

INDUSTRIAL BURNERS

H A N D B O O K

INDUSTRIAL COMBUSTION SERIES

Edited by Charles E. Baukal, Jr.

PUBLISHED TITLES

Computational Fluid Dynamics in Industrial Combustion

Charles E. Baukal, Jr., Vladimir Y. Gershtein, and Xianming Li

Heat Transfer in Industrial Combustion

Charles E. Baukal, Jr.

The Industrial Combustion Handbook

Charles E. Baukal, Jr.

The John Zink Combustion Handbook

Charles E. Baukal, Jr.

Oxygen-Enhanced Combustion

Charles E. Baukal, Jr.

INDUSTRIAL BURNERS

H A N D B O O K

E D I T E D B Y

CHARLES E. BAUKAL, JR.



CRC PRESS

Boca Raton London New York Washington, D.C.

Library of Congress Cataloging-in-Publication Data

Industrial burners handbook / edited by Charles E. Baukal, Jr.

p. cm.

Includes bibliographical references and index.

ISBN 0-8493-1386-4 (alk. paper)

1. Heating—Equipment and supplies—Handbooks, manuals, etc. 2. Combustion engineering—Handbook, manuals, etc. I. Baukal, Charles E.

TJ254.5.I517 2003

621.402'3—dc21

2003051466

This book contains information obtained from authentic and highly regarded sources. Reprinted material is quoted with permission, and sources are indicated. A wide variety of references are listed. Reasonable efforts have been made to publish reliable data and information, but the author and the publisher cannot assume responsibility for the validity of all materials or for the consequences of their use.

Neither this book nor any part may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, microfilming, and recording, or by any information storage or retrieval system, without prior permission in writing from the publisher.

All rights reserved. Authorization to photocopy items for internal or personal use, or the personal or internal use of specific clients, may be granted by CRC Press LLC, provided that \$1.50 per page photocopied is paid directly to Copyright clearance Center, 222 Rosewood Drive, Danvers, MA 01923 USA. The fee code for users of the Transactional Reporting Service is ISBN 0-8493-1386-4/04/\$0.00+\$1.50. The fee is subject to change without notice. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

The consent of CRC Press LLC does not extend to copying for general distribution, for promotion, for creating new works, or for resale. Specific permission must be obtained in writing from CRC Press LLC for such copying.

Direct all inquiries to CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation, without intent to infringe.

Visit the CRC Press Web site at www.crcpress.com

© 2004 by CRC Press LLC

No claim to original U.S. Government works

International Standard Book Number 0-8493-1386-4

Library of Congress Card Number 2003051466

Printed in the United States of America 1 2 3 4 5 6 7 8 9 0

Printed on acid-free paper

Preface

This book focuses specifically on industrial burners. This book should be of interest to anyone working in or with the field of industrial combustion. This includes burner designers, researchers, end users, furnace designers, government regulators, and funding agencies. It can also serve as a reference work for those teaching and studying combustion. The book covers a wide range of burner designs used in a broad array of applications in the metals, minerals, incineration, hydrocarbon/petrochemical, and power generation industries. The authors represent a number of prominent burner suppliers and have hundreds of years of combined experience with industrial burners.

The book is organized in three sections. Section I deals with the basics of combustion in industrial applications. It includes five general chapters on heat transfer, fluid flow, combustion, and computer modeling. These chapters are written from the narrow scope of how they apply to burners. Section II concerns burner fundamentals. It includes five chapters on the topics of burner heat transfer, burner noise, burner controls, burner testing, and burner physical modeling. Section III deals with 11 specific burner designs, including chapters on high-velocity burners, regenerative burners, thermal radiation burners, radiant tube burners, radiant wall burners, natural-draft burners, boiler burners for single-burner applications, boiler burners for multi-burner applications, duct burners, air-oxy/fuel burners, and oxy/fuel burners.

There are very few books that consider burners used in industrial applications. Combustion textbooks contain little if anything on practical combustion equipment such as burners. There are several books that consider industrial burners in differing levels of detail. The *North American Combustion Handbook* (two volumes: Vol. 1, 3rd edition, 1986; Vol. 2, 3rd edition, 1997; published by North American Manufacturing Co.) has been the industry standard since the 1950s and discusses many aspects of practical combustion systems, including burners. However, it does not go into much detail on burners, nor does it cover the range of burner types that are considered here. Another book that is longer in print, but considers industrial burners, is entitled *Combustion Engineering and Gas Utilization* (3rd edition, E&FN Spon, 1992, edited by J.R. Conforth, and sponsored by British Gas in the U.K.). It has two detailed and generously illustrated chapters on burners, but specifically focuses on natural gas applications. The Industrial Heating Equipment Association (IHEA) is comprised of most of the U.S. industrial burner manufacturers. The IHEA publishes a book entitled *Combustion Technology Manual* (5th edition, IHEA, 1994), which contains several brief chapters on industrial burners.

As with any book of this type, there are some topics that are not covered and some that are not treated extensively. Because the vast majority of industrial applications use gaseous fuels, that is the focus of this book, with limited discussion of liquid fuels and no discussion of solid fuels. This book concerns atmospheric-pressure combustion, which is the predominant type used in industry. There are some burner designs that are not considered, particularly those intended for narrow and limited applications.

As with any book of this type, there are sure to be author preferences and biases, but the coverage is fairly extensive and comprehensive. There are also generous discussions of many common industrial applications to help the reader better understand the requirements for different burner designs. Particularly because of the increasing emphasis on the environment, the design of most industrial burners continues to change and improve to reduce pollutant emissions. While industrial burner design and development is a dynamic area of continuing research, the principles considered here are expected to be applicable well into the foreseeable future.

About the Editor

Charles E. Baukal, Jr., Ph.D., P.E., is the Director of the R&D Test Center, the John Zink Institute, and Burner and Flare R&D for the John Zink Co., LLC (Tulsa, OK) which is a leading supplier of industrial combustion equipment in the chemical, petrochemical, and power generation industries. He previously worked for 13 years at Air Products and Chemicals, Inc. (Allentown, PA) in the areas of oxygen-enhanced combustion and rapid gas quenching in the ferrous and nonferrous metals, minerals, and waste incineration industries. He has also worked for Marsden, Inc. (Pennsauken, NJ) in the paper, printing, and textile industries and Selas Corp. (Dresher, PA) in the metals industry, both in the area of industrial combustion equipment. He has more than 20 years of experience in the fields of industrial combustion, pollution, and heat transfer and has authored more than 70 publications in those areas. He is the editor of the books *Oxygen-Enhanced Combustion*, *Computational Fluid Dynamics in Industrial Combustion*, and *The John Zink Combustion Handbook*, the author of the book *Heat Transfer in Industrial Combustion*, and the general editor of the *Industrial Combustion* series, all with CRC Press (Boca Raton, FL).

He has a Ph.D. in mechanical engineering from the University of Pennsylvania (Philadelphia), a B.S. and M.S. in mechanical engineering from Drexel University (Philadelphia), an M.A. in Biblical Studies from Dallas Theological Studies (Dallas, TX), and is working on an M.B.A. from the University of Tulsa (Tulsa, OK). He is a licensed Professional Engineer in the state of Pennsylvania, a certified Diplomate Environmental Engineer (DEE), and a Qualified Environmental Professional (QEP). He has been an adjunct instructor at several colleges, is an expert witness in the field of combustion, has nine U.S. patents, and is a member of several *Who's Who* compilations. He is a member of the American Society of Mechanical Engineers, the Air and Waste Management Association, the Combustion Institute, the American Society of Safety Engineers, and several honor societies.

Acknowledgments

Chuck Baukal would like to thank his wife Beth and his daughters Christine, Caitlyn, and Courtney for their patience and help during the writing of this book. He would also like to thank the good Lord above, without whom this would not have been possible.

Joe Colannino dedicates his work to Jesus the Christ, his wife Judy, and their three children, F. Christian, Nathanael J., and Jamie D.

Tom Eldredge would like to express thanks to his wife Nancy, who always encourages him to be the best he can be. Additionally, he is thankful to his Lord and Savior, Jesus Christ, for every good gift, and for his vocation as a mechanical engineer.

Abraham Lincoln once said “Everything I am,... I owe to my angel mother.” Joseph Smith would like to gratefully acknowledge his family, friends, and associates for the part they have had in shaping his life. He expresses his thanks to Dr. Chuck Baukal for his encouragement and example in taking time to contribute to the scientific literature, and to the publisher for supporting this effort. Lastly, he expresses deepest gratitude to his wife, Eileen, and his children. They have made life worth living!

Rémi Tsiava thanks Olivier Charon, his former manager who was the first contact for this work. Special thanks to Bernard Labégorre who is the major pusher to perform this work. Also thanks to Bernard Zamuner and Bertrand Leroux for data collection.

Lev Tsirulnikov would like to dedicate his work to the memory of his teachers in low-NO_x combustion and boiler fields — J.B. Zeldovich, V.V. Pomerantsev, N.V. Koznetsov, and A.D. Garbanenko.

Timothy Webster would like to thank his wife Sharon for all her love, support, and encouragement.

Contributors

Bruce B. Abe is a Combustion and Process Control Specialist at The North American Manufacturing Company, Ltd., Cleveland, OH, where he has worked with combustion controls for 30 years in an engineering and sales/marketing capacity. He is a frequent lecturer on combustion controls at North American Combustion and Controls Seminars and at the Industrial Heating Equipment Association's annual Safety Standards Seminar for Industrial Furnaces and Ovens.

Wes Bussman, Ph.D., is a Senior Development Engineer at the John Zink Company, LLC (Tulsa, OK). He has more than 10 years of experience as a research and product development engineer for the company, and has a Ph.D. in mechanical engineering from the University of Tulsa. He holds five U.S. patents, and has authored several publications. He has taught undergraduate courses in mechanical engineering at the University of Tulsa. Honors include Kappa Mu Epsilon Mathematical Society and Sigma Xi Research Society.

Michael G. Claxton is a Senior Principal Engineer in the Burner Process Engineering Group of the John Zink Company, LLC (Tulsa, OK). He has a B.S. in Mechanical Engineering from the University of Tulsa and has worked for the John Zink Co. in the field of industrial burners and combustion equipment since 1974. He has co-authored a number papers and presentations covering combustion, combustion equipment, and combustion-generated emissions, and is co-holder of several combustion-related patents.

Joseph Colannino, P.E., is the Director of Engineering and Design at the John Zink Company, LLC (Tulsa, OK) and a chemical engineer. He has more than 15 years of experience in the combustion arts and over 20 publications to his credit. He is listed in *Who's Who in Science and Engineering* and *Who's Who in California*. Joseph is a member of the American Chemical Society (ACS) and the American Statistical Association (ASA).

Tom Eldredge, Ph.D., currently works as a combustion and modeling engineer at the John Zink Company, and is involved in both computational and physical fluid flow modeling of burners and boiler components. He previously worked for more than 5 years at the Lehigh University Energy Research Center. He has worked on optimizing combustion on coal and natural gas fired boilers over the past 9 years. He worked on a project team as a primary developer of software for combustion optimization of coal-fired boilers. He is well experienced in computational fluids modeling as well as physical fluids modeling. He has a number of publications related to modeling of power plant components, power plant emissions reductions, and performance improvements. He holds a Ph.D. in mechanical engineering from the University of Tennessee, and is a member of the American Society of Mechanical Engineers and The Combustion Institute.

Mahmoud Fleifil, Ph.D., is the Acoustics Engineer of John Zink Company, LLC (Tulsa, OK). He has a Ph.D. in mechanical engineering from a co-supervisory program between Ain Shams University and MIT. His areas of expertise are fluid dynamics, combustion instability, and noise control. He has more than 20 publications on Active Control of Combustion Instability in *IEEE*, *Combustion Science and Technology*, and *Combustion and Flame* journals. He is listed in *Who's Who in America*, *Who's Who in Science and Engineering*, *Lexington Who's Who*, and *The National Aviation and Space Exploration Wall of Honor*. He is a member of the ASME and AIAA.

Joe Gifford is a Senior Engineer, Instrumentation and Control Systems, at the John Zink Company, LLC (Tulsa, OK). He has worked in the field of control and facilities design for 40 years and has a B.S. in physics. For many years he has conducted company training classes for control engineers and technicians. He has received numerous awards for innovative control system designs throughout his career, including the General Electric Nuclear Energy Division's Outstanding Engineering Award. Technical society memberships have included the Pacific Association of General

Electric Scientists and Engineers (PAGESE), the Instrument Society of America (ISA), the American Society of Mechanical Engineers (ASME), and the National Fire Protection Association (NFPA).

John P. Guarco is the Combustion Specialist for the TODD Combustion Group of John Zink Company. He joined John Zink in September of 1993 as a utility project engineer. In 1995, he added the role of R&D Engineer to his portfolio. In 1998, he assumed the responsibility of heading up TODD's physical modeling effort, focusing on streamlining the modeling process, while generating new opportunities for business and product development. John has authored papers on several combustion topics, including field results of low-NO_x combustion in several utility boilers, ultra-low emission burners, field results of gas-coal co-firing, physical modeling, and other NO_x reduction techniques for boilers. He is also one of the contributing authors of *The John Zink Combustion Handbook*. John received both a bachelor's and master's degree in mechanical engineering from the University of Connecticut, as well as an MBA from the University of New Haven.

R. Robert Hayes is a combustion engineer at the John Zink Company LLC (Tulsa, OK). He holds a Master's degree in mechanical engineering from Brigham Young University and has worked in the fields of combustion and thermal sciences for 7 years. He is the author or co-author of more than ten publications in the fields of combustion and heat transfer and two patents pending.

Eric M. Hixson joined the CD adapco group in January 2003 as an engineer of CDa-access, a wholly owned subsidiary of adapco. Before joining CD adapco, Hixson worked as a CFD engineer for the John Zink Company (Tulsa, OK).

Jaiwant D. Jayakaran (Jay Karan) is a director in the Technology & Commercial Development Group at the John Zink Company LLC (Tulsa, OK). He has worked in the fields of combustion, petrochemicals, and power for 17 years, with responsibilities in R&D, plant operations, and engineering. Jay has an M.S. in mechanical engineering from Texas Tech University. He has authored several technical articles and papers, and has several patents pending.

Hisashi (Sho) Kobayashi, Ph.D., is a Corporate Fellow at Praxair, Inc. (Danbury, CT). He has developed oxygen combustion systems and processes for glass, steel, aluminum, petrochemical, power plant, and other industries for 27 years, and has authored or co-authored more than 40 U.S. patents and over 50 technical papers. He has a B.S. in aeronautical engineering from the University of Tokyo and M.S. and Ph.D. degrees in mechanical engineering from the Massachusetts Institute of Technology.

Zachary Kodesh, P.E., is a controls engineer at John Zink Company (Tulsa, OK). He has more than 12 years of experience as a process design and controls engineer. He has a Master's degree in mechanical engineering from Oklahoma State University.

Russ Lang is a project manager at The North American Manufacturing Company, Ltd., Cleveland, OH. He has an associate's degree in mechanical technology from Cuyahoga Community College. At North American since 1978, he has worked in project and systems engineering and management, with regenerative burner systems as a specialty. He is co-holder of several combustion-related patents.

Jeff Lewallen, P.E., is an account manager at the John Zink Company LLC (Tulsa, OK). He has worked in the field of combustion for 11 years. He graduated from the University of Tulsa in 1992 and holds a B.S. in mechanical engineering.

Michael Lorra, Ph.D., started working for John Zink Co. LLC as a CFD engineer in 1999 after finishing his Ph.D. (Dr.-Ing.) at Ruhr-Universitaet (Bochum, Germany). He worked at Gaswaerme-Institut (Essen, Germany), a well-known and established research facility, for 9 years. He gained experience in NO_x reduction techniques, especially reburning technology. During his time at Gaswaerme Institut, he developed his own CFD code for the calculation of turbulent reacting flows including chemistry with the laminar flamelet-libraries. Parts of his research have been presented at international conferences and are published in *Gaswaerme-International*.

Clive Lucas is a product manager at The North American Manufacturing Company, Ltd., Cleveland, OH. He has a B.S. in mechanical engineering from Cleveland State University and has worked for North American in the field of industrial burners and combustion systems since 1994,

with specific responsibility for the company's direct-fired regenerative burner line. He is co-holder of a patent for a diaphragm-actuated cycle valve.

Todd A. Miller is a research and design engineer at The North American Manufacturing Company, Ltd., Cleveland, OH. He has a B.S. in mechanical engineering technology from Cleveland State University and has worked for North American on burner product design and development since 1983. He is co-holder of several combustion-related patents.

John Newby is Vice President for The North American Manufacturing Company, Ltd., Cleveland, OH. His career spans over 35 years in the industrial combustion field, where he has worked in all major industrial areas of the world. Formerly the managing director of Hotwork Development Ltd. in England, he operated reGen Systems Inc. in the U.S. until 1986 when he joined North American. He has authored and co-authored numerous papers and presentations on combustion equipment, systems, and applications, and is co-holder of several combustion-related patents.

Dennis E. Quinn is manager of market development at The North American Manufacturing Company, Ltd., Cleveland, OH. For over 20 years he has worked in various development, engineering, and design capacities with lead responsibilities for custom burner designs and their applications. He has co-authored papers and presentations for the Industrial Heating Equipment Association and is co-holder of several combustion-related patents. He is a graduate of Cleveland State University's Fenn College of Engineering and has a B.S. in mechanical engineering and combustion application.

Tom Robertson is manager of research and development at The North American Manufacturing Company, Ltd., Cleveland, OH, where he has, for over 18 years, worked in the field of fundamental and applied combustion. He has co-authored papers and taught classes in applied combustion technology at North American Manufacturing and the Center for Professional Advancement. He is a graduate of Case Western Reserve University and has a B.S. and an M.S. in fluid and thermal science, and is co-holder of several combustion-related patents.

Joseph D. Smith joined the CD adapco group in January 2003 as president of CDa-acces, a wholly owned subsidiary of adapco. CDa-acces' main goal is to establish StarCD, adapco's CFD-based engineering software, as the premier tool to help solve problems with turbulent reacting flow systems unique to the hydrocarbon and chemical process industries. Joseph's expertise includes CFD, waste incineration, pulverized-coal combustion/gasification, fumed metal-oxides production, and gas flaring, all with a special emphasis on reaction engineering. Before joining CD adapco, Joseph worked as director of flare technology and computational fluid dynamics for the John Zink Company. He has taught at Tennessee Technological University, the University of Michigan, and the University of Illinois-Urbana/Champaign. He currently serves as an adjunct professor and teaches at Oklahoma State University and the University of Tulsa. Joseph has also consulted for The Dow Chemical Company, Destec Energy Systems, Southern Company Services, and several others. He holds six patents, and has authored more than 30 published articles and more than 40 conference papers. He is an active member of AIChE and has served as chair of both the Tulsa and Mid-Michigan Sections of AIChE. He has also served as national chair of the Student Chapters Committee. He is also a member of Sigma-Xi and Tau Beta Pi. He received B.S., M.S., and Ph.D. degrees in chemical engineering from Brigham Young University.

Thomas M. Smith is the President and CEO of Marsden, Inc., a leading manufacturer of high-efficiency, zero-pollution gas thermal radiation emitters. He studied mechanical/industrial engineering at the Drexel Institute of Technology (Philadelphia, PA) and business management at Rutgers University (Camden, NJ). He worked at TRW, Philco-Ford, and HRB Singer as an industrial engineer and senior industrial engineer over a 10-year period before joining a manufacturers representative firm as a sales engineer. He first became a business owner when he purchased the manufacturers' representative firm in 1972. In 1976, he applied for the first of over 50 granted U.S.A. and foreign Letters Patent on various embodiments of gas thermal radiation emitters. He formed Marsden, Inc. in 1976 to manufacture and market worldwide the unique Marsden Infrared equipment. Mr. Smith has taught national TAPPI courses and has had articles published in various technical journals and magazines.

Stephen L. Somers is a senior process engineer at the John Zink Company, LLC (Tulsa, OK). He has over 30 years of experience in combustion and process design, with the past 15 years in the application and design of duct burners for HRSG supplementary firing. He has an M.S. in chemical engineering from the University of Oklahoma and a B.S. in chemical engineering from the University of Tulsa.

Rémi Tsiava, Ph.D., is an engineer at Air Liquide (France) in the R&D Combustion Division and is responsible for burner conception, design, and development. He has expertise in combustion and industrial processes. He previously worked as an engineer in the Burner Division of the Stein Heurtey Company. He has a Ph.D. from Université Paul Sabatier (Toulouse, France), and has published papers on the use of oxy/fuel combustion in the glass and metals industries.

Lev Tsirulnikov, Ph.D., is a senior research engineer for the John Zink Company, LLC/Todd Combustion Group (Shelton, CT). He has developed low-emission combustion technologies, low-NO_x burners, and other equipment for gas/oil fired utility and industrial boilers. He holds 49 patents in the combustion/boiler field, and has published more than 100 technical papers, including four books. He is also a contributing author to *The John Zink Combustion Handbook*.

Demetris Venizelos, Ph.D., has been actively involved in the combustion field for the last sixteen years, including working for two burner companies, John Zink Company, LLC and Zeeco, Inc. He received his Ph.D. in mechanical engineering from Louisiana State University. Dr. Venizelos has conducted basic scientific research work, industrial technology research and development, and combustion design engineering. He has experience in premixed and lean-premixed combustion, industrial combustion systems, and laser and optical combustion diagnostics, as well as numerical modeling. He has authored several peer-reviewed technical papers, government technical reports, technical articles, and patent applications.

Richard T. Waibel, Ph.D., is a Senior Principal Engineer in the Burner Process Engineering Group at the John Zink Company, LLC (Tulsa, OK). He works in the field of burner design and development and has a doctorate in fuel science from the Pennsylvania State University. He has published over 70 technical papers, publications, and presentations. Dr. Waibel has been the Chairman of the American Flame Research Committee since 1995.

Timothy Webster is the director of power systems at the John Zink Company, LLC. He has worked in the field of industrial combustion for 10 years and is a licensed professional mechanical engineer in California. He holds a B.S. degree in mechanical engineering from San Jose State University and a Master of Engineering degree from the University of Wisconsin. He has authored more than 20 publications on combustion and emissions reduction.

Table of Contents

Section I

Industrial Combustion Basics

Chapter 1 Introduction

Charles E. Baukal, Jr., Ph.D., P.E.

Chapter 2 Heat Transfer

Charles E. Baukal, Jr., Ph.D., P.E.

Chapter 3 Fluid Flow

*Wes Bussman, Ph.D., Demetris Venizelos, Ph.D.,
and R. Robert Hayes*

Chapter 4 Combustion Basics

Joseph Colannino, P.E.

Chapter 5 CFD in Burner Development

*Joseph D. Smith, Michael Lorra, Ph.D., Eric M. Hixson,
and Tom Eldredge, Ph.D.*

Section II

Burner Fundamentals

Chapter 6 Heat Transfer from Burners

Charles E. Baukal, Jr., Ph.D., P.E.

Chapter 7 Burner Noise

*Mahmoud Fleifil, Ph.D., Jay Karan,
and Wes Bussman, Ph.D.*

Chapter 8 Combustion Controls

Joe Gifford and Zachary Kodesh, P.E.

Chapter 9 Burner Testing

Jeffrey Lewallen, P.E. and Charles E. Baukal, Jr., Ph.D., P.E.

Chapter 10 Burner Physical Modeling

John P. Guarco and Tom Eldredge, Ph.D.

Section III Burner Designs

Chapter 11 High-Velocity Burners

Tom Robertson, Todd A. Miller, and John Newby

Chapter 12 Regenerative Burners

Russ Lang, Bruce B. Abe, Clive Lucas, and John Newby

Chapter 13 Thermal Radiation Burners

Thomas M. Smith and Charles E. Baukal, Jr., Ph.D., P.E.

Chapter 14 Radiant Tube Burners

Dennis E. Quinn and John Newby

Chapter 15 Radiant Wall Burners

Demetris Venizelos, Ph.D., R. Robert Hayes, and Wes Bussman, Ph.D.

Chapter 16 Natural-Draft Burners

Charles E. Baukal, Jr., Ph.D., P.E.

Chapter 17 Burners for Industrial Boilers

Lev Tsirulnikov, Ph.D., John Guarco, and Timothy Webster

Chapter 18 Multi-Burner Boiler Applications

Lev Tsirulnikov, Ph.D., John Guarco, and Timothy Webster

Chapter 19 Duct Burners

Stephen L. Somers

Chapter 20 Air-Oxy/Fuel Burners

Charles E. Baukal, Jr., Ph.D., P.E.

Chapter 21 Oxy-Fuel Burners

Hisashi Kobayashi, Ph.D. and Rémi Tsiava, Ph.D.

Section IV

Appendices

Appendix A Common Conversions

Appendix B Design Data

Appendix C Material Properties