

Gurbinder Kaur

Solid Oxide Fuel Cell Components

Interfacial Compatibility of SOFC Glass
Seals

 Springer

Solid Oxide Fuel Cell Components

Gurbinder Kaur

Solid Oxide Fuel Cell Components

Interfacial Compatibility of SOFC Glass Seals

 Springer

Gurbinder Kaur
Thapar University
Patiala
India

ISBN 978-3-319-25596-5 ISBN 978-3-319-25598-9 (eBook)
DOI 10.1007/978-3-319-25598-9

Library of Congress Control Number: 2015953005

Springer Cham Heidelberg New York Dordrecht London
© Springer International Publishing Switzerland 2016

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.

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media
(www.springer.com)

A dedication to my teachers, who have such big souls ... (Dr. O.P. Pandey, Dr. Kulvir Singh, Dr. B. Chudasama, Dr. Gary Pickrell, Dr. N. Sriranganathan and the Physics Department, GNDU, Amritsar).

Acknowledgments

During my journey of writing this book, there were many people who knowingly and unknowingly helped me in the successful completion of this project. At this overwhelming moment of accomplishment, first of all I am indebted to Drs. O.P. Pandey, Kulvir Singh, B. Chudasama, Gary Pickrell and N. Sriranganathan, whose understanding, encouragement and personal attention have always provided decisive and energetic support. Dr. Pandey stood by me during my struggling days and is one of the strongest pillars of my career. Without his support I would have never been able to accomplish most of the milestones of my career. Dr. Singh always invested extra hours in my work to churn the best out of it and was a wonderful mental booster. He gives reasonable freedom to his students so that they can add wings to their imagination. I feel honoured to have worked as a Ph.D. graduate under such talented supervisors, whose souls are big enough to accommodate every aspect of their students. Their diligence, persistence and vitality are highly admirable.

I have never seen a more dedicated and hardworking supervisor than Dr. Chudasama who always came forward for his students and never left any stone unturned so as to help them reach the zenith. Drs. Gary Pickrell and N. Sriranganathan provided the most conducive and comfortable environment to me during my stay in the United States and were superb mentors; they were an indispensable part of my journey.

A big chunk of thanks goes to Dr. Gopalan, Director, Thapar University for endowing us all with a zeal to move forward. His rational attitude toward problem analysis is really laudable. All the faculties and staff of the Physics Department (Guru Nanak Dev University), SPMS (Thapar University) and MSE (Virginia Tech, USA) are acknowledged, as they never turned me down whenever I approached them for help. I cannot forget the very supportive and cordial attitude of Dr. Manoj Sharma, HOD, SPMS, who is always ready to help his students. This truly demonstrates his excellent administrative qualities. I also cannot forget the support provided by Dr. S.S. Sekhon during the toughest phase of my life. His motivation and zeal for hard work enlightened my path always. I am so grateful to the UGC,

New Delhi for the financial assistance provided to me [F.15-1/2013-14/PDFWM-2013-14-GE-PUN-14803(SA-II)] during the course of my work.

This book emerged amid friendships that provided lasting lessons. It is a pleasure to mention my good friends, especially from the Functional Materials Lab, Ceramic Research Lab, Nanomedicine Lab and NanoMaterials Lab, who made my working atmosphere very conducive.

Finally, my greatest personal source of gratitude is my soul mate and my husband, Dr. Vishal Kumar, who is my enduring strength. He erased the word 'nightmare' from the dictionary of my life. During every downturn of my life, he uplifted my spirits and helped me in innumerable ways. It is only due to him that I could put in a lot of working hours tirelessly. He sheltered me through every situation and took my entire burden off my shoulders. He was full of patience and support when my work schedule became too hectic. This book would not have been possible without him. He was concerned about my important schedules and kept reminding me about them, along with my diet chart!

Dear Mom and Dad, I have let so many years pass without thanking you both for your unconditional love. I am thankful to my parents and to my parents-in-law for their support, encouragement, care, understanding and for creating a pleasant atmosphere for me. My father-in-law, Sh. Surinder Kumar, and my father, Sh. Harbhajan Singh, have both been strong pillars of my career and have always motivated me to fly high and transform my dreams into realities. I am lucky to have such wonderful in-laws to whom I am more like a daughter. I doubt that I will ever be able to convey my appreciation fully, but I owe them my eternal gratitude.

Above all, thanks to the Almighty for bestowing me with his precious blessings! With every passing day, I believe in the Almighty more and more as He has filled my life with wonderful things which I could never have imagined. Thanks for protecting me, sheltering me and for blessing me in the best ways possible!!

Dr. Gurbinder Kaur

Contents

1	Introduction to Fuel Cells	1
1.1	History of Fuel Cells	1
1.2	Types of Fuel Cells	4
1.2.1	Alkaline Fuel Cells (AFC)	4
1.2.1.1	Basic Principle	4
1.2.1.2	Electrolytes for AFC	6
1.2.1.3	Electrodes for AFC	7
1.2.1.4	Types of Alkaline Fuel Cells	7
1.2.2	Polymer Exchange Membrane Fuel Cell (PEMFC)/ Polymer Electrolyte Fuel Cell (PEFC)	13
1.2.2.1	Cell Components.	13
1.2.2.2	Water Retention in the Membranes	16
1.2.2.3	Contamination of PEMFC	17
1.2.2.4	Bipolar Plates for PEMFC	18
1.2.3	Direct Methanol Fuel Cell (DMFC)	19
1.2.4	Phosphoric Acid Fuel Cell (PAFC).	22
1.2.5	Molten Carbonate Fuel Cell (MCFC)	24
1.2.5.1	Impurities and Their Effects	27
1.2.6	Microbial Fuel Cell (MFC)	28
1.2.6.1	Microbes and Substrates in MFC.	29
1.2.6.2	Components of MFC	32
1.2.6.3	Designs of MFC	32
1.2.7	Direct Carbon Fuel Cell (DCFC)	34
1.2.7.1	DCFC with Aqueous Hydroxide Electrolyte	35
1.2.7.2	DCFC with Molten Hydroxide Electrolyte	36
1.2.7.3	DCFC with Molten Carbonate Electrolyte.	37
1.2.7.4	DCFC with Oxide Ion Conducting Solid Electrolyte	39

1.2.8	Direct Borohydride Fuel Cell (DBFC)	40
1.2.9	Solid Oxide Fuel Cell (SOFC).	41
	Bibliography.	41
	Suggested Bibliography	41
2	Cell Voltages, Polarisations and Performances.	43
2.1	Electromotive Force of Fuel Cell	43
2.2	Cell Efficiency.	47
2.3	Polarisation and Cell Losses	49
2.3.1	Activation Losses.	50
2.3.2	Ohmic Losses (Resistive Losses)	52
2.3.3	Concentration Losses (Mass Transport Losses).	53
2.3.4	Fuel Crossover Losses	55
2.3.5	Summation of Losses	56
2.4	Performance of Fuel Cells.	57
2.4.1	Performance of PAFC.	61
2.4.2	Performance of AFC	65
2.4.3	Performance of PEMFC	66
2.4.4	Performance of MFC	70
2.4.5	Performance of DCFC	72
2.4.6	Performance of MCFC	74
	Bibliography.	77
	Suggested Bibliography	77
3	SOFC Technology: Its Working and Components	79
3.1	Fundamentals of SOFC.	79
3.2	Early History of Solid Oxide Fuel Cell.	81
3.3	Operating Temperature Range of SOFC	85
3.4	Components of SOFC	85
3.4.1	Electrolytes	86
3.4.1.1	Fluorite Structured Electrolytes	87
3.4.1.2	Perovskite Structured Electrolytes	91
3.4.1.3	Brownmillerite Structured Electrolytes	94
3.4.1.4	Aurivillius Structured Electrolytes	94
3.4.1.5	Proton Conducting Electrolytes	98
3.4.2	Cathodes.	99
3.4.2.1	Lanthanum Strontium Manganate (LSM) Cathodes	101
3.4.2.2	Lanthanum Ferrite/Cobaltite Cathodes	104
3.4.2.3	Lanthanum Ferro-Cobaltite Cathodes	105
3.4.2.4	Lanthanum Nickelate and $A_2BO_{4+\delta}$ Cathodes	107
3.4.2.5	LSM Composite Cathodes	108

3.4.3	Anodes	110
3.4.3.1	Ni–YSZ Cermet	111
3.4.3.2	Ceria-Based Anodes.	113
3.4.3.3	Titanium-Based Anodes	114
3.4.4	Interconnects	115
3.4.4.1	Ceramic Interconnects	116
3.4.4.2	Metallic Interconnects	118
	Bibliography	119
	Suggested Bibliography	120
4	Thermodynamics, Performance, and Configurations of SOFC	123
4.1	Ideal Reversible SOFC Thermodynamics	123
4.2	Performance of SOFC	127
4.2.1	Effect of Gas Composition and Utilisation.	127
4.2.2	Effect of Temperature and Pressure	129
4.2.3	Effect of Current Density, Cell Life, and Impurities	130
4.3	Designs of SOFC.	131
4.3.1	Requirements for SOFC Designs	131
4.3.2	Single Cell Configuration	132
4.3.3	Designs of SOFC Stacks.	134
4.3.3.1	Tubular Cell Design (Seal-Less)	138
4.3.3.2	Microtubular Cells Design	143
4.3.3.3	Planar Cell Design (Bipolar/Flat-Plate Design)	146
	Bibliography	147
	Suggested Bibliography	148
5	Sealing Concepts: Glasses as Sealants	149
5.1	Why Sealants Are Required?	149
5.2	Criteria for the Sealants	150
5.3	Different Types of Sealants	152
5.3.1	Compressive Seals	153
5.3.1.1	Metallic Gaskets	154
5.3.1.2	Mica-Based Seals	154
5.3.2	Compliant Seals.	157
5.3.2.1	Brazing	157
5.3.2.2	Bonded Compliant Seals	159
5.3.3	Rigid Seals	160
5.3.3.1	Glasses/Glass–Ceramics Seals	160
5.3.3.2	Ceramic Seals.	160
5.4	Introduction to Glasses	161
5.4.1	Enthalpy/Temperature Curve of Glass.	162
5.4.2	Viscosity, Fragility, and Specific Heat of Glasses.	164
5.4.3	Density and Thermal Expansion Behaviour	168

5.5	Glass Constituents	171
5.6	Preparation Techniques for Glasses	174
5.7	Theories of Glass Formation	178
5.7.1	Structural Theories of Glass Formation	178
5.7.1.1	Goldschmidt's Criterion	178
5.7.1.2	Zachariasen Random Network Theory	178
5.7.1.3	Smekal Theory	179
5.7.1.4	Dietzel Theory	179
5.7.1.5	Sun Theory.	180
5.7.1.6	Stanworth Theory	180
5.7.1.7	Rawson Theory.	181
5.7.2	Kinetic Theories of Glass Formation.	181
5.8	Structures for Oxides Glasses	185
5.9	Glasses as Sealants.	189
5.10	Crystallisation of Glasses	203
5.11	Glasses in Contact with Adjacent Components of SOFC.	210
	Bibliography.	210
	Suggested Bibliography	211
6	Interfacial Compatibility of Glasses and Interconnects.	215
6.1	Different Interconnects for SOFC.	215
6.2	Compound Formation at Glass/Interconnect Interface	220
6.3	Chemical Compatibility of Glass/Interconnect	222
6.3.1	Alkali Metal-Based Glasses/Interconnects Interface.	222
6.3.2	Alkaline Earth Metal-Based Glasses/Interconnects Interface	232
6.3.2.1	Magnesium-Based Glasses/Interconnect Interface.	232
6.3.2.2	Calcium-Based Glasses/Interconnect Interface.	236
6.3.2.3	Strontium-Based Glasses/Interconnect Interface.	243
6.3.2.4	Barium-Based Glass/Interconnect Interface.	252
	Bibliography.	259
	Suggested Bibliography	260
7	Mixed Alkaline/Composite Glasses and Coated Interconnects.	261
7.1	Mixed Alkaline Earth Glasses and Their Interaction with Interconnects.	261
7.1.1	Magnesium–Calcium Glasses/Interconnect Interface	261
7.1.2	Calcium–Strontium Glasses/Interconnects Interface.	266
7.1.3	Strontium–Barium Glasses/Interconnect Interface	275
7.1.4	Barium Magnesium Glasses/Interconnect Interface	278
7.1.5	Barium–Calcium Glasses/Interconnect Interface	286

7.1.6	Barium–Calcium–Magnesium–Strontium Glasses/Interconnect Interface	294
7.2	Coatings on Interconnect.	302
	Bibliography.	313
	Suggested Bibliography	314
8	Interaction of Glass Seals/Electrodes and Electrolytes	315
8.1	Different Types of Electrolytes	315
8.2	Enhancing the Conductivity of Electrolytes	320
8.3	Interaction of Electrolyte and Glasses.	324
8.3.1	Alkali Metal-Based Glasses/Electrolytes Interface.	324
8.3.2	Magnesium-Based Glasses/Electrolyte Interface	329
8.3.3	Calcium-Based Glasses/Electrolyte Interface	337
8.3.4	Strontium-Based Glasses/Electrolyte Interface	342
8.3.5	Barium-Based Glasses/Electrolyte Interface	346
8.4	Mixed Alkaline Earth Glasses/Electrolyte Interface.	349
8.4.1	Calcium–Strontium-Based Glasses/Electrolytes Interfaces	350
8.4.2	Barium–Magnesium–Strontium-Based Glasses/ Electrolyte Interface	352
8.5	Interaction of Cathode and Electrolytes.	359
8.6	Interaction of Cathodes and Interconnect.	365
8.7	Interaction of Anode and Electrolyte	365
	Bibliography.	372
	Suggested Bibliography	372
9	Fuel Cell Status	375
	Vishal Kumar	
9.1	Fuel Cell Design	375
9.2	Global Scenario of Fuel Cells	375
9.3	Source to Speed Analysis	377
9.3.1	Source to Supply Analysis	377
9.3.2	Source to Speed Analysis in North America	378
9.4	Power Circuit Analysis.	378
9.5	Reforming.	380
9.5.1	Types of Fuels.	380
9.6	Fuel Reforming	382
9.6.1	Internal Reforming.	382
9.6.1.1	Direct Internal Reforming.	383
9.6.1.2	Indirect Internal Reforming.	384
9.6.2	Reformation by Partial Oxidation, Steam, and CO ₂ Steam	384
9.6.2.1	Partial Oxidation	385
9.6.2.2	CO ₂	386

- 9.6.2.3 Carbon Deposition 386
- 9.6.2.4 Sulphur Compounds and Their Removal 387
- 9.7 Designs of SOFC System 387
 - 9.7.1 Siemens Westinghouse Distributed Power Generations SOFC System 388
 - 9.7.2 Auxiliary Power SOFC System 388
- 9.8 Current Status of Fuel Cell Industry 389
 - 9.8.1 Portable Applications 390
 - 9.8.1.1 Auxiliary Power Units 390
 - 9.8.1.2 Military Applications 391
 - 9.8.1.3 Stationary Applications 393
 - 9.8.1.4 Prime Power 393
 - 9.8.1.5 Fuel Cell Energy 393
 - 9.8.1.6 Bloom Energy 394
 - 9.8.1.7 Micro-Combined Heat and Power 394
 - 9.8.1.8 Grid-Support and Off-Grid Powers 395
 - 9.8.2 Transport Industry 395
 - 9.8.2.1 Automobile Industry 396
 - 9.8.2.2 Buses 397
- Suggested Bibliography 399
- Index 403**

Author Biography



Dr. Gurbinder Kaur received her B.Sc (Hons. Physics) and M.Sc. (Hons. Physics) from Guru Nanak Dev University, Amritsar. Dr. Gurbinder began her teaching career at D.A.V. College, Amritsar, where she taught from 2004 to 2005. Her second academic appointment was at RR Bawa DAV College, Batala, where she served as Head of the Physics Department from 2005 to 2009. Then, she moved to Thapar University, Patiala, to pursue her research work in the field of solid oxide fuel cells (SOFCs) and received her doctorate in 2012. Her Ph.D. dissertation was based on ‘Investigations on interfacial interaction of glass sealants with electrolytes and interconnect for solid oxide fuel cells (SOFC)’.

She has published more than 35 research papers in the field of materials science. She has published a book on *Modern Physics* by McGraw Hill Pvt. Ltd. She has also carried out research in the field of biomedical engineering and bioglasses. She is a recipient of a research fellowship of the RFSMS scheme of the University Grants Commission (UGC). She also received a fellowship under the Women Scientist Scheme, DST, New Delhi, from 2010 to 2012. After completing her doctorate, she moved to Virginia Tech, USA, to work as a postdoctoral fellow with Dr. Gary Pickrell. She is a recipient of a postdoc scholarship from UGC, New Delhi, for pursuing research work in the field of bioglasses. She works on a variety of different materials and applications including high-temperature energy materials, bioactive materials and optical materials.

Contributor Biography



Dr. Vishal Kumar completed his M.Tech (materials science and engineering) from Thapar University, Patiala, in 2007. He was awarded his Ph.D. in 2010 on the topic ‘Study of SiO_2 - B_2O_3 based glasses and glass ceramics as sealants’. He has been granted scholarships by funding agencies including CSIR and DST, New Delhi, to pursue his research work. He was awarded a Fulbright Fellowship by USIEF to pursue his research on glasses with Dr. Kathy Lu at Virginia Tech, Blacksburg, USA. His objective was “Study and development of materials for increasing the power generation efficiency of Solid Oxide Fuel Cells (SOFC).”