

Green Energy and Technology

More information about this series at <http://www.springer.com/series/8059>

Medhat A. Nemitallah ·
Mohamed A. Habib · Hassan M. Badr

Oxyfuel Combustion for Clean Energy Applications

 Springer

Medhat A. Nemitallah
TIC in CCS and Mechanical
Engineering Department
King Fahd University of Petroleum
and Minerals
Dhahran, Saudi Arabia

Mohamed A. Habib
TIC in CCS and Mechanical
Engineering Department
King Fahd University of Petroleum
and Minerals
Dhahran, Saudi Arabia

Hassan M. Badr
TIC in CCS and Mechanical
Engineering Department
King Fahd University of Petroleum
and Minerals
Dhahran, Saudi Arabia

ISSN 1865-3529

ISSN 1865-3537 (electronic)

Green Energy and Technology

ISBN 978-3-030-10587-7

ISBN 978-3-030-10588-4 (eBook)

<https://doi.org/10.1007/978-3-030-10588-4>

Library of Congress Control Number: 2018965458

© Springer Nature Switzerland AG 2019, corrected publication 2019

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

The problem of global warming is becoming one of the most important problems facing mankind because of its direct effect on the entire planet (coastal flooding, heat waves, rainfalls, wildfires, food production, and many others). The emission of greenhouse gases resulting from the burning of fossil fuels has been identified as the main cause of current climatic changes. Currently, about 80% of the global energy demand comes from the burning of fossil fuel, resulting in the emission of a huge amount of CO₂ to the atmosphere. Also, the burning of coal, natural gas, and oil for electricity and heat is the largest single source of global greenhouse gas emissions. Researchers and scientists are currently striving to find different means for tackling this problem either by increasing the efficiency of all equipment involved in the processes of energy production or energy consumption. Also, increasing the utilization of clean energy sources such as solar energy, hydroelectric power, and geothermal energy represents another way to reduce CO₂ emissions. The third option is to achieve clean combustion through the modification of various combustion processes in order to enable carbon capture and its utilization in other industries or its sequestration in underground aquifers.

This book is intended to be a basic reference for graduate students, practicing engineers, and young researchers in the area of clean combustion. The motivation for writing this book originates from the current international thrust for reducing greenhouse gas emission to the atmosphere for the sake of reducing global warming. As a result, very many industries worldwide start modifying their existing processes/equipment to comply with the Paris Agreement (Paris Climate Conference, December 2015) adopted by 195 countries. Accordingly, it becomes essential for engineers and scientists to develop green combustion systems that are friendly to the environment. Currently, gas turbines used for power generation, boilers used for steam generation, and cogeneration plants are the largest sources of greenhouse gas emissions. This book contains an extensive review of different carbon capture methodologies associated with fuel combustion. Novel approaches for clean combustion are introduced including design and performance analysis of burners. The feasibilities of different combustion technologies are also presented and discussed. Special emphasis is given to basic formulation of various

combustion processes and computational modeling of conventional combustors together with applications to gas turbines and boilers supported by numerical results and detailed discussions for a number of case studies.

This book consists of six chapters: The first chapter is an overview of the greenhouse gas emission problem and brief presentation of the current carbon capture and sequestration technologies. The second chapter introduces oxy-fuel combustion technologies with emphasis on system efficiency, combustion and emission characteristics, applications, and related challenges. The third chapter focuses on the recent developments in ion transport membranes and their performance in oxygen separation units and oxygen transport reactors. The fourth chapter presents novel approaches for clean combustion in gas turbines. The fifth chapter presents the computational modeling and optimization of combustion in gas turbine combustors with some numerical results and detailed analyses. The sixth chapter presents the replacement of conventional combustion systems by oxygen transport reactors of distinctive designs together with applications in gas turbine combustors and furnaces of fire tube boilers.

The authors wish to acknowledge the support received from King Fahd University of Petroleum & Minerals under Grant # BW171005 for the preparation of this book.

Dhahran, Saudi Arabia

Medhat A. Nemitallah
Mohamed A. Habib
Hassan M. Badr

The original version of the book was revised: Incorrect grant number has been corrected. The correction to the book is available at https://doi.org/10.1007/978-3-030-10588-4_7

Contents

1	Introduction	1
1.1	Global Warming	1
1.2	Carbon Budget for the 2 °C Limit	2
1.3	Status of Renewable Energies	3
1.3.1	Market and Industry Trends	5
1.3.2	Renewables for Global Warming Control	7
1.4	Carbon Capture and Storage (CCS) Techniques and Limitations	9
1.4.1	Carbon Capture Technologies	9
1.4.2	Carbon Storage Techniques	18
1.4.3	Carbon Utilization Techniques	20
1.5	Bio-energy with CCS (BECCS) for Negative CO ₂ Emissions	22
1.5.1	Concept of BECCS	23
1.5.2	Status of BECCS	23
1.6	Approaches for Oxy-fuel Combustion Technology	23
1.6.1	Conventional Combustion Systems	24
1.6.2	Oxygen Transport Reactors (OTRs)	25
1.7	Why Oxy-combustion	26
1.8	Oxy-combustion in Gas Turbines	27
1.8.1	Required System Modifications	27
1.8.2	Gas Turbine Performance Under Oxy-combustion	28
1.8.3	Combustion and Emission Characteristics	29
1.8.4	Flame Stability	30
1.9	Conclusions	32
	References	33
2	Application of Oxy-fuel Combustion Technology into Conventional Combustors	43
2.1	Introduction	43
2.2	Oxy-fuel Combustion Characteristics	46

2.2.1	Reactions and Emission Characteristics	46
2.2.2	Oxy-combustion Systems	48
2.3	Oxy-combustion Alternatives	49
2.3.1	Using Air Separation Unit and Conventional Combustion Chamber	50
2.3.2	Using Membrane Reactor Technology	57
2.4	Oxy-fuel Combustion in Conventional Combustion Systems	58
2.4.1	Gaseous Fuel Operation	58
2.4.2	Liquid Fuel Operation	64
2.4.3	Coal Fuel Operation	68
2.4.4	Recent Advances and Technology Readiness Level (TRL)	73
2.5	Trends of Oxy-combustion Technology	75
2.5.1	Oxy-combustion Integrated Power Plants	75
2.5.2	Third-Generation Technologies for CO ₂ Capture	78
2.6	Conclusions	80
	References	80
3	Ion Transport Membranes (ITMs) for Oxygen Separation	91
3.1	Introduction	91
3.2	Oxygen Separation Membranes	93
3.3	Gaseous Oxy-fuel Combustion in OTRs	98
3.4	Trending Applications of OTR Technology	100
3.4.1	OTRs for Syngas Production	100
3.4.2	Combustion Utilizing Liquid Fuels in OTRs	104
3.4.3	Membranes for Splitting H ₂ O to Produce H ₂	106
3.4.4	Membranes for CO ₂ Utilization	113
3.5	Conclusions	121
	References	122
4	Novel Approaches for Clean Combustion in Gas Turbines	133
4.1	Introduction	133
4.2	Adaptation of Gas Turbines to Regulations of Pollutant Emissions	136
4.2.1	Emission Regulatory Overview	136
4.3	Types of Flame	138
4.3.1	Non-premixed/Premixed Flames	138
4.3.2	MILD/Flameless Combustion	140
4.3.3	Colorless Distributed Combustion (CDC)	143
4.3.4	Low-Swirl Injector (LSI) Combustion	144
4.4	Burner Design	147
4.4.1	Swirl-Stabilized Burners	147
4.4.2	DLN/DLE Burners	151
4.4.3	Catalytic Combustion	155

4.4.4	Perforated Plate Burners	156
4.4.5	Environmental EV/SEV/AEV Burners	158
4.4.6	Micromixer Burners	161
4.5	Fuel Flexibility	164
4.5.1	Effects of Fuel Flexibility on Gas Turbine Operation	165
4.5.2	H ₂ -Enriched Premixed Combustion	166
4.5.3	Concerns on Fuel Flexibility	166
4.6	Oxidizer Flexibility	168
4.6.1	Oxy-fuel Combustion	168
4.7	Other Routes for NO _x Formation and Treatment	174
4.8	Parallel Development of Combustor Liner Materials	175
4.9	Feasibility of Different Combustion Technologies and Future Challenges	176
4.10	Conclusions	179
	References	180
5	Modeling of Combustion in Gas Turbines	193
5.1	Introduction	193
5.2	General Conservation Equations	196
5.3	Modeling of Turbulent Reacting Flows	197
5.3.1	Modeling Non-premixed Turbulent Combustion	198
5.3.2	Modeling Turbulent Premixed Combustion	200
5.4	Modeling of Radiation	229
5.4.1	Simple Gray Gas (SGG) Model	230
5.4.2	Exponential Wideband Model (EWBM)	231
5.4.3	Leckner Model	232
5.4.4	Perry Model	234
5.4.5	Weighted-Sum-of-Gray-Gas (WSGG) Model	234
5.5	Modeling Species Transport	235
5.6	Modeling Reaction Kinetics	237
5.6.1	Chemistry Reduction/Acceleration Techniques	237
5.6.2	Modified Two-Step Model for Oxy-combustion of Methane	240
5.6.3	Modified JL Mechanism for Oxy-combustion of H ₂ -Enriched Methane	242
5.7	H ₂ -Enriched Methane Oxy-combustion in a Model Gas Turbine Combustor: A Case Study	243
5.7.1	Boundary Conditions and Solution Technique	243
5.7.2	Results and Discussions	245

5.8	Investigation of a Turbulent Premixed Combustion Flame in a Backward-Facing Step Combustor; Effect of Equivalence Ratio: A Case Study	256
5.8.1	Operating and Boundary Conditions	256
5.8.2	LES Model	260
5.8.3	Combustion Modeling Technique	260
5.8.4	Results and Discussions	261
5.9	Conclusions	270
	References	271
6	Applications of OTRs in Gas Turbines and Boilers	275
6.1	Introduction	275
6.2	Development of Oxygen Permeation Model	277
6.2.1	Concept of Operation of Ceramic-Based Membranes	278
6.2.2	Oxygen Transport Mechanism	279
6.2.3	Oxygen Permeation with Chemical Reactions	284
6.3	CFD Modeling of OTR	288
6.4	Modeling of Reaction Kinetics and Radiation	290
6.5	Integration of OTRs with Conventional Combustors for ZEPP Applications	292
6.6	Application of OTR into Gas Turbine Combustor	293
6.6.1	Monolith Structure Design OTR for Replacement of a Gas Turbine Combustor	293
6.6.2	Design of a Multi-can Carbon-Free Gas Turbine Combustor Utilizing Multiple Shell-and-Tube OTRs for ZEPP Applications	312
6.7	Application of OTR into Fire Tube Boilers	339
6.7.1	Reactor Features and Boundary Conditions	340
6.7.2	Methodology of the Numerical Solution	342
6.7.3	Model Validation	344
6.7.4	OTR Design for Boiler Furnace Substitution	346
6.7.5	Operation Under Co-current Flow Configuration	348
6.7.6	Operation Under Counter-Current Flow Configuration	352
6.7.7	Influence of Fuel Concentration	359
6.8	Conclusions	362
	References	363
	Correction to: Oxyfuel Combustion for Clean Energy Applications	C1