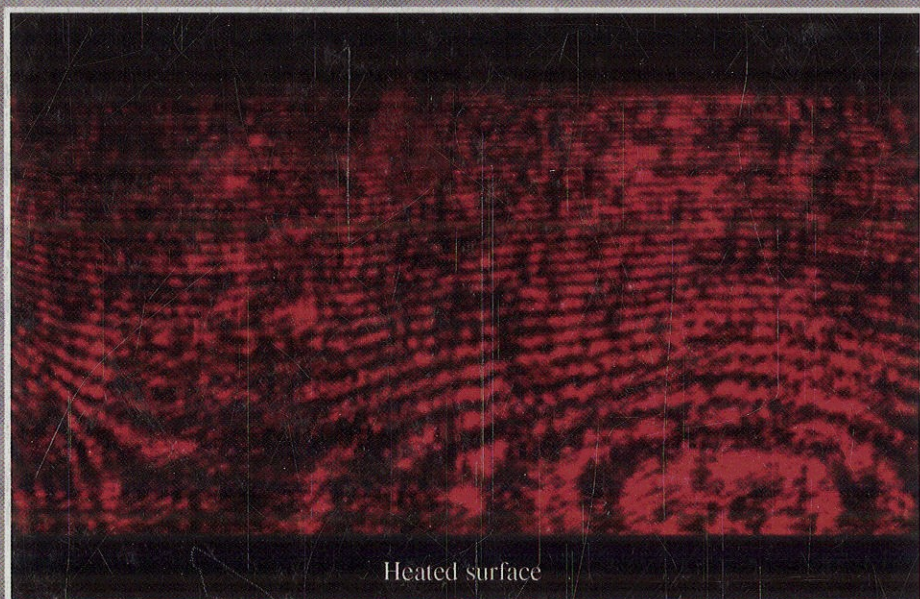


Microscale and Nanoscale Heat Transfer

Fundamentals and
Engineering Applications



C. B. Sobhan
G. P. Peterson



CRC Press
Taylor & Francis Group

Contents

Preface.....	xi
Acknowledgments.....	xiii
Authors.....	xv
Nomenclature.....	xvii
Greek Symbols.....	xxi
Subscripts.....	xxiii

Chapter 1 Introduction to Microscale Heat Transfer 1

1.1	Microscale Heat Transfer: A Recent Avenue in Energy Transport	1
1.2	State of the Art: Some Introductory Remarks	2
1.3	Overview of Microscale Transport Phenomena	4
1.3.1	Microchannel Flow and Convective Heat Transfer.....	5
1.3.2	Phase Change and Two-Phase Flow	8
1.3.3	Conduction and Radiation in the Microscale	9
1.4	Discussions on Size-Effect Behavior.....	11
1.4.1	Comments on Contradictory Observations in Microscale Convection	14
1.4.2	Recent Trends	15
1.5	Fundamental Approach for Microscale Heat Transfer	15
1.5.1	Microscopic View Point and Energy Carriers.....	16
1.5.2	Boltzmann Transport Equation	16
1.5.3	Electromagnetic Waves and Maxwell's Equations.....	17
1.5.4	Basics of Molecular Dynamics Modeling	19
1.6	Introduction to Engineering Applications of Microscale Heat Transfer.....	20
1.6.1	Thin Films.....	20
1.6.2	Microchannel Heat Exchangers	21
1.6.3	Micro Heat Pipes and Micro Heat Spreaders	22
1.6.4	Other Applications	24
1.7	Concluding Remarks.....	26
	References	27

Chapter 2 Microscale Heat Conduction 31

2.1	Review of Conduction Heat Transfer.....	31
2.2	Conduction at the Microscale	33
2.3	Space and Timescales	35
2.4	Fundamental Approach.....	38
2.5	Thermal Conductivity	43

2.5.1	Thermal Conductivity Models	44
2.5.1.1	Thermal Conductivity Expression from Kinetic Theory.....	44
2.5.1.2	Thermal Conductivity Models for Solids.....	45
2.5.1.3	Thermal Conductivity of Liquids.....	50
2.5.1.4	Thermal Conductivity of Solid–Liquid Suspensions	51
2.5.2	Thermal Conductivity Prediction Using Molecular Dynamics.....	52
2.6	Boltzmann Equation and Phonon Transport.....	54
2.7	Conduction in Thin Films.....	55
2.7.1	Superconducting Films.....	58
2.7.2	Laser-Induced Heating	61
2.8	Heat Conduction in Electronic Devices.....	68
2.9	Measurement of Heat Conduction in the Microscale	72
2.9.1	Electrical Probe Techniques.....	73
2.9.2	Optical Methods.....	76
2.10	Conduction in Semiconductor Devices	81
2.10.1	Conduction in Dielectric Films.....	82
2.10.2	Conduction in Crystalline Substances	85
2.11	Concluding Remarks.....	88
	References	90

Chapter 3 Fundamentals of Microscale Convection 95

3.1	Introduction	95
3.2	Convective Heat Transfer in Microtubes and Channels.....	97
3.2.1	Thermodynamic Considerations	97
3.2.1.1	Continuum Approach	98
3.2.1.2	Conservation Laws and Governing Equations.....	99
3.2.1.3	Solution in Size-Affected Domains.....	101
3.2.2	Single-Phase Forced Convection in Microchannels	101
3.2.2.1	Flow Regimes and Flow Transition	102
3.2.2.2	Hydrodynamic and Thermal Entry Lengths.....	104
3.2.3	Nonconventional Analysis Methods	105
3.2.3.1	Electric Double Layer Theory for Ionic Fluids.....	106
3.2.3.2	Augmented Equations for Micropolar Fluids	110
3.2.3.3	Slip Flow Models for Gas Flow.....	111
3.2.4	Boiling and Two-Phase Flow	113
3.2.4.1	Two-Phase Flow Patterns.....	115
3.2.4.2	Boiling Curve and Critical Heat Flux	116
3.2.4.3	Boiling Nucleation and Two-Phase Flow in Microchannels	117
3.2.5	Condensation in Microchannels.....	120
3.3	Concluding Remarks.....	122
	References	122

Chapter 4	Engineering Applications of Microscale Convective Heat Transfer	125
4.1	Introduction	125
4.2	Research and Development	125
4.2.1	Early Investigations on Microscale Convective Heat Transfer	125
4.2.1.1	Single-Phase Liquid Flow	126
4.2.1.2	Gas Flow in Microchannels	131
4.2.1.3	Phase Change and Two-Phase Flow	134
4.2.2	Recent Advances in Microscale Convective Heat Transfer	139
4.2.2.1	Single-Phase Liquid Flow	139
4.2.2.2	Gas Flow	164
4.2.2.3	Phase Change and Two-Phase Flow	166
4.2.2.4	Design Optimization	173
4.2.2.5	Review Papers	173
4.3	Analysis of Systems for Engineering Applications	174
4.3.1	Computational Analysis of Microchannel Heat Sinks	174
4.3.1.1	Analysis of Rectangular Microchannels	175
4.3.1.2	Micro Fin Arrays in the Slip Flow Domain	183
4.3.2	Optical Measurements	190
4.3.2.1	Concentration and Diffusion Measurements	192
4.3.2.2	Temperature Field and Heat Transfer in Mini Channels	193
4.3.3	Other Visualization Methods	196
4.3.4	Micro Heat Pipes and Micro Heat Spreaders	197
4.3.4.1	Modeling of Conventional Micro Heat Pipes	200
4.3.4.2	Wire-Sandwiched (Wire-Bonded) Micro Heat Pipes	212
4.3.4.3	Flat Plate Micro Heat Spreaders	219
4.3.4.4	Other Innovative Designs of Micro Heat Pipes	222
4.3.4.5	Comparative Study of Micro Heat Pipes	226
4.3.5	Integration of Microchannel Heat Sinks to Substrates	226
4.4	Concluding Remarks	237
	References	237
Chapter 5	Microscale Radiative Heat Transfer	251
5.1	Macroscopic Approach	251
5.2	Microscopic Approach	253
5.3	Microscales in Radiative Transfer	255
5.3.1	Spatial Microscales for Radiation	255
5.3.2	Temporal Microscales	258
5.4	Investigations of Microscale Radiation	259
5.4.1	Radiation Interaction with Microstructures and Materials	260
5.4.1.1	Radiation Scattering by Microstructures	261
5.4.2	Studies on Silicon Films	262
5.4.3	Superconducting Materials and Films	263

5.5	Modeling of Microscale Radiation	264
5.5.1	Particulate Systems: Modeling with Electrical Field.....	265
5.5.2	Thin Metallic Films: Boltzmann and Maxwell Equations	266
5.5.3	Short-Pulse Laser Interactions: Deviations from Classical Models	268
5.6	Radiation Properties in the Microscale Regime	273
5.7	Recent Developments in Theoretical Modeling	282
5.8	Concluding Remarks.....	284
	References	285
Chapter 6	Nanoscale Thermal Phenomena	289
6.1	Introduction.....	289
6.1.1	Length Scales for Nanoscale Heat Transfer	290
6.1.2	Heat Transfer Modes in Nanoscale Size-Affected Domains.....	291
6.1.3	Application Areas of Nanoscale Heat Transfer	293
6.2	Nanoparticles and Nanofluids.....	293
6.2.1	Preparation of Nanofluids	296
6.2.2	State of the Art in Experimental Investigations	297
6.2.2.1	Determination of Effective Thermal Conductivity	297
6.2.2.2	Studies on Thermal Conductivity	300
6.2.2.3	Transport Phenomena in Nanoparticle Suspensions.....	304
6.3	Measurements in Nanofluids	307
6.3.1	Thermal Conductivity	307
6.3.1.1	Effect of Temperature and Volume Fraction on Thermal Conductivity	310
6.3.1.2	Effect of Particle Size on Thermal Conductivity.....	314
6.3.1.3	Transient and Steady-State Experimental Methods for Nanofluids	316
6.3.2	Viscosity Measurements	318
6.3.3	Surface Tension	321
6.3.4	Onset of Natural Convection	322
6.3.5	Forced Convection in Heat Exchangers	326
6.3.6	Phase Change Heat Transfer.....	329
6.3.6.1	Boiling.....	331
6.3.6.2	Burnout Heat Flux	333
6.3.6.3	Effects of Agitation Time and Sedimentation on Burnout	333
6.4	Theoretical Investigations	335
6.4.1	Molecular Dynamics Simulation	336
6.4.1.1	Molecular Dynamics for Nanofluids.....	343
6.4.1.2	General Methodology	345
6.4.1.3	Simulations for Thermophysical Properties.....	346
6.4.1.4	Modeling of Thermal Phenomena	350

6.5	Special Topics in Thermal Phenomena	356
6.5.1	Natural Convection under Various Heating Conditions.....	356
6.5.2	Mixing Effect Due to Brownian Motion	360
6.5.3	Microconvection in Nanofluids	362
6.6	Concluding Remarks.....	369
	References	370
Chapter 7	Numerical Examples.....	379
7.1	Microscale Conduction	379
7.2	Microscale Convective Heat Transfer	381
7.3	Microscale Radiation	391
7.4	Nanoscale Thermal Phenomena.....	394
Index		399