

# HANDBOOK OF NATURAL GAS TRANSMISSION AND PROCESSING

PRINCIPLES AND PRACTICES

THIRD EDITION



SAEID MOKHATAB, WILLIAM A. POE, AND JOHN Y. MAK



# Handbook of Natural Gas Transmission and Processing

## Principles and Practices

### Third Edition

**Saeid Mokhatab**

Gas Processing Consultant, Canada

**William A. Poe**

Senior Principal Technical Consultant,  
Schneider Electric, USA

**John Y. Mak**

Technical Director and Senior Fellow, Fluor, USA



AMSTERDAM • BOSTON • CAMBRIDGE • HEIDELBERG  
LONDON • NEW YORK • OXFORD • PARIS • SAN DIEGO  
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO  
Gulf Professional Publishing is an imprint of Elsevier



Gulf Professional Publishing is an imprint of Elsevier  
225 Wyman Street, Waltham, MA 02451, USA  
The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, UK

Copyright © 2015 Elsevier Inc. All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: [www.elsevier.com/permissions](http://www.elsevier.com/permissions).

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

### Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

### British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

### Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress

ISBN: 978-0-12-801499-8

For information on all Gulf Professional Publishing  
visit our website at <http://store.elsevier.com/>



Working together  
to grow libraries in  
developing countries

[www.elsevier.com](http://www.elsevier.com) • [www.bookaid.org](http://www.bookaid.org)

# Handbook of Natural Gas Transmission and Processing

# Disclaimer

This book is intended to be a learning tool. The materials discussed in this book are presented solely for educational purposes and are not intended to constitute design specifications or gas plant operating procedures. While every effort has been made to present current and accurate information, the authors assume no liability whatsoever for any loss or damage resulting from using them.

All rights reserved. This book is sold subject to the condition that it shall not by way of trade or otherwise be resold, lent, hired out, stored in a retrieval system, reproduced or translated into a machine language, or otherwise circulated in any form of binding or cover, other than that in which it is published, without the prior written permission of the authors and without a similar requirement including these conditions being imposed on the subsequent purchaser.

*This book is dedicated to all professionals that preceded us; researchers, scientists, engineers, operators, and educators in the natural gas industry, who inspire us to assemble their knowledge and experience, manifesting this book that is much needed in today's changing landscape of natural gas.*

With contribution by

**Wim Van Wassenhove**

AspenTech, Belgium

Author of Chapter 15,

Dynamic Simulation of Gas Processing Plants

# About the Authors

**Saeid Mokhatab** is one of the most recognizable names in the natural gas community through his contributions to advancing the technologies in the natural gas processing industry. He has worked in a variety of senior technical and managerial positions with major petroleum companies and has been actively involved in several large-scale gas-field development projects, concentrating on design, precommissioning, and start-up of processing plants. He has presented numerous invited lectures on gas processing technologies, and has authored or coauthored over 200 technical publications including two well-known Elsevier's handbooks, which are considered by many as major references to be taken into account for any gas processing/LNG project in development. He founded the world's first peer-reviewed journal devoted to the natural gas science and engineering (published by Elsevier, the United States); has held editorial positions in many scientific journals/book publishing companies for the hydrocarbon processing industry; and served as a member of technical committees for a number of professional societies and famous gas-processing conferences worldwide. As a result of his outstanding work in the natural gas industry, he has received a number of international awards/medals including the Einstein Gold Medal of Honor and Kapitsa Gold Medal of Honor; and his biography has been listed in highly prestigious directories.

**William A. "Bill" Poe** is a Senior Principal Technical Consultant at the Invensys Division of Schneider Electric, the United States. He has over 30 years of international business and industrial experience in design, operations, and project management of gas processing plants with a special focus on automation, multivariable predictive control (MPC), advanced process control (APC), optimization design and implementation, and real-time performance monitoring. Bill started his career at Shell Oil Company, the United States, in 1981, working over a decade in natural gas processing plants operations and engineering as well as management of multimillion-dollar projects. In 1993, he joined Continental Controls to lead the process engineering department in support of executing contracts with the Gas Research Institute, the United States, where he developed new multivariable control applications in the natural gas industry. After joining GE as part of the Continental Controls acquisition, he became vice president of this division of GE where his responsibilities included direction of product development, projects, technical sales support, and customer service for multivariable control and optimization applications in the natural gas industry. In 2001, Bill joined Invensys Process Systems, the United States, where he has developed APC and Optimization Master Plans for international companies such as Saudi Aramco, ADNOC, Statoil, and PDVSA, as well as automation and advanced process control feasibility studies for over 100 natural gas processing plants



worldwide. Bill is an Associate Editor of the *Journal of Natural Gas Science and Engineering*, has authored or coauthored more than 50 technical papers, and made numerous technical presentations at prestigious international conferences. He received the GE Innovators Award in 1999 and attained the Invensys Circle of Excellence in 2011.

**John Y. Mak** is a Senior Fellow and Technical Director at Fluor, the United States, and leads the technology and design development for the chemical and energy sectors at Fluor. He has been with Fluor for over 40 years and has been leading domestic and global oil and gas and refinery projects from conceptual design, feasibility study, FEED and detailed engineering to plant start-up and operation. John has made significant contributions to the technologies in natural gas treating, NGL recovery, LNG liquefaction and regasification, coal gasification, and carbon capture. He is the coauthor of the *Handbook of Liquefied Natural Gas*—first edition (2013) published by Elsevier, the United States, and has presented over 60 technical papers at the GPA (Gas Processors Association) and LRGCC (Laurance Reid Gas Conditioning Conference), China Coal Forum, and other technical conferences. John is the inventor of over 80 patent and patent-pending processes, which have been used in projects at Fluor. His patented technologies have been proven to improve energy efficiency, lower emissions, and reduce cost for many of his clients. John's current focus is on liquid recovery for shale gas projects and treating of the difficult gases, such as the high-carbon dioxide and nitrogen content gases for offshore projects.

# Foreword

Natural gas is an environment friendly, clean-burning fuel, offering important environmental benefits compared to other fossil fuels. It is also a remarkably safe source of energy when transported, stored, and used. The emergence of natural gas in the global markets further underscores the importance of gas transmission and processing. In this regard, it is fitting that technical books covering these subjects become required reading for technical specialists and project planners. While several books exist for natural gas upstream engineering, the literature has lacked a comprehensive book that captures the midstream and downstream sectors of the natural-gas value chain. This book provides well-organized, theoretical, and technical background knowledge on natural gas transmission and processing; and covers subject areas missed by other books in these areas. Because the authors have extensive experience in the design and operation of natural gas processing plants throughout the world, this book has attempted to concentrate upon what they perceive to be modern and proven practices. To keep things interesting for the experts, they have included some of the latest innovations and developments reported in the recent published works, although some material also reflects their own research involvement in problems related to natural gas transmission and processing. In summary, this book is a major contribution to the professional literature and will serve as a valuable desk reference for scientists, researchers, and engineers working in the upstream, midstream, and downstream sectors of natural gas industry. Literature references for in-depth study enhance the reference aspect of this comprehensive work. The organization of materials also permits flexibility in designing courses in the gas processing field for university students in chemical/petroleum engineering curricula.

Professor Kenneth R. Hall, PhD.,  
Jack E. and Frances Brown, Chair and Professor, Department of Chemical  
Engineering, Texas A&M University, College Station, TX, USA;  
Associate Dean, Research and Graduate Studies,  
Texas A&M University at Qatar, Doha, Qatar.

# Preface to the Third Edition

Many interesting and exciting developments in the natural gas industry have occurred since the publication of the second edition in 2012 that make it necessary to revise portions of the book and include additional materials that are becoming important in the gas processing industry. This realization has led us to embark on updating our work to make it a more complete, refreshed, and comprehensive reference for all major aspects of natural gas transmission and processing. The operating practices and guidelines for the gas processing units have been added and updated where we feel they are relevant. In this respect, we hope that the basic contents are useful as introductory materials in the chemical and petroleum engineering fields and the more detailed description of design and operation are useful for the engineers and plant operators.

The preparation of a book that covers such a broad subject requires many sources of information. There are many contributors of technical materials and we gratefully acknowledge our indebtedness to all of the individuals who contributed to the development of this book. An invaluable contribution to this edition is the insight by experts in their specialties and applications. Special thanks are due to friends and colleagues, who encouraged, assessed, and made this book possible. Among them are Dr Louis Mattar and Dr Mehran Pooladi-Darvish of the Fekete Associates Inc., Canada, who prepared the section on “Natural Gas Exploration and Production” in Chapter 1. We also appreciate Mr Cris Heijckers of Kranji Solutions Pte Ltd, Singapore, for preparing a section on “Practical Design of Separation Systems” in Chapter 4. We deeply acknowledge the greatest help of Dr Rainer Kurz of Solar Turbines Inc., the United States, in updating Chapter 11. We thank Mr Sidney P. Santos of At Work Rio Engineering and Consulting Ltd, Brazil, for his constructive comments and suggestions on Chapter 12. We also express our sincere thanks to Professor Kenneth R. Hall of the Texas A&M University, the United States, who accepted to write its foreword. Finally, we appreciate the editorial staff members of Elsevier who have been an excellent source of strong support during the preparation and publication of this book.

We know that this handbook required updating to reflect the current state of the art in the changing landscape of natural gas processing. In order to meet this requirement, the authors have endeavored to assemble the best available knowledge and expertise to make this work as current as possible, but by no means is this work perfect. The accelerated delivery of information contained in this handbook is important as we all desire to make use of the latest technology for a greener and safer environment through the effective use of natural gas. Our ultimate mission is to continuously follow progress in this exciting industry and

add innovations as well as expanded topics in future editions of this handbook while retaining the basic fundamental and practical materials already available in this edition.

**Saeid Mokhatab**  
**William A. Poe**  
**John Y. Mak**

# Endorsements for the Third Edition

*This handbook is a valuable reference that covers all aspects of the natural gas transmission and processing industries. It contains much needed design, operation and optimization information, all in a single source and does an excellent job of highlighting the key considerations for any gas processing project, as well as providing innovative solutions in natural gas liquids recovery and treating high nitrogen and carbon dioxide content gases in unconventional gas plants. It is a key addition to any gas processing professional's library.*

**Jason Kraynek, Vice President of Business Transformation & Innovations,  
Fluor, USA.**

*This well-balanced handbook is the only book of its kind, covering all aspects of natural gas transmission and processing in more details. I believe it will serve as a valuable desk reference for practicing gas engineers and technologists, and as a text for graduate students in the gas engineering curriculum.*

**Dr J.C. Kuo, Senior Advisor of Gas Team, Process Engineering, Chevron ETC, USA.**

*This high quality, comprehensive book gives an accurate picture of where the natural gas transmission and processing industry stands today, and describes some relatively new technologies that could become important in the future. I recommend this book for any professional gas processing engineer and technologist.*

**David Messersmith, Bechtel Fellow and Manager of LNG Technology  
and Services Group, Bechtel OG&C, USA.**

*This is the only book that covers all technical and operational aspects of natural gas transmission and processing as well as subject areas missed by other similar references. I recommend that if you work in the natural gas industry, you have this unique reference available.*

**Dr Jaleel V. Valappil, Manager, Advanced Simulation/Process,  
Bechtel OG&C, USA.**

*This is a valuable handbook to both the experienced engineer and the graduate just commencing in natural gas engineering. It provides practical advice for design and operation based on sound engineering principles and established techniques as well as introducing process solutions based on new and emerging technologies.*

**Adrian Finn, Manager of Process Technology, Costain Natural Resources, UK.**

*This book does an excellent job of describing the fundamental handling of natural gas from the wellhead to the consumer. I particularly found the*

*segment on natural gas liquids recovery most informative. I plan to make this very informative publication available to my employees as an excellent training tool as well.*

**Randy Johnson, Operations Manager, LNG, Energy Transfer, USA.**

*Must have book for anyone in the Gas Processing Industry. The authors did an incredible job at covering the process dynamics and introducing control theories for optimal operation. Absolutely enjoyed the descriptive nature of the chapters without compromising technical details.*

**Cesar A. Felizzola, Process Control Engineer, South Region Engineering,  
DCP Midstream, USA.**

*This comprehensive book provides in-depth coverage of all technical aspects of natural gas transmission and processing, beyond those addressed in other books. This is a "must addition" to library of anyone working in the midstream and downstream sectors of natural gas utilization to achieve higher career goals. I commend the authors' continuous effort to make it an excellent source book for all professionals, engineers, and scientists in the natural gas industry.*

**Dr Suresh C. Sharma, ONEOK Chair Professor and Director of Natural Gas  
Engineering and Management, University of Oklahoma, USA.**

*This comprehensive book provides a state-of-the-art treatment of the different aspects of natural gas transmission and processing from the fundamental principles to the latest technology developments. It is a unique reference for all professionals involved in natural gas industry and an excellent textbook for graduate programs on the subject.*

**Dr Valerio Cozzani, Professor of Chemical Engineering and Director of Post-  
Graduate Program on Oil & Gas Process Design, University of Bologna, Italy.**

*This unique handbook, written by internationally renowned gas-engineering experts, is a major contribution to the professional and scholarly literature, offering an excellent coverage of key topics in the natural gas supply chain. It addresses the principles, practices, advanced technologies, new issues and challenges related to the natural gas transmission and processing industry, which have not been addressed in depth in any existing books. I recommend it highly, as a reference and textbook.*

**Dr Brian F. Towler, Professor and Chair of Petroleum Engineering,  
University of Queensland, Australia.**

# Contents

About the Authors .....	xxiii
Foreword .....	xxv
Preface to the Third Edition .....	xxvii
Endorsements for the Third Edition .....	xxix

<b>CHAPTER 1</b>	<b>Natural Gas Fundamentals .....</b>	<b>1</b>
1.1	Introduction .....	1
1.2	Natural gas history .....	1
1.3	Natural gas origin and sources .....	2
1.4	Natural gas composition and classification .....	3
1.5	Natural gas phase behavior .....	4
1.6	Natural gas properties .....	6
1.6.1	Chemical and physical properties .....	6
1.6.2	Thermodynamic properties .....	15
1.7	Natural gas reserves .....	16
1.8	Natural gas exploration and production .....	16
1.8.1	Conventional gas .....	17
1.8.2	Unconventional gas .....	20
1.8.3	Well deliverability .....	22
1.9	Natural gas transportation .....	24
1.9.1	Pipelines .....	25
1.9.2	Liquefied natural gas .....	25
1.9.3	Compressed natural gas .....	26
1.9.4	Gas-to-liquids .....	27
1.9.5	Gas-to-solid .....	28
1.9.6	Gas-to-wire .....	29
1.9.7	Comparison of various methods .....	30
1.10	Natural gas processing .....	33
1.11	Sales gas transmission .....	33
1.12	Underground gas storage .....	33
1.12.1	Depleted reservoirs .....	34
1.12.2	Aquifers .....	34
1.12.3	Salt caverns .....	34
	References .....	35
<b>CHAPTER 2</b>	<b>Raw Gas Transmission .....</b>	<b>37</b>
2.1	Introduction .....	37
2.2	Multiphase flow terminology .....	37

2.2.1	Superficial velocity .....	38
2.2.2	Mixture velocity .....	38
2.2.3	Holdup .....	38
2.2.4	Phase velocity .....	39
2.2.5	Slip .....	39
2.2.6	Mixture density .....	40
2.2.7	Mixture viscosity .....	40
2.2.8	Mixture pressure drop .....	41
2.2.9	Mixture enthalpy .....	41
<b>2.3</b>	<b>Multiphase flow regimes .....</b>	<b>42</b>
2.3.1	Two-phase flow regimes .....	42
2.3.2	Three-phase flow regimes .....	48
2.3.3	Gas-condensate flow regimes .....	49
<b>2.4</b>	<b>Determining multiphase flow design parameters .....</b>	<b>49</b>
2.4.1	Steady-state two-phase flow .....	50
2.4.2	Steady-state three-phase flow .....	56
2.4.3	Transient multiphase flow .....	57
2.4.4	Multiphase gas and condensate flow .....	59
<b>2.5</b>	<b>Predicting temperature profile of multiphase pipeline .....</b>	<b>60</b>
<b>2.6</b>	<b>Velocity criteria for sizing multiphase pipelines .....</b>	<b>64</b>
<b>2.7</b>	<b>Multiphase pipeline operations .....</b>	<b>65</b>
2.7.1	Leak detection .....	65
2.7.2	Pipeline depressurization .....	66
2.7.3	Pigging .....	66
<b>2.8</b>	<b>Multiphase flow assurance .....</b>	<b>68</b>
2.8.1	Gas hydrates .....	68
2.8.2	Corrosion .....	86
2.8.3	Wax .....	90
2.8.4	Slugging .....	102
2.8.5	Flow assurance risk management .....	111
	References .....	114

<b>CHAPTER 3</b>	<b>Basic Concepts of Natural Gas Processing .....</b>	<b>123</b>
<b>3.1</b>	<b>Introduction .....</b>	<b>123</b>
<b>3.2</b>	<b>Natural gas processing objectives .....</b>	<b>123</b>
<b>3.3</b>	<b>Gas processing plant configurations .....</b>	<b>124</b>
3.3.1	Gas plant with hydrocarbon dewpointing .....	125
3.3.2	Gas plant for NGL production .....	128
<b>3.4</b>	<b>Finding the best gas processing route .....</b>	<b>131</b>
<b>3.5</b>	<b>Support systems .....</b>	<b>132</b>
3.5.1	Utility and off-site .....	132
3.5.2	Process control .....	132
3.5.3	Safety systems .....	133



3.6	Contractual agreements .....	133
3.6.1	Keep-whole contracts .....	134
3.6.2	Flat fees contracts .....	134
3.6.3	Percentage of proceeds contracts .....	134
3.6.4	Processing fee contracts .....	135
	References .....	135
<b>CHAPTER 4</b>	<b>Phase Separation .....</b>	<b>137</b>
4.1	Introduction .....	137
4.2	Gravity separators .....	137
4.2.1	General description .....	138
4.2.2	Separator selection .....	140
4.2.3	Gravity separation theory .....	142
4.2.4	Design considerations .....	144
4.3	Multistage separation .....	145
4.4	Centrifugal separators .....	145
4.5	Twister supersonic separator .....	146
4.6	Slug catchers .....	148
4.7	High-efficiency liquid/gas coalescers .....	150
4.7.1	Aerosols .....	150
4.7.2	Coalescer construction/operation principles .....	151
4.7.3	Modeling the liquid/gas coalescer .....	154
4.7.4	Coalescer performance/operational limits .....	157
4.7.5	Liquid/gas coalescer applications .....	157
4.8	High-efficiency liquid-liquid coalescers .....	157
4.8.1	Emulsions .....	157
4.8.2	Coalescer principles and materials of construction .....	158
4.8.3	Coalescer mechanism of operation .....	158
4.8.4	Liquid-liquid coalescer performance .....	161
4.8.5	Limitations of using coalescers .....	162
4.8.6	Applications .....	162
4.9	Practical design of separation systems .....	162
	References .....	165
<b>CHAPTER 5</b>	<b>Condensate Production .....</b>	<b>169</b>
5.1	Introduction .....	169
5.2	Condensate stabilization .....	170
5.2.1	Stabilization by cascade flash separation .....	170
5.2.2	Stabilization by distillation .....	171
5.2.3	Design considerations .....	173
5.2.4	Operating problems .....	174
5.3	Condensate hydrotreating .....	174
5.4	Effluent treatment .....	176