ELECTROMECHANICS OF PARTICLES

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Introduction

1.1 Background and motivation

Small particles in the size range from approximately one micron (10^{-6} m) up to one millimeter (10^{-3} m) are very important in today's technological world. Though often hidden from our view, they serve as tireless workhorses in many mechanisms and devices, from electrostatic copiers and printers to powder couplings to fluidized beds. Particles are used in new colloidal suspensions called *electrorheological fluids,* which respond to an applied electric field by rapidly changing their apparent viscosity. Particles are also employed in manufacturing operations including packed and fluidized bed reactors, powder coating machines, powder injection molding, etc. Many of the raw materials used in the agricultural, food, mining, and metallurgical industries are received in particulate form to be separated, beneficiated, or processed. Likewise, modern chemical technology is heavily based upon the processing of feedstocks into powdered, granular, or pelletized dry products.

Particulates, so useful and necessary in modern materials and manufacturing, can also be a nuisance or outright hazard in other situations. For example, particulate pollution is a recognized environmental and industrial health hazard. Characterization of pollutants in particulate form is an important aspect of modern environmental health science. The collection and removal of particulate matter from combustion gases is the goal of electrostatic precipitators, packed bed filters, and other pollution control apparatus. Similarly, preservation of water quality in lakes and rivers depends on removal of certain particulate matter from industrial waste water. Another example, vital in today's electronics industry, is control of submicron contaminants during fabrication and processing of solid-state devices. This hard-to-control contamination is a significant contributing factor to the high rejection rates often experienced in the fabrication of very large scale integrated (VLSI) electronic chips. Finally, airborne dust is a well-known fire and explosion hazard in certain polymer and metallurgical manufacturing operations.

One rapidly emerging branch of particulate science and technology concerns particles of biological origin, such as cells and DNA. Cells sized from less than a micron on up to several hundreds of microns make up all living organisms. The characterization, handling, and manipulation of individual cells and DNA molecules have become major thrusts of modern biomedical science and engineering. At the same time, flow cytometry has revolutionized biological assay methods by making it possible to sort and separate literally millions of cells in minutes.

Some materials technologists have labeled the decade of the 1990s the "particle age" – a fitting recognition of the tremendous advances in the manufacture of new particulate materials and the applications being discovered for them in new products and processes.

1.2 Objectives of this book

Because all particles have electrical and magnetic properties associated with their shape and with the materials of which they are constituted, they experience forces and torques when subjected to electric and/or magnetic fields. Furthermore, particles will exhibit mutual interactions – often quite strong – through the agency of their own electrical charge, polarization, or magnetization. *Particle electromechanics*, the subject of this book, may be defined as follows:

Particle electromechanics: Forces and/or torques exerted on small particles (and collections of such particles) less than approximately 10^{-3} meters in diameter through the action of an electric or magnetic field, and also the mechanics and dynamics induced by these forces and torques. The electric or magnetic field may be imposed by external means (via electrodes, magnetic pole pieces, etc.) or by other nearby charged, polarized, or magnetized particles or particle ensembles. This definition extends to the mechanics of static particle beds and to the dynamics of moving particle beds when subject to electric or magnetic fields.

The above definition encompasses the subjects of electrophoresis and dielectrophoresis; electrorheological fluids; the mechanics of electrofluidized, electrospouted, and electropacked beds; electrostatic precipitation; electrostatic particle adhesion; high-gradient magnetic separation; the magnetostabilized bed; magnetic powder couplings; magnetic field–coupled particle flow control devices; and the magnetic brush electrophotographic copier/printer. It is not the author's objective to stake out or otherwise mark such a broad ground, but rather to offer some common terminology for the subject of field–particle interactions and to provide a framework for the contributions of many engineers and researchers – past, present, and future – who work in these diverse fields.

What impresses the student of particle electromechanics is an immediately recognizable set of common phenomena manifested in diverse physical situations. For example, the same dielectrophoretic force experienced by biological cells in aqueous suspensions can also be significant in electrostatic precipitation and certain electrophotographic development processes. An analogous magnetophoretic force is exploited in high-gradient magnetic separators to filter out magnetizable particles. The exemplar of commonality is the ubiquitous phenomenon of particle chaining, which can be anticipated whenever uncharged dielectric particles, loose or in fluid suspension, are subjected to a strong electric field, or when magnetizable particles are placed in a magnetic field. Another kind of unity is found in the fundamental connection of both electromechanical forces and torques to the effective dipole moment. The point of view taken in this book is that these commonalities and interrelationships are not mere academic curiosities, but the mortar binding together a large collection of seemingly unrelated phenomena into a viable scientific and technical discipline, namely, particle electromechanics.

1.3 Limitations and caveats

As defined here, the subject of particle electromechanics can hardly be done full justice by any single volume. Therefore, certain limitations have been imposed in writing this monograph, the focus of which is the electromechanics of dielectric, conducting, and magnetizable particles in the diameter size range from about 1 μm ($\sim 10^{-6}$ m) to about 1 mm($\sim 10^{-3}$ m). This book does not supplant the late Prof. Herbert Pohl's classic text on dielectrophoresis (Pohl, 1978), but rather places that subject into a larger context. In fact, Chapter 3 covers the fundamentals of dielectrophoresis and will serve as a graduate-level introduction to the subject; however, the serious investigator of biological dielectrophoresis will be drawn inevitably to Pohl's definitive volume.

Excellent works on the physics of *electrically charged* particles are widely available in technical libraries; therefore, except in Chapter 7 where electrostatic adhesion is briefly reviewed, particle charge is not considered. The lower size limit ($\sim 10^{-6}$ m) is imposed because the mechanics of submicron particles are strongly influenced by random thermal (Brownian) motions and van der Waals forces, while the upper limit ($\sim 10^{-3}$ m) is based on a reasonable working definition of what constitutes a classical particle. We may confidently predict the rapid emergence of ultrafine particle technology and, thus, the need for a volume on the mechanics of particles smaller than 1 μm. The author of such a book will be faced with the challenging task of folding the subjects of particle electromechanics, aerosol science, and adhesion science into the unique and somewhat perplexing set of physical properties exhibited by ultrafine particles.

Another subject not covered in this book is colloidal electro-optics (and magneto-optics), which concerns the influence of electric (or magnetic) fields on the optical properties of colloidal suspensions. While particle orientation (the subject of Chapter 5) and field-induced particle chaining (discussed in Chapters 6 and 7) are electromechanical mechanisms responsible for some of the important electro-optic effects, no attention to the optics side of the problem is given here. The reader interested in electro-optics is referred to the excellent treatise on this subject by S. P. Stoylov (1991).

The subjects of electrohydrodynamics (EHD) and electroconvection, as they relate to particles, droplets, and bubbles, are not covered in the present volume. Therefore, bubble and droplet deformations induced by an electric (or magnetic) field are not considered. Likewise, no treatment of the important subject of electrophoresis of particles in aqueous suspension is provided. Only simple dielectric models for biological cells and particles in aqueous media are examined; the neglect of surface charging guarantees that the dielectric models for particles in aqueous suspension, especially biological cells, are deficient at very low frequencies. One more limitation of this book is that chain interactions among nonspherical particles have not been considered.