A Multidisciplinary Introduction to Desalination

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A Multidisciplinary Introduction to Desalination

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Dedicated to our firstborn son, Iman, who is as old as this book.
You are God's precious gift, and our greatest venture.

Contents

Foreword I

Emilio Gabbrielli[1]

[1]President of the International Desalination Association (IDA)

It is always a great honor to be invited to write the Foreword to an ambitious volume like this one, but it is also a greater responsibility as it needs to set the scene for the reader, and has to be an inspiring piece. Having reflected on the task at hand, on the "what's" and "why's" of this book, I feel that the task of writing a foreword should not be hard at all, because desalination *is* itself inspiring. Desalination benefits mankind, and its importance in a world of increasing population can only increase. Let us see if you share my view.

Desalination is one of the oldest processes known to mankind and has been used since antiquity. Its practice based on simple evaporation followed by condensation became systematic with applications aboard ships with the advent of the trans-oceanic voyages of the Europeans in the XVI Century. In the second half of the XIX Century, several industrial manufactures appeared, and desalination units based on evaporation then started to be used on land all over the world.

Its use has kept growing since then, introducing technologies based on different principles, in particular reverse osmosis, to nearly 100 million m^3/day of installed capacity at the time I write this. This is a lot of fresh water, something like 20 times the average flow rate of the river Thames.

When looking at the well-known graph of installed capacity growth over the last 40 years, it is quite easy to notice that overall installed capacity was growing at a more or less constant rate until 1995. Its growth sped up dramatically through the start of the new millennium, until 2005, when growth once again continued at a rather constant rate, but this time twice as fast as in the period pre-1995.

The increase was definitely driven by the increased scarcity of fresh water resources everywhere, but what made it possible was the dramatic decline in the unit cost of desalination by reverse osmosis from 1995 to 2005. This occurred mainly thanks to the development of energy recovery devices, which

basically cut in half the energy needed to desalinate. The cost for desalting sea water fell to an average reference figure of 1 US$/m^3 all included. This is a value in many cases competitive or cheaper than treating traditional sources of poor quality water or transferring water from increasingly distant places to quench the thirst of ever increasing urban populations.

It means that in the new millennium, desalination has become a mainstream water supply alternative, and this includes reuse. As such, it should always be routinely considered in medium/long term planning of fresh water resources. The relevance of desalination technologies has also been enhanced by climate change, because it relies on a non-traditional, always available, water source like the sea, or effluent from waste water treatment plants in the case of reuse.

Although the availability of reliable fresh water supplies is crucial to society, many of the applications of desalination being considered today would have been simply economically and environmentally non-viable just 20 years ago, when the energy for producing fresh water with reverse osmosis was still 2 to 3 times the present value.

This is why the world has to be thankful to the Middle East, Northern Africa, the Caribbean and elsewhere, which took on the higher costs of desalination and adopted desalination on a large scale from the 1970s onwards. The early adopters in these regions showed the way, and allowed the further development and dramatic decline in the cost of the technology, making it affordable to other countries.

As a matter of fact, the application of desalination in more than three quarters of the world's countries shows that it has definitely become more widely affordable. In the coming years, it will become more and more part of normal water supplies around the world, both in potable and industrial water applications, and increasingly in agricultural applications as well.

The full potential and associated benefits of desalination have yet to be fully realized because there is still a misconception that desalination technologies are too expensive and not generally affordable. This cannot be surprising, as the lowering of unit costs happened so fast, in a decade or even less. Still, the reality is that desalination and reuse technologies are here to stay as crucial water supply alternatives and potential key contributors to sustainable growth and our planet's well-being. This realization is becoming more widespread and as a result, society and government officials around the world are recognizing its value more broadly.

With this backdrop, an ambitious volume like this one could not come at a more appropriate moment, when more and more people are becoming

interested and want to refer to the principles and features of desalination technologies. At the same time, one might ask for how long this book will remain up-to-date and a useful reference for those involved in desalination technology, given the speed with which scientific developments and advancements in technology occur.

In my view, the answer is easy: for a long time. The basic principles of desalination have not changed for centuries; even osmosis was already known in the XVIII Century. In terms of large installations, it is easy to forecast that RO will remain the primary desalination technology for a long time, with MED/MSF continuing their application in co-generation applications in the Middle East.

As this book proves, these technologies are all established, well understood and reliable. However, with the thirst of the world increasing and problems of scarcity widening, research for cheaper and more effective ways to desalt water is, and will continue, to increase.

In due course, a real breakthrough will happen and a much cheaper way to desalinate water will be found, possibly with some totally new technology: all of this for the best of the world. Mankind needs it! However, before any new way becomes commercially available and useful for large applications, several years will pass, probably decades, during which time the core content of this volume will remain an up-to-date reference to the mainstream technologies.

Moreover, a successful desalination project does not rely just on the plant and its economics; it has to rely on several associated technologies and chemistry fundamentals plus a cohesive approach to the social, political and environmental aspects, all of which are duly covered within the multidisciplinary approach that Dr. Bazargan has envisaged for this book. As no deeper understanding of the present can ever be reached without the perspective of where we are coming from, it is good that the origins of desalination are also given due attention.

It is increasingly evident that desalination and reuse will play a more and more important role in securing our future. Many have said and are still saying that future wars will be fought over water and not oil. In a world of increasing belligerent actions and words, the technologies covered by this volume are definitely going in the opposite direction of peaceful co-existence. This because their ultimate goal and potential is to guarantee plentiful affordable quantities of fresh water for all from non-traditional sources like the sea, which are practically unlimited.

Foreword II

Neil Palmer[1,2,3]

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[2]Former Chief Executive Officer, National Centre of Excellence in Desalination, Australia
[3]World's most influential water leader (2015), Water & Wastewater International

Water touches everyone.

This indispensable part of each of our lives, from intimate personal use to keeping our great industries running, is rarely appreciated until it becomes scarce. But the notion of water scarcity is a conundrum when we consider water covers seventy percent of our Earth's surface.

But almost all of it is salty.

So this monumental volume ***A Multidisciplinary Introduction to Desalination*** provides a scholarly and comprehensive starting point to the art and science of man's attempts to make fresh water from salt water.

But wait – doesn't ***all*** our fresh water come from natural desalination powered by renewable energy?

On 6 June 2016, the Australian Bureau of Meteorology recorded that more than 5 mm of rain had fallen on a third of the Australian continent the previous day, some 2 million square kilometres. 10,000 gigalitres were desalinated by natural evaporation of seawater from the warmth of the sun, transported by the wind and distributed evenly over a massive land area.

To obtain perspective, this is enough to supply the 4 million people who live in Sydney for 17 years. From one day's weather. There is much, it would seem, we can learn from the principles of nature.

This book explores desalination from its earliest history and delves into politics, economics, technology and practicalities. Desalination offers hope to those parts of the world where water is scarce or unreliable. From serious development of artificial desalination in the 1950s, people are working out how to emulate nature in supplying affordable and sustainable fresh water from our abundant impaired water sources. We have seen significant improvement of desalination techniques using new materials to separate salt from water and more efficient pre-treatment and pumping systems along with new ways of using energy from the wind, the sun and nuclear power.

This book contains sufficient easily readable detail to satisfy not only the engineers and scientists who research, design and build desalination infrastructure, but also students, community leaders and policy makers.

We have come 60 years since the first seriously large thermal desalination plants were built in the Caribbean and the Middle East, and the very first reverse osmosis membranes were produced.

Given the relentless pursuit of continuous improvement, we can only wonder with a sense of anticipation what the next 60 years will bring.

Preface

In the summer of 2015, Mark de Jongh, the man who would later become my publisher, posed a simple question: would I be interested in putting together a book on desalination? It was a simple-enough question, but for a person who doesn't commit to something unless he's sure he can do it right, I needed time to think. Although I had previously published my research in reputable academic journals, and had written a hefty dissertation during my PhD, this would undoubtedly be my biggest academic undertaking to date. Now, exactly two years and hundreds of hours of hard work later, I am glad I said yes.

This book, as its name implies, is aimed at giving an overall review of the entire desalination ecosystem; this means that in addition to the technological aspect which is an inseparable part of any introductory book on desalination, it also includes topics which more often than not are missing in our understanding of the bigger picture. Hence, in the process of choosing authors and chapter topics, I have methodically tried to include an assortment of what I think is relevant. The scope of topics covered in the book will hopefully allow for any reader to obtain a well-balanced understanding of what desalination is all about. I personally believe that the contributors have provided ample rich insight which allows this volume to effectively function as a textbook, both at the undergraduate and postgraduate levels. Of course, the list of chapters is not exhaustive, and there is always more that could have been said.

In the process of writing this book, I am proud to have met and collaborated with some of the world's most renowned experts. Most notably, I would like to thank Dr. Jim Birkett, who with his blessing and contribution of a chapter, really helped propel the project to a world-class undertaking. For newcomers to the field who might not know him, Jim is considered one of the desalination industry's most respected professionals, with more than four decades of experience under his belt. Most importantly, he was the first elected President of the International Desalination Association (IDA), and later served as Treasurer and Director for many years, helping shape the entire

modern desalination industry as we know it. As others have put it, he is the desalination industry's "de facto historian".

I would also like to take this opportunity to unreservedly thank two of the industry's giants who have written forewords for the book: Emilio Gabbrielli who is the current President of the IDA as well as the Director of Overseas Business Development for Toray; and Dr. Neil Palmer, the former CEO of the National Centre of Excellence in Desalination Australia, who was designated as the most influential leader in the water industry by Water & Wastewater International in 2015, and again a top candidate in 2017. It is truly an honor for me to have my work validated by these two gentlemen.

In addition, I wish to thank all the chapter authors who have kindly contributed to this book. I am proud of each and every one of their contributions, and say to them: "I am sorry if I pushed you too hard, but I'm sure you would agree that it has all paid off."

During these two years, I have personally reviewed all chapters several times and -with the help of external reviewers- have made the necessary modifications. Some chapters have gone through extensive editing and are indistinguishable from the original submitted manuscript, while others have remained virtually unchanged. I have tried to ensure both the scientific rigor and correctness of the language. As an example, the body of water located at the heart of the Middle East is referred to as the "Persian Gulf" as advised by the United Nations and the International Hydrographic Organization; and fabricated and false names such as the "Arabian Gulf" or merely "The Gulf" have been avoided.

It should also be noted that although as editor I am responsible for the factual correctness of the material within the book, but, the responsibility of proper citations and copyright issues are outside my domain of accountability, and lie with the respective chapter authors.

The list of external reviewers who have helped peer-review the chapters are as follows:

- Adil Bushnak
  Chairman and CEO of Bushnak Group, Jeddah, Saudi Arabia

- Steward Burn
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- Arun Subramani
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- Kim Choon Ng
  Environmental Science and Engineering Department, King Abdullah University of Science and Technology, Saudi Arabia

- Wang Meng
  College of Chemistry and Chemical Engineering, Ocean University of China, China

In the end, I would like to thank Noor Vijeh Company (NVCO), Iran's most reputable investor, designer, builder and operator of reverse osmosis desalination plants. With more PPP desalination projects than any other private company in Iran, NVCO was kind enough to provide me with the resources I needed to undertake this project, and collaborate with the acclaimed experts who have helped write this book.

Sincerely,

Dr. Alireza Bazargan
June 2017
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List of Abbreviations

AD	Adsorption Desalination
AGMD	Air Gap Membrane Distillation
AM	anion exchange membrane
AWWA	American Water Works Association
BOO	Build Own Operation
BOT	Build-Operate-Transfer
BW	Brackish Water
BWRO	Brackish water reverse osmosis
CA	Cellulose Acetate
CAPEX	Capital Expenditures
CCD	Closed-Circuit Desalination
CDI	Capacitive Deionization
CDR	Coefficient of Desalination Reality
CEM	Cation Exchange Membrane
CFD	Computational Fluid Dynamics
CG	Cogeneration
CHP	Combined-Heat and Power
CIP	Clean In Place
CM	cation exchange membrane
CNT	Carbon Nanotubes
CP	Concentration Polarization
CTA	Cellulose Triacetate
Da	Daltons
DAF	Dissolved air flotation
DAFF	Dissolved air flotation and filtration
DB	Design-Build
DBB	Design-Bid-Build
DBO	Design-Build-Operate
DCMD	Direct Contact Membrane Distillation
ED	Electrodialysis
ED(R)	Electrodialysis (Reversal)

EDI	Electrodeionization
EDL	Electrostatic Double Layer
EDR	Electrodialysis Reversal
EEA	European Environment Agency
ERD(s)	Energy Recovery Device(s)
ERTs	Energy Recovery Turbines
FO	Forward Osmosis
GAC	Granular activated carbon
GCC	Gulf Cooperation Council
GHG	Greenhouse Gas
GO	Graphene Oxide
HPP	High Pressure Pump
HTI	Hydration Technologies Inc.
IEM	Ion-Exchange Membrane
kDA	kiloDaltons
LC	Liquid Crystal
LEED	Leadership in Energy and Environmental Design
LSI	Langelier Saturation Index
(M)CDI	(Membrane) Capacitive Deionization
MD	Membrane Distillation
MDC	Microbial Desalination Cells
MED	Multi-Effect Distillation
MEMD	Multi-Effect Membrane Distillation
MENA	Middle East and North Africa
MF	Microfiltration
MGD	Million Gallons per Day
MGMD	Material Gap Membrane Distillation
MPD	m-phenylenediamine
MSF	Multi-Stage Flash
MVC	Mechanical Vapor Compression
MVD	Mechanical Vapor Distillation
MWCO	Molecular Weight Cut Off
Na-EDTA	Sodium Ethylenediaminetetraacetic acid
NDP	Net Driving Pressure
NF	Nanofiltration
NIPS	Non-solvent induced phase separation
NOM	Natural organic matter
NTU	Nephelometric turbidity units
O&M	Operational & Maintenance

OPEX	Operational & Maintenance Expenditures
P&F	Plate and frame
PA	Polyamide
PD	Positive Displacement
PEEK	poly(ether ether ketone)
PEI	polyethylene imine
PGMD	Permeate Gap Membrane Distillation
PRO	Pressure Retarded Osmosis
PSI	Pond per square inch
PTFE	polytetrafluoroethylene
PV	Photovoltaic
PVDF	polyvinylidene fluoride
PWR	Power to Water Ratio
RO	Reverse Osmosis
SDI	Silt Density Index
SEC	Specific Energy Consumption
SEM	Scanning Electron Microscope
SGMD	Sweep Gas Membrane Distillation
STPP	Sodium Tripolyphosphate
SW	Seawater
SWRO	Seawater Reverse Osmosis
TBT	Top Brine Temperature
TDS	Total Dissolved Solids
TFC	Thin Film Composite
TMC	trimesoyl chloride
TMP	Trans-membrane Pressure
TOC	Total organic carbon
TSS	Total suspended solids
TVC	Thermal Vapor Compression
UF	Ultrafiltration
VC	Vapor Compression
VMD	Vacuum Membrane Distillation
V-MEMD	Vacuum-Multi-Effect Membrane Distillation
WDR	Water Desalination Report
WWTP	Waste Water Treatment Plant