POWDER TECHNOLOGY SERIES

PARTICLE TECHNOLOGY

Hans Rumpf

Translated by F.A. Bull

CHAPMAN AND HALL

Particle Technology

HANS RUMPF
Late Professor of Mechanical Process Technology at the University of Karlsruhe

Translated by
F. A. BULL M.Sc. (Melb), Dr.rer.nat. (Karlsruhe)
Formerly Senior Lecturer, Department of Chemical Engineering, University of Melbourne

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technology at the University of Karlsruhe has been based. In these lectures the theoretical and physical foundations of the subject have been dealt with according to a unified point of view, i.e. not bound up with technically and practically oriented unit operations. These unit operations are the concern of other, subsequent, lecture courses which build upon the fundamental lectures.

The chapter 'Mechanical Process Technology' from *Chemical Technology* by Winnacker and Küchler [29, Vol. 7], which appears here as a monograph, emphasizes the scientific fundamentals and thereby follows the above-mentioned lecture course.

Of course, there is not enough room to permit a more extensive explanatory presentation; this must be reserved for a textbook. A solution has been sought in the form of a compromise that ought to meet the requirements of a handbook. In Chapters 2 and 3, whose purpose is to present the fundamentals, the main questions are addressed and their theory is presented in sufficient detail to enable the methodology to be grasped and understanding of the subject to be pursued. In many cases the derivation of formulae has been dispensed with. The reader who is more interested in a general survey of the subject and less interested in its actual mathematical presentation can ignore the formulae. Even then he will be able to obtain an insight into the questions arising in mechanical process technology and into its scientific development.

I wish to thank numerous colleagues in my department for discussions and practical help. They are mentioned in the particular chapters. Messrs W. Gleißle and G. Schädel were responsible for the formal completion of the manuscript and the preparation of the figures, and rendered valuable help.

Translator's preface

The inspiration for translating this classic text came during a sabbatical year spent at the University of Karlsruhe in 1974.

Under the leadership of the late Professor Hans Rumpf, the Institut für Mechanische Verfahrenstechnik, Karlsruhe, from the early 1960s onwards, by extensive research and advanced teaching had promoted the discipline of mechanical process technology, a branch of process engineering which had been rather neglected, especially in many chemical engineering departments of universities in the English-speaking world.

There is a need for texts of this kind, particularly for the more specialized teaching that has to be done during the later stages of engineering courses. This work, which is really a monograph, serves as a concise and compact introduction, albeit at an advanced level, to all those functions of process engineering that have to do with the handling and treatment of particulate matter and bulk solids. Much of this information has previously been scattered around journals and other books and not brought together in one work. Furthermore, Rumpf has emphasized the physical and theoretical foundations of the subject and avoided a treatment that is simply empirical.

I am indebted to two of his former colleagues, Professor Klaus Schönert and Professor Friedrich Löffler, for supporting me in this translating venture, and especially to Dr John C. Williams, former Dean of Engineering at the University of Bradford, who has edited the English text and at whose university I began the translation some years ago. I am also much obliged to Mr John C. Barton for a very thorough reading of the proofs.

F. A. Bull
Melbourne, March 1989

Preface

Mechanical processes for transforming materials, such as milling, mixing, agglomerating, sedimenting, the winnowing of grain etc., are among the oldest useful arts practised by mankind. At the beginning of the modern industrial era extensive knowledge and experience of many industrial applications, e.g. in mining, in the manufacture of ceramics, chemicals and textiles, in the production of paper and in food technology, had already been accumulated. This practical knowledge was substantially broadened in the course of technical developments, especially as many completely new processes came into being and the traditional methods were adjusted to the advancing state of technology. Science concerned itself with the systematic understanding and design of processes and equipment. At the same time the concept of **unit operations** was pursued whereby the whole field is divided into a larger number of basic processes that are defined according to their purposes. The principal groups into which these processes fall are those of separating and mixing without any intentional changes in particle size, and those where the particle size is altered, as in comminution and grain enlargement. In addition, there are the procedures of conveying, dumping and feeding. This classification is also followed in the survey of these processes given in Chapter 4 of this monograph.

Empiricism still plays a large part in the practical application of these unit operations, i.e. basic processes. Consequently the scientific expositions are in many cases merely descriptive. However, the value of the information obtainable from comprehensive descriptions of processes is limited. For the solution of particular problems more exact information is necessary than can be provided by a detailed descriptive presentation of the subject which, in its technical features, is extraordinarily complex.

The essential unity of the subject would also not become apparent in a predominantly descriptive account of the basic processes. This unity rests on common scientific foundations. Up to now these have been dealt with only in individual publications and, to some extent, in books which have concerned themselves with the whole of process technology or branches thereof.

However, the foundations of mechanical process technology have not yet been collectively promulgated. They have been elaborated during the period 1960–1974 in a course of lectures entitled 'Fundamentals of Mechanical Process Technology', on which the teaching of mechanical process

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1 Introduction

1.1 THE DEFINITION OF MECHANICAL PROCESS TECHNOLOGY

Mechanical process technology deals with the transformation of material systems by predominantly mechanical operations. It embraces the whole field of particle technology, by which we mean the transformation and transport of particulate systems susceptible to change by mechanical means. The size of the particles in such systems extends from about 10 m down to the colloidal range, although with decreasing particle size the mechanical operations possible become less effective in comparison with thermal, electrical and chemical influences; in other words, this technology is concerned with the whole range of particulate, i.e. disperse, systems from the coarse down to the colloidal.

The elements of the disperse systems of mechanical process technology are generally particles which are distinguishable from one another. In addition to such systems, mechanical process technology is also concerned with those systems in which no discernible particles occur but where continuous phases mutually permeate one another as is the case, for example, in coloured plasticine. The solid–pore system of a sponge is also of this type. The flow through such a system of pores is still a matter for mechanical process technology because it is no different in principle from the flow through a porous bed of discrete particles.

Mechanical process technology is also concerned with mixing, whether this has to do with phases consisting of discrete particles, continuous fluid phases or mutually soluble phases, i.e. mixing on the molecular scale.

Single-phase flow, as such, is a matter for fluid mechanics; mechanical process technology uses this as a basis. To deal scientifically with mechanical process technology, a knowledge of the fundamental principles governing the flow of Newtonian fluids must be assumed as well as a knowledge of the mechanics of solids. Rheology, which is also a science in its own right, provides in its theoretical structure the overall basis for the mechanics of elastic and flowable materials. This does not prevent mechanical process technology from concerning itself with certain rheological topics such as the flow of non-Newtonian fluids, the rheology of suspensions or the flow of bulk solids.

The important changes of state and transport phenomena of the various branches of process engineering are set out schematically in Fig. 1.1. The important transformations in chemical process technology are those brought about by chemical reactions; in thermal process technology they are changes of phase and heat and mass transfer between thermodynamically defined phases. In both cases the states of equilibrium towards which the systems tend to move are determined by the laws of thermodynamics. These states of equilibrium depend thermodynamically upon the intensive variables, pressure and temperature, and the composition of the system, and not directly upon any motion imparted to it. In mechanical process technology the changes in the state of aggregation of systems, ranging from coarse to colloidal, consist of alterations in the degree of dispersity and the extent of mixing of such disperse systems with continuous fluid phases. The alteration in the state of dispersity can take the form of the nebulization of liquids or the sifting of solid particles. It is evident that the state reached

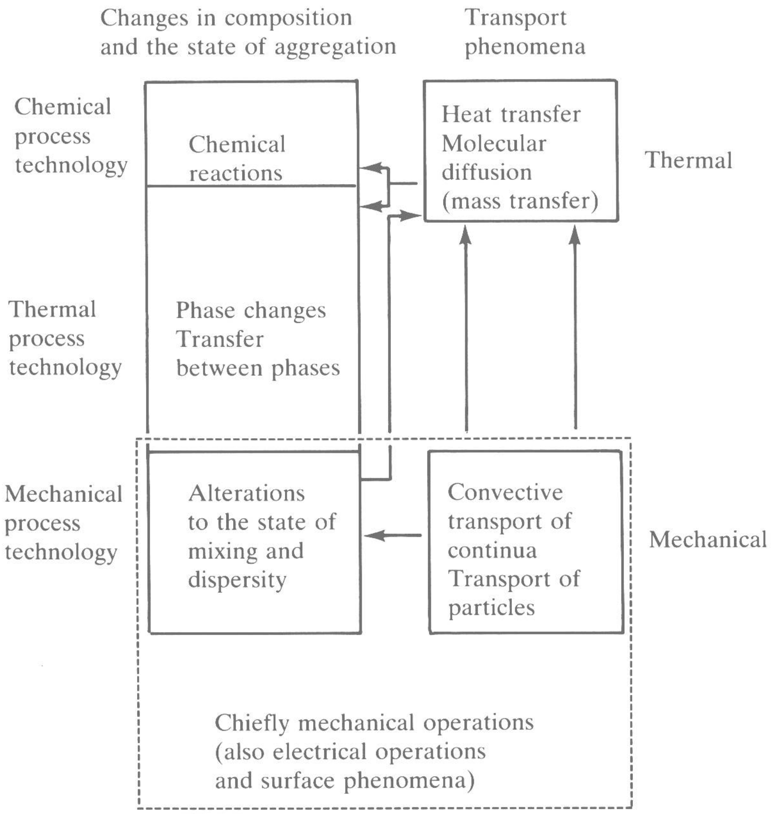

Figure 1.1 Changes of state and transport phenomena in process engineering.

by the system depends upon the forces exerted on its elements and the motion imparted to these. Thus the state of the system does not change in a direction determined by its intensive properties, as these are independent of its motion.

1.2 THE PURPOSE OF MECHANICAL PROCESS TECHNOLOGY

Mechanical processes first enable chemical and thermal processes to be carried out effectively, and they frequently precede thermal and chemical processes or are often directly associated with them. Indeed, the beneficial effects of mechanical treatment for chemical and thermal processes can first ensue when the product is used by the consumer. For example, cement clinker is ground at the cement works to a particular particle size distribution so that the concrete mixture used on a building site will attain the necessary strength within the setting time allowed. In other cases mechanical processes are important in their own right for obtaining products with the required properties. Sugar as lump sugar, ordinary sugar crystals or castor sugar should dissolve sufficiently quickly, i.e. possess thermal reactivity. At the same time, however, properties suiting particular applications are demanded which are associated with sugar cubes or coarse crystals or castor sugar or with powdered sugar in the form of coarse granules.

Some properties of disperse systems which depend upon particle size are listed in Table 1.1. For example, chemical and mineralogical homogeneity is of supreme importance in ore dressing or flour milling. Chemical and thermal reactivity have already been referred to. When using abrasives, a certain grinding performance must be achieved; however, in the case of optical glasses, for example, a surface whose structure is uniform and free from scratches is required. White pigments should reflect incident light as diffusely and completely as possible and must have no coarse grains which impair the gloss of the surface finish. With coloured pigments there must be a definite ratio of the amount of light selectively absorbed to the amount scattered. Insecticides should, like pollen, be as dusty as possible but not so fine that they agglomerate. The sensation of taste is strongly affected by the fineness of particles; for example, sugar particles larger than 25 μm make chocolate seem gritty and sugar which is too fine makes the chocolate unpleasantly sweet and viscid, whereas cocoa particles which are ground as fine as possible give their full aroma to the cocoa butter. Particle size also influences the flowability of the chocolate paste. On economic grounds alone various properties always compete with one another. The loose demand, made all too often, that a material should be 'as fine-grained as possible' is inadmissible. With increasing fineness the

Table 1.1 Properties of disperse systems which depend upon particle size

Properties of single particles	
1	Homogeneity (increasing): chemical homogeneity, e.g. in minerals and ores; mineralogical homogeneity, when various crystal modifications exist; physical homogeneity, i.e. homogeneity with regard to certain physical properties. Distinction between properties unaffected by structure, e.g. elasticity, specific heat capacity, optical absorption and properties which are affected, e.g. plasticity, strength
2	Elastic–plastic behaviour (usually increased ductility)
3	Probability of breakage (decreasing), strength (increasing)
4	Wear behaviour, suitability for mechanical surface treatment
5	Properties resulting from competition between volume and surface forces, e.g. adhesion, agglomeration, suspendability, mobility in an electric field (increasing)
Properties of particle assemblies	
1	Bulk density (decreasing)
2	Rheological behaviour: elasticity, yield point, internal friction, viscosity of a suspension (mostly increasing)
3	Trickling capability (decreasing), flow properties
4	Miscibility (first increasing, then decreasing)
5	Separability (decreasing)
6	Wetting (decreasing)
7	Capillary pressure in solid–liquid systems (increasing)
8	Strength of agglomerates and briquettes (increasing)
9	Fluid and particle mechanics: permeability, fluidizability, settling velocity of clusters
10	Thermal properties: heat and mass transfer
11	Ignitability, explosive behaviour (increasing)
12	Properties as regards taste
13	Optical properties (extinction, diffuse reflection)

The direction in which the properties tend to change with decreasing particle size is given in parentheses.

cost of milling becomes progressively greater. In addition, other properties change in such a way that, in practice, they have very complicated and expensive, if not prohibitive, consequences. For example, the tendency to agglomerate and stick to walls increases, the flow properties become extremely poor, the permeability decreases and separation from air and water becomes much more difficult.

In formulating what mechanical process technology is about, it is thus a matter of knowing in each case how the product properties of interest depend upon those properties of particulate systems which can be changed by mechanical means, such as the particle size distribution, the concentration, the state of mixing, the state of agglomeration etc. Opposing the role of these properties is that of the factors representing the costs of producing the desired degree of dispersity. Furthermore, if indices can be specified which quantify the value of the product's properties, then an optimal solution to a given task in mechanical process technology can be found with regard to the expense entailed. Usually the basis for such an optimization is not available. In particular, much effort is required to measure the effects of the properties because, for this purpose, it is necessary to produce size fractions of the products involved and various mixtures of such fractions and to measure the properties of these products. That is often worthwhile only for mass production or with very expensive materials.

1.3 MAIN TOPICS AND PROCESSES

The **changes of state** which are brought about mechanically in disperse systems can be divided into two main groups: changes in which the particles of the system alter in size, shape and surface properties; changes in which the particles remain unaltered or do not participate.

The physical changes in the first group are the province of solid state physics, the mechanics of solids and the physics and chemistry of surfaces; those of the second group are the province of fluid mechanics and the kinematics of rigid bodies. The rigid and yield behaviour of rheological systems which can possess both solid and fluid properties, e.g. high polymers or cohesive bulk solids, falls in a transitional region. Following the conventional division of process engineering into unit operations, the first group comes under comminution and grain enlargement and the second group under separation and mixing. Also involved is the handling of continuous media, e.g. the stirring of liquids or the kneading of highly viscous masses.

If we look at the individual operations of a technical process, we notice that all the above-mentioned physical changes of state can occur in each operation. For example, agglomeration occurs during comminution and, conversely, comminution often takes place during agglomeration, e.g. in briquetting. Dynamic processes obviously play an important role in both comminution and agglomeration. The operations of separating and mixing are frequently and often quite decisively influenced by agglomerating and comminuting phenomena.

Included amongst the **transport phenomena** of mechanical process technology, considered more broadly, are storing, feeding and discharging, dosing, and packaging and conveying. All operations present their particular difficulties. The lengthy storage of powdery materials, or of granular materials such as grain, in large silos and storage sheds demands constant or periodic handling of the product because otherwise the condition of the material will change through agglomeration, warming and chemical reactions.

The flow properties of a bulk material must be considered when feeding it into and removing it from a device or storage bin. Special problems occur with the transport of granular material against a larger pressure difference or out of a monte-jus when the material is not sufficiently self-sealing. Likewise the packaging and feeding of granular materials is quite decisively influenced by the flow properties and, in addition to these, by the packing properties such as the bulk volume and the homogeneity and stability of the poured material.

Particle size measurement is a technique of mechanical process technology. It is used to measure the state of the system with regard to its disperity, i.e. to determine particle size distributions, specific surface areas, dust contents, particle velocities, specific material properties of particles and the like. The use of particle size measurement, along with the measurement of other properties, must not be avoided since otherwise essential information about the system under consideration would be unavailable. Particle size distributions, dust contents etc. are generally much more difficult to determine than pressures or temperatures. That is why the measurement of particle size demands considerable effort and great care.

Only a few processes in mechanical process technology work with such low concentrations of particles that the mutual interactions between them can be neglected. In practice such processes are the separation of particles from aerosols and the removal of solids in the treatment of feed water for boilers and water for drinking As a general rule the mutual interactions of particles with one another, with a fluid and with the walls of the apparatus play an important role. The laws governing these mutual interactions are complicated and for the most part not yet properly understood. Therefore many practical applications cannot be designed exactly in advance on the basis of an understanding of the actual physical phenomena. This also explains why many processes have been developed empirically, why the use of more demanding scientific methods is avoided in practice and why such methods are not used to an extent corresponding to the technical and economic importance of the mechanical process. This attitude is thought to be justified on the grounds that scientific research has preferred to investigate the theoretical aspects of simpler problems, e.g. the motion of isolated individual particles in a fluid, which are of only limited interest for direct practical application.

Scientific research, for its part, must pursue two paths: first the systematic phenomenological study of practical processes and the collection of the most reliable data from practical experience within the framework of definable limits of validity, and secondly the study of individual phenomena and mutual interactions. In this connection, the concentration limits beyond which mutual interactions come into play are of great interest.

Some processes with mutual interactions, such as comminution, agglomeration and de-agglomeration, can be quantitatively described using the methods of reaction kinetics. Here we must distinguish between the macrokinetic and microkinetic approaches. **Macrokinetics** is concerned with the course of a reaction in an apparatus; this is always influenced by the apparatus and often by individual variable factors associated with its use. **Microkinetics** describes in detail those processes which depend upon the material. The crushing of single grains and the adhesion between particles are the concern of microkinetics, whereas the course of events in a mill and in a pelletizing drum are matters for macrokinetics.

These opening remarks are intended to serve as an introduction to the outline of the whole field of mechanical process technology which now follows. In this outline the subject is not primarily divided according to the unit operations involved. The general principles are presented first, and they are followed by a description of the processes of separation, mixing, comminution and agglomeration. Basic texts relevant to this subject are those of Brauer [3], Grassmann [6], Rumpf and Schönert [20], Schubert [23] and Ullricht [28].