

ELECTROMECHANICS OF PARTICLES

THOMAS B. JONES

University of Rochester



Published by the Press Syndicate of the University of Cambridge
The Pitt Building, Trumpington Street, Cambridge CB2 1RP
40 West 20th Street, New York, NY 10011-4211, USA
10 Stamford Road, Oakleigh, Melbourne 3166, Australia

© Cambridge University Press 1995

First published 1995

Library of Congress Cataloging-in-Publication Data

Jones, T. B. (Thomas B.)

Electromechanics of Particles / Thomas B. Jones.

p. cm.

Includes bibliographical references (p.).

ISBN 0-521-43196-4

1. Dielectrophoresis. 2. Particles. 3. Electromechanical analogies. I. Title.

QC585.7.D5J6 1995

543'.0871 - dc20

94-38849

CIP

A catalog record for this book is available from the British Library

ISBN 0-521-43196-4 Hardback

Transferred to digital printing 2003

Contents

<i>Preface</i>	page xiii
<i>Nomenclature</i>	xvii
1 Introduction	1
1.1 Background and motivation	1
1.2 Objectives of this book	2
1.3 Limitations and caveats	3
2. Fundamentals	5
2.1 Introduction	5
A. Electromechanics of particles	5
B. Force on an infinitesimal dipole	6
C. Torque on a dipole	8
2.2 Lossless dielectric particle in an electric field	9
A. Induced multipolar moments	9
B. Effective dipole moment of dielectric sphere in dielectric medium	10
C. Conducting sphere in uniform DC field	12
D. Lossless spherical shell in lossless medium with uniform field	12
E. Lossless dielectric sphere in lossless dielectric medium in field of point charge	14
2.3 Dielectric particle with loss in an electric field	16
A. Homogeneous sphere in an AC electric field	17
B. Shells with ohmic loss in an AC electric field	20
C. Summary	21
2.4 Effective moment calculation of force and torque	24
A. Hypothesis and definitions	24
B. Lossless particles	25
C. Particles with ohmic (or dielectric) loss	28
2.5 Theory of Sauer and Schlögl	30

A.	Summary of their result	31
B.	Reconciliation with effective moment method	31
C.	Discussion	32
3	Dielectrophoresis and magnetophoresis	34
3.1	Introduction	34
A.	Phenomenological definition	35
B.	Further delineation of dielectrophoretic effect	35
3.2	DEP phenomenology for lossless spherical particle	36
A.	Dielectrophoretic force expression	36
B.	Phenomenology of DEP	37
C.	Higher-order multipolar force terms	38
3.3	Frequency-dependent DEP phenomenology	39
A.	Homogeneous sphere with ohmic loss	39
B.	Time-dependent DEP	42
C.	Layered spherical shells with loss	42
D.	Generalized definition for +DEP and -DEP	43
E.	Examples of lossy spherical shells	43
3.4	DEP levitation	49
A.	DEP levitation theory	49
B.	Dynamic model of DEP levitator	52
C.	Passive DEP levitation	55
D.	Feedback-controlled DEP levitation (+DEP)	58
E.	Discussion of DEP levitation technique	60
3.5	Magnetophoresis	62
A.	Theory	63
B.	Magnetically linear particle	65
C.	Nonlinear magnetic media	66
D.	Magnetophoresis with eddy current induction	69
E.	Force on superconducting particles	73
3.6	Applications of dielectrophoresis and magnetophoresis	74
A.	Biological DEP	74
B.	Microactuators	78
C.	DEP mineralogical separations	79
D.	High-voltage liquid insulation	79
E.	MAP separation technologies	80
F.	Magnetic particle levitation	81
4	Particle rotation	83
4.1	Introduction	83
4.2	Theory for particle rotation	84
A.	Particle interactions with a rotating electric field	84

B.	Electric torque on homogeneous dielectric particle with ohmic loss	86
C.	Turcu's bifurcation theory	88
4.3	Rotational (relaxation) spectra	92
A.	General theory	92
B.	Sample spectra	94
C.	Argand diagrams	98
4.4	Quincke rotation in DC electric field	98
A.	Theory	98
B.	Experimental results	100
4.5	Rotation of magnetizable particles	101
A.	Induction	101
B.	Nonlinear effects	103
4.6	Applications of electrorotation	105
A.	Cell characterization studies	106
B.	Cell separation	108
C.	Practical implications of the Quincke effect	108
5	Orientation of nonspherical particles	110
5.1	Introduction	110
5.2	Orientation for lossless homogeneous ellipsoids	111
A.	Isotropic ellipsoid in a uniform electric field	111
B.	Alignment torque expressions	113
C.	Two special cases: prolate and oblate spheroids	115
D.	DEP force on ellipsoidal particle	118
5.3	Orientation for lossy dielectric ellipsoids	119
A.	Theory for homogeneous particles	119
B.	Alignment behavior of homogeneous particles	120
C.	Orientation of layered particles	121
5.4	Experimental orientational spectra	124
5.5	Static torque on suspended particle	125
A.	Basic model for torque calculation	126
B.	Rotational torque on suspended particle	128
C.	Alignment torque on suspended particle	130
5.6	Orientation of magnetizable particles	132
A.	Magnetically linear particles with anisotropy	132
B.	Prolate spheroidal crystals	134
C.	Thin disks and laminae	135
D.	Isotropic particle with remanent magnetization	135
5.7	Applications of orientational phenomena	136
A.	Dielectric particles	136

B.	Magnetizable particle applications	137
6	Theory of particle chains	139
6.1	Introduction to chaining and review of previous work	139
6.2	Linear chains of conducting spheres	142
A.	Solution using the method of images	142
B.	Solution using geometric inversion	149
C.	Alignment torque for chain of two identical conducting spheres	153
D.	Spheres of unequal radii	154
E.	Intersecting spheres	155
F.	Discussion of results for short chains of contacting particles	156
6.3	Chains of dielectric (and magnetic) spheres	159
A.	Simple dipole approximation	160
B.	Accuracy considerations	162
C.	General expansion of linear multipoles	164
D.	Experimental measurements on chains	166
6.4	Frequency-dependent orientation of chains	172
6.5	Heterogeneous mixtures containing particle chains	173
A.	Mixture theory	175
B.	Suspensions of chains	177
6.6	Conclusion	180
7	Force interactions between particles	181
7.1	Introduction	181
7.2	Theory	181
A.	Force between conducting spheres	183
B.	Force between dielectric spheres	185
C.	Current-controlled interparticle forces	187
7.3	Experiments	188
A.	Interparticle force measurements	188
B.	Measurements on longer chains and planar arrays	189
C.	Nonlinear effects	192
7.4	Electrostatic contributions to adhesion	194
A.	Phenomenological force expression	194
B.	Image force contributions	196
C.	Detachment force contribution	203
D.	Induced moment contributions	204
E.	Generalized model of Fowlkes and Robinson	204
7.5	Mechanics of chains and layers	207
A.	Chains of magnetizable particles	209

Contents

B. Mechanics of particle beds	209
7.6 Discussion of applications	211
A. Electrofusion of biological cells	211
B. Chaining in electrorheological fluids	212
C. Electrofluidized and electropacked beds	214
D. Magnetopacked and magnetofluidized beds	215
7.7 Closing prospect	216
<i>Appendix A: Analogies between electrostatic, conduction, and magnetostatic problems</i>	218
<i>Appendix B: Review of linear multipoles</i>	222
<i>Appendix C: Models for layered spherical particles</i>	227
<i>Appendix D: Transient response of ohmic dielectric sphere to a suddenly applied DC electric field</i>	236
<i>Appendix E: Relationship of DEP and ROT spectra</i>	238
<i>Appendix F: General multipolar theory</i>	248
<i>Appendix G: Induced effective moment of dielectric ellipsoid</i>	251
<i>References</i>	253
<i>Index</i>	263

1

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 $1\ \mu\text{m}$ ($\sim 10^{-6}\ \text{m}$) to about $1\ \text{mm}$ ($\sim 10^{-3}\ \text{m}$). 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 ($\sim 10^{-6}\ \text{m}$) 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 ($\sim 10^{-3}\ \text{m}$) 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 non-spherical particles have not been considered.