Contents

Preface ................................................................. ix

1 Porous Media Fundamentals ................................ 1
  1.1 Structure ......................................................... 1
    1.1.1 Microporous Media ........................................ 5
    1.1.2 Mesoporous Media ........................................ 6
    1.1.3 Macroporous Media ........................................ 7
  1.2 Mass Conservation ............................................. 7
  1.3 Darcy Flow and More Advanced Models .................... 10
  1.4 Energy Conservation .......................................... 17
  1.5 Heat and Mass Transfer ....................................... 23
    1.5.1 Fluid Flow ............................................... 28
    1.5.2 Heat Flow .................................................. 29

2 Flows in Porous Media ............................................ 31
  2.1 Use Simple Methods First .................................... 31
  2.2 Scale Analysis of Forced Convection Boundary Layers .... 33
  2.3 Sphere and Cylinder with Forced Convection .............. 37
  2.4 Channels with Porous Media and Forced Convection ....... 38
  2.5 Scale Analysis of Natural Convection Boundary Layers ... 40
  2.6 Thermal Stratification and Vertical Partitions .......... 42
  2.7 Horizontal Walls with Natural Convection ................. 45
  2.8 Sphere and Horizontal Cylinder with Natural Convection 46
  2.9 Enclosures Heated from the Side ............................ 47
  2.10 Enclosures Heated from Below .............................. 53
  2.11 The Method of Intersecting the Asymptotes ............... 58
    2.11.1 The Many Counterflows Regime ......................... 60
    2.11.2 The Few Plumes Regime ................................ 61
    2.11.3 The Intersection of Asymptotes ....................... 64
## Contents

### 3 Energy Engineering

- 3.1 Thermodynamics Fundamentals: Entropy Generation or Exergy Destruction .......................... 67
- 3.2 Exergy Analysis ........................................... 71
- 3.3 Thermal Energy Storage .................................. 76
- 3.4 Sensible Heat Storage .................................... 80
- 3.5 Aquifer Thermal Energy Storage .......................... 87
- 3.6 Latent Heat Storage ........................................ 89
- 3.7 Cold Thermal Energy Storage .............................. 96
- 3.8 Porous Medium Model of a Storage System with Phase-Change Material ............................... 100
- 3.9 Fuel Cell Principles and Operation ...................... 105
- 3.10 Fuel Cell Structure and Performance ..................... 109
- 3.12 Exergy, Environment, and Sustainable Development .......... 120

### 4 Environmental and Civil Engineering

- 4.1 The Energy–Environment Interface ....................... 125
- 4.2 Wakes: Concentrated Heat Sources in Forced Convection ......................................................... 126
- 4.3 Plumes: Concentrated Heat Sources in Natural Convection ....................................................... 127
- 4.4 Penetrative Convection ..................................... 130
- 4.5 Aerosol Transport and Collection in Filters .................. 134
- 4.6 Filter Efficiency and Filtration Theories ................... 139
- 4.7 Pressure Drop, Permeability, and Filter Performance ....... 146
- 4.8 Ionic Transport .............................................. 152
- 4.9 Reactive Porous Media ..................................... 156
- 4.10 Electrodiffusion ............................................ 162
- 4.11 Tree-Shaped Flow Networks ............................... 166
- 4.12 Optimal Size of Flow Element ............................. 173
- 4.13 Hot Water Distribution Networks .......................... 177
- 4.14 Minimal Resistance Versus Minimal Flow Length ........... 183

### 5 Compact Heat Transfer Flow Structures

- 5.1 Heat Exchangers as Porous Media ......................... 194
- 5.2 Optimal Spacings in Natural Convection ................... 201
- 5.3 Optimal Spacings in Forced Convection ..................... 207
- 5.4 Pulsating Flow ............................................ 212
- 5.5 Optimal Packing of Fibrous Insulation ..................... 216
- 5.6 Optimal Maldistribution: Tree-Shaped Flows ................ 218
- 5.7 Dendritic Heat Exchangers ................................ 224
  - 5.7.1 Elemental Volume ...................................... 224
5.7.2 First Construct ........................................ 229
5.7.3 Second Construct ...................................... 230
5.8 Constructal Multiscale Structure for Maximal Heat Transfer Density .................. 238
  5.8.1 Heat Transfer ........................................ 241
  5.8.2 Fluid Friction ........................................ 242
  5.8.3 Heat Transfer Rate Density: The Smallest Scale .................................. 243
5.9 Concluding Remarks ...................................... 245

6 Living Structures ........................................ 247
  6.1 Respiratory System ...................................... 247
    6.1.1 Airflow Within the Bronchial Tree .................. 249
    6.1.2 Alveolar Gas Diffusion .............................. 250
    6.1.3 Particle Deposition .................................. 251
  6.2 Blood and the Circulatory System ....................... 253
  6.3 Biomembranes: Structure and Transport Mechanisms .............. 254
    6.3.1 Cell Membrane ...................................... 254
    6.3.2 Capillary Wall ...................................... 263
  6.4 Transport of Neutral Solutes Across Membranes ............... 266
  6.5 Transport of Charged Solutes Across Membranes ............... 275
    6.5.1 Membrane Potential .................................. 276
    6.5.2 Electrical Equivalent Circuit ........................ 278
  6.6 The Kidney and the Regulation of Blood Composition ........... 279
    6.6.1 Kidney Failure and Dialysis .......................... 280
    6.6.2 Pumping Blood Through Semipermeable Membranes ..................... 281

7 Drying of Porous Materials ................................ 283
  7.1 Introduction ............................................ 283
  7.2 Drying Equipment ...................................... 284
  7.3 Drying Periods .......................................... 284
  7.4 Basic Heat and Moisture Transfer Analysis ................... 285
  7.5 Wet Material ........................................... 288
  7.6 Types of Moisture Diffusion ............................. 294
  7.7 Shrinkage ................................................ 295
  7.8 Modeling of Packed-Bed Drying ........................... 298
  7.9 Diffusion in Porous Media with Low Moisture Content ........... 302
  7.10 Modeling of Heterogeneous Diffusion in Wet Solids ............. 303
    7.10.1 Mass Transfer ...................................... 304
    7.10.2 Heat Transfer ...................................... 305
    7.10.3 Boundary Conditions ................................. 306
7.10.4 Numerical Analysis ................................................. 306
7.10.5 Heat and Mass Transfer Coefficients ......................... 308
7.11 Correlation for the Drying of Solids ........................... 310

8 Multidisciplinary Applications ....................................... 315
8.1 Walls with Cavities: Insulation and Strength Combined .... 315
8.2 Fibers Coated with Phase-Change Material ..................... 326
8.3 Methane Hydrate Sediments: Gas Formation and Convection ............................................................ 337

Nomenclature ............................................................... 349

References ..................................................................... 359

Index ............................................................................ 389
Porous and Complex Flow Structures in Modern Technologies represents a new approach to the field, considering the fundamentals of porous media in terms of the key roles played by these materials in modern technology. Intended as a text for advanced undergraduates and as a reference for practicing engineers, the book uses the physics of flows in porous materials to tie together a wide variety of important issues from such fields as biomedical engineering, energy conversion, civil engineering, electronics, chemical engineering, and environmental engineering.

For example, flows through porous ground play a central role in energy exploration and recovery (oil, geothermal fluids), energy conversion (effluents from refineries and power plants), and environmental engineering (leachates from waste repositories). Similarly, the demands of miniaturization in electronics and in biomedical applications are driving research into the flow of heat and fluids through small-scale porous media (heat exchangers, filters, gas exchangers). Filters, catalytic converters, the drying of stored grains, and myriad other applications involve flows through porous media.

Another new feature is the ‘constructal’ approach to the generation of flow structures for maximal global performance (e.g. maximal heat transfer density) at decreasing length scales. In this direction, the optimized structures become ‘designed porous media’.

By providing a unified theoretical framework that includes not only the traditional homogeneous and isotropic media but also coarse structures in which the assumptions of representative elemental volumes or global thermal equilibrium fail, the book provides practicing engineers the tools they need to analyze complex situations that arise in practice. This volume includes examples, a large number of current references, and an extensive glossary of symbols.