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NIKOLAY VOUTCHKOV

DESALINATION ENGINEERING

OPERATION AND MAINTENANCE

海水淡化工程：运行及维护

影印版



哈爾濱工業大學出版社
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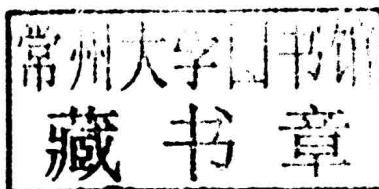
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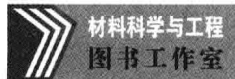
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Desalination Engineering

Operation and Maintenance

Nikolay Voutchkov



for the water quality professional

Water Environment Federation Alexandria, Virginia



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About the Author

Nikolay Voutchkov, PE, BCEE, is an internationally recognized expert in the field of membrane water and wastewater treatment with extensive experience in the development of seawater desalination projects. He is the president of Water Globe Consulting, LLC, which provides independent engineering advisory services to the desalination and water reuse industry. Mr. Voutchkov is an active member of the WaterReuse Association's Desalination Committee, the American Water Works Association's Desalination and Membrane Processes Committees, the American Membrane Technology Association, and the International Desalination Association. He is the author of *Desalination Engineering: Planning and Design*.

About WEF

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**To my dear wife Valentina, the woman of my life,
with genuine appreciation for her support, practical
advice, and inspiration**

Preface

Desalination, along with water reuse, is gaining popularity as an alternative water supply resource worldwide, as many municipalities and utilities are facing increasing population growth pressures, shortage of suitable local water resources, and more stringent water quality regulations. Over the past 30 years, desalination technology has made great strides in many arid regions of the world such as the Middle East and the Mediterranean. Today, over 15,000 desalination facilities operate in more than 120 countries worldwide. Countries such as Cyprus, Malta, Saudi Arabia, Oman, and the United Arab Emirates rely on desalinated water for more than 70 percent of their water supply.

At present, membrane reverse osmosis (RO) desalination is the fastest growing technology for the production of fresh water from saline water sources. Desalination plants use more energy and chemicals to produce the same volume of fresh water than conventional water supply technologies. Operation and maintenance of such plants are more complex and demanding in terms of professional skills, knowledge, and understanding of treatment processes, technologies, and equipment employed in the desalination processes. As the number of desalination plants worldwide increases at a near-exponential rate every year, the efficient and cost-effective operation and maintenance of desalination plants become critical for securing a long-term affordable, sustainable, and reliable water supply for many municipal urban centers around the world.

This book provides detailed practical information on the operation and maintenance of brackish and seawater RO desalination plants. The book's content covers practically all aspects of membrane desalination, from RO process fundamentals and water quality characterization to critical issues associated with the efficient operation, maintenance, and troubleshooting of key desalination plant components such as intake, pretreatment facilities, RO system, desalinated water post-treatment, and concentrate management. The book is also a comprehensive source of proven solutions for the troubleshooting of operational problems and performance challenges commonly encountered in RO membrane desalination plants worldwide. This book's content is complementary to a previous book, *Desalination Engineering: Planning and Design* (Voutchkov, 2012), which is a compendium of in-depth knowledge on planning, environmental review, and engineering of RO membrane desalination plants.

This book consists of eight chapters that follow the key treatment steps employed in typical brackish and seawater desalination plants. For each treatment step it includes essential knowledge, numerous practical tips, and rules of thumb for monitoring, operation, inspection, maintenance, and troubleshooting of critical processes and equipment. Moreover, this book describes practical methods and tools to diagnose plant performance challenges that have the greatest impact on fresh water production capacity and efficiency.

Chapter 1 contains background information on RO process fundamentals; readers are acquainted with the function of key components of typical desalination plants, as well as process and performance parameters used for the monitoring and control of the daily operation and maintenance of desalination facilities and equipment. This chapter focuses on source water quality characterization tailored to the needs of plant operators, which allows them to gain an in-depth understanding of how factors such as RO membrane fouling, scaling, and oxidation impact plant product water quality and quantity, energy use, membrane replacement frequency, and chemical demand. Chapter 1 also defines criteria for a well-operating plant, which are founded on a comprehensive critical analysis and evaluation of long-term operational data and practices of over 30 best-in-class RO desalination facilities worldwide built in the past decade. All other chapters are focused on RO desalination processes, equipment, and technologies as they apply to the sequential treatment of the saline source water.

Chapter 2 presents the purpose and function of open and subsurface intakes for saline water. This chapter addresses operational considerations for key open intake system components, including source water intake towers and conduits, intake screens, and pump stations. Chapter 2 presents detailed, step-by-step descriptions of innovative methods for intake pipe cleaning and maintenance. Practical directions are also given regarding intake source water quality monitoring, as well as troubleshooting of common problems associated with the operation of intake facilities. In addition, this chapter provides guidance for routine and preventive maintenance of subsurface intake wells and pumps. The issues discussed are well illustrated with photos, schematics, and examples from full-scale plants, and the recommended maintenance actions and troubleshooting solutions are presented in an easy-to-use table format.

Chapter 3 describes common practices for operation and maintenance of chemical conditioning systems employed for enhanced pretreatment of saline water. This chapter also discusses operational and maintenance aspects of dissolved air flotation, granular media filtration, and membrane ultrafiltration and microfiltration technologies. Source water conditioning technologies addressed in Chap. 3 include coagulation and flocculation, as well as the addition of scale inhibitors, biocides, acids, and sodium hydroxide. This chapter also provides best-in-class practices for routine operation, performance monitoring, and troubleshooting of single- and dual-stage granular media filters, dissolved air flotation and of commonly used membrane pretreatment technologies. Critical issues associated with the operation and replacement of cartridge filters are accompanied with examples of issues and solutions associated with their function, fouling, and performance. Similar to the previous chapter, key issues frequently encountered with the operation of granular media and membrane pretreatment systems and their diagnostics and troubleshooting are well illustrated, with examples from full-scale plants and presented in step-by-step guidelines in an easy-to-use table format.

Chapter 4 provides an overview of key RO system components, including filtered water transfer pumps, high-pressure feed pumps, high-pressure piping, spiral-wound RO membrane elements, and energy recovery systems. This chapter discusses widely used alternative approaches for RO system operation. Special attention is given to areas of application, advantages, and disadvantages of the most commonly used and innovative energy recovery devices, such as isobaric pressure exchangers. The main advantages and disadvantages of alternative operation strategies of RO systems are described and discussed, and practical recommendations are given to avoid common operational traps and problems. Chapter 4 also emphasizes commonly applied methods for RO system performance data collection and analysis, and offers systematic, step-by-step guidance for the use of the collected information to optimize plant operations. The chapter contains relevant information, practical examples, recommendations, and proven practices for RO membrane flushing, shutdown, and long-term preservation. Key criteria for membrane cleaning, rotation, and replacement are summarized in an easy-to-use format.

Chapter 5 presents and discusses typical RO system performance challenges such as permeate production below target flow rate, inadequate permeate water quality, excessive membrane cleaning frequency, and high energy use. For each typical RO system deficiency, the main causes are explained, discussed, and illustrated with relevant examples. Recommended operation and maintenance actions and troubleshooting solutions in this chapter are derived from comprehensive full-scale operational experience, and are given in table format. Chapter 5 also features state-of-the-art methods for diagnosing RO membrane integrity problems, fouling, and scaling issues. In addition, this chapter illustrates typical methods used for RO membrane autopsy, and is supplemented with photos and practical examples from full-scale desalination plants.

Chapter 6 presents typical operational and maintenance challenges associated with commonly used RO permeate remineralization technologies such as lime conditioning and calcite contact filtration. Proven efficient methods for process troubleshooting and optimization are described in a clear systematic manner to facilitate their practical implementation. Special attention is given to common challenges and deficiencies associated with the design and operation of lime and carbon dioxide post-treatment systems, which often present bottlenecks to meeting desalination plant product water quality specifications. This chapter also discusses disinfection issues and considerations specific to post-treatment of desalinated water.

Chapter 7 is dedicated to operation, maintenance, and water quality monitoring issues associated with the most commonly applied methods for concentrate management, with an emphasis on disposal to surface waters through new outfalls or discharge structures of existing wastewater treatment plants and power generation stations. The chapter emphasizes practical guidance for operation, maintenance, and troubleshooting of processes and equipment commonly applied for the treatment of spent pretreatment filter backwash and other nonconcentrate side streams, as well as for the handling of sludge produced as a result of desalination plant operations.

Chapter 8 provides practical considerations for routine inspection, maintenance, and troubleshooting of key equipment commonly used in desalination plants, such as pumps, air blowers, motors, valves, bearings, chemical feed systems, and automatic samplers. This chapter contains guidelines for inspection and preventive maintenance in an easy-to-use table format that identify key activities recommended for the preservation of the useful life of plant equipment and frequency of their implementation.

This book is intended for desalination plant operators and managers; water utility engineers; equipment, membrane, and chemical procurement staff; consulting engineers and designers; operation and troubleshooting specialists; and students and teachers in the desalination field. The book contains need-to-know operations and maintenance practices that would benefit practitioners, decision-makers, and scholars alike.

Reference

Voutchkov, N., *Desalination Engineering: Planning and Design*, McGraw-Hill, New York, 2012.

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Finally, a special note of appreciation to Mr. Wade Miller, executive director of the WateReuse Association, for his encouragement to write this book.

Nikolay Voutchkov

Abbreviations

ACP	Activated carbon powder
AOC	Assimilable organic carbon
AOM	Algogenic organic matter
A_{ro}	Total membrane surface area of one reverse osmosis (RO) element
ATD	Anti-telescoping device
ATP	Adénosine-5'-triphosphate
AWWA	American Water Works Association
B	Boron
Ba	Barium
BaSO ₄	Barium sulfate
BFR	Biofilm formation rate
BOD	Biological oxygen demand
Br	Bromide
BW	Backwash water volume
BWRO	Brackish water reverse osmosis
°C	Degree Celsius
Ca	Calcium
CaCO ₃	Calcium carbonate
CaSO ₄	Calcium sulfate
CEB	Chemically enhanced backwash
CFU	Colony-forming units
ClO ₂	Chlorine dioxide
CIP	Clean-in-place
CO ₂	Carbon dioxide
Cr	Chromium
CT	Core tube leaks (for membrane integrity)
Cu	Copper
d	Day

Da	Dalton, unit of weight
DAF	Dissolved air flotation
DBNPA	2,2-dibromo-3-nitrilopropionamide
DBP	Disinfection byproduct
DO	Dissolved oxygen
DOC	Dissolved organic carbon
DWEER	Dual work exchanger energy recovery
EC	Electrical conductivity
EDaX	Energy dispersive x-ray
EDTA	Ethylenediaminetetraacetic acid
EPA	Environmental Protection Agency
EPS	Extracellular polymeric substances
ERD	Energy recovery device
ERI	Energy Recovery International
F	Fluor
°F	Degree Fahrenheit
FeCl ₃	Ferric chloride
Fe(OH) ₃	Ferric hydroxide
Fe ₂ (SO ₄) ₃	Ferric sulfate
FI	Fouling indicator
F_p	Feed pressure
FRP	Fiberglass-reinforced plastic
ft	Foot
ft ²	Square foot
ft ³	Cubic foot
FTIR	Fourier transform infrared (spectroscopy)
gal/min	Gallons per minute
gfd	Gallons per square foot per day
gpm	Gallons per minute
GRP	Glass-reinforced plastic
GWA	Government of Western Australia
h	Hour
HAA	Haloacetic acid
HCl	Hydrochloric acid
HDPE	High-density polyethylene
Hg	Mercury
H ₂ S	Hydrogen sulfide
H ₃ PO ₄	Phosphoric acid

18 Abbreviations

hp	Horsepower
HTB	Hydraulic turbo booster
IDA	International Desalination Association
ISD	Interstage design
J	Membrane permeate flux
kg	Kilogram
km	Kilometer
L	Liter
lb	Pound
lb/in ²	Pound per square inch (psi)
Lmh	Liters per square meter per hour
LOEC	Lowest Observed Effect Concentration
LOET	Lowest Observed Effect Time
LSI	Langelier Saturation Index
m	Meter
m ²	Square meter
m ³	Cubic meter
m ³ /d	Cubic meter per day
MCF	Membrane compaction factor
meq	Milliequivalent
MF	Microfiltration
Mg	Magnesium
mg/L	Milligrams per liter
mgd	Million gallons per day
MgSO ₄	Magnesium sulfate
mi	Mile
min	Minute
mL	Milliliter
mm	Millimeter
Mn	Manganese
Mo	Molybdenum
MPN	Most probable number
mV	Millivolt
µg/L	Micrograms per liter
µm	Micrometer
µS/cm	Micro-Siemens per centimeter
N	Nitrogen
N_{epv}	Number of elements per RO vessel

N_t	Number of RO trains
N_{vpt}	Number of vessels per RO train
Na	Sodium
NaHSO_3	Sodium bisulfite
NaOH	Sodium hydroxide
$\text{Na}_2\text{S}_2\text{O}_4$	Sodium hydrosulfite
$\text{Na}_2\text{S}_2\text{O}_5$	Sodium metabisulfite
NDMA	<i>N</i> -nitrosodimethylamine
NDP	Net driving pressure
NF	Nanofiltration
Ni	Nickel
NL	No leaks (for membrane integrity)
NOEC	No Observed Effect Concentration
NOET	No Observed Effect Time
NOM	Natural organic matter
NPDES	National Pollutant Discharge Elimination System
NPF	Normalized permeate flow
NPSH	Net positive suction head
NTU	Nephelometric turbidity unit
O&M	Operation and maintenance
O_p	Average osmotic pressure
ORP	Oxidation-reduction potential
P	Phosphorus
PA	Polyamide
PACL	Polyaluminum chloride
P_d	Pressure drop
PE	Polyethylene
PES	Polyethersulfone
pH	Indication of acidity or basicity of solution
P_p	Permeate pressure
ppt	Part per thousand (1 ppt = 1,000 mg/L)
P_r	Permeate recovery rate
PREN	Pitting resistance equivalent number
psi	Pounds per square inch (unit of pressure, lb/in ²)
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl chloride
PVDF	Polyvinylidene difluoride
PVP	Polyvinylpyrrolidone

PX	Pressure exchanger
Q_{bw}	Daily volume of backwash water
Q_c	Daily volume of desalination plant concentrate
Q_f	Saline source water daily flow
Q_p	Volume of the plant fresh water production (daily permeate flow)
Q_s	Volume of the saline source water (daily flow)
R	Plant recovery
R_{new}	Resistance of new membranes
RO	Reverse osmosis
R_t	Membrane resistance after given time of operation
s	Second
S	Membrane area of an element
SBS	Sodium bisulfate
SCADA	Supervisory control and data acquisition
scfm	Standard cubic feet per minute
SEM	Scanning electron microscopy
SDI	Silt density index
SDSI	Stiff-Davis saturation index
Si	Silicon
SMP	Specific membrane permeability
SO_4	Sulfates
S_p	Salt passage
S_r	Salt rejection
Sr	Strontium
SWRO	Seawater reverse osmosis
SUVA	Specific ultraviolet (UV) absorbance
TCF	Temperature correction factor
TDS	Total dissolved solids
TDS_c	Concentrate salinity
TDS_f	Feed water salinity
TDS_p	Permeate salinity
THM	Trihalomethanes
Ti	Titanium
TMP	Transmembrane pressure
TN	Total nitrogen
TOC	Total organic carbon
TP	Total phosphorus
TSS	Total suspended solids

TUa	Acute toxicity
TUc	Chronic toxicity
UAE	United Arab Emirates
UC	Uniformity coefficient
UF	Ultrafiltration
U.S.	United States (of America)
U.S. EPA	United States Environmental Protection Agency
USBR	U.S. Bureau of Reclamation
UV	Ultraviolet irradiation
UV ₂₅₄	UV absorbance at 254 nm
VFD	Variable frequency drives
$V_{RO\ system}$	Volume of the RO system
WET	Whole effluent toxicity
WHO	World Health Organization
WWTP	Wastewater treatment plant
Y	Desalination plant recovery
yr	Year