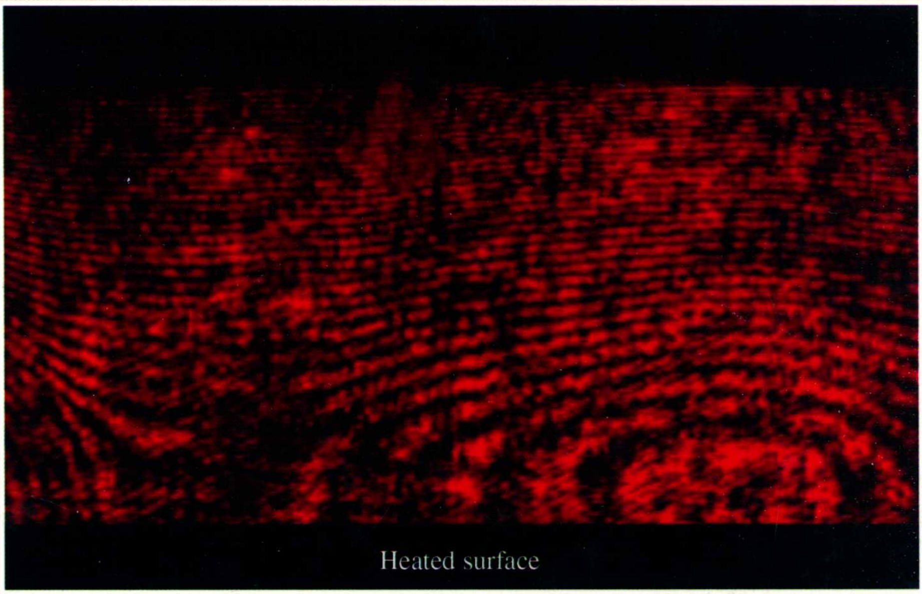
Microscale and Nanoscale Heat Transfer

Fundamentals and Engineering Applications



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Preface

Heat transfer in size-affected domains has become one of the most widely studied areas in thermal science and engineering in recent times. The ever increasing quest for miniaturization, especially in relation to microelectronics, has made this a topic of considerable interest over the past decade. The possibility of including heat sinks as an integral part of individual components, and the operational- and fabrication-related challenges in ensuring effective heat dissipation, have inspired investigators to focus their attention on heat transfer problems at very short length scales. This has led to a tremendous growth of research and the resultant publications in this field, particularly with regard to experimental and computational analyses. The size effect, which becomes more and more pronounced when the domain size is reduced, offers special challenges to the researcher; whether the approach is based on microscale and nanoscale measurements using advanced (microelectrical systems) MEMS applications or on conventional, modified, or discrete computational methods.

The past few years have seen an enormous amount of literature being published in the area of microscale and nanoscale thermal phenomena. One of the objectives of this work is to compile and discuss the most relevant findings from these investigations, comparing and contrasting the methods and observations related to size-affected domains with conventional heat transfer analyses. Being active in research on microscale and nanoscale thermophysical phenomena in fluid domains, the authors have attempted to provide extensive discussions, based on work accomplished by their research groups, as well as those published in the open literature. Although not the authors' direct areas of research, microscale conduction and radiation are presented as additional areas, based on information obtained from excellent research material published by eminent researchers on these topics.

The opening chapter of the book provides an introduction to microscale heat transfer, where the general trends and observations in the technological area are discussed, focusing on both the early work and the more recent contributions. Chapter 2 deals with microscale conduction heat transfer, wherein application-oriented research, basic thermal conductivity models, microscale conduction measurement methods, and related topics are presented based on information taken from the most relevant publications and treatises. Chapters 3 and 4 present material on the fundamentals and engineering applications of microscale convective heat transfer, respectively. Several methods of special analysis pertaining to microscale domains have been discussed in Chapter 3. Analysis and design aspects pertaining to engineering applications, related to microchannels, slip flow domains, and micro heat pipes are included in Chapter 4. Experimental studies using optical techniques for flow and heat transfer in small channels are also included in this chapter. A comprehensive review of microscale convective heat transfer, related to engineering applications, is also presented. Chapter 5 deals with the fundamentals of microscale radiation, and some case studies from the literature on microscale radiation phenomena, which require special treatment. Important analysis methods and results from microscale radiation literature are reproduced and discussed in this chapter. Chapter 6 on nanoscale thermal phenomena emphasizes nanofluids, and their thermal behavior. A large fraction of the material presented in Chapters 4 and 6 is the result of the original efforts undertaken at the authors' laboratories in the United States and India.

Worked out numerical examples have been included in the last chapter (Chapter 7). It is expected that these examples will help the reader in the application of the results of microscale and nanoscale heat transfer analysis in practical design problems, where such results can be directly applied. However, it should be noted that a majority of the microscale heat transfer problems require special analysis utilizing particular formulation methods and solution approaches. Still, the problems presented in Chapter 7, covering all the modes of heat transfer discussed in the book, are meant to throw light on some of the differences and deviations to be taken into consideration while developing engineering designs related to microscale systems.

One of the limitations while dealing with dynamic emerging technologies is the difficulty in being comprehensive and inconclusive in the treatment of the subject in the form of a book. Notwithstanding this difficulty, and within the limited exposure to the vast resources of the subject matter, the authors do expect that the information provided would be useful and of interest to the graduate and research communities in this exciting new domain of knowledge.

C.B. Sobhan
G.P. Peterson

Acknowledgments

This book is an outcome of the ongoing academic and research collaboration between the authors, which began in 2003, when C.B. Sobhan spent a sabbatical year at the Two-Phase Heat Transfer Laboratory headed by G.P. Peterson at Rensselaer Polytechnic Institute, Troy, New York. G.P. Peterson has subsequently relocated to the University of Colorado at Boulder. The contents of the book include a large amount of original work performed in the authors' laboratories, in the United States and in India, and they would like to thank their institutions for providing the resources to accomplish this research.

The first major opportunity for C.B. Sobhan to enter the exciting area of microscale heat transfer was provided by Professor Suresh V. Garimella at Purdue University, West Lafayette, Indiana, in 1999, whose encouragement and motivation are gratefully acknowledged. G.P. Peterson first became involved in the field following an introductory course taught by A. Bar-Cohen and A. Kraus in 1981.

A number of the authors' students and research scholars have contributed to this book, through valuable research findings, discussions, and support in manuscript preparation. In particular, C.B. Sobhan would like to acknowledge the contributions of Sankar Narayanan, Nithin Mathew, V. Sajith, U.B. Jayadeep, and Shijo Thomas toward the material for the book. The tremendous help offered by K. Prabhul and Praveen P. Abraham, who spent many hours on manuscript editing, and the helping hands extended by Rahul Jayan, Raison Chacko, Jose Devachan, Satish Kumar Pappu, Yadu Vasudev, Divya Haridas, and P. Nithin at various stages of the work are gratefully acknowledged. The drawings were prepared by P. Beljith, and his efforts in this regard are acknowledged. Also of particular note is the work of J. Ochterbeck, A. Duncan, B. Babin, J.T. Dickey, J.M. Ha, B.H. Kim, H.B. Ma, Y. Wang, J. Li, C.H. Li, and C. Li, all of whom have taught GPP more than what he could have ever learned on his own.

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Professor Sobhan received his bachelor of technology degree in 1984 from Regional Engineering College, Calicut, India. He obtained his master of technology and PhD from the Indian Institute of Technology, Madras, India in 1986 and 1990, respectively. Since then, he has been working as a faculty member in the Department of Mechanical Engineering at Regional Engineering College, Calicut, which is now National Institute of Technology, Calicut. He became a professor of mechanical engineering at the institute in 2006.

Professor Sobhan has been a visiting faculty member at Rensselaer Polytechnic Institute, Troy, New York (2003–2006) and a visiting scholar at the Cooling Technologies Research Consortium, School of Mechanical Engineering, Purdue University, West Lafayette, Indiana (1999–2000). He has also held postdoctoral research positions at Nanyang Technological University, Singapore (1997–1999), and the University of Wisconsin, Milwaukee (1999).

Professor Sobhan's background is on research topics such as interferometric measurement of heat transfer, heat pipes, heat exchangers, microchannels, and micro heat pipes. His current research interests are in optical measurements at the microscale, molecular dynamics modeling of nanoscale thermal phenomena, thermal management of electronics, and numerical modeling of phase change heat spreaders and heat pipes. He has been a reviewer for (American Society of Mechanical Engineers) ASME and (American Institute of Aeronautics and Astronautics) AIAA journals, the *International Journal of Heat and Mass Transfer, Nanoscale and Microscale Thermophysical Engineering, Elsevier Journal of Aerospace Science and Technology, Journal of Microfluidics and Nanofluidics*, and *Heat Transfer Engineering*.

Professor Sobhan performs collaborative research internationally with research groups at the Stokes Research Institute, University of Limerick, Ireland, and National Research Laboratory, Dong-A University, South Korea, in addition to the group at the Two-Phase Heat Transfer Laboratory, University of Colorado at Boulder. He has coauthored more than 50 papers in refereed international journals and conferences, and a chapter in the *MEMS Handbook*.

George P. Peterson is currently the chancellor at the University of Colorado at Boulder, Colorado. Before his appointment as chancellor in July 2006, Professor Peterson served for six years as provost at Rensselaer Polytechnic Institute in Troy, New York. He received his BS in mechanical engineering in 1975, a BS in mathematics in 1977, and an MS in engineering in 1980, all from the Kansas State University, and a PhD in mechanical engineering from Texas A&M University in

1985. In 1981 and 1982, Professor Peterson was a visiting research scientist at the NASA Johnson Space Center, and in 1985 he moved to a faculty position in the mechanical engineering department at Texas A&M University, where he conducted research and taught courses in thermodynamics and heat transfer. In 1990, he was named the Halliburton Professor of Mechanical Engineering and in 1991 was named the College of Engineering's Tenneco Professor. In 1993, Professor Peterson was invited to serve as the Program Director for the Thermal Transport and Thermal Processing Division of the National Science Foundation (NSF) where he received the NSF award for outstanding management. From June 1993 through July 1996, he served as head of the Department of Mechanical Engineering at Texas A&M University and in 1996 was appointed to the position of executive associate dean of the College of Engineering, where he also served as the associate vice chancellor for the Texas A&M University system. Before joining Texas A&M University, Professor Peterson was head of the General Engineering Technology Department at Kansas Technical Institute (now Kansas State University, Salina).

Throughout his career, Professor Peterson has played an active role in helping to establish the national education and research agendas, serving on numerous industry, government, and academic task forces and committees. In this capacity, he has served as a member of a number of congressional task forces, research councils, and advisory boards, most recently serving as a member of the board of directors and vice president for education for the AIAA. In addition, he has served in a variety of different roles for federal agencies, such as the Office of Naval Research (ONR), the National Aeronautics and Space Administration (NASA), and the Department of Energy (DOE), and for national task forces and committees appointed by the National Research Council (NRC) and the National Academy of Engineering (NAE). He is currently serving on a number of national groups whose focus is on postsecondary education, such as the American Association of Colleges and Universities, the Middle States Commission on Higher Education, and the New England Association of Schools and Colleges, where he is currently serving as accreditation team chair.

A fellow of both the ASME and AIAA, Professor Peterson is the author/coauthor of 12 books/book chapters, 160 refereed journal articles, more than 150 conference publications, and holds 8 patents. He has been an editor or associate editor for eight different journals and is currently serving on the editorial advisory board for two other journals. He is a registered professional engineer in the state of Texas, and a member of Pi Tau Sigma, Tau Beta Pi, Sigma Xi, and Phi Kappa Phi societies. He has received several professional society awards, which include the Ralph James and the O.L. Andy Lewis awards from ASME, the Dow Outstanding Young Faculty Award from ASEE, the Pi Tau Sigma Gustus L. Larson Memorial Award from ASME, the AIAA Thermophysics Award, the ASME Memorial Award, the AIAA Sustained Service Award, and the Frank J. Malina Award from the International Astronautical Society. While at Texas A&M, Professor Peterson was selected to receive the Pi Tau Sigma, J. George H. Thompson Award for excellence in undergraduate teaching and the Texas A&M University Association of Former Students Outstanding Teaching Award at both the college and university levels.

Nomenclature

A, A_c	cross-sectional area
a	lattice constant
a_λ	absorption coefficient
B	body force term
C, c	specific heat
C_p, c_p	specific heat at constant pressure
C_v, c_v	specific heat at constant volume
C_f	specific heat of the film
C_l	specific heat of the liquid
C_{sub}	specific heat of the substrate
C_f	skin friction coefficient
c_o	light velocity in vacuum
c_T	speed of temperature propagation
D	diffusion coefficient
D_h	hydraulic mean diameter
d	one side of a channel
dA	strip area
E	energy of a quantized energy packet
E_l	total energy of the liquid per unit volume $[E_l = \rho_l(C_l T + 1/2u_l^2)]$
E_v	total energy of the vapor per unit volume
E_o	original amplitude of electric field $[E_v = \rho_v(C_v T + 1/2u_v^2)]$
F	force vector
f	friction coefficient
f	particle distribution function
f_o	Fermi–Dirac distribution function
G	mass velocity
g	gravitational constant
g^*	imposed acceleration in reduced units
Gr	Grashof number
H	height
H_c	channel height
h	heat transfer coefficient
h	Planck's constant
h_{fg}	latent heat of vaporization
h_l	local heat transfer coefficient
h_o	heat transfer coefficient at the condenser
i	grid number in x-direction
j	grid number in y-direction

k	thermal conductivity
k^*	thermal conductivity ratio with respect to copper
k_{conv}	convective component of thermal conductivity
k_{CP}	thermal conductivity according to Cahill–Pohl model
k_E	thermal conductivity according to Einstein's model
k_{eff}	effective thermal conductivity
k_f	thermal conductivity of the fluid
k_f	film component of thermal conductivity
k_g	lattice component of thermal conductivity
k_m	measured thermal conductivity of metallic crystal
k_p	thermal conductivity of particle
k_φ	molecular vibration component of thermal conductivity
k_n	thermal conductivity in direction n
k_s	thermal conductivity of substrate
k_{sub}	substrate component of thermal conductivity
k_{ph}	phonon wave vector
Kn	Knudsen number
L	characteristic length
L	length of the heat pipe
L	length of fin array
L_c	condenser section length
L_e	evaporator section length
L_e	entrance length
L_h	hydrodynamic entry length
L_t	thermal entry length
l	shortest length dimension
M	atomic mass
m	complex refractive index
N	number density of atoms
N	number density of molecules in Equation 2.48
n	number density of atoms
n	direction of heat flux
$\bar{n}$	average number of free electrons per unit volume
n	refractive index
n	real part of complex refractive index
Nu	Nusselt number
P	pressure
ΔP	pressure drop
P'	power dissipation per unit length
p	momentum
Pe	Peclet number
Pr	Prandtl number
P_{sat}	saturation pressure
Q	heat transfer rate

Q_{in}	heat input to the heat sink
Q_{in}*	heat input to the individual micro heat pipe
Q_m	mass flow rate in the microchannel
q, q''	heat flux
q_{in}	heat flux into the heat sink
$q''_{ONB,exp}$	onset heat flux from experiment
$q''_{ONB,mod}$	onset heat flux from model
q_n, q_n''	heat flux in direction n
q_{im}	imaginary part of the wave vector
R	gas constant
R	overall thermal resistance
R	radial coordinate
r	radius of curvature of the meniscus
r	dimensionless thermal resistance
r	position vector
r	radius of curvature of liquid–vapor meniscus
r_0	initial radius of curvature of the meniscus
Re	Reynolds number
Re_{cri}	critical Reynolds number
R_{th}	theoretical thermal resistance
S	fin spacing
S_x	component of Poynting vector in x direction
T, t	temperature
t	time
ΔT	temperature difference
ΔT_{sub}	substrate component of temperature oscillation
T_{amb}	ambient temperature
T_b	bulk temperature
T_w	wall temperature
T_α	free stream temperature
U	dimensionless velocity in x-direction
u	velocity in x-direction
V	dimensionless velocity in y-direction
V, v	velocity
V_{il}	interfacial liquid velocity
V_{iv}	interfacial vapor velocity
V_{tv}	thermal voltage noise
V_z	velocity in the flow direction in Equation 3.12.
V	volume
v	particle velocity
v	sound velocity
$\underline{v}$	velocity in y-direction
v_e	electron velocity
W	width of the metal

We	Weber number ($G^2L/\rho\sigma$)
W_T	width of the substrate
X	dimensionless distance along the x-direction
ΔX	dimensionless grid size in the x-direction
x	distance coordinate
x	displacement of an atom in CP model
Δx	distance
Y	dimensionless distance along the y-direction
ΔY	dimensionless grid size in the y-direction

Greek Symbols

α	ratio of thermal conductivities of particle and base fluid
α	thermal diffusivity
β	coefficient of volumetric expansion
β_i, β_l, β_{lw}	geometric area coefficients
γ	coefficient in Equation 2.38
ζ	Fermi energy
ζ	zeta potential
η	joule heating frequency
θ	dimensionless temperature
θ	nondimensional temperature difference
κ	extinction coefficient
Λ	mean free path
λ	wavelength of the heat carriers
λ_o	wave length in vacuum
λ_{ph}	phonon wavelength
μ, μ_f	dynamic viscosity
μ, μ_1, μ_2	coefficients of viscosity
μ	magnetic permeability
ν	frequency
ν	kinematic viscosity
γ	wave number
Ξ	total energy of phonons
Ξ_{ph}	energy in any phonon mode
ξ	dimensionless vorticity
ρ	density
ρ_f	density of fluid
ρ	electrical resistivity
σ	surface tension
σ	accommodation coefficient
σ	characteristic distance
τ	relaxation time
τ	dimensionless time
$\Delta\tau$	dimensionless time step
Φ	viscous dissipation term
φ	heat generation per unit volume
Ψ	coefficient for heat spreading in the film
ψ	dimensionless stream function
ω	angular frequency
ω_{ph}	phonon angular frequency

Subscripts

0	base
∞	ambient
a	atmosphere
av	average
c	condenser
cav	center line average up to the fin height
e	evaporator
f	fin
fav	fin average
i	interface
j	temperature jump at gas flow boundary
l	liquid
li	liquid interface
lw	liquid wall
max	maximum
s	slip at gas flow boundary
sc	scattering
t	energy
u	momentum
v	vapor
vi	vapor interface
vw	vapor wall
w	wall
x	local

Contents