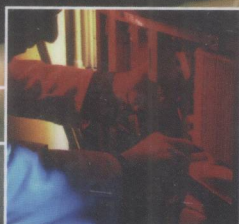


Colleen S. Spiegel



Designing & Building Fuel Cells



TN1911.4
S755

Designing and Building Fuel Cells

Colleen Spiegel



E2008001224

**Mc
Graw
Hill**

New York Chicago San Francisco Lisbon London Madrid
Mexico City Milan New Delhi San Juan Seoul
Singapore Sydney Toronto

Library of Congress Cataloging-in-Publication Data

Spiegel, Colleen.

Designing and building fuel cells / Colleen Spiegel.—1st ed.
p. cm.

ISBN 0-07-148977-0 (alk. paper)

1. Fuel cells—Design and construction. I. Title.

TK2931.S65 2007

621.31'2429—dc22

2007007508

McGraw-Hill books are available at special quantity discounts to use as premiums and sales promotions, or for use in corporate training programs. For more information, please write to the Director of Special Sales, Professional Publishing, McGraw-Hill, Two Penn Plaza, New York, NY 10121-2298. Or contact your local bookstore.

Designing and Building Fuel Cells

Copyright © 2007 by The McGraw-Hill Companies. All rights reserved. Printed in the United States of America. Except as permitted under the Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a database or retrieval system, without the prior written permission of publisher.

1 2 3 4 5 6 7 8 9 0 DOC DOC 0 1 9 8 7

ISBN-13: 978-0-07-148977-5

ISBN-10: 0-07-148977-0

Sponsoring Editors

Kenneth P. McCoombs

Larry Hagar

Editorial Supervisor

Jody McKenzie

Project Manager

Vastavikta Sharma, International
Typesetting and Composition

Acquisitions Coordinator

Laura Hahn

Copy Editor

Michael McGee

Proofreader

Mona Mehra

Indexer

Steve Ingle

Production Supervisor

George Anderson

Composition

International Typesetting and
Composition

Illustration

International Typesetting and
Composition

Art Director, Cover

Jeff Weeks

Cover Designer

Libby Pisacreta

Information has been obtained by McGraw-Hill from sources believed to be reliable. However, because of the possibility of human or mechanical error by our sources, McGraw-Hill, or others, McGraw-Hill does not guarantee the accuracy, adequacy, or completeness of any information and is not responsible for any errors or omissions or the results obtained from the use of such information.

*To my husband, Brian,
who inspires me to be a better person every day,
encourages me to pursue all of my dreams,
and has the patience and endurance to stand by me
while I work at them.*

*To my unborn son, Howard,
who had to endure endless sleepless nights with me
while completing this book.*

ABOUT THE AUTHOR

Colleen S. Spiegel is the founder of Clean Fuel Cell Energy, LLC. She has been an R&D manager and chemical engineer for more than seven years, and has expertise in the areas of fuel cell design and modeling. Ms. Spiegel is a member of the American Institute of Chemical Engineers (AIChE) and the Institute of Electrical & Electronic Engineers (IEEE).

Foreword

The creation and consumption of energy is a necessity in today's world. It has drastically increased the quality of life of modern society and has allowed the rapid advancement of modern technology. The majority of energy required to power our homes, offices, and automobiles is created from fossil fuels, and though they are essential to our society, use of fossil fuels has also resulted in increased health risks and global warming. Their diminishing supply is also causing international tension and contributing to high inflation. Thankfully, fuel cell technology has the potential to meet the energy needs of our ever-growing population, resolve many of the conflicts fossil fuels are causing, and will accomplish these goals in an environmentally friendly way.

During the last decade, fuel cells have been researched and developed more quickly than at any time since their discovery in 1839. Interest in them has increased tremendously as international tensions have intensified due to increasing fossil fuel prices, the scarcity of fossil fuels, the power of countries with national fossil fuel resources, and the threat of global warming. The study of fuel cells crosses many academic disciplines, such as mechanical, chemical, environmental, and electrical engineering, as well as chemistry and material science. The writing of this book was motivated by the need to have a practical, informational fuel cell reference that could aid someone who has never built a fuel cell before, yet provide enough theory to help accurately design a state-of-the-art fuel cell.

The primary audience of this textbook is professional engineers and scientists who need an all-encompassing fuel cell guide. It is also intended for the professional or student who wants to design and build commercial-grade fuel cells; therefore, it incorporates a unique balance of theory, practical knowledge, and design. This book is also meant to be an engineering or science text, and it includes examples and problems

to help students bridge the gap between the various interdisciplinary sciences needed to accurately design and build fuel cells.

The text is organized into 17 chapters. The first four chapters provide an overview of fuel cell technology, types, applications, and offers a peek at the coming hydrogen economy. The first chapter describes the basics of fuel cells and compares them with batteries and heat engines, outlining fuel cell markets, and the history and fundamentals of how fuel cells work. Chapter 2 describes fuel cells and the hydrogen economy. It compares hydrogen with other fuel types, and describes how the hydrogen economy can be developed. Hydrogen production, storage, and distribution are discussed, as well as those countries working on building a hydrogen economy. Chapter 3 describes different fuel cell types. It also explores a few fuel cell types sometimes not considered fuel cells, or that are in mostly the R&D stage. Chapter 4 discusses the main applications of commercial and R&D fuel cells such as portable power, backup power, transportation, and stationary power applications.

Chapters 5 through 9 provide an introduction to the necessary science involved in predicting fuel cell performance. Chapter 5 covers basic fuel cell thermodynamics and demonstrates the calculation of theoretical fuel cell voltage, theoretical fuel cell efficiency, fuel cell temperature, and pressure. Chapter 6 describes the basics of fuel cell electrochemistry and introduces electrode kinetics, voltage losses, internal and crossover currents, and improved kinetic performance. Chapter 7 explores fuel cell charge transport especially in fuel cell electrolytes, while Chapter 8 covers fuel cell mass transport and specifically discusses diffusive transport in fuel cell electrodes, convective transport in flow channels, and concentration polarization. Chapter 9 is devoted to heat transfer, and covers the topics of energy balance, heat conduction, active heat removal, stack heat dissipation, and stack cooling options. Chapter 10 describes fuel cell modeling and uses the concepts outlined in Chapters 5 through 9 to model the fuel cell layers.

Chapters 11 through 14 discuss the basic materials and plant subsystems used for building a fuel cell system. Chapter 11 details state-of-the-art fuel cell materials for the electrolyte, catalyst, and electrode layers, and explores processing techniques for creating the fuel cell. Chapter 12 tackles fuel cell stack components and materials, and specifically discusses bipolar plate materials, flow-field design, channel shape, and dimensions. It also delves into bipolar plate manufacturing techniques, gaskets, and end plates. Chapter 13 is about fuel cell design and explores stack sizing, the number of cells, stack configuration, cell interconnection, stack clamping, and how to put a fuel cell stack together. Chapter 14 covers fuel cell system design and introduces fuel cell plant components and the electrical parts of the system.

The remaining chapters (15 to 17) explain fuel types, fuel cell operating conditions, and testing. Chapter 15 compares fuel types, storage, and processing. It specifically covers hydrogen, methanol, ethanol, metal hydrides, chemical hydrides, ammonia, propane, and petroleum-based fuels. Chapter 16 shows how to calculate fuel cell operating conditions based upon operating temperature, pressure, flow rates, humidity, and mass balances. Finally, Chapter 17 summarizes popular methods of characterizing fuel cells and describes common fuel cell test methods.

I would like to acknowledge all of the teachers, engineers, and scientists that have contributed to my learning and knowledge of this subject. I also want to express my heartfelt gratitude to my husband for his continued patience, understanding, and encouragement throughout the writing of this text, and for being a loving partner as we move on toward life's other goals together.

Colleen Spiegel
Clearwater, Florida, USA

Contents

Foreword xii

Chapter 1. An Introduction to Fuel Cells	1
1.1 What Is a Fuel Cell?	3
1.1.1 Comparison with batteries	4
1.1.2 Comparison with heat engine	5
1.2 Why Do We Need Fuel Cells?	6
1.2.1 Portable sector	7
1.2.2 Transportation sector	7
1.2.3 Stationary sector	7
1.3 History of Fuel Cells	7
1.3.1 PEM fuel cells	9
1.3.2 Solid oxide fuel cells	10
1.3.3 Molten carbonate fuel cells	10
1.3.4 Phosphoric acid fuel cells	11
1.3.5 Alkali fuel cells	11
1.4 How Do Fuel Cells Work?	12
Chapter Summary	13
Problems	13
Bibliography	13
Chapter 2. Fuel Cells and the Hydrogen Economy	15
2.1 Characteristics of Hydrogen	16
2.1.1 Safety aspects of hydrogen as a fuel	18
2.2 World Energy Demand	19
2.3 Development of the Hydrogen Economy	21
2.4 Hydrogen Production, Distribution, and Storage	22
2.4.1 Technologies for hydrogen production	22
2.4.2 Technologies for hydrogen storage	24
2.4.3 Worldwide hydrogen refueling stations	25

2.5 Investment of Hydrogen Infrastructure	26
2.5.1 Government support	28
2.5.2 Long-term projections of hydrogen use	28
2.5.3 Key players in hydrogen R&D	29
Chapter Summary	33
Problems	33
Bibliography	34
Chapter 3. Fuel Cell Types	35
3.1 Polymer Electrolyte Membrane Fuel Cells (PEMFCs)	36
3.2 Alkaline Fuel Cells (AFCs)	39
3.3 Phosphoric Acid Fuel Cells (PAFCs)	40
3.4 Solid Oxide Fuel Cells (SOFCs)	42
3.5 Molten-Carbonate Fuel Cells (MCFCs)	43
3.6 Direct Methanol Fuel Cells (DMFCs)	44
3.7 Zinc Air Fuel Cells (ZAFCS)	46
3.8 Protonic Ceramic Fuel Cells (PCFCs)	47
3.9 Biological Fuel Cells (BFCs)	49
Chapter Summary	50
Problems	51
Bibliography	51
Chapter 4. Fuel Cell Applications	53
4.1 Portable Power	53
4.2 Backup Power	55
4.2.1 Basic electrolyzer calculations	56
4.3 Transportation Applications	57
4.3.1 Automobiles	58
4.3.2 Buses	66
4.3.3 Utility vehicles	66
4.3.4 Scooters and bicycles	69
4.4 Stationary Power Applications	72
Chapter Summary	83
Problems	84
Bibliography	84
Chapter 5. Basic Fuel Cell Thermodynamics	87
5.1 Basic Thermodynamic Concepts	87
5.2 Fuel Cell Reversible and Net Output Voltage	92
5.3 Theoretical Fuel Cell Efficiency	99
5.3.1 Energy efficiency	100
5.4 Fuel Cell Temperature	101
5.5 Fuel Cell Pressure	102
Chapter Summary	104
Problems	104
Bibliography	105
Chapter 6. Fuel Cell Electrochemistry	107
6.1 Electrode Kinetics	110
6.2 Voltage Losses	112

6.3 Internal Currents and Crossover Currents	116
6.4 Improving Kinetic Performance	117
Chapter Summary	118
Problems	118
Bibliography	119
Chapter 7. Fuel Cell Charge Transport	121
7.1 Voltage Loss Due to Charge Transport	121
7.2 Microscopic Conductivity in Metals	126
7.3 Ionic Conductivity in Aqueous Electrolytes	126
7.4 Ionic Conductivity of Polymer Electrolytes	127
7.5 Ionic Conduction in Ceramic Electrolytes	130
Chapter Summary	131
Problems	132
Bibliography	132
Chapter 8. Fuel Cell Mass Transport	133
8.1 Convective Mass Transport from Flow Channels to Electrode	134
8.2 Diffusive Mass Transport in Fuel Cell Electrodes	135
8.3 Convective Mass Transport in Flow Structures	139
8.3.1 Mass transport in flow channels	139
8.3.2 Pressure drop in flow channels	144
Chapter Summary	149
Problems	149
Bibliography	150
Chapter 9. Heat Transfer	151
9.1 Fuel Cell Energy Balance	152
9.1.1 General energy balance procedure	152
9.1.2 Energy balance of fuel cell stack	154
9.1.3 General energy balance for fuel cell	154
9.1.4 Energy balance for fuel cell components and gases	155
9.2 Heat Generation and Flux in Fuel Cell Layers	158
9.3 Heat Conduction	158
9.4 Heat Dissipation Through Natural Convection and Radiation	159
9.5 Fuel Cell Heat Management	160
9.5.1 Heat exchanger model	162
9.5.2 Air cooling	163
9.5.3 Edge cooling	166
Chapter Summary	167
Problems	168
Bibliography	168
Chapter 10. Fuel Cell Modeling	171
10.1 Conservation of Mass	175
10.2 Conservation of Momentum	175

10.3	Conservation of Energy	176
10.4	Conservation of Species	177
10.5	Conservation of Charge	178
10.6	The Electrodes	178
10.6.1	Mass transport	179
10.6.2	Electrochemical behavior	181
10.6.3	Ion/electron transport	183
10.6.4	Heat transport in the electrodes	184
10.7	The Electrolyte	185
	Chapter Summary	186
	Problems	187
	Bibliography	187
Chapter 11.	Fuel Cell Materials	189
11.1	Electrolyte Layer	190
11.1.1	PEMFCs and DMFCs	192
11.1.2	PAFCs	195
11.1.3	AFCs	196
11.1.4	MCFCs	196
11.1.5	SOFCs	198
11.2	Fuel Cell Electrode Layers	199
11.2.1	PEMFC, DMFC, and PAFC catalysts	201
11.2.2	PEMFC, DMFC, and PAFC gas diffusion layers	205
11.2.3	AFC electrodes	207
11.2.4	MCFC electrodes	208
11.2.5	SOFC electrodes	208
11.3	Low-Temperature Fuel Cell Processing Techniques	210
11.4	SOFC manufacturing method	212
11.5	Method for Building a Fuel Cell	213
11.5.1	Preparing the polymer electrolyte membrane	213
11.5.2	Catalyst/electrode layer material	214
11.5.3	Hot-pressing the MEA	215
	Chapter Summary	217
	Problems	217
	Bibliography	218
Chapter 12.	Fuel Cell Stack Components and Materials	221
12.1	Bipolar Plates	221
12.1.1	Bipolar plate materials for low and medium temperature fuel cells	223
12.1.2	Coated metallic plates	224
12.1.3	Composite plates	226
12.2	Flow-Field Design	227
12.3	Materials for SOFCs	232
12.4	Materials for MCFCs	233
12.5	PAFC Materials and Design	234
12.6	Channel Shape, Dimensions, and Spacing	235
12.7	Bipolar Plate Manufacturing	235
12.7.1	Nonporous graphite plate fabrication	235
12.7.2	Coated metallic plate fabrication	236
12.7.3	Composite plate fabrication	237

12.8 Gaskets and Spacers	237
12.8.1 PEMFCs/DMFCs/AFCs	238
12.8.2 SOFC Seals	238
12.9 End Plates	240
12.10 Constructing the Fuel Cell Bipolar Plates, Gaskets, End Plates, and Current Collectors	241
12.10.1 Bipolar plate design	241
12.10.2 Gasket selection	242
12.10.3 End plates	243
12.10.4 Current collectors	244
Chapter Summary	244
Problems	245
Bibliography	245
Chapter 13. Fuel Cell Stack Design	247
13.1 Fuel Cell Stack Sizing	249
13.2 Number of Cells	254
13.3 Stack Configuration	255
13.4 Distribution of Fuel and Oxidants to the Cells	260
13.5 Cell Interconnection	262
13.5.1 SOFCs	263
13.5.2 AFCs	264
13.6 Stack Clamping	264
13.7 Water Management for PEMFCs	265
13.7.1 Water management methods	266
13.8 Putting the fuel cell stack together	267
Chapter Summary	268
Problems	269
Bibliography	269
Chapter 14. Fuel Cell System Design	273
14.1 Fuel Subsystem	276
14.1.1 Humidification systems	276
14.1.2 Fans and Blowers	281
14.1.3 Compressors	284
14.1.4 Turbines	289
14.1.5 Fuel cell pumps	291
14.2 Electrical Subsystem	296
14.2.1 Power diodes	297
14.2.2 Switching devices	298
14.2.3 Switching regulators	300
14.2.4 Inverters	303
14.2.5 Supercapacitors	304
14.2.6 Power electronics for cellular phones	305
14.2.7 DC-DC converters for automotive applications	306
14.2.8 Multilevel converters for larger applications	307
14.3 Fuel Cell Hybrid Power Systems	308
14.4 System Efficiency	308
Chapter Summary	310
Problems	311
Bibliography	311

Chapter 15. Fuel Types, Delivery, and Processing	313
15.1 Hydrogen	315
15.1.1 Gas	315
15.1.2 Liquid	320
15.1.3 Carbon nanofibers	322
15.2 Other Common Fuel Types	324
15.2.1 Methanol	324
15.2.2 Ethanol	325
15.2.3 Metal hydrides	325
15.2.4 Chemical hydrides	328
15.2.5 Ammonia	331
15.2.6 Natural gas	333
15.2.7 Propane	333
15.2.8 Gasoline and other petroleum-based fuels	333
15.2.9 Bio-fuels	334
15.3 Fuel Processing	334
15.3.1 Desulfurization	336
15.3.2 Steam reforming	337
15.3.3 Carbon formation	339
15.3.4 Internal reforming	339
15.3.5 Direct hydrocarbon oxidation	341
15.3.6 Partial oxidation	341
15.3.7 Pyrolysis	343
15.3.8 Methanol reforming	343
15.4 Bioproduction of Hydrogen	344
15.4.1 Photosynthesis	344
15.4.2 Digestion processes	345
15.5 Electrolyzers	346
15.5.1 Electrolyzer efficiency	347
15.5.2 High pressure in electrolyzers	347
Chapter Summary	348
Problems	349
Bibliography	349
Chapter 16. Fuel Cell Operating Conditions	353
16.1 Operating Pressure	353
16.2 Operating Temperature	356
16.3 Flow Rates of Reactants	357
16.4 Humidity of Reactants	361
16.5 Fuel Cell Mass Balance	363
Chapter Summary	370
Problems	370
Bibliography	371
Chapter 17. Fuel Cell Characterization	373
17.1 Fuel Cell Testing Setup	373
17.2 Verification of the Assembly	376
17.3 Fuel Cell Conditioning	376
17.4 Baseline Test Conditions and Operating Parameters	377
17.4.1 Temperature	378
17.4.2 Pressure	378

17.4.3	Flow rate	378
17.4.4	Compression force	378
17.5	Polarization Curves	378
17.6	Fuel Cell Resistance	380
17.6.1	Current interrupt	381
17.6.2	The AC resistance method	382
17.6.3	The high-frequency resistance (HFR) method	382
17.6.4	Electrochemical (EIS) impedance spectroscopy	383
17.6.5	Stoichiometry (utilization) sweeps	385
17.6.6	Limiting current	386
17.6.7	Cyclic voltammetry	387
17.7	Current Density Mapping	388
17.8	Neutron Imaging	388
17.9	Characterization of Fuel Cell Layers	388
17.9.1	Porosity determination	389
17.9.2	BET surface area determination	389
17.9.3	Transmission electron microscopy (TEM)	390
17.9.4	Scanning electron microscopy (SEM)	390
17.9.5	X-ray diffraction (XRD)	390
17.9.6	Energy dispersive spectroscopy (EDS)	390
17.9.7	X-ray fluorescence (XRF)	391
17.9.8	Inductively coupled plasma mass spectroscopy (ICP-MS)	391
	Chapter Summary	391
	Problems	392
	Bibliography	392
	Appendix A. Useful Constants and Conversions	395
	Appendix B. Thermodynamic Properties of Selected Substances	397
	Appendix C. Molecular Weight, Gas Constant and Specific Heat for Selected Substances	399
	Appendix D. Gas Specific Heats at Various Temperatures	401
	Appendix E. Specific Heat for Saturated Liquid Water at Various Temperatures	403
	Appendix F. Thermodynamic Data for Selected Fuel Cell Reactants at Various Temperatures	405
	Appendix G. Binary Diffusion Coefficients for Selected Fuel Cell Substances	413
	Appendix H. Product Design Specifications	415
	Appendix I. Fuel Cell Design Requirements and Parameters	417

An Introduction to Fuel Cells

The current movement towards environmentally friendlier and more efficient power production has caused an increased interest in alternative fuels and power sources. Fuel cells are one of the older energy conversion technologies, but only within the last decade have they been extensively studied for commercial use. The reliance upon the combustion of fossil fuels has resulted in severe air pollution, and extensive mining of the world's oil resources. In addition to being hazardous to the health of many species (including our own), the pollution is indirectly causing the atmosphere of the world to change (global warming). This global warming trend will become worse due to an increase in the combustion of fossil fuels for electricity because of the large increase in world population. In addition to health and environmental concerns, the world's fossil fuel reserves are decreasing rapidly. The world needs a power source that has low pollutant emissions, is energy efficient, and has an unlimited supply of fuel for a growing world population. Fuel cells have been identified as one of the most promising technologies to accomplish these goals.

Many other alternative energy technologies have been researched and developed. These include solar, wind, hydroelectric power, bioenergy, geothermal energy, and many others. Each of these alternative energy sources have their advantages and disadvantages, and are in varying stages of development. In addition, most of these energy technologies cannot be used for transportation or portable electronics. Other portable power technologies, such as batteries and supercapacitors also are not suitable for transportation technologies, military applications, and the long-term needs of future electronics.

The ideal option for a wide variety of applications is using a hydrogen fuel cell combined with solar or hydroelectric power. Compared to other fuels, hydrogen does not produce any carbon monoxide or other pollutants. When it is fed into a fuel cell, the only by-products are oxygen and heat. The oxygen is recombined with hydrogen to form water when power is needed.

Fuel cells can utilize a variety of fuels to generate power—from hydrogen, methanol, and fossil fuels to biomass-derived materials. Using fossil fuels to generate hydrogen is regarded as an intermediate method of producing hydrogen, methane, methanol, or ethanol for utilization in a fuel cell before the hydrogen infrastructure has been set up. Fuels can also be derived from many sources of biomass, including methane from municipal wastes, sewage sludge, forestry residues, landfill sites, and agricultural and animal waste.

Fuel cells can also help provide electricity by working with large power plants to become more decentralized and increase efficiency. Most electricity produced by large fossil-fuel burning power plants are distributed through high voltage transmission wires over long distances [1]. These power plants seem to be highly efficient because of their large size; however, a 7 to 8 percent electric energy loss in Europe, and a 10 percent energy loss in the United States occurs during long distance transmission [1]. One of the main issues with these transmission lines is that they do not function properly all the time. It would be safer for the population if electricity generation did not occur in several large plants, but is generated where the energy is needed. Fuel cells can be used wherever energy is required without the use of large transmission lines.

Fossil fuels are limited in supply, and are located in select regions throughout the world. This leads to regional conflicts and wars which threaten peace. The limited supply and large demand dries up the cost of fossil fuels tremendously. The end of low-cost oil is rapidly approaching. Other types of alternative energy technology such as fuel cells, can last indefinitely when non-fossil fuel-based hydrogen is used.

This chapter discusses the basics of fuel cells:

- What is a fuel cell?
- Why do we need fuel cells?
- The history of fuel cells
- How do fuel cells work?

By discussing the fuel cell basics, one can appreciate the relevance and significance of fuel cells in addressing environmental and industrial problems, as well as the physical and chemical mechanisms that underlie fuel cell operation.