Fundamentals and Applications of Micro- and Nanofibers

A comprehensive exposition of micro- and nanofiber forming, this text provides a unified framework of the relevant processes (melt- and solution blowing, electrospinning, etc.) and describes their foundations, development, and applications. It provides an up-to-date, in-depth physical and mathematical treatment, and discusses a wide variety of applications in different fields, including nonwovens, energy, healthcare, and the military. It further highlights the challenges and outstanding issues from the perspective of an interdisciplinary basic science and technology, incorporating both fundamentals and applications.

Ideal for researchers, engineers, and graduate students interested in formation of micro- and nanofibers and their use in functional smart materials.

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In this book, three leaders in the understanding, production, and application of fibers collect and summarize a wealth of information about polymer and glass fibers in the contemporary range of diameters that extends from a few nanometers to a few microns.

Fiber forming technology, using long polymer molecules, evolved in the textile industry during the past century, to large arrays of spinnerets, high-pressure pumps, and fiber spooling machines involving huge masses of polymer, high temperatures, and large costs. Scientific and empirical advances combined to serve the textile industry we know. But the scale and sophistication of the fiber making industry could not be matched in research laboratories where new polymers and new uses were developing.

A renaissance of interest in making fibers with diameters ranging from that of a few molecules to that of a thin textile fiber emerged in the 1990s, and grew exponentially, as it became possible to produce new kinds of fibers from small quantities of polymer synthesized in an organic chemist's laboratory, to connect fiber and polymer research at the laboratory scale, to design air filters that captured very small particles, to serve rapidly growing needs arising in biomaterials research, and to make many useful inventions.

This book covers state-of-the-art information and existing challenges related to micro- and nanofibers. The topics include interdisciplinary science and technology, and deal with both fundamental aspects and applications. The main modern processes for forming micro- and nanofibers including melt blowing, solution blowing, electrospinning, force spinning, and several other methods are covered. Fiber formation from petroleum-derived polymers, degradable biopolymers, and glasses are discussed. The fundamentals of micro- and nanofiber forming processes are linked to polymer physics, rheology, non-Newtonian hydrodynamics, electrohydrodynamics, aerodynamics, and applied mathematics. Defense and biomedical applications of micro- and nanofibers, in filters, membranes, electrodes, coatings, nanofluidic devices, sensors, and optical fibers are described.

Researchers, engineers, and post-graduate students interested in engineering, materials science, applied chemistry, physics, and process development will find this book to be of interest. Specialists interested in applications of micro- and nanofibers as functional smart materials, innovative filter media, and membranes will find interesting information. Nonwovens finding new application in defense, biomedical, and healthcare products are also described.

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Preface

Fiber-forming processes and the resulting fibers have become a key element in many modern technologies. Today, practically everyone is directly or indirectly using these fibers. Manmade macroscopic fibers are widely used in our garments and many other items of everyday life. On the other hand, much smaller microscopic and, especially, nanofibers are only beginning their path to prominence. The chemical, physical and technological aspects of manufacturing of such fibers are still weakly linked and not fully understood. Two main processes associated with formation of micro- and nanofibers are melt- or solution blowing and electrospinning. They require concerted interaction of synthetic chemistry, responsible for polymers used as raw materials, polymer physics, providing a link to their viscoelastic behavior, rheological characterization of flow properties, non-Newtonian fluid dynamics of polymer solutions and melts, aerodynamics, associated with gas blowing, and electrohydrodynamics, in the case of electrospinning. The key element of the fiber-forming processes is a thin jet of polymer solution or melt, which rapidly changes its three-dimensional configuration under the action of the aerodynamic or electric forces applied to its surface and the internal viscous and elastic stresses. There is a definite and imperative need to interpret and rationalize these phenomena, which requires acquisition of extensive experimental data and establishment of an appropriate theoretical framework as an essential element in the further technological design and optimization. In addition to the above-mentioned broad spectrum of disciplines, this involves different aspects associated with materials science, such as the methods developed in polymer crystallography, and elasticity and plasticity theory. Although many aspects of fiber-forming processes can today be considered as uncovered and well described, either experimentally or theoretically/numerically, numerous important details are still to be explored. The importance of this subject is attested by an exponential increase in scientific publications devoted to microscopic and nanofibers and a broad involvement of the industries associated with fiber media, nonwovens, nano-textured materials, novel biomedical and healthcare products and optical fibers, as well as defense applications.

The idea of writing this book was motivated by the need for a comprehensive exposition of different aspects of fiber-forming processes including the fundamental polymer science facts, rheology, non-Newtonian fluid dynamics and electrohydrodynamics, applied mathematics, materials science, process development and applications. Numerous recent experimental and theoretical achievements on this subject can now be tied in an integrated text covering significant advances in our understanding of the micro- and nanofiber-forming processes, which are radically different from those well documented for macroscopic fibers. There is still no other book in the field of micro- and nanofibers that exposes the subject with the breadth and depth of the seminal book by A. Ziabicki, *Fundamentals of Fibre Formation*, published 50 years ago and devoted to macroscopic fibers. The present book aims at charting the domain of our state-of-the-art knowledge in the field of micro- and nanofibers, and also highlighting the not yet fully understood challenges and outstanding issues from the perspective of interdisciplinary basic science and technology, incorporating both fundamentals and applications. We have endeavoured to contribute to a wide audience of researchers, engineers and post-graduate students from various disciplines, i.e. engineering, applied chemistry and physics and materials science, as well as technology and process development, interested in the formation of micro- and nanofibers and their use in functional smart materials, such as novel filter media, nonwovens, membranes, biomedical and healthcare products, fluffy electrodes for fuel cells and batteries, polarization-maintaining optical fibers, etc.

The book is a monograph significantly based on the results published by the authors in the peer-reviewed journals over the last 14 years. These works covered a wide range of the inter-related topics and in part inspired the idea to write a comprehensive monograph encompassing the scattered mosaic of our own journal publications and the related important results of the other groups. The present book is the culmination of these efforts. The structure of the book is rooted in its goals. The introductory Chapter 1 exposes the history of artificial macroscopic fiber technology and some basic aspects of the existing technology and its foundations. Chapter 2 contains the basic facts from the field of polymer physics and rheology needed for the understanding and description of flows of polymer solutions and melts, their solidification and crystallization. The fundamentals of the hydrodynamics of free liquid jets moving in air, i.e. the quasi-one-dimensional equations of such jets and basic instability phenomena are described in Chapter 3. These equations are applied to the analysis of polymer melt- and solution blowing in Chapter 4. In Chapter 5 these equations are supplemented by elements of electrohydrodynamics and similarly applied to the analysis of electrospinning of polymer nanofibers. Several other methods of forming of polymer nanofibers and optical glass microfibers are summarized in Chapter 6. Polymer fibers and their nonwovens are frequently subjected to post-processing, aimed at improving their properties, which is discussed in Chapter 7. The tensile properties and strength of the individual nanofibers and nanofiber mats are described in Chapter 8. Chapter 9 introduces a range of applications of nanofibers and their mats as filters and membranes, catalyst supports, fluffy electrodes, nanotextured coatings that facilitate heat removal from high heat-flux surfaces, and in nanofluidics. Military applications of nanofiber mats for decontamination, and protection from nuclear, biological and chemical warfare, as well as nanofiber-based sensors are summarized in Chapter 10. Numerous applications of micro- and nanofibers and nanoparticles for healthcare and drug delivery, as well as the physical mechanisms involved, are discussed in Chapter 11. All references are combined in the end of the book chapters in a strictly alphabetic order. References in the text with coinciding names of the first author and the publication year are distinguished by an additional suffix added to the year, e.g. Smith *et al*. (2011a) and Smith *et al*. (2012b). In the list of references these two works can be separated by several others due to the alphabetic order of the initials or/and the second etc. co-authors' names. Moreover, in the list of references Smith *et al*. (2012b) can even precede Smith *et al*. (2011a) if the former is Smith A.B., and the latter is Smith C.D.

The book allows for selective reading and Chapters 1, 2, 6–11 can be read stand-alone. On the other hand, reading about the modeling aspects of melt- and solution blowing in Chapter 4 and electrospinning in Chapter 5 imply understanding of the general quasi-one-dimensional equations described in Chapter 3. The book contains a wide range of references to the relevant existing literature, albeit the description of all the subjects treated in the book is practically self-contained, covered in depth and in sufficient detail.

This book is written for the benefit of senior-year undergraduate students, graduate students (as a text book), researchers, engineers, and consultants and practitioners in industry (as a reference book). The scope of the book is related to the growing number of specialists in non-Newtonian fluid mechanics, rheology, electrohydrodynamics and applied mathematics, materials scientists and engineers, textile and nonwoven engineers, nanotechnologists, micro- and nanoscale engineers, design engineers, sustainability engineers, energy engineers, chemical engineers, biotechnologists, bioengineers, biomedical engineers, environmental scientists and engineers, life scientists, physicists, chemists, food scientists and engineers, etc. Readers with basic knowledge of materials science and engineering, physics, chemistry and mathematics will be able to follow the contents of the book.

Special thanks are directed to our families, Liliya, Naomi, Shirley and Leonid Yarin, Atefeh, Roxana and Neda Pourdeyhimi, and Sridhar, Sundar and Susithra. Without their encouragement and help this book could not have appeared.