60 Years of the Loeb-Sourirajan Membrane

Principles, New Materials, Modelling, Characterization, and Applications

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Preface

It has been over 60 years since the development of the first asymmetric polymeric membrane by Dr. Sidney Loeb and Dr. Srinivasa Sourirajan (University of California, Los Angeles, United States) for seawater desalination. Research in membrane science and technology has progressed rapidly over the past decades, and many new and advanced materials (both organic and inorganic) have been discovered and employed in the fabrication of membranes and the modification of their properties. It is therefore of paramount importance to summarize the fundamental understanding of and information about these membranes and their distinctive applications. In this book a comprehensive overview of membrane technology is presented, from the fundamental knowledge of fabrication principles and separation mechanisms to a wide range of applications, including new and emerging processes.

In more detail, this book provides essential guidance for students, researchers, and scientists working in the field of membrane science and technology. The fundamentals of membranes in different technologies, including their working principles, transport mechanisms, and requirements for practical applications, are discussed in this book. Key references and practical sources are also provided, enabling an in-depth understanding of the numerous aspects of membrane science and technology.

Furthermore, studies on membranes and their applications, such as in water and wastewater treatment, chemical and biomedical processes, gas separation, and renewable power generation, are reviewed in this book. For instance, recent advances in three-dimensional membranes for water applications, organosilica and metal-organic framework membranes for gas separation, high-performance membranes for vanadium redox flow batteries and vanadium-air redox flow batteries, ceramic membranes for fuel cells, and membranes with enhanced safety for lithium-ion batteries are summarized and discussed extensively. Recent advances in modeling and simulations of different membranes and their components, such as spiral-wound membranes and spacer-filled channels, are also included to provide better insights.

To facilitate a comprehensive characterization of membranes at different levels, the book also presents the common testing methods, along with some cutting-edge techniques for the accurate evaluation of the membrane properties and performances, which are of vital importance to the future development of advanced membranes. For instance, the advanced characterization for membrane surface fouling is discussed in detail.

Finally, to enable a better understanding of the latest trends and current research on membrane technology, the most up-to-date details on the use of advanced organic and inorganic materials and novel membrane fabrication techniques for the development of membranes are also reviewed. The advantages of these new materials along with the superiority of the newly developed fabrication methods in comparison to conventional strategies are also extensively discussed.

This book will equip future researchers with the ideas and directions that they need to understand the great potential and prospects of next-generation membrane fabrication. It is also the aim of this book to reflect the ample research activities and outcomes in the membrane field with an eye toward global utilization and impact.

This book is an essential reference resource not only for students and researchers but also for professionals and policymakers around the globe working in three main sectors: academia, industry, and government.

We would like to express our gratitude to all the authors who contributed to this book and shared their valuable state-of-the-art knowledge and experience with the associated topics. Last but not the least, we acknowledge the professional staff of Elsevier for their continuous support.

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Contents

CHAPTER 15

Modelling flow and mass transfer inside spacer-filled channels for reverse osmosis membrane modules

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CONTENTS

15.1 Introduction

Desalination has progressed rapidly since the 1980s as freshwater is becoming more scarce as a result of the fast-growing population size and global climate change. To relieve this situation, membrane processes are recognized as promising approaches to purifying brackish and ocean water to meet the global water demand. Among the membrane technologies, reverse osmosis (RO) has gained the most attention and is used in half of the desalination plants in the world (Goh et al., 2018; Qasim et al., 2019). RO is used in water purification to effectively remove unwanted solutes (particularly dissolved ions) in the water by means of membrane permeation. The global RO membrane market was $6.9 billion in 2017 and is estimated to show an almost double increase by 2025 (Toh et al., 2020a).

Spiral-wound membrane (SWM) modules were invented in the 1960s and have become one of the most common membrane arrangements for water applications. SWMs are composed of membrane leaves, feed spacers, permeate spacers, and a permeate tube. For their construction, the membrane leaves are first folded in half to form an envelope. The permeate spacer is then inserted into the envelope to form the permeate channel, with the sides glued together to force the permeate to flow in the direction of the permeate tube. Next, a feed spacer is inserted between a pair of membrane envelopes to form a feed channel. These steps are repeated to form several membrane layers, and these layers are wrapped spirally to form a cylindrical module, as

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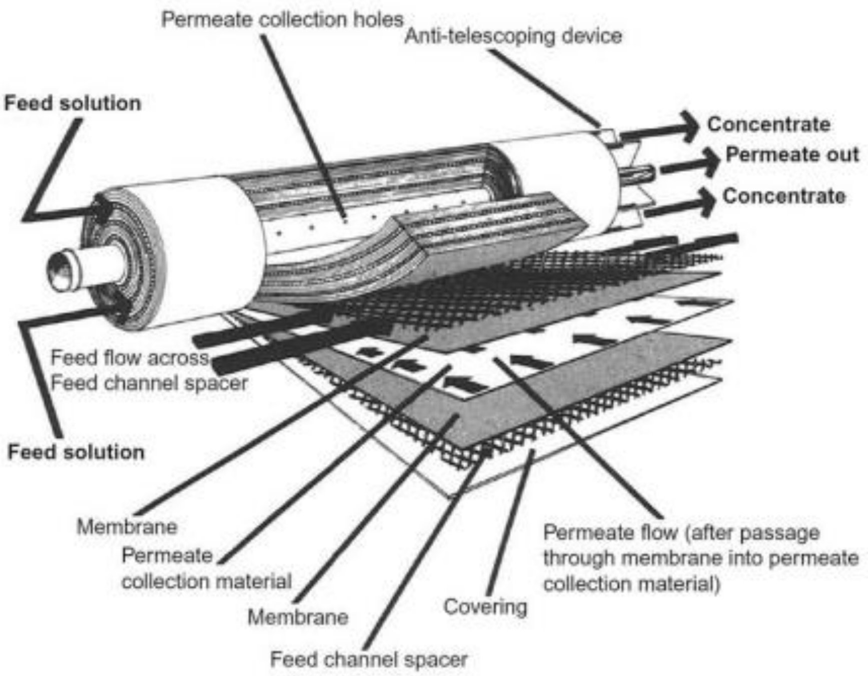

FIGURE 15.1
Configuration of spiral-wound membrane for reverse osmosis (Sparks & Chase, 2016).

depicted in Fig. 15.1 (Sparks & Chase, 2016). The feed passes through the feed channel, and the water selectively permeates across the RO membrane to the permeate channel as the result of applied pressure, overcoming the osmotic pressure. The rejected salt becomes concentrated in the feed channel solution, forming the brine that exits the module from the opposite side of the feed channel. The purified water exits the module via the permeate tube as permeate.

The SWM design offers several benefits, such as (1) high packing density to give larger surface area per volume (Qasim et al., 2019), (2) low manufacturing and operating costs compared to flat plate and tubular modules (Belfort, 1988; El-Ghaffar & Tieama, 2017), and (3) being more robust against membrane breakage compared to hollow-fiber membrane (Lu & Chung, 2019). However, concentration polarization and fouling are common serious problems in SWMs.

To reduce the drawbacks associated with RO membrane operations and to optimize SWM performance in water desalination, intensive experimental studies have been conducted through approaches such as varying the feed conditions (Goosen et al., 2002; Madaeni & Koocheki, 2006) or modifying the geometrical structure of SWMs (Sablani et al., 2002). Although less intrusive experimental methods (e.g., particle image velocimetry) have been developed, the resolution of those methods is insufficient to study the mass transport within the boundary layer (Fimbres-Weihs & Wiley, 2010). Therefore CFD aids the process by nonintrusively visualizing the intricate local and time dependent phenomena of flow and mass transfer enhancement.

Initially the modelling of SWMs for RO membrane operations was focused on prediction of the permeate flux and permeate concentration. One-dimensional (1D) models have been developed through either numerical or analytical solutions based on the fundamental concepts of mass and momentum balance. Since the 2000s, computers have faster rates of calculation and can access larger memory sizes, making it possible to solve larger and more complex problems. Since then, CFD has become a powerful and reliable tool to simulate fluid flow and to provide high-resolution visualization of hydrodynamic and concentration profiles inside the feed channel of SWMs. The SWM feed channel was first modeled as two-dimensional (2D) in the early 2000s, then evolved into three-dimensional (3D) models with greater resolution. Fig. 15.2 summarizes the evolution of CFD studies for RO feed spacers. In view of the significant progress of modelling flow and mass transfer inside spacer-filled channels for RO membrane modules, the chapter aims to discuss the recent research of these one-dimensional (1D), 2D, and 3D simulation models, followed by the studies of unsteady shear strategies, novel spacer geometries, and fouling reduction.

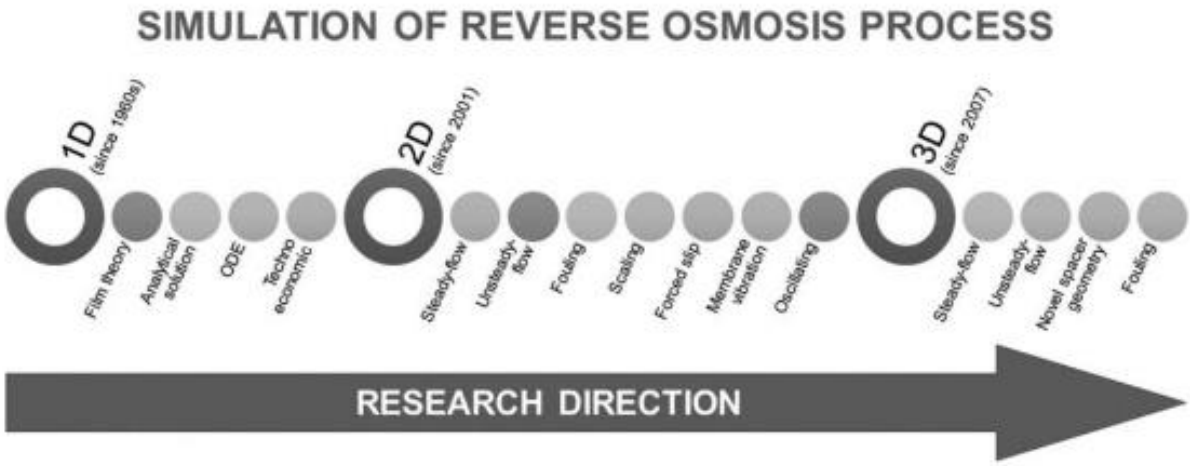

FIGURE 15.2

The research direction of the simulation of reverse osmosis process since the 1900s.

15.2 One-dimensional model

In RO systems, solvent transport is driven by the pressure gradient and resisted by the osmotic pressure. At the same time, the dissolved solutes move toward the membrane through convective flux and move away from the membrane through diffusive flux due to membrane rejection. This leads to the accumulation of rejected solute near the membrane surface, forming a concentration boundary layer, which is also known as CP. Film theory assumes mass balance at a steady state, such that the convective flux of solute is equal to the diffusive flux of solute:

$$J(C - C_p) - D_S \frac{dC}{dy} = 0 \tag{15.1}$$

where J is the permeate flux, C is the solute concentration, and D_S is the solute diffusivity. By integrating Eq. (15.1) with the boundary conditions $C = C_w$ at $y = 0$ and $C = C_b$ at $y = \delta$, the CP modulus can be expressed as:

$$\gamma = \frac{C_w - C_p}{C_b - C_p} = \exp\left(\frac{J}{k_{\mathrm{mt}}}\right) \tag{15.2}$$

where the mass transfer coefficient, $k_{\mathrm{mt}} = D_S/\delta$.

Film theory gives a simplified view of the concentration profile in a boundary layer of thickness δ, which is located between the membrane wall and the bulk solution, as shown in Fig. 15.3. This theory assumes that the axial solute convection near the membrane wall and the local changes of liquid density can be neglected.

However, the simplicity of film theory has some limitations, as it neglects several effects, including the axial convection term near the membrane wall,

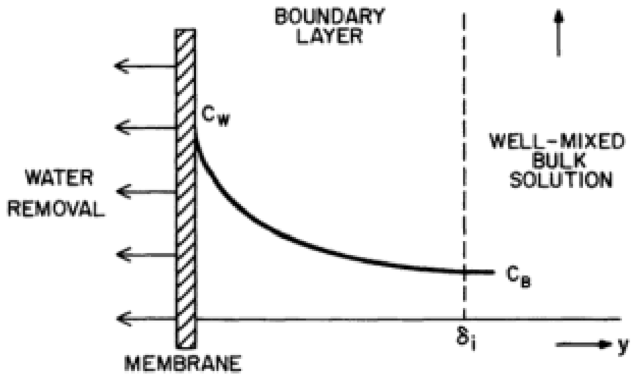

FIGURE 15.3
Concentration profile in boundary layer (Blatt et al., 1970).

Index

Note: Page numbers followed by "*f*" and "*t*" refer to figures and tables, respectively.

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