative volume (V_R)*: relative volume can be defined as the ratio of the experimental volume of sample (V_E) under specific conditions of the experiment to the true volume (V_T) of the powdered solid sample, i.e.

$$V_R = \frac{V_E}{V_T} \qquad [1.1]$$

Relative volume tends to approach unity if the experimental volume of the sample (VE) becomes equal to the true volume (VT), i.e. under compressive force, all of the air voids will be eliminated from the particular packing of the powdered solid.

1.3.1.2. *Density*

The density (ρ) of the powdered solid is defined as the ratio of the mass of the solid to the volume occupied by the solid

$$\textit{density of the solid } (\rho) = \textit{mass of solid } (M)/\textit{volume of solid } (V) \qquad [1.2]$$

Based on the three types of volumes discussed above, the density of the powder is also classified as the following:

– *True density (ρ_T)*: this is the ratio of the mass of the powder to the true volume of the powder

true density (ρ_T) = mass of powder (M)/true volume of powder (V_T) [1.3]

– *Granular density (ρ_G)*: this is the ratio of the mass of the powder to the true volume of the powder

granular density (ρ_G) = mass of powder (M)/granular volume of powder (V_G) [1.4]

– *Bulk density (ρ_B)*: this is the ratio of the mass of the bulk powder to the bulk volume of powder, especially when a particular mass of the powdered solid is poured into a cylinder with flow under gravity

bulk density (ρ_B) = mass of powder (M)/bulk volume of powder (V_B) [1.5]

– *Relative density (ρ_R)*: if ρ is the density of the sample under specific experimental conditions and ρ_T is the true density, and then the relative density is defined as the ratio of ρ/ρ_T

$$\rho_R = \frac{\rho}{\rho_T} \quad [1.6]$$

The relative density tends to unity if $\rho = \rho_T$ when all of the air spaces or voids are eliminated from the particular packing of the powdered solid.

1.3.1.3. *Porosity (ε)*

The air voids present in powdered solid packing are of more importance as compared to the solid mass (Dudhat 2022). Therefore, the porosity of the powdered solid is the ratio of the total volume occupied by the air voids (V_V) to the bulk volume of the powdered solid (V_B)

$$\varepsilon = \frac{V_V}{V_B} \quad [1.7]$$

The total volume occupied by the air voids (V_V) is also given by the difference in the bulk volume and true volume of the powdered solid,

$$V_V = V_B - V_T \quad [1.8]$$

On equating equations [1.7] and [1.8], we get

$$\varepsilon = \frac{(V_B - V_T)}{V_B} = \left[1 - \left(\frac{V_T}{V_B}\right)\right] \quad [1.9]$$

The percentage porosity is given by

$$\%\varepsilon = \left[1 - \left(\frac{V_T}{V_B}\right)\right] x\ 100 \quad [1.10]$$

Porosity is an important factor while studying the compression behavior of tablets, which helps to determine the disintegration time, dissolution rate, friability and drug absorption mechanism.

1.3.1.4. *Flow properties*

In the tableting process, when pharmaceutical powder is poured into the die to make a compact tablet, it is required that the powdered solid have good or excellent flow properties so that the die should be filled properly during compression and the tablet formed has enough mechanical strength (Mohan 2012). The flow behavior depends upon the following factors.

1.3.1.4.1. Particle size

The rate of flow of the powdered solid is directly proportional to the size of the particles. The particles having small diameters cohere with each other due to van der Waal's forces, electrostatic attraction and surface tension. These attractive forces result in poor flow behavior of particles, whereas particles with large diameters decrease the cohesion of particles, which enhances the flow property due to the lesser influence of gravitational force.

1.3.1.4.2. Particle shape

Those particles having spherical shapes with smooth surfaces of contact show good flow behavior as compared to the needle type or elongated particles with rough surfaces. The roughness of the surface tends to increase the friction factor and cohesiveness of the particles, which leads to poor flow behavior of powdered solids.

1.3.1.4.3. Porosity and density

As discussed above, density and porosity are two important physical properties of powdered solids. High-density particles have a large mass-by-volume ratio, which leads to good flow behavior, whereas large porosity decreases the flow characteristic of particles.

1.3.1.4.4. Moisture content

Powdered solid containing high moisture content has large cohesion and adhesion properties. When particles get stuck to each other, they cause poor powder flow properties. Therefore, dry mass enhances the flow properties of the powdered solid.

1.4. Powdered characterization techniques

1.4.1. *Determining flow properties and compressibility*

There are two main parameters to measure the flow behavior of pharmaceutical powdered solid, i.e. angle of repose and compressibility factor/compressibility index (Garg et al. 2018).

1.4.1.1. *Angle of repose*

The angle of repose is one of the simplest methods to determine the flow behavior of powdered solids. It is that the critical angle (θ) at which the powdered solid forms a conical heap relative to the horizontal base when it is allowed to fall through the funnel under gravity onto the horizontal surface

$$angle\ of\ repose\ (\theta) = \tan^{-1}\frac{h}{r} = \tan^{-1}\frac{2h}{D} \quad [1.11]$$

where:

– h = height of the heap of the powdered solid;

– D = diameter of the heap base;

– r = radius of the heap base;

– θ = angle of repose.

S. No.	Angle of repose (in degree)	Type of flow
1	25–30	Excellent
2	31–35	Good
3	36–40	Fair
4	41–45	Passable
5	46–55	Poor
6	56–65	Very poor
7	More than 66	Poorest

Table 1.1. *Angle of repose versus flow behavior*

Therefore, the angle of repose of the pharmaceutical powder can be determined by measuring the height and base diameter or radius of the heap formed by the

powdered solid when it falls through the funnel under gravity. The greater the angle of repose, the better the flow ability will be. Table 1.1 gives the relationship between the angle of repose and the flow behavior.

Fine, cohesive or sticky materials have a larger angle of repose. Therefore, it has been observed that the angle of repose increases with an increased moisture content due to the formation of aggregates.

1.4.1.2. *Compressibility factor/compressibility index (I)*

The compressibility index is also helpful in determining the flow behavior of powdered solids. The compressibility index is the measure of the decrease in volume of matter when placed under pressure. When pressure is applied on the bed of powdered solid, the volume of powder decreases until all of the air voids or spaces are removed.

The compressibility factor can be measured by pouring the powdered solid into a measuring cylinder without any disturbance. The volume occupied by the undisturbed powder (V_O) and compressed powder (V) (i.e. after applying external force when there is no air void or space between the particles of powder) will be noted down and used to determine the compressibility index/compressibility factor (I)

$$compressibility\ index\ (I) = \frac{(V_o - V)}{V_o} = \left[1 - \left(\frac{V}{V_o}\right)\right] \quad [1.12]$$

where:

– V = volume occupied by the powdered solid after compression;

– V_O = volume occupied by the undisturbed powdered solid before compression.

S. no.	**Compressibility index**	**Type of flow**
1	≤ 10	Excellent
2	11–15	Good
3	16–20	Fair
4	21–25	Passable
5	26–31	Poor
6	32–37	Very poor
7	> 38	Poorest

Table 1.2. *Compressibility index versus flow behavior*

Therefore, the compressibility index can be defined as the ratio of the decrease in the volume of powder after applying pressure to that of the undisturbed volume of powder solid.

Percentage compressibility can be determined as

$$percentage\ compressibility\ index\ (\%I) = \left[1 - \left(\frac{V}{V_o}\right)\right] x\ 100 \qquad [1.13]$$

Table 1.2 represents the values of the compressibility index relative to the particular type of flow behavior of the powdered solid.

1.4.2. *Determination of tapped density and bulk density*

The compressibility index in terms of bulk density and tapped density is given by

$$compressibility\ index\ (I) = \frac{tapped\ density - bulk\ density}{tapped\ density} \qquad [1.14]$$

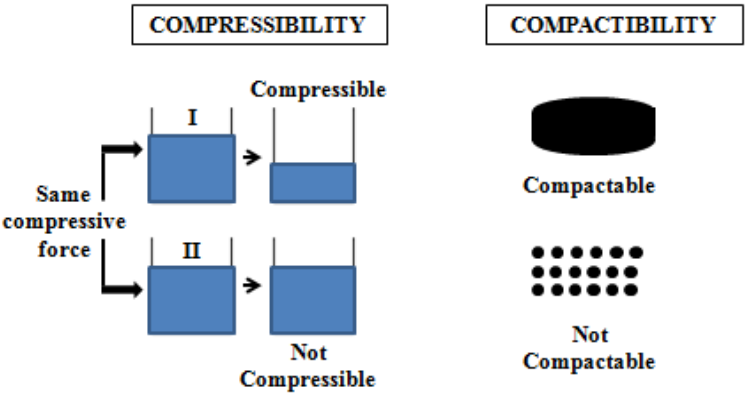

Figure 1.4. *Compressibility and compactability (prepared for this work)*