Particulate Science and Technology

by

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The motif is the Sanscrit for "Particle." This ancient root of Indo-European languages serves to illustrate the antiquity of particulate technology as an art.

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PREFACE

Unity in Diversity

An essay to integrate the field of particulate science and technology seems opportune. Concern with specialized interest areas results in slow and usually steady progress and is a comfortable situation to work in. However, particularity of interest constrains ideas, whereas a sound unifying concept knows no natural boundary. Our field is currently asking searching questions and seeking definitive answers to broaden our outlook. We are ready to see what the other person is up to, to learn from the observations of others, and profit by interrelating their ideas.

However, in a broader and more fundamental sense, most of us who work in the field of finely divided matter would assert that, collectively, our present knowledge is only a promise of what it will be. Further, we individually know so little of what we need to know and, to add to our troubles, we realize that new knowledge is being accumulated at a pace faster than we can injest on a regular diet of reading and study.

A rewarding approach to the problems inherent in mastering this diversity is to develop an appreciation for the wholeness of the field. Necessary specialized excursions can then be related to the whole-field view and fitted into a rational scheme of scientific explanation. This book is an attempt to provide a methodical whole-field view of fine particle science and technology. It in no way pretends to be exhaustive. There is a rich abundance of searching treatises on particular subjects available now to the specialist, so a general view both unifying the good work already accomplished and providing a comprehensive structure for guiding what is to come seems appropriate at this juncture.

Particulate science and technology is a fascinating field of study. I don't know anyone working in it who does not find it somewhat exciting. It is an ancient art and a baffling science simultaneously. I count myself among the lucky ones who wonder why matter in finely divided form behaves as it does.

INTRODUCTION

"There is a tide. . ."

UNDERDEVELOPED TECHNOLOGY

The science of the nature and behavior of fine particles, like an underdeveloped country surrounded on all sides by highly structured industrial states, looks wistfully at developed entities like physics, chemistry, mathematics, biology, material science, engineering sciences, and computer science, to mention but a few well-structured disciplines. As with all cases of underdevelopment, a great deal of "aid" from these technically advanced neighbors is needed if progress in fine particle science is to materialize. However, the drive to progress must be derived from the urgencies sensed by those already working in the field who have the wit and foresight to develop and implement the creative necessities.

In any field of human technical endeavor where progress is made there is an advantageous juxtaposition of three elements: industrial and commercial need, intellectual challenge, and the possibility of success. For the study of particulate matter all three elements now coexist in good measure, but they have only just come together. The efforts of many have made this conjunction possible and although it is unfair to mention some and omit others who have made their contributions, still it seems appropriate to mention some major contributors.[1–19]

In this century the sciences have been developing new knowledge at a frenetic pace in a direction predetermined by the discovery of electricity. The physicist has become interested in the very small and, with the engineer, in the macroscopic to the spectacularly large, and the chemist is concerned with structures ranging up to molecular sized units. This pattern of study has left the great middle ground of fine particles in a relatively unexplored condition. During the past 200 years, we have seen the armies of science in their inexorable advance on the relationships between the structure and properties of solids, liquids, and gases. It is now the turn of matter in finely divided form to be comprehended and exploited. We can only guess why it has taken so long to reach this stage, but one can imagine that it may have something to do with the extreme difficulty of theoretical and experimental work in the area, the staggering diversity of particulate matter in finely divided form, and the glamor of the older established disciplines which enjoy a hard won prestige.

Within the last 20 years or so there have been signs of a gradually developing awareness and interaction among those concerned with particulate matter. Although we still have the ceramicists and the powder metallurgists, the pharmacists and the chemical engineers are still ploughing their own furrow, though they interact more with each other than ever before. This seems to be true on campus, in the meeting hall, and especially in industry. Perhaps the most public manifestation is in the start-up of the journal "Powder Technology" in the 1960's; in the change of name of the "International Journal of Powder Metallurgy" to that of "International Journal of Powder Metallurgy and Powder Technology" in the 1970's. Other evidence includes: the publishing of Orr's book on *Particulate Technology* by Macmillan in 1966, the holding of a workshop on "Fine Particle Technology" in 1975 (National Science Foundation)*, the publication of various series of texts on different aspects of particulate matter on both sides of the Atlantic, the founding of the Fine Particle Society and its aspiration to correlate and serve the needs of its members in this field, in Japan the foundation of the Research Association for Powder Technology, the establishment of the International Powder Institute, the formation of the International Fine Particle Research Institute, and the services of the Powders Advisory Center. We can conclude, therefore, that there are serious efforts being made to move in the direction of integration so that we can better focus on our needs and coordinate our energies to meet them.

The key to success lies in our educating ourselves. In Europe a number of research centers like Karlsruhe Erlangen, Bradford, and Loughborough and in Canada, Laurentian University, are studying and teaching. But in one major industrial enterprise of this world, the United States of America, there is no single institution devoted to the study of matter in finely divided form, although there are numerous individual students scattered throughout the country. Some have said that there is a pressing need for establishing an American institution, many others have nodded their assent, but to date none has been organized. Apparently, the greatest single obstacle to this development is not the lack of funds, but the absence of a developed

*Program Director, Dr. Morris Ojalvo

consensus of the whole field view and a realization of its potential long-term benefits to us all. This situation exists because of the lack of serious discussion about the problems inherent in formulating policy, developing structure, and implementing the former through the latter. *In essence, just how do we conjoin the academic with the industrial, and reward the components in such a diverse interdisciplinary field as particulate matter and at the same time avoid the production of a new breed of specialist who will fragment the very cohesion that is so vital and so assiduously being developed.*

RESEARCH AND DEVELOPMENT NEEDS

Our technological requirements for comprehending the state and behavior of particulate matter during the next decade have been admirably summed up in the NSF Workshop Report.[20] They fall into four main categories.

Particulate Properties and Structure

The description of particle shape by means of morphological analysis of particle profiles offers a promising way of expressing visual images mathematically in a variety of functional forms. The functions can then be related to the properties of the particulate matter. Fundamental investigations of particle surface phenomena are required to establish the basic geometric properties of particulate matter so that they may then be related to their physico-chemical properties. Coordinately, establishment of the relationships between surface, subsurface, and interior structures and particle properties must be another of the goals of fine particle research and development. There is also a major experimental challenge to learn more about the electrical, optical, thermal, and magnetic characteristics of fine particles. Further, as more and more industrial processing becomes automated, there is an increasing need for the on-stream testing-cum-monitoring of powder technology operations. This demand raises a further need for study in this area because we do not know enough about what technology there is available.

Particle-Fluid Separation

There is an urgent need for developing dynamic concepts about the methods for the separation of very fine particles (less than 0.5 micron) from gases. More direct approaches to the study of the structure of flocs and of agglomerates generally are necessary. In particular, there is a need to establish the pattern of relationships between the development and form of floc structures and the behavior of sedimentation, thickening, and dewatering processes at all of their stages. Moreover, developing methods for studying the behavior of individual particles in rheologically complex fluids as well as in their deposition on collecting surfaces is a prerequisite to understanding the mechanisms and improving the technology. The transmission of interparticle forces in changing conditions (e.g., the alteration of particle-fluid drag or the change of applied pressure level, etc.) and the way in which the particles become rearranged must be directly observed under carefully controlled experimental conditions if we are to master the complexities of the motion of particle sets in dynamic environments.

Particle Handling

The following quotation from Zenz is an eloquent indicator of the formidable nature of our problems in this area:[21] "As mundane as it might first appear, there is today no universally guaranteed design procedure for assuring that a bin filled with any powder will be able to be emptied whenever desired." A new approach to the problems of mixing and blending must take into account the complex properties of the particualte matter being handled. When particles are being moved, usually entrained in a fluid, their level of interaction with each other and with the carrier fluid and also with the system surfaces and measuring devices should be related to the basic properties of the particles, the fluid, and the overall system. Phenomena to be studied include bridging, flow, choking, saltation, resilience and elutriation, to name but a few.

Controls

Minimizing the deleterious effects of applying powder technology requires controls. In general these systems problems are extremely involved. Dealing with only single phase liquids (for example) is a sufficiently complex system control problem, but effectively controlling in detail the behavior of particulate matter in different situations (as outlined in the immediately preceding sections of this introduction) raises the difficulty of our task to a high level. In brief, we have to adopt an overall systems approach which will take into account technical, economic, health, social, and political factors inherent in a given situation. Just a glance at some of the industrial hygiene and related journals reveals the extent and seriousness of the problems of minimizing unfavorable effects from the industrial use of fine particles.

ABOUT THIS BOOK

The general concept offered in this book and some of the more important conclusions and observations that I have developed during the course of its writing are stated and examined in Chapter 1. Chapter 2 emphasizes the primacy of the individual particle in particulate science and technology. Chapters 3 and 4 may be said to deal with PARTICULATE TECHNOLOGY; they describe the ways in which particles are formed, the various production methods associated with each, followed by a descriptive treatment of some of the standard processing steps for dealing with finely divided matter. The next three chapters deal with what might be appropriately termed PARTICULATE SCIENCE. In Chapter 5 there is a discussion of a number of descriptors with particular emphasis on fine particle statistical descriptors. Chapter 6 reviews some of the more recent work on particle shape characterization and particle size analysis. Chapter 7 examines the nongeometric properties of fine particles including optical, electrical, magnetic, thermal, and chemical properties, and relates them to various aspects of particle settling and diffusion.

The essential message of the final Chapter 8 is vital to all of those working in the fine particle field. Particulate hazards are insidious: if they don't blow you up or irreparably damage your health they may just ruin your landholding quietly and steadily. Some of what must be learned and some presently known means for protecting us against folly in the use of fine particles are explored. Fine particles should be treated with the greatest of respect.

THE APPROACH

The individual particle may range in size from the vanishingly small to the visually obvious and may be simply shaped or multifaceted in outline. Regardless, we have to be able to identify and collect the shape-size information, and to condense it without losing the pattern that the information represents. This is no easy task and we have yet to solve it. Chapter 2, entitled "The Single Particle," is presented early in the book in order to focus attention on the fact that the single particle is indeed the fulcrum of our study. We have to develop a precise method for collecting the size-shape information and handling it for the single particle. Then we can confidently describe sets of particles with a corresponding general description (coupled with their chemical and physical properties), and then be able to relate particle properties to their behavior so that we can make predictions of their behavior in known conditions and thereby control them.

Chapters 5, 6, and 7 can be read following Chapter 2 without disturbing the continuity. Although particle size measurement is discussed, it is treated generally because there are already very informative specialist texts on the subject. Particle morphology analysis is treated at greater length because there is no other current source on this topic (outside of the journal literature) and also because this subject is important to the development of fine particle science. The approach taken in Chapter 6 might, at first, seem complicated, but in light of the overall strategy it is not. Thus, to obtain the necessary information and to analyze the morphology of a particle (and then many more) require sophisticated image analysis capability and the ability to handle and condense large amounts of information. At the present time, there are instruments available with the requisite image analyzing capabilities. By using these in conjunction with an appropriate set of information handling techniques (pattern recognition, orthogonal functions, fuzzy sets, etc.) advances are being made in the morphological analysis of particles. A crucual part of this program is the development of a physically meaningful set of morphological descriptors which can be culled from the information gathered about the particle. Chapter 7 discusses some of the physical and chemical properties of fine particles including electric, magnetic, optical, and thermal properties as well as settling. Nowhere in this chapter is there a statement about the effect of morphology upon particle physical-chemical properties,* because their interrelations are unknown. At the present time, therefore, we investigate

*With one exception, Chapter 7, section

and study the sets of characteristics discussed in chapters 6 and 7 respectively. We are not yet able to describe one particle in terms of its associated size-shape/chemistry-physics continuum. This dichotomy is real and profound and the literature presents it this way. Clearly it must be eliminated in the course of time so that we can better describe the reality that is, and build our science on that.

Many advances have been made and continue to be made in particle production, in the understanding of mechanisms of particle formation, and in particle handling and processing. For those familiar with these aspects of finely divided matter, Chapters 3 and 4 may be overlooked or read cursorily. The beginning student will find these two chapters essential. The treatment is not surfeit with references but there are significant ones so that the reader can find the original sources and related items. The chapter on hazards is last in order but not in importance; it should not be overlooked.

Chapter 1

IN THE SCHEME OF THINGS

1.1 PARTICULATE SCIENCE AND TECHNOLOGY

The objective of this book is to establish the concept that the behavior of fine particles when a specific force is applied to them in a particular medium is determined by their structure; by their geometric, chemical, and physical properties; and by their interactions among themselves with the applied forces and the medium. Fine particle science describes the macroscopic, microscopic, and atomic level structures of individual particles and their sets in terms of the fundamentals of physics, chemistry, and mechanics, and interrelates these three levels with the behavior of a set (powder) and its component particles to permit the development of technology.

The study of particulate science and the consequent technology is a field of considerable intellectual, economic, and industrial magnitude. It is not an exaggeration to say that our whole industrial civilization is based upon the processing of particulate matter, yet until recently it has been largely uninvestigated by the scientist and engineer. Despite the fact that particulates have become important during the last half century, studies are still relatively unorganized, uncoordinated, and unrecognized. Neither the industrial nor the academic communities have yet perceived the predominating importance of particulates in the affairs of mankind. Our industrial and commercial progress is becoming more and more dependent upon our understanding and our mastery of the complex and broad science and technology of fine particles. Consequently, more work is urgently needed in the particulate field. It is also imperative that those of us who are working in the field make every effort to disseminate and correlate information concerning the knowledge that we have gained to date, and, in addition, to proselytize others to join in the exciting and revolutionary advances that are going to be made in the next twenty years or so.

Industrial applications have long been made, but new demands arise continually. The aspirin tablet and the powder metallurgy gear are produced by powder compaction in a die. Plastics granules are thermomechanically molded. Pottery is fired in an oven; bread is baked in an oven; powder metallurgy parts are sintered in a furnace; sinter cake is produced for blast furnace burden; some liquid phase sintering occurs during the production of cement clinker in a rotary kiln. Most mineral processing activity includes a great expenditure of effort and resources to separate the valued mineral from the gangue; effluent from industrial plants must be cleansed of noxious gases and liquids (if they are present) and especially particulate matter, which is almost always present.

Matter in finely divided form is often much more reactive than the same substance in solid form and this instability can lead to fires, explosions, and, in the case of protein material, to spoilage. An important fraction of the world's electric power is consumed in the crushing and grinding of macroscopically continuous solids in order to produce finely divided particles. The list of processes for treating particulate matter is so large that it would appear to be never ending: food technology; minerals processing; ceramics and refractories production; paints, inks, and dyes manufacture; cement, hard metal, welding rod, and building product industries.

Earth moving and soil mechanics are generally important provinces of fine particle science and technology, as well as many agricultural operations. Chemical engineering processing deals with large amounts of finely divided matter. Metallurgy deals with continuous solids but upon closer examination it can be observed that the continuous phases contain dispersions of other phases, precipitates, and inclusions. Geology looks to particles to explain earth movements and to trace the results of forces operating on and in our planet.

The behavior of finely divided matter in the more mobile gaseous and liquid continua is an important area of study in the engineering disciplines. In pharmacy, the production of solid dosage forms is a sophisticated branch of particulate technology which is complicated even more by the interactions within the human system that the medication may undergo.

No matter what their individual processes, material, or end product, all of those persons involved in fine particle technology require adequate samples of what they process and appropriate concepts, methods, and tools with which to characterize these samples. It is possible to obtain data of this type that is reproducible and that can be related in a descriptive way to the subsequent events that the particulate matter is to pursue. However, with our present methods we are not able to do much more than establish general patterns of relationships. The reasons for this limitation are not hard to fathom. For example, consider the more or less standard requirement to determine the particle size. Such determinations are linked to the property of particle shape. Therefore when a "size" is quoted, in a very fundamental sense we only have a small item of needed information with which we can characterize the complex population of particles. It is for this reason that there is currently a push to develop useful ways to measure particle morphology.

However, a set of particles represents a total surface area that is large in comparison with that of the same mass in the form of a single solid. Methods are available to determine surface area and it is therefore convenient to relate this measure to some property of the set of particles that is of concern (for example, the reactivity). However, the viewpoint that such properties of a rather small portion of solid are determined by a thin, two-dimensional external layer is too limited because we clearly have to consider the material directly underneath this extremum. As in the case of particle shape, this area of structure too is in the melting pot.

When we can interrelate particle size, morphology, chemistry, and physics we will have a fine particle science capable of generating new technologies so badly needed in this field. Within such a diversity of industrial activity the implementation of new technologies will likewise have broadside benefits for society. We are not yet in this happy condition. However, the encouraging developments in particle morphology analysis, in structural analysis, and in related areas ensures our eventual success.

1.2 OUR REALM

Matter, whether in a solid, a liquid, or a gaseous state, can exist in the form of finely divided particles. Familiar examples are dust and powder, both solid particles in a gaseous medium. Mist and spray are examples of fine liquid droplets in a gaseous medium. Bubbles in a liquid are gas particles, and perhaps pores in a solid are examples of finely divided particles called cavities in continuous media. The schematic diagram in Fig. 1.1 illustrates the range of fine particle systems that are encountered.

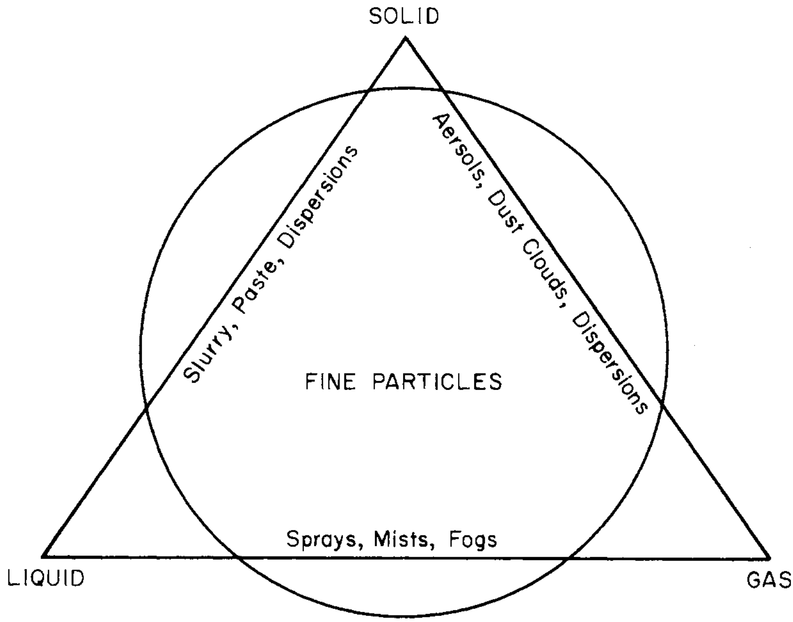

Fig. 1.1

Fig. 1.1 serves to emphasize two major points that should be kept in mind:

1. For the most part, particulate systems involve sets of particles interacting with each other and with the enveloping medium, all within one or more force fields.
2. An understanding of fine particle systems necessitates corresponding understanding of solids, liquids, and gases as states of matter, all of which can be divided into fine particles and all of which are media for particles of another state.

These two considerations alone tend to call for better models than those available to date, as well as removing the deficiencies due to the morphology/chemical-physical dichotomy already alluded to. The basic reason for calling particulate science and technology interdisciplinary is simply that a cohesive discipline must be constructed from many diverse fields. Perhaps another and equally valid reason is that the complexity of the problems inherent in this field defy the aspirations of individuals working separately to solve them. When we work together, sharing disciplines and exchanging information, we develop an interdisciplinary science with which to continue to advance our knowledge and our technology.

In the following chapters, an examination of some of the more basic aspects of the subject serves to illustrate the great advances in particulate science and technology that are being initiated. In summary, it is a wide open, dynamic field that challenges fruitful investigation.

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