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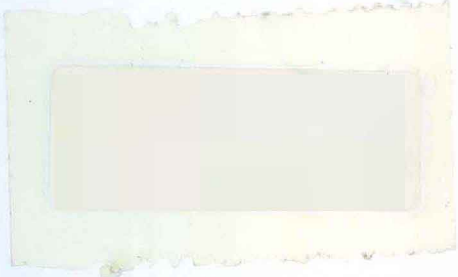
The MBR Book:
Principles and Applications of Membrane Bioreactors for Water and Wastewater Treatment (Second edition)

膜生物反应器
水和污水处理的原理与应用
（原著第2版）



Simon Judd , Claire Judd

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导　读

全球淡水资源短缺，水环境质量持续恶化，污水回用是解决水资源危机，满足日益严格的水环境要求的有效办法。膜分离在水处理过程中具有高效、节能、环保以及过程简单、易于控制等特性，得到了广泛的发展。随着膜科学技术日新月异的发展，膜生物反应器（Membrane Bioreactor，MBR）越来越广泛地应用于污水处理领域。到2011年底，全世界投入运行及在建的MBR系统已超过15 000套。

作为膜分离与生物技术有机结合的污水处理新工艺，MBR由于其出水水质优良稳定，装置占地面积小等显著优点，使其在城市污水和工业废水处理和回用方面表现出良好的竞争力，并在全球范围受到高度重视，是公认的21世纪最具吸引力和竞争力的污水处理与回用技术。近年来，全球MBR市场发展极为迅速，预计到2015年，全球MBR市场规模将超过13亿美元。

本书是《膜生物反应器：水和污水处理的原理与应用》的第二版，是英国克兰菲尔德大学水科学课题组编写的第四本有关膜方面的书籍。本书的第一版原著出版于2006年，虽然仅仅相隔四年，但此期间MBR市场扩展迅速，因此本书比第一版总篇幅增加了约45%，反映了当前国际上MBR技术的最新研究进展和应用现状，是MBR领域的又一经典之作。

本书采用将理论与工程分开的编写方式，旨在提供尽可能多的实用信息。整体内容分为五章：

第1章为MBR概述，该章由MBR的定义出发，首先回顾了膜与MBR的发展史及MBR市场的扩展过程，然后总结了MBR的市场现状及其发展的主要推动力。目前，MBR系统已经在200多个国家和地区实施，除久保田、GE泽能、三菱丽阳三家占主导地位的供应商外，市场上还补充了许多其他的MBR膜产品和MBR技术供应商。在全球范围内，生产性MBR装置也有明显的上升趋势。由于各地区经济发展和基础设施的状态不同，MBR的增长速度和执行程度亦有所差异，本章详细介绍了包括中国在内的13个国家MBR的发展推动力。本章最后还提及了MBR技术的学术研究现状，并指出较高的投资成本和运行费用依旧是制约该技术发展的主要因素。

第2章是对MBR基本原理的详细阐述，2.1节在引入膜和膜分离技术之后，重点对膜材料、膜构型和膜工艺运行进行了阐述。生物处理是一种典型的污水处理工艺，相关著作较多，因此本书2.2节仅对生物处理工艺相关方面进行了简单介绍。2.3节则详细阐述了MBR技术。MBR既可用于好氧生物处理

工艺，也可用于厌氧生物处理工艺，其构型主要包括浸没式（iMBR）和分置式（sMBR），除常用的截留微生物的 MBR 外，还存在萃取和扩散 MBR 两种工艺模式，但浸没式截留微生物 MBR 仍是所有 MBR 构型中应用最广的一种。作者还介绍了 MBR 在饮用水脱氮中的应用。此外，膜特性、进水水质和微生物特性、MBR 工艺运行、MBR 污染机理、膜污染控制与改善以及出水水质也是本节的重点论述内容。目前，对于 MBR 基础理论方面的研究还在继续，以开发新的膜和反应器系统。除理论研究之外，也可从中试和生产性处理装置的运行数据中获得许多实际信息，这些信息有助于考察现有商业技术的处理效果。

第 3 章探讨了 MBR 的设计、运行和维护。作者首先介绍了 MBR 设计的主要关注点和关键设计参数，对于浸没式 MBR 的设计需了解进水水质和控制膜污染所需的曝气量。然后列举了 5 个污水处理厂或大学实验室开展的比较性中试研究，通过对这些中试和已有生产性装置运行数据的比较和总结，探讨了浸没式 MBR 工艺中膜通量、透水率和比曝气量间的关系，及其适用的预处理方法和膜清洗方案，以指引市政浸没式 MBR 的设计。最后分别讨论了稳态模式和动态模式下浸没式 MBR 的设计方法，并从投资成本、运行费用和投资灵敏度分析三方面介绍了 MBR 的投资收益分析。本章对 MBR 的运行与维护的介绍很全面，不仅包括膜堵塞、膜污染和清洗、膜的完整性等膜本身的问题，也包括前处理、泡沫、生物学作用及过程控制等外围设备的问题。尽管 MBR 工艺具有很多优点，但与传统活性污泥工艺相比，其在设计和运行维护上都较复杂，因此发生工艺故障的运行风险较高。采用相对保守的运行参数可以减少故障的发生，但需要更多的投资和运行费用。

由于已有的及研发中的 MBR 相关产品数量众多，本书很难对所有技术进行全面介绍，因此仅列出一些主要厂商，其详细技术信息见第 4 章。作者在该部分共介绍了 30 余类技术产品，其中浸没式平板膜产品主要介绍了 kubota、A3 等 16 家公司，浸没式中空纤维膜产品主要介绍了 GE、Asahi Kasei 等 20 家公司。同时，简单介绍了分置式 MBR 膜产品及技术供应商。通过阅读本章，读者可以深入了解各公司膜产品的技术参数及其 MBR 工艺的设计特点和应用领域，有助于对不同公司产品的比较研究或选择适合自己项目的 MBR 产品。

第 5 章根据膜构型和具体工艺，介绍了第 4 章所列部分膜产品的应用情况，例举了涉及浸没式平板膜、浸没式中空纤维膜以及分置式 MBR 的 21 家 MBR 产品公司的近 60 个工程实例，其中包括部分中国的膜供应商和 MBR 工程。这些工程实例由不同的膜厂商、承包商和最终用户提供。主要的工程实例都详细介绍了工程背景、装置设计及运行和处理效果，并以图和表的形式表示其工艺流程、操作参数、水质数据等，其中包括很多 MBR 装置外观图、示意图，污水处理厂外观图、平面布置图，使读者在阅读时可以获得更好的感性认

识，具有很高的参考价值。对工程实例感兴趣的读者可直接参阅本章。

由于研究者国籍不同，难免存在名词术语、符号和缩略词不一致的情况，因此本书最后附有符号说明、术语表和缩略词表，供读者查阅。

本书主编 Simon Judd 教授是英国克兰菲尔德大学水科学学院院长，并担任欧洲发起的 EUROMBRA 项目指导委员会主席，发表过大量的学术论文，合编了三本膜与 MBR 技术方面的教科书，是 MBR 技术领域的国际著名专家。本书内容丰富、构思新颖，对 MBR 的基础知识、设计维护、商业化技术、工程实例进行了全面的论述和总结。

虽然我国对 MBR 的应用研究起步相对较晚，但发展非常迅速，最近几年在技术应用方面与国外几乎同步，并且项目规模和数量位居全球前列。但不少项目在调试或者投入运行后出现了一些问题，说明 MBR 是新生事物与技术，我们在研究和工程应用方面还有大量的工作需要去做。希望本书的出版和引进能给读者和业内带来帮助和启示，也希望读者能从中受益，共同促进我国 MBR 技术的健康、快速发展！

陈福泰　黄霞

清华大学环境学院膜技术研发与应用中心

前　言

本书是《膜生物反应器：水和污水处理的原理与应用》的第二版（第一版出版于2006年），同时也是英国克兰菲尔德大学水科学课题组编写的第四本有关膜方面的书籍。第一本是由Tom Stephenson，Simon Judd，Bruce Jefferson和Keith Brindle共同编写的《膜生物反应器污水处理技术》（2000年出版，IWA出版），该书也是最早的针对膜生物反应器的专著。紧接着是2003年出版的《膜技术与工业废水回用》（Simon Judd和Bruce Jefferson编写，Elsevier出版）。之后，一系列污水处理领域的膜技术书籍陆续出版，其中三本均出版于2006年，包括《膜系统废水处理技术》（WEF出版，2006）、《废水处理膜技术》（Johannes Pinnekamp和Harald Friedrich编写，FiW-Verlag出版，2006）以及《膜生物反应器：水和污水处理的原理与应用》（Elsevier出版，2006）。巧合的是，本书第二版又与另外两本废水处理膜技术参考书籍同年出版：《MBR实践报告：大型市政污水处理膜生物反应器的运行》（Christoph Brepols编写，IWA出版）和《废水回用膜技术指南》（Mark Wilf组织编写，Balaban出版）。

此外，在生物处理技术和膜技术方面还有很多相关书籍，其中包含部分针对MBR的章节，但在此无法将这些书籍一一列出。其中最新的两本（均出版于2008年）分别为《废水生物处理原理、模型和设计》（Mogens Henze，Mark van Loosdrecht，George Ekama和Damir Brdjanovic编写，IWA出版）和《高级膜技术及应用》（Norman Li，Tony Fane，Winston Ho和Takeshi Matsuura编写，Wiley出版，2008）。但也有一些书籍试图采用比《膜生物反应器：水和污水处理的原理与应用》更全面的方式覆盖膜技术或生物处理。生物处理的教科书包括Metcalf和Eddy编写的权威之作：《污水工程——处理与回用》（George Tchobanoglous，Franklin Burton和David Stensel编写，McGraw Hill出版，2003），以及同样值得推荐的Leslie Grady，Glen Daigger和Nancy Love编写的《废水生物处理》（该书的第三版也于2010年由IWA出版）。

编者最初将《膜生物反应器：水和污水处理的原理与应用》第二版的撰写视为一项简单的工作，因为可以直接使用第一版的编写格式，只需要将内容由过去四五年更新至今即可。然而由于这几年间MBR市场发展迅速，编者向出版商提出的第二版比第一版内容不会超过30%的承诺最终被证实是过于保守的。在此期间，MBR膜产品的数量是第一版的两倍多，并且文中介绍的44种膜产品仅仅是主要产品。过去五年中，也建立了一些处理能力超过11万m^3/d（110MLD）的重要标志性处理设施。MBR方面的学术论文仍保持着较高的增

长速度——自 20 世纪 90 年代中期以来，均以每年约 20%的速率增长。正是这样的发展，使得第二版的总篇幅比第一版增加了约 45%。

与第一版相同，第二版仍采用将工程与理论分开的编写方式，尽量避免混淆。本书旨在提供尽可能多的实用信息，同时也涵盖理论与技术。全书分为五章，第 2 章介绍了膜技术和生物学原理，包括大部分学术研究成果；第 4 章对商业化 MBR 膜产品进行了总结；第 5 章则列举了这些膜产品在废水处理中的应用；我们对第 5 章的内容进行了汇编并用于第 3 章的设计部分。与第一版不同的是，第二版的第 1 章简要介绍了涉及 13 个国家的 MBR 市场现状及研究趋势。第 3 章则全部重新编写，以建立一个投资模型和投资收益分析方法，同时增加了运行与维护部分。因此第 3 章的内容较第一版更加详实，这一点得到了业内专家的肯定。章节间广泛的交叉引用（包括引用其他章节的图或表）使得整本书十分连贯。

本书最后附有符号说明、术语表和缩略词，其中与膜技术关系特别紧密的几项在附录 C 中作为商业化 MBR 膜组件详细说明中列出。由于某些术语和缩略词较其他词使用广泛，但并非全球通用，编者在此列出清单以避免读者混淆（见下表）。但 MBR 技术中用于描述膜构成的术语存在严重的不一致现象，特别是“组件”（见附录 C）和“污染”的用法等。这应该是由水环境联合会解决的问题。

术语	含义
常用单位	
MLD	兆升/天（千立方米/天）
LMH	L/（m^2 • h）（升/（平方米 • 小时））
Billion	十亿
工艺构型	
iMBR	浸没式（内置）MBR
sMBR	分置式（外置）MBR
a-l sMBR	气提分置式 MBR
an MBR	厌氧 MBR
膜构型	
FS	平板式（板框式、板式）
HF	中空纤维式
MT	多管式
膜污染	
可逆污染	可物理清洗去除，如反清洗或膜松弛

续表

术语	含义
不可逆污染	不可用物理方法去除，但可通过化学清洗去除
不可恢复性污染	不可去除
曝气	
SAD	比曝气量，与膜面积（SAD_m）或出水流量（SAD_p）有关

由于相关者范围广泛，出现术语、符号和缩略词不一致的情况是不可避免的。同样的，尽管尽了最大努力，文本中一些错误和遗漏之处仍在所难免，对此作者不承担责任。虽然我们已经尽可能地确保资料的准确与完整，但由于膜技术本身的复杂性，强烈建议有兴趣的读者在采用本书提供的资料前与相关人员就事实和数据进行核对。

在此向所有为本书编写做出贡献的人（超过 150 人）致以最诚挚的谢意，其中包括产品供应商、技术提供商、咨询顾问、承包商、最终用户和研究者。本书中绝大部分实际运行数据来源于技术提供商，但也有部分信息来自最终用户。所有信息提供者均在随后部分及每章的标题页中列出，十分感谢他们的友好帮助，特别是对作者所提很多细节问题的耐心解答。科研人员和学生也为本书的编写做出了贡献，他们主要来自英国克兰菲尔德大学。特别感谢水科学课题组的在读及刚刚毕业的学生，尤其是（按字母顺序排列）Harriet Fletcher，Wenjing Ma，Ignacio Martin，Ewan McAdam，Ana Santos 和 Bart Verrecht。同样感谢新南威尔士大学的 Pierre Le-Clech 对第 2 章膜污染行为部分的更新补充，感谢根特大学应用数学系、生物识别及过程控制系的许多工作人员对第 3 章建模部分的重大贡献。

也特别感谢专家小组成员：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），第 3 章中运行与维护一节的大部分内容是由他们的启发性评论组成的。我们也非常感谢 GE 公司的 Enrico Vonghia，其在 MBR 膜产品市场上渊博的知识对本书有很大帮助。

最后，我们鼓励读者参加现有的几个专注于膜生物反应器技术讨论的在线论坛中的一个（或更多），特别是由我们主办的 MBR 专题组。

我们的联系方式见下一部分，欢迎广大读者对本书提出宝贵意见和建议。

SJ and CJ

（陈福泰　译）

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

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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

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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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