
CONTENTS

Preface	xiii
Acknowledgments	xix
1 Introduction	1
1.1 Historical Background	3
1.2 Basic Experimental Approach	7
1.3 Description of Electrostatic Spinning	9
1.3.1 Droplet Generation	10
1.3.2 Taylor's Cone Formation	13
1.3.3 Launching of the Jet	14
1.3.4 Elongation of Straight Segment	16
1.3.5 Whipping Instability Region	18
1.3.6 Solidification into Nanofiber	22
1.4 Nanofiber Application Areas	23
1.4.1 Filtration and Protective Apparel	24
1.4.2 Tissue Scaffolding and Drug Delivery	25
1.4.3 Nanocomposites	25
1.4.4 Sensor Applications	26
2 Introduction to Polymer Solutions	27
2.1 Average Molecular Weight	28
2.2 Selecting Solvents: Solubility Parameter	31
2.3 Thermodynamic Criterion for Solubility	35
2.3.1 Change in Entropy	36
2.3.2 Change in Enthalpy (ΔH_{mix})	39
2.4 Macromolecular Models	41
2.5 Viscosity of Dilute Polymer Solutions	45
2.6 Concentrated Polymer Solutions	50

3 Electrospinning Basics	55
3.1 Molecular Weight Effects	56
3.1.1 The Simha–Frisch Parameter, $[\eta]c$	56
3.1.2 Solution Entanglement Number n_e	63
3.2 Electrical Charge	68
3.3 Bead Formation in Electrospinning	71
3.4 Introduction to Electrospinning Practice	76
4 Factors Affecting Nanofiber Quality	81
4.1 The Polymer Solution	83
4.1.1 Concentration Effects	83
4.1.2 Solvent System	86
4.1.3 Conductivity	88
4.1.4 Surface Tension	91
4.1.5 Dielectric Constant ϵ	93
4.1.6 Volatility	96
4.2 Environment	97
4.3 Collector	99
4.3.1 Collector Geometry	99
4.3.2 Collector Material	101
4.4 Applied Potential	102
4.4.1 Applied Voltage V	102
4.4.2 Polarity of the Tip	103
4.5 Feed Rate	105
4.6 Capillary Tip	106
4.7 Gap Distance	108
4.8 Relative Importance of Variables	108
4.9 Examples of Reported Data	109
5 Characterization of Nanofibers and Mats	111
5.1 Mat Porosity and Pore Size Distribution	115
5.1.1 Mercury Intrusion Porosimetry	117
5.1.2 Liquid Extrusion Porosimetry	119
5.1.3 Capillary Flow Porometry	121
5.1.4 Brunauer, Emmett, and Teller (BET) Surface Area	123
5.1.5 Other Approaches	125

5.2	Nanofiber Diameters and Pore Sizes by Microscopy	126
5.2.1	Atomic Force Microscopy Technique	129
5.3	Mechanical Properties of Mats	133
5.3.1	Mat-Related Variables	135
5.4	Single-Fiber Characterization	139
5.4.1	Using the AFM for Single-Nanofiber Measurement	141
5.4.1.1	Nanoindentation	142
5.4.1.2	Bending Test	143
5.4.1.3	Uniaxial Extension	145
5.5	Nanofiber Crystallinity	146
5.5.1	Differential Scanning Calorimetry (DSC) Technique	146
5.5.2	X-ray Diffraction Methods	148
6	Composite Nanofibers	153
6.1	Carbon Nanotubes in Nanofibers	156
6.1.1	Dispersion of Nanotubes	158
6.1.2	Orientation of Nanotubes	164
6.1.3	Other Carbons	168
6.2	Metal–Nanofiber Composites	169
6.2.1	Direct Electrospinning	169
6.2.2	Reductive Post-Reaction	171
6.2.3	Gas-Phase Post-Reaction	172
6.3	Polymer–Clay Composites	173
6.4	Decorated or Exocomposite Nanofibers	177
6.4.1	Nanofiber–Nanoparticle Composites	177
6.4.1.1	Dry Methods	177
6.4.1.2	Wet Methods	180
6.4.2	Nanofiber–Nanotube Composites	180
7	Biomedical Applications of Nanofibers	183
7.1	Drug Delivery Applications	184
7.1.1	Drug-Loaded Fibers	186
7.1.2	Controlled Delivery of Macromolecules	191
7.2	Scaffolding Applications of Nanofibers	194
7.2.1	Natural Biopolymers	198

7.2.1.1	Collagen and Elastin	199
7.2.1.2	Fibrinogen	202
7.2.1.3	Silk	203
7.2.1.4	Chitin/Chitosan	206
7.2.1.5	Poly(3-hydroxybutyrate- <i>co</i> -3-hydroxyvalerate) (PHBV)	208
7.2.2	Synthetic Polymers	208
7.2.2.1	Polyglycolides (PGA)	209
7.2.2.2	Polylactide (PLA)	210
7.2.2.3	Poly(ϵ -caprolactone) (PCL)	211
7.2.3	Scaffolding with Stem Cells	216
7.3	Other Applications	218
7.3.1	Wound Care Applications	218
7.3.2	Immobilized Bioactive Moieties on Nanofibers	220
7.4	Future Directions	222
8	Applications of Nanofiber Mats	225
8.1	Introduction to Air Filtration	225
8.1.1	Nanofiber Filter Performance	232
8.1.2	Filters with Nanofibers	233
8.2	Nanofiber Sensors	235
8.2.1	Gravimetric Sensors	236
8.2.2	Conductivity Sensors	237
8.2.3	Optical Sensors	240
8.3	Inorganic Nanofibers	241
8.3.1	Sol–Gel Chemistry	241
8.3.2	Oxide Nanofibers	242
9	Recent Developments in Electrospinning	249
9.1	Nanofibers with Surface Porosity	249
9.1.1	Extraction of a Component from Bicomponent Nanofibers	250
9.1.2	Phase Separation During Electrospinning	252
9.2	Core–Shell Nanofibers	257
9.2.1	Coaxial Electrospinning	258
9.2.2	Core–Shell Geometry by Post-Treatment of Nanofibers	263

9.3	Highly Aligned Nanofiber Mats	265
9.3.1	Parallel Electrode Collector	266
9.3.2	Rotating Cylinder Collectors	267
9.3.3	Chain Orientation During Fiber Alignment	271
9.3.4	Infrared Dichroism	272
9.4	Mixed Polymer Nanofibers and Nanofiber Mats	274
9.5	Crosslinked Nanofibers	277
9.5.1	Photocrosslinked Nanofibers	277
9.5.2	Crosslinking Agents	279
Appendix I	Electrospun Polymers Used in Tissue Engineering and Biomedical Applications	283
Appendix II	Summary Table of Electrospun Polymer Nanofibers	291
References		329
Index		389