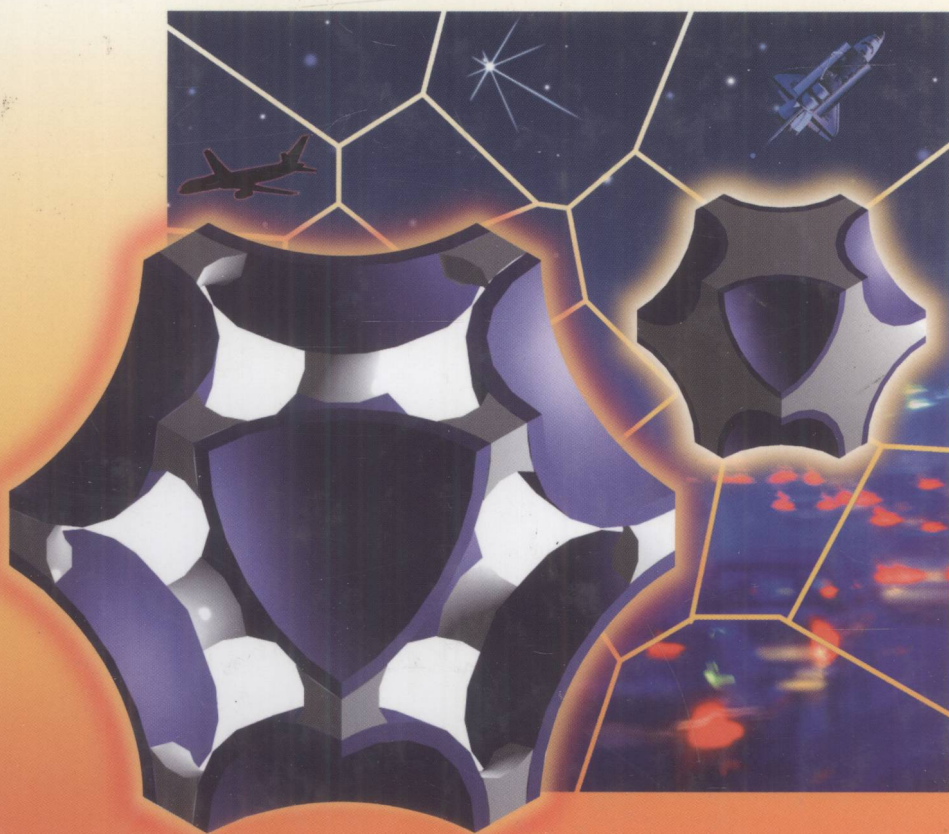


Andreas Öchsner, Graeme E. Murch,
Marcelo J. S. de Lemos (Eds.)

 WILEY-VCH

Cellular and Porous Materials

Thermal Properties Simulation and Prediction



TB383
C393

Cellular and Porous Materials

Thermal Properties Simulation and Prediction

Edited by
Andreas Öchsner, Graeme E. Murch,
and Marcelo J. S. de Lemos



E2008000641

WILEY-VCH Verlag GmbH & Co. KGaA

The Editors

Prof. Dr.-Ing. Andreas Öchsner
Technical University of Malaysia
Faculty of Mechanical Engineering
81310 UTM Skudai, Johor
Malaysia

Prof. Dr. Graeme E. Murch
The University of Newcastle
School of Engineering
University Drive
Callaghan, New South Wales 2308
Australia

Prof. Dr. Marcelo J. S. de Lemos
Instituto Tecnológico de Aeronautica – ITA
Departamento de Energia – IEME
12228-900 São José dos Campos, SP
Brazil

■ All books published by Wiley-VCH are carefully produced. Nevertheless, authors, editors, and publisher do not warrant the information contained in these books, including this book, to be free of errors. Readers are advised to keep in mind that statements, data, illustrations, procedural details or other items may inadvertently be inaccurate.

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek
Die Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <<http://dnb.d-nb.de>>.

© 2008 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

All rights reserved (including those of translation into other languages). No part of this book may be reproduced in any form – by photoprinting, microfilm, or any other means – nor transmitted or translated into a machine language without written permission from the publishers. Registered names, trademarks, etc. used in this book, even when not specifically marked as such, are not to be considered unprotected by law.

Printed in the Federal Republic of Germany
Printed on acid-free paper

Cover Design Adam Design, Weinheim
Typesetting Thomson Digital, Noida, India
Printing Strauss GmbH, Mörlenbach
BookBinding Litges & Dopf GmbH, Heppenheim

ISBN 978-3-527-31938-1

Cellular and Porous Materials

Edited by
Andreas Öchsner, Graeme E. Murch,
and Marcelo J. S. de Lemos

Further Reading

S. Kaskel

Porous Materials

Introduction to Materials Chemistry, Properties, and Applications

2009

ISBN: 978-3-527-32035-0

M.J. Sailor

Porous Silicon in Practice

Preparation, Characterization and Applications

2008

ISBN: 978-3-527-31378-5

M. Scheffler, P. Colombo (Eds.)

Cellular Ceramics

Structure, Manufacturing, Properties and Applications

2005

ISBN: 978-3-527-31320-4

Preface

Nature frequently uses cellular and porous materials for creating load-carrying and weight-optimized structures. Thanks to their cellular design, natural materials such as wood, cork, bones, and honeycombs fulfill structural as well as functional demands. For a long time, the development of artificial cellular materials has been aimed at utilizing the outstanding properties of biological materials in technical applications. As an example, the geometry of honeycombs was identically converted into aluminum structures which have been used since the 1960s as cores of lightweight sandwich elements in the aviation and space industries. Nowadays, in particular, foams made of polymeric materials are widely used in all fields of technology. For example, Styrofoam[®] and hard polyurethane foams are widely used as packaging materials. Other typical application areas are the fields of heat and sound absorption. During the last few years, techniques for foaming metals and metal alloys and for manufacturing novel metallic cellular structures have been developed. Owing to their specific properties, these cellular materials have considerable potential for applications in the future. The combination of specific mechanical and physical properties distinguishes them from traditional dense metals, and applications with multifunctional requirements are of special interest in the context of such cellular metals. Their high stiffness, in conjunction with a very low specific weight, and their high gas permeability combined with a high thermal conductivity can be mentioned as examples. Cellular materials comprise a wide range of different arrangements and forms of cell structures. Metallic foams are being investigated intensively, and they can be produced with a closed- or open-cell structure. Their main characteristic is their very low density. The most common foams are made of aluminum alloys. Quite a regular arrangement of cells is obtained in structures, e.g. with hollow spheres. A perfect regular structure results from interconnecting networks of straight beams; materials of this type are known as lattice block materials. What all these different cellular materials have in common is that their physical properties are not only determined by their cell wall material but also significantly by their microstructure.

Several textbooks cover the topic of cellular materials in general and give an introduction to the whole range of physical properties and possible applications. The books by L. J. Gibson and M. F. Ashby (Pergamon Press, 1988), M. F. Ashby *et al.*

(Butterworth Heinemann, 2000), and H.-P. Degischer and B. Kriszt (Wiley-VCH, 2002) are recognized as standard works on this topic and give the most comprehensive general overview of cellular and porous materials.

The idea of this book is to cover one of the important physical characteristics, i.e. thermal properties, in detail from different points of view. This book aims to provide readers not only with a good understanding of the fundamentals but also with an awareness of recent advances in properties determination and applications of cellular and porous materials. The book contains 12 chapters written by experts in the relevant fields from academia and from major national laboratories/research institutes. The first part of the book introduces in detail different numerical and analytical methods in order to characterize and predict the effective thermal properties. Each of these chapters focuses on a detailed introduction of the theoretical and/or experimental method(s) which are applied to the characterization of different materials. The first part of the book introduces aspects relevant even for a non-specialist, i.e. to provide information which is normally omitted in the scope of journal publications. Different characterization approaches are presented and applied to different types of cellular and porous materials in order to reveal a spectrum for the investigation of effective thermal properties. The second part of the book addresses various types of applications and specialized topics related to the context of thermal properties of cellular and porous materials.

The editors wish to thank all the chapter authors for their participation and cooperation which made this text possible.

Finally, we would like to thank the team at Wiley-VCH, especially Dr. Rainer Münz and Dr. Martin Ottmar, for their excellent cooperation during the whole phase of the project.

January 2008

*Andreas Öchsner
Graeme E. Murch
Marcelo J. S. de Lemos*

List of Contributors

Dominique Baillis

Centre Thermique de Lyon
(CETHIL, CNRS/INSA Lyon/UCBL)
Bâtiment Sadi Carnot, 2ème étage
20 Avenue A. Einstein
69621 Villeurbanne
France

Irina V. Belova

School of Engineering, Building ES
University of Newcastle Callaghan
New South Wales 2308
Australia

Eduardo L. Cardoso

State University of Santa Catarina
Center for Technological Sciences
Department of Mechanical Engineering
University Campus Prof. Avelino
Marcante
89223-100 Joinville-SC
Brazil

Hiroshi Chiba

Mechanical Technology Department
Advanced Technology R&D Center
Mitsubishi Electric Corporation
8-1-1, Tsukaguchi Honmachi
Amagasaki
Hyogo 661-8661
Japan

Rémi Coquard

Centre Thermique de Lyon
(CETHIL, CNRS/INSA Lyon/UCBL)
Bâtiment Sadi Carnot, 2ème étage
20 Avenue A. Einstein
69621 Villeurbanne
France

Marcelo J. S. de Lemos

Departamento de Energia – IEME
Instituto Tecnológico de
Aeronautica – ITA
12228-900 Sao Jose dos Campos – SP
Brazil

Thomas Fiedler

Centre for Mechanical Technology and
Automation
Department of Mechanical Engineering
University of Aveiro
Campus Universitario de Santiago
3820-193 Aveiro
Portugal

Suresh V. Garimella

School of Mechanical Engineering
Purdue University
585 Purdue Mall
West Lafayette, IN 47907-2088
USA

Liwen Jin

School of Mechanical and Aerospace
Engineering
Nanyang Technological University
50 Nanyang Avenue
Singapore 639798
Republic of Singapore

Renata Jecl

Faculty of Civil Engineering
University of Maribor
Smetanova ulica 17
2000 Maribor
Slovenia

Kouichi Kamiuto

Department of Mechanical and
Energy Systems Engineering
Oita University
Dannoharu 700
Oita, 870-1192
Japan

Janja Kramer

Faculty of Civil Engineering
University of Maribor
Smetanova ulica 17
2000 Maribor
Slovenia

Shankar Krishnan

Purdue University
School of Mechanical Engineering
585 Purdue Mall
West Lafayette, IN 47907-2088
USA
Currently
Bell Labs Ireland
Alcatel–Lucent
Dublin
Ireland

Kai Choong Leong

School of Mechanical and Aerospace
Engineering
Nanyang Technological University
50 Nanyang Avenue
Singapore 639798
Republic of Singapore

Vladimir V. Mityushev

Department of Mathematics
Krakow Pedagogical Academy
ul. Podchorazych 2
Krakow 30-084
Poland

Pablo A. Muñoz-Rojas

State University of Santa Catarina
Center for Technological Sciences
Department of Mechanical Engineering
University Campus Prof. Avelino
Marcante
89223-100 Joinville – SC
Brazil

Graeme E. Murch

School of Engineering, Building ES
University of Newcastle
Callaghan, New South Wales 2308
Australia

Jayathi Y. Murthy

School of Mechanical Engineering
Purdue University
585 Purdue Mall
West Lafayette, IN 47906
USA

Hideo Nakajima

The Institute of Scientific and
Industrial Research
Osaka University
8-1, Mihogaoka, Ibaraki
Osaka 567-0047
Japan

Emilio C. Nelli Silva

Department of Mechatronics and
Mechanical Systems Engineering
Mechanical Engineering Building
University of São Paulo
05508-900 São Paulo – SP
Brazil

Andreas Öchsner

Technical University of Malaysia
Faculty of Mechanical Engineering
81310 UTM Skudai, Johor
Malaysia

Tetsuro Ogushi

Department of Mechanics and
Robotics
Faculty of Engineering
Hiroshima International University
5-1-1, Hirokoshingai Kure
Hiroshima 737-0112
Japan

Ekaterina Pesetskaya

Department of Mathematics
University of Aveiro
Campus Universitario de Santiago
3810-193 Aveiro
Portugal

Sergei V. Rogosin

Faculty of Mathematics and Mechanics
Belarusian State University
4, Nezavisimosti ave
220030 Minsk
Belarus

Marcelo B. Saito

Departamento de Energia – IEME
Instituto Tecnológico de
Aeronautica–ITA
12228-900 Sao Jose dos Campos – SP
Brazil

Ramvir Singh

Department of Physics
University of Rajasthan
Jaipur 302 004
India

Leopold Škerget

Faculty of Mechanical Engineering
University of Maribor
Smetanova ulica 17
2000 Maribor
Slovenia

Masakazu Tane

The Institute of Scientific and Industrial
Research
Osaka University
8-1, Mihogaoka, Ibaraki
Osaka 567-0047
Japan

Miguel Vaz Junior

State University of Santa Catarina
Center for Technological Sciences
Department of Mechanical Engineering
University Campus Prof. Avelino
Marcante
89223-100 Joinville – SC
Brazil

Contents

Preface XIII

List of Contributors XV

1	Interfacial Heat Transport in Highly Permeable Media: A Finite Volume Approach	1
	<i>Marcelo J.S. de Lemos and Marcelo B. Saito</i>	
1.1	Introduction	1
1.2	Governing Equations	3
1.2.1	Microscopic Transport Equations	3
1.2.2	Decomposition of Flow Variables in Space and Time	4
1.2.3	Macroscopic Flow and Energy Equations	5
1.2.4	Macroscopic Two-Energy Equation Modeling	8
1.2.5	Interfacial Heat Transfer Coefficient	10
1.3	Numerical Determination of h_i	12
1.3.1	Physical Model	12
1.3.2	Periodic Flow	14
1.3.3	Film Coefficient h_i	15
1.4	Results and Discussion	16
1.4.1	Array of Square Rods	16
1.4.2	Array of Elliptic Rods	16
1.4.3	Correlations for Laminar and Turbulent Flows	20
1.5	Conclusions	27
	References	27
2	Effective Thermal Properties of Hollow-Sphere-Structures: A Finite Element Approach	31
	<i>Andreas Öchsner and Thomas Fiedler</i>	
2.1	Introduction	31
2.1.1	Finite Element Method and Heat Transfer Problems	31
2.1.2	Hollow-Sphere Structures in the Context of Cellular Metals	33

2.2	Finite Element Method	37
2.2.1	Basics of Heat Transfer	37
2.2.2	Weighted Residual Method	38
2.2.3	Discretization and Principal Finite Element Equation	39
2.2.4	Four-Node Planar Bilinear Quadrilateral (Quad4)	42
2.2.4.1	General Rectangular Quad4 Element	48
2.2.4.2	Postprocessing	51
2.2.5	Nonlinearities	53
2.3	Modelling of Hollow-Sphere-Structures	56
2.3.1	Geometry, Mesh and Boundary Conditions	56
2.3.2	Material Properties	58
2.4	Determination of the Effective Thermal Conductivities	59
2.4.1	Influence of the Morphology and Joining Technique	60
2.4.2	Influence of the Topology	62
2.4.3	Temperature-Dependent Material Properties	65
2.4.3.1	Low Temperature Gradient	65
2.4.3.2	High Temperature Gradient	66
2.4.4	Application Example: Sandwich Structure	67
2.5	Conclusions	68
	References	69
3	Thermal Properties of Composite Materials and Porous Media: Lattice-Based Monte Carlo Approaches	73
	<i>Irina V. Belova and Graeme E. Murch</i>	
3.1	Introduction	73
3.2	Monte Carlo Methods of Calculation of the Effective Thermal Conductivity	73
3.2.1	The Einstein Equation	74
3.2.2	Fick's First Law (Fourier Equation)	80
3.3	Monte Carlo Calculations of the Effective Thermal Conductivity	81
3.3.1	Effective Diffusion in Two-Component Composites/ Porous Media	81
3.3.2	Effective Diffusion in Three-Component Composites	90
3.4	Determination of Temperature Profiles	91
	References	94
4	Fluid Dynamics in Porous Media: A Boundary Element Approach	97
	<i>Leopold Škerget, Renata Jecl, and Janja Kramer</i>	
4.1	Introduction	97
4.1.1	Transport Phenomena in Porous Media	97
4.1.2	Boundary Element Method for Fluid Dynamics in Porous Media	98
4.2	Governing Equations	99
4.3	Boundary Element Method	101
4.3.1	Velocity–Vorticity Formulation	102
4.3.2	Boundary Domain Integral Equations	102

4.3.3	Discretized Boundary Domain Integral Equations	105
4.3.4	Solution Procedure	106
4.4	Numerical Examples	107
4.4.1	Double-Diffusive Natural Convection in Vertical Cavity	107
4.4.2	Double-Diffusive Natural Convection in a Horizontal Porous Layer	113
4.5	Conclusion	117
	References	117
5	Analytical Methods for Heat Conduction in Composites and Porous Media	121
	<i>Vladimir V. Mityushev, Ekaterina Pesetskaya, and Sergei V. Rogosin</i>	
5.1	Introduction	121
5.2	Mathematical Models for Heat Conduction	122
5.2.1	General	122
5.2.2	Boundary Value Problems	127
5.2.3	Conjugation Problem	128
5.2.4	Complex Potentials	129
5.2.5	Periodic Problems	132
5.3	Effective Conductivity Tensor	134
5.4	Review of Known Formulas	137
5.4.1	Laminates	137
5.4.2	Clausius–Mossotti Approximation (CMA)	137
5.4.3	Effective Medium Theory (EMT)	141
5.4.4	Duality Theory for 2D Media	144
5.5	Network Approximations	146
5.6	Doubly Periodic Problems	149
5.6.1	Introduction to Elliptic Function Theory	149
5.6.2	Method of Functional Equations	154
5.7	Representative Cell	156
5.8	Nonlinear Heat Conduction	159
	References	160
6	Modeling of Composite Heat Transfer in Open-Cellular Porous Materials at High Temperatures	165
	<i>Kouichi Kamiuto</i>	
6.1	Introduction	165
6.2	Governing Equations	166
6.3	Transport Properties and Heat Transfer Correlation	168
6.3.1	Effective Thermal Conductivities	168
6.3.2	Thermal Dispersion Conductivities	171
6.3.3	Radiative Properties	173
6.3.4	Fluid Mechanical Properties	174
6.3.5	Volumetric Heat Transfer Coefficient	178
6.4	Radiative Transfer	179

6.5	Combined Conductive and Radiative Heat Transfer	183
6.6	Combined Forced-Convective and Radiative Heat Transfer	186
6.6.1	Analysis of Gas Enthalpy-Radiation Conversion System	187
6.6.2	Analysis of Transpiration Cooling System in a Radiative Environment	189
6.7	Conclusions and Recommendations	194
	References	197
7	Thermal Conduction Through Porous Systems	199
	<i>Ramvir Singh</i>	
7.1	Introduction	199
7.2	Theoretical Models	201
7.2.1	Models for Thermal Conductivity	201
7.2.2	Discussion	219
7.3	Experimental Techniques	221
7.3.1	Thermal Conductivity Probe	221
7.3.1.1	Theory	223
7.3.2	Differential Temperature Sensor Technique	224
7.3.2.1	Mathematical Analysis	225
7.3.3	Probe-Controlled Transient Technique	227
7.3.3.1	Mathematical Analysis	227
7.3.4	Plane Heat Source	230
7.3.4.1	Theory	230
7.3.5	Transient Plane Source (TPS)	234
7.3.5.1	Theory	234
7.3.6	Discussion	236
	References	237
8	Thermal Property of Lotus-Type Porous Copper and Application to Heat Sinks	239
	<i>Tetsuro Ogushi, Hiroshi Chiba, Masakazu Tane, and Hideo Nakajima</i>	
8.1	Introduction	239
8.2	Effective Thermal Conductivity of Lotus-Type Porous Copper	241
8.2.1	Measurement	241
8.2.1.1	Definition of Effective Thermal Conductivity	241
8.2.1.2	Experimental Method	242
8.2.1.3	Specimen Preparation	243
8.2.2	Thermal Conductivity Parallel to Pores	244
8.2.3	Thermal Conductivity Perpendicular to Pores	245
8.2.4	Effect of Pore Shape on Thermal Conductivity	248
8.2.5	Effect of Pore Orientation on Thermal Conductivity	251
8.2.5.1	Introduction	251
8.2.5.2	EMF Theory	251
8.2.5.3	Application of Extended EMF Theory to Lotus Metals	252
8.3	Application of Lotus-Type Porous Copper to Heat Sinks	255

8.3.1	Analysis of Fin Efficiency	255
8.3.1.1	Straight Fin Model	255
8.3.1.2	Numerical Analysis	256
8.3.2	Experiments of Heat Transfer Characteristics	258
8.3.2.1	Experimental Method	258
8.3.2.2	Investigated Heat Sinks	259
8.3.3	Predictions of Heat Transfer Characteristics	260
8.3.3.1	Conventional Groove Fins and Microchannels	260
8.3.3.2	Lotus-Type Porous Copper Fins	260
8.3.4	Comparison of Experiments with Predictions	261
8.4	Conclusions	264
	References	265
9	Thermal Characterization of Open-Celled Metal Foams by Direct Simulation	267
	<i>Shankar Krishnan, Suresh V. Garimella, and Jayathi Y. Murthy</i>	
9.1	Introduction	267
9.2	Foam Geometry	269
9.3	Mathematical Modeling	271
9.3.1	Effective Thermal Conductivity	271
9.3.2	Computation of Flow and Heat Transfer Through Foam	272
9.3.2.1	Flow and Temperature Periodicity	272
9.3.2.2	Governing Equations	273
9.3.2.3	Computational Details	274
9.4	Results and Discussion	274
9.4.1	Direct Simulations of Foams: BCC Model	275
9.4.1.1	Effective Thermal Conductivity	276
9.4.1.2	Pressure Drop and Heat Transfer Coefficient	278
9.4.2	Direct Simulations of Foams: Effect of Unit Cell Structure	283
9.4.2.1	Effective Thermal Conductivity	284
9.4.2.2	Pressure Drop and Nusselt Number	285
9.5	Conclusion	286
	References	288
10	Heat Transfer in Open-Cell Metal Foams Subjected to Oscillating Flow	291
	<i>Kai Choong Leong and Liwen Jin</i>	
10.1	Introduction	291
10.1.1	Fluid Flow and Heat Transfer in Open-Cell Foams	292
10.1.2	Oscillating Flow Through Porous Media	295
10.2	Fluid Behavior of Oscillatory Flow in Open-Cell Metal Foams	296
10.2.1	Critical Properties of Open-Cell Foams	297
10.2.2	Analysis of Similarity Parameters	299
10.2.3	Oscillatory Flow Through a Channel Filled with Open-Cell Foams	302

10.2.3.1	Effects of Kinetic Reynolds Number and Dimensionless Flow Amplitude	303
10.2.3.2	Friction Factor in Metal Foam	306
10.3	Heat Transfer Characteristics of Oscillatory Flow in Open-Cell Foams	309
10.3.1	Theoretical Analysis of Forced Convection in Oscillating Flow	309
10.3.2	Oscillatory Heat Transfer in Open-Cell Metal Foams	313
10.3.3	Effects of Oscillation Frequency and Flow Amplitude	315
10.3.4	Heat Transfer Rate in Metal Foams	318
10.4	Thermal Management Using Highly Conductive Metal Foams	323
10.4.1	Steady and Oscillating Flows in Open-Cell Metal Foams	323
10.4.1.1	Thermal Performance of Open-Cell Metal Foams	323
10.4.1.2	Comparison of Steady and Oscillating Flows	326
10.4.2	Pumping Power of Oscillatory Cooling System	331
10.5	Conclusions	333
	References	337
11	Radiative and Conductive Thermal Properties of Foams	343
	<i>Dominique Baillis and Rémi Coquard</i>	
11.1	Introduction	343
11.2	Description of Cellular Foam Structure	344
11.2.1	Open-Cell Foams	344
11.2.2	Closed-Cell Foams	344
11.3	Modeling of Foam Structure	346
11.3.1	Cell Modeling	346
11.3.2	Particle Modeling	347
11.4	Determination of Foam Conductive Properties	347
11.4.1	Analytical/Semi-analytical Models	348
11.4.1.1	Polymer Foams	348
11.4.1.2	Ceramic, Metallic and Carbon Foams	350
11.4.2	Numerical Models	352
11.4.2.1	Polymer Foams	352
11.4.2.2	Ceramic, Metallic and Carbon Foams	353
11.5	Determination of Cellular Foam Radiative Properties	355
11.5.1	Theoretical Prediction of Radiative Properties of Particulate Media	356
11.5.1.1	Single-Particle Properties	356
11.5.1.2	Dispersion Properties	357
11.5.2	Parameter Identification Method	357
11.5.3	Application to Open-Cell and Closed-Cell Foams	359
11.5.3.1	Open-Cell Carbon Foam	359
11.5.3.2	Metallic Foam	361
11.5.3.3	Closed-Cell Foam: Case of Low-Density EPS Foams	362
11.5.3.4	Closed-Cell Foam: Case of XPS and PUR Foams	367

11.6	Combined Conductive and Radiative Heat Transfer in Foam	369
11.6.1	Heat Transfer Equations for Cellular Foam Insulation	369
11.6.2	Resolution of the Heat Transfer Equations	370
11.6.2.1	Resolution of the Radiative Transfer Equation/Rosseland Approximation	370
11.6.2.2	Resolution of the Radiative Transfer Equation/Discrete Ordinates Method	371
11.6.2.3	Resolution of the Energy Equation	372
11.6.3	Equivalent Thermal Conductivity Results	372
11.6.3.1	Closed-Cell EPS Foams	372
11.6.3.2	Closed-Cell XPS and PUR Foams	375
11.6.3.3	Metallic Open-Cell Foams	376
11.6.3.4	Open-Cell Carbon Foams	380
11.7	Conclusions	381
	References	382
12	On the Application of Optimization Techniques to Heat Transfer in Cellular Materials	385
	<i>Pablo A. Muñoz-Rojas, Emilio C. Nelli Silva, Eduardo L. Cardoso, and Miguel Vaz Junior</i>	
12.1	Introduction	385
12.2	Optimization Approaches	386
12.2.1	Evolutionary Algorithms (EAs)	387
12.2.1.1	Basic Concepts in Evolutionary Algorithms	387
12.2.2	Mathematical Programming using Gradient-Based Procedures	389
12.3	Periodic Composite Materials	389
12.3.1	Homogenization of Heat Properties in Periodic Composite Materials	390
12.3.2	Functionally Graded Materials	394
12.3.3	Numerical Implementation of Homogenization	395
12.3.4	Material Design: Shape and Topology Optimization of a Unit Cell	397
12.3.4.1	Shape Optimization	398
12.3.4.2	Topology Optimization	401
12.4	General Applications Review	403
12.5	Results Obtained with the FGM Approach in this Work	410
12.6	Conclusions	413
	References	414

Index	419
--------------	------------