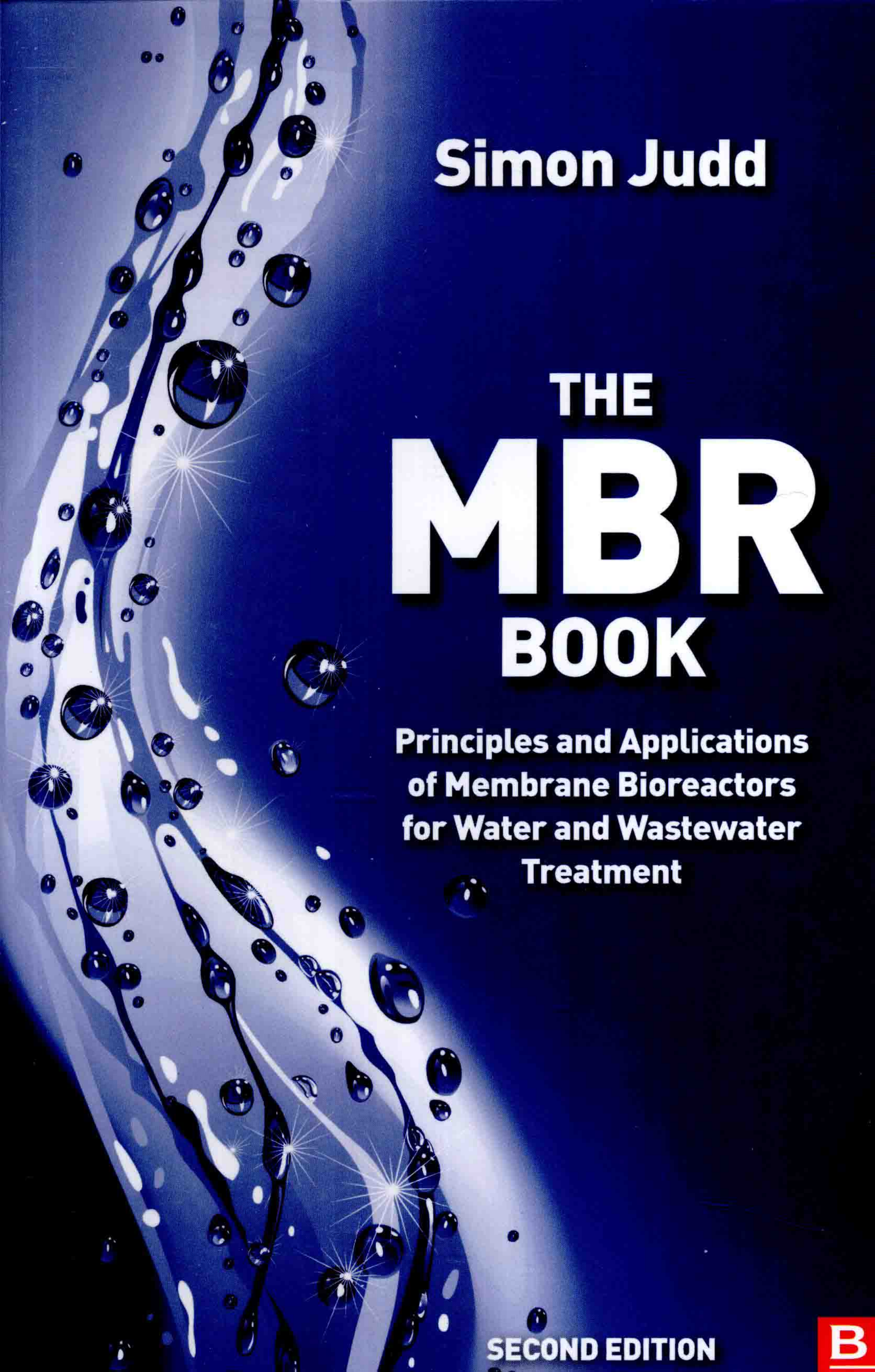

Simon Judd

THE MBR BOOK

Principles and Applications of Membrane Bioreactors for Water and Wastewater Treatment

SECOND EDITION

The MBR Book

Principles and Applications
of Membrane Bioreactors for Water
and Wastewater Treatment

Second edition

Edited by
Simon Judd
Claire Judd

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The MBR Book

Principles and Applications of Membrane Bioreactors for Water and Wastewater Treatment

Dedication

Once again, for Oliver and Samuel. And also for our family – Ivor and Margaret, Lorna, Ciss, Robert and Jane, Daisy and Heyes, John and Patricia, Lucy, Cameron and Dynamite.

Preface

This is only the second edition of *The MBR Book*, the first edition having been published in 2006, but it's the fourth on membrane technology from the Centre for Water Science at Cranfield University in the United Kingdom. The first of these was the original book on membrane bioreactors: *Membrane Bioreactors for Wastewater Treatment* by Tom Stephenson, Simon Judd, Bruce Jefferson and Keith Brindle, which came out in 2000 (IWA Publishing). This was followed in 2003 by *Membranes for Industrial Wastewater Recycling and Reuse*, by Simon Judd and Bruce Jefferson (Elsevier). Since then there have been a few books dedicated to membrane technology for wastewater treatment, three of which were all published in 2006: *Membrane Systems for Wastewater Treatment* (WEFPress, 2006), *Membrane Technology for Waste Water Treatment* (Johannes Pinnekamp and Harald Friedrich, FiW-Verlag, 2006) and *The MBR Book* (Elsevier, 2006). As a poignant demonstration of history repeating itself, the publication year of the second edition is the same as that of two other wastewater membrane reference texts: *MBR Practice Report: Operating Large Scale Membrane Bioreactors for Municipal Wastewater Treatment*, by Christoph Brepols (IWA Publishing) and *The Guidebook to Membrane Technology for Wastewater Reclamation*, led by Mark Wilf (Balaban Publishers). Membrane wastewater books are, it seems, like London buses.

There have also been many more books, both on biological treatment and membrane technology, which have included sections on MBRs. A comprehensive listing of these would be challenging. Two of the most recent, both from 2008, are *Biological Wastewater Treatment, Principles, Modelling and Design*, by Mogens Henze, Mark van Loosdrecht, George Ekama and Damir Brdjanovic from IWA Publishing, and *Advanced Membrane Technology and Applications*, by Norman Li, Tony Fane, Winston Ho and Takeshi Matsuura from Wiley (2008). However, there are several books which similarly aim to cover either membrane technology or biological treatment in a rather more comprehensive manner than provided in *The MBR Book*. Biological treatment texts include the biotreatment 'bible' of Metcalf and Eddy: *Wastewater Engineering – Treatment and Reuse* by George Tchobanoglous, Franklin Burton and David Stensel (McGraw Hill, 2003) and also the commendable *Biological Wastewater Treatment* by Leslie Grady, Glen Daigger and Nancy Love, the third edition of which is also due out in 2010 (IWA Publishing).

Writing the second edition of *The MBR Book* was initially viewed as being a simple enough task, with the format used for the first edition being serviceable enough, only requiring updates from the past four to five years. However, there has been an explosion of activity over this period; assurances to the publisher that this edition would not exceed 30% of the first have proven woefully under-conservative. In the intervening period the number of discernible MBR membrane products has more than doubled that of the first edition, and it is acknowledged that the 44-or-so membrane products identified and described cannot be considered comprehensive. The past five years have also seen some important landmark plants installed – up to 110 megalitres/day in capacity. Scientific studies of MBRs have continued to be published at much the same rate as ever – about 20% exponential growth each year since the mid-1990s. It is these developments that have contributed to a 45% expansion of the original text to produce the second edition.

As with first edition, the second edition of *The MBR Book* is set out in such a way as to segregate the science from the engineering, in an attempt to avoid confusing, irritating or offending anyone of either persuasion. The book is meant to include as much practical information as possible, whilst still covering the science and technology. There are five chapters, with the membrane and biological fundamentals covered in Chapter 2 along with most of the scientific studies. The commercial MBR membrane products are summarized in Chapter 4 and their application to wastewater treatment is described in Chapter 5; the information from Chapter 5 is compiled and used for the design section in Chapter 3. New to the second edition are, in Chapter 1, summaries of the status of the technology across 13 countries and a brief précis of research trends. Also, Chapter 3 has been completely redrafted to provide a cost modelling and cost benefit analysis method, as well as a section on operation and maintenance. The latter is considerably more extensive than in the first edition, and has been informed by an expert panel of practitioners. Extensive cross-referencing between sections and chapters, including figures or tables in other chapters, is employed to try to ensure a degree of coherence throughout the tome.

A list of symbols and a glossary of terms and abbreviations are included at the end of the book, and those relating specifically to the membrane technology are outlined in Appendix C as a preface to the commercial MBR membrane module specifications. However, since a few terms and abbreviations are more extensively used than others, and possibly not universally recognized, it is probably prudent to list these to avoid confounding some readers (see following table). It is acknowledged that resolution of the inconsistencies in the use of terms to describe the membrane component of MBR technologies has not been possible, specifically the use of the terms 'module' (see Appendix C) and 'fouling'. This is something which is to be addressed by the Water Environment Federation (and the best of luck with that one).

Term	Meaning
Common units	
MLD	Megalitres/day (thousands of cubic metres per day)
LMH	L/(m^2 h) (litres per square metre per hour)
Billion	1000 Million
Process configurations	
iMBR	Immersed (internal) MBR
sMBR	Sidestream (external) MBR
a-lsMBR	Air-lift sidestream MBR
anMBR	Anaerobic MBR
Membrane configurations	
FS	Flat sheet (plate-and-frame, planar)
HF	Hollow fibre
MT	Multitube
Fouling	
Reversible	Removed by physical cleaning, such as backflushing or relaxation
Irreversible	Not removed by physical cleaning but removed by chemical cleaning
Irrecoverable	Cannot be removed
Aeration	
SAD	Specific aeration demand, either with respect to the membrane area (SAD_m) or permeate flow (SAD_p)

Given the broad range of stakeholders encompassed, it is inevitable that inconsistencies in terminology, symbols and abbreviations have arisen. It is also certain that, despite the best efforts, the text includes a number of inaccuracies and omissions, for which the authors cannot be held liable. We have, naturally, done everything we could to ensure that the information presented is as accurate and complete as possible, but, notwithstanding this and because of the complex nature of the subject, interested parties are strongly advised to check facts and figures with the relevant organisations before acting on any information provided.

It would be remiss to preface this book without offering the most grateful and sincere thanks to the many contributors – more than 150 in total. These include product suppliers, technology providers, consultants, contractors, end users and academics. Almost all the practical operational data provided have been supplied by the technology providers, although corroboration of some information from end users has been possible in some cases. All information providers are listed in the following section and on the title page of each chapter, and their assistance, kindness and, at times, superhuman patience in responding to a plethora of detailed queries by the authors are gratefully acknowledged. Contributions have also come from academic staff and students – predominantly from Cranfield University in the United Kingdom. With regard to the latter, specifically most grateful thanks is offered to current students of, and recent graduates from, the Centre for Water Science and, in particular (in alphabetical order), Harriet Fletcher, Wenjing Ma, Ignacio Martin, Ewan McAdam, Ana Santos and Bart Verrecht. Gratitude is similarly expressed to the incomparable Pierre Le-Clech from the University of New South Wales, who took on the unenviable task of updating the sections on membrane fouling behaviour in Chapter 2, and to the various members of the Department of Applied Mathematics, Biometrics and Process Control at Ghent University, who contributed to the modelling sections in Chapter 3.

Special thanks are also given to the Expert Panel members: Christoph Brepols (Erftverband), Dave Hemmings (Aquabio Ltd), Stephen Kennedy (Ovivo), Wilfred Langhorst (Waterschap Hollandse Delta), Dennis Livingston (Ovivo), Heribert Moeslang (Aquantis GmbH), Sameer Sharma (Tecton Engineering LLC) and Vincent Urbain (Vinci Environnement), whose enlightening comments make up the bulk of the operation and maintenance section of Chapter 3. We are also extremely grateful to Enrico Vonghia at GE, whose encyclopaedic knowledge of even the most obscure MBR membrane product market is truly something to behold.

Finally, we would encourage readers to participate in one (or more) of the now several on-line forums dedicated to the discussion of membrane bioreactor technology, especially ours (The MBR Group – Membrane Bioreactors at www.linkedin.com).

As with any piece of work, the editors would welcome any comments from readers, critical or otherwise, and our contact details are included in the following section.

SJ and CJ

About the Editors

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Simon Judd is Professor in Membrane Technology at the Centre for Water Science at Cranfield University, United Kingdom, where he has been on the academic staff since August 1992. Since abandoning a chequered career in hairdressing, Simon has co-managed most of the biomass separation MBR programmes conducted within the School, comprising 15 individual research project programmes and encompassing 13 doctorate students dating back to the mid-1990s. He has been principal or co-investigator on three major UK Research Council-sponsored programmes dedicated to MBRs with respect to in-building water recycling, sewage treatment and contaminated groundwaters/ landfill leachate, and is also Chairman of the Project Steering Committee on the multi-centred EU-sponsored EUROMBRA project. As well as publishing extensively in the research literature, Simon has co-authored three textbooks in membrane and MBR technology, and delivered a number of keynote presentations at international membrane conferences on these topics. He is the manager of *The MBR Group*, an online discussion forum on LinkedIn (www.linkedin.com).

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A number of individuals and organizations have contributed to this book, in particular to the product descriptions in Chapter 4 and the case studies referenced in Chapter 5. The editors would like to thank all contributors for their co-operation, sometimes at short notice, and acknowledge the particular contribution of the following (listed in alphabetical order, by organization and last name; websites, where listed, were accessed in July 2010):

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Contents

Chapter 1

Introduction

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1.1. DEFINITION

The term 'membrane bioreactor' (MBR) applies to all water and wastewater treatment processes integrating a permselective membrane with a biological process. All currently available commercial MBR processes employ the membrane ostensibly as a filter, rejecting the solid materials developed by the biological process to provide a clarified and disinfected product. It is this type of MBR, the biomass rejection MBR (Section 1.1), which forms the primary focus of this book. The progress of technological development and market penetration of MBRs can be viewed in the context of their historical development (Section 1.2), current market penetration (Section 1.3), key drivers

(Section 1.4) and the status of MBR research (Section 1.5), all impacting to some degree on the future prospects of the technology (Section 1.6).

1.2. HISTORICAL PERSPECTIVE

1.2.1. Membranes and Membrane Technology

The membrane industry did not exist until the early twentieth century; the main research on membrane separation phenomena was aimed at elucidating the physico-chemical principles of the process, and the mechanism of diffusion. However, some of these early-stage achievements still impact on the academic research and industrial applications today. These include Fick's (1855) phenomenological laws of diffusion, van't Hoff's (1887, 1888) osmotic pressure equation, for which he was awarded the first Noble Prize in Chemistry in 1901, and Thomas Graham's pioneering work in gas separation using both porous membranes and dense membranes is still relevant today. Graham discovered that rubber exhibits selective permeability to different gases, and also found low-molecular weight substances to be concentrated in the permeated gas when the membrane pore size is close to the mean free path of gas molecules (Graham, 1861, 1866). Graham's work was inspired by Schmidt's (1856) earlier study, where he had used bovine heart membranes (the pore dimension being 1−50 nm) to separate soluble *Acacia* − arguably the first documented ultrafiltration (UF) experiment.

The first synthetic UF membranes were prepared by Bechhold from collodion (nitrocellulose). Bechhold was also the first to measure membrane bubble points, and to propose the term 'ultrafilter' (Bechhold, 1907). Other important early researchers, Elford, Zsigmondy, Bachmann, and Ferry, etc., further developed Bechhold's membrane preparation method. Commercial application of collodion porous membranes can be attributed to Zsigmondy's laboratory at the University of Goettingen, Germany; Zsigmondy and Bachmann were the first to propose a method to produce porous collodion membrane in an industrial scale (Zsigmondy & Bachmann, 1918, 1922). Based on this technology, the world's first commercial microporous membrane supplier, Sartorius Werke GmbH, was established in Goettingen in 1925, although its products were mostly sold to research laboratories. The early porous collodion membrane formation method was named 'dry inversion', which is still in use today.

During World War II, damage to German distribution networks by bombing raids led to the development of techniques for rapid analysis for bacteria in water supplies. Using Sartorius membranes, Müller and others at Hamburg University developed an effective method to cultivate micro-organisms in drinking water. This was the first large-scale application of microfiltration (MF) membranes. Following on from this work and in recognition of the strategic importance of MF membranes, Alexander Goetz, a professor in the California