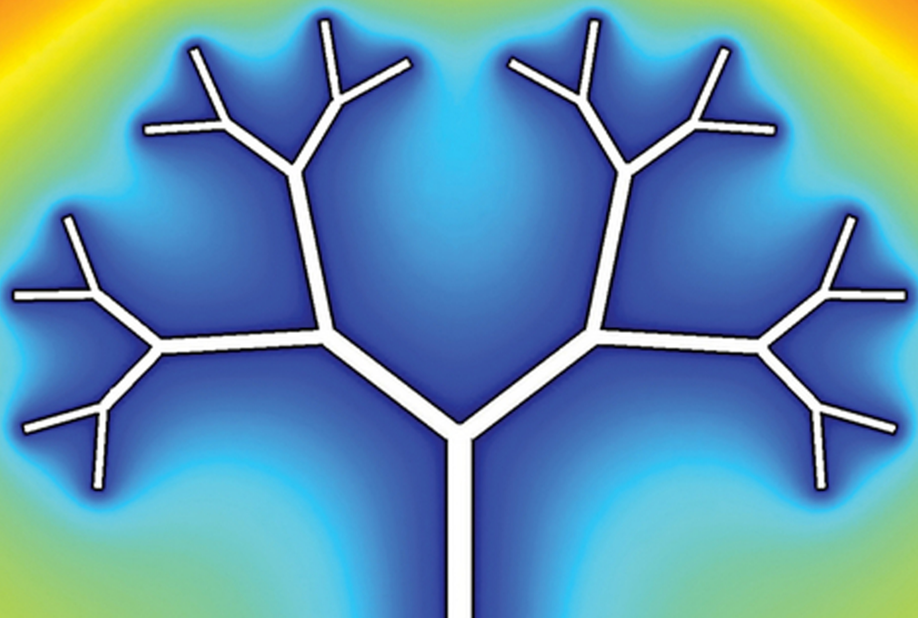
CONVECTION HEAT TRANSFER

FOURTH EDITION



ADRIAN BEJAN

WILEY

CONVECTION HEAT TRANSFER

Other books by Adrian Bejan:

Entropy Generation Through Heat and Fluid Flow, Wiley, 1982.

Advanced Engineering Thermodynamics, Third Edition, Wiley, 2006.

Thermal Design and Optimization, with G. Tsatsaronis and M. Moran, Wiley, 1996.

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Design with Constructal Theory, with S. Lorente, Wiley, 2008.

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Convection in Porous Media, with D. A. Nield, Fourth Edition, Springer, 2013.

CONVECTION HEAT TRANSFER

FOURTH EDITION

Adrian Bejan

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WILEY

Cover image: Courtesy of Adrian Bejan

Cover design: John Wiley & Sons, Inc.

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Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada

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ISBN 978-0-470-90037-6; ISBN 978-1-118-33008-1 (ebk); ISBN 978-1-118-33282-5 (ebk); ISBN 978-1-118-33448-5 (ebk); ISBN 978-1-118-51975-2 (ebk); ISBN 978-1-118-51976-9 (ebk)

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

The entrepreneur, as a creator of the new and a destroyer of the old, is constantly in conflict with convention. He inhabits a world where belief precedes results, and where the best possibilities are usually invisible to others. His world is dominated by denial, rejection, difficulty, and doubt. And although as an innovator, he is unceasingly imitated when successful, he always remains an outsider to the ‘‘establishment.’’

Theodore Forstmann, 2003.

In science, the ‘‘entrepreneur’’ is the one who gets the unusual idea, climbs out on a limb, jumps, and runs with it on the landscape. His fate at the feet of the establishment is the same.

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PREFACE

An author is fortunate if his book is popular enough to merit a second edition somewhere down the line, yet the flow of ideas that grew around this book since the first edition (1988) has been beyond expectations. I will let others comment on this flow. In this brief Preface, I comment on just one feature of the flow of ideas and one bit of history.

The flow of ideas is illustrated by the changes made in this new edition. Good ideas (in this or any other field) attract interesting minds—researchers, educators, and authors with ideas. These minds grow the field the way that the yeast grows the cake. While revising this edition, it was not possible to keep up with this growth, but I tried, even though this meant abandoning some of the material from earlier editions. The new growth is represented by the impact of the science of discovering effective flow configurations (constructal theory and design), the streamlining of the discipline along methods that are direct, muscular, and at the same time lean (scale analysis, intersection of asymptotes, heatlines), the oneness with thermodynamics through the irreversibility (entropy generation) phenomenon, and new references and problems at the end of chapters.

Because we know where convection and thermodynamics come from, this growth illustrates that science (education, knowledge, information) is an evolutionary design [1–4], a flow system that constantly morphs and improves so that our own movement and life are facilitated and extended on the landscape. This is nature, the animate and the inanimate alike.

Because research is autobiographical, good research is a book of wonderful memories. I close this preface with the story of how the first edition of this book was born. It was an accident, literally. At age 33, I was behaving as if I was meant to play basketball forever, and I was wrong. During a game in January 1982, one of my Achilles' tendons was severed, and I ended up in a wheelchair for the entire semester. I had to teach my convection course, for which I had written notes, but this time I was forced to write each lecture on transparencies, for the screen. My first graduate student, Shigeo Kimura, now professor at Kanazawa University, Japan, was my teaching assistant. He would wheel me into the classroom every morning, and my convection book would come to life, one original drawing at a time, one original (solved) problem after another. One such problem was the method of intersecting the asymptotes and the back-of-the-envelope prediction of optimal spacings (Problem 11, Chapter 4, p. 157, in the first edition).

There was so much richness during the spring of 1982 that the accident was a blessing.

Adrian Bejan

Duke University

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PREFACE TO THE THIRD EDITION

Research is autobiographical. I often say this when I lecture, and I find it true as I look at this new edition of *Convection Heat Transfer*. It is even more true as I look at all three editions together. This book is a chronicle of the heat transfer side of my career, the methods I developed and taught along the way, and the great fortune I had to work with extremely gifted colleagues. The three editions are also a story of how the field has grown and prospered. It has done so based on new challenges and especially, new ideas.

One trend that is made visible (and useful, I hope) in this edition is the new emphasis on *design as science*—the generation of flow configuration based on principle. For many years, the field of convection was preoccupied with documenting the transport characteristics of various but simple flow configurations—relationships between temperature differences and heat transfer rates. This information is essential in the modeling and simulations that are necessary in design. The reality, however, is harsh: Constraints exist, and one overriding constraint is space (size, volume, weight). Putting more and more heat transfer into a given volume has been the objective, from the compact heat exchangers of my MIT years to the heat transfer augmentation techniques and the cooling of electronics packages of today. Doing more with limited resources has been the driving force.

Miniaturization marches forward, but this is not even half of the story. The reason is that the devices we touch must be made at our scale—they must be macroscopic, no matter how small the smallest components. The more successful we are in making smaller components, the greater the challenge to install larger numbers of such components and to connect them with currents (heat, fluid, electricity), to keep them *alive*. The challenge is to ‘‘construct,’’ to assemble and design while assembling (i.e., to design complexity and to *deduce* the flow configuration of the macroscopic device).

Construction must be shouted from the rooftops, especially today as the crowd marches toward smaller scales. To construct is to proceed in the opposite direction, from small to large, because only in this direction can the small scales be made useful. Only after the achievement of constructal assembly can small-scale components deliver high densities of heat transfer.

In this new edition, the first steps toward constructs with high heat transfer density are used as an introduction to *constructal theory and design**: the generation of flow architecture in the pursuit of maximal global performance subject to global constraints, when the flow architecture is free to morph. The focus is on method, on design as science, on the generation of optimal and complex architectures based on the constructal law. To emphasize this facet of the third edition is appropriate not only because of its importance today, but also because it had its start in the 1984 edition [see the optimization of spacings with natural convection (p. 157, Problem 11, Chapter 4).

The focus on methodology is why in this new edition I chart the progress made by three other methods that were pioneered in the 1984 edition. These methods have become recognized and now occupy growing sections of the literature:

The intersection of asymptotes method, which delivered in amazingly direct fashion the optimal spacing for natural convection (see above), has since been extended to spacings for forced convection and the constructal theory prediction of all the basic features of Bénard convection. The intersection of asymptotes is also useful pedagogically, in the teaching of the concept of *transition* (e.g., laminar–turbulent flow, natural–forced convection).

Heatlines are now being used to visualize the true paths followed by convection: the paths of energy flow, not fluid flow. They were introduced in the 1984 edition, with an example of natural convection in an enclosure. The concept has since been extended to mass transfer and a variety of basic and applied configurations with natural and forced convection in fluids and fluid-saturated porous media. This method of visualization is particularly well suited for computational heat transfer and should be included in commercial computational packages.

Scale analysis continues to be the main method for teaching the basics of convection in this new edition. The rules and promise of scale analysis as a problem-solving method were first formulated in the 1984 edition. Today the method is used widely, and this makes it even more essential in a basic course of convection. The increased importance of scale analysis is also due to the proliferation of computational heat transfer. If done correctly, scale analysis can shed light on what the deluge of numerical results is trying to tell us. Even more, to teach scale analysis is to remind the student not to give up on pencil and paper. Not everything must be done on the computer.

Porous media were brought into a heat transfer course for the first time by the 1984 edition of this book. Since then, convection in porous media has developed into a field of its own. In this edition we continue to emphasize the basic method and the most basic results. A connection is also made between porous media and

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*A. Bejan, *Shape and Structure, from Engineering to Nature*, Cambridge University Press, Cambridge, 2000.

designed complex flow structures,* and this serves as one more bridge to the constructal design method.

Interdisciplinary teaching and research is one of the missions of this course, but with this warning: Learn your disciplines first; only then you will be strong on the interdisciplinary frontiers. The teaching of convection in porous media is a good example. This is presented not as a self-standing subject but as an interaction between principles of convection in pure fluids, which we all learn, and newly emerging technological applications that employ porous flow structures.

In my work on this new edition I benefited from the help and ideas offered by Professors C. Biserni, J. Bonjour, I. Dincer, M. Feidt, D. Gobin, Y. Fautrelle, S. J. Kim, A. D. Kraus, S. Lorente, E. Lorenzini, G. Lorenzini, N. Mazet, F. Meunier, A. F. Miguel, W. J. Minkowycz, P. Neveu, D. A. Nield, A. H. Reis, E. Sciubba, B. Spinner, F. B. Tehrani, J. V. C. Vargas, M. E. Weber, and C. Zamfirescu. In particular, I wish to thank my doctoral students Y. Azoumah, T. Bello-Ochende, A. K. da Silva, L. Gosselin, J. C. Ordonez, Luiz A. O. Rocha, and W. Wechsatol.

ADRIAN BEJAN

Durham, North Carolina
April 2004

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*A. Bejan, I. Dincer, S. Lorente, A. F. Miguel, and A. H. Reis, *Porous and Complex Flow Structures in Modern Technologies*, Springer-Verlag, New York, 2004.

PREFACE TO THE SECOND EDITION

I want to thank John Wiley & Sons, Inc. and the users of my *Convection Heat Transfer* for giving me this opportunity to prepare a second edition. The changes and additions that I made are due to the suggestions received from many colleagues and students, and to the evolution of my own research activity.

I made changes in both format and content. The format is now based on numbered sections and equations, to make it easier for the first-time user to use this book as a reference. I assembled all the symbols in a list that precedes the text. The Author Index acknowledges one more time the individuals whose work is quoted in the text. The Solutions Manual is now produced on the word processor, and has the appearance of a companion book.

The changes in content are more significant and at more than one level. New topics covered in the second edition are convection with change of phase (condensation, boiling, melting), the cooling of electronic packages by forced and natural convection, lubrication by contact melting, and several examples of conjugate heat transfer, i.e., convection coupled with conduction or radiation. I augmented most chapters with results, namely, formulas, tables, charts, and appendixes that are recommended for use in engineering design work. And, speaking of design, many of the new problems at the end of chapters refer to basic principles of thermal design.

Relative to the first edition, the chapters dealing with laminar and, especially, turbulent forced convection have been expanded. To make room for the new material and still respect the prescribed space limits, I had to eliminate the chapter on numerical methods, and to condense the treatment of convection in porous media. Numerical methods are now covered in courses devoted entirely to computational fluid dynamics and heat transfer. For porous media, I recently completed with Professor D. A. Nield a separate textbook, *Convection in Porous Media* (Springer, 1992; now in 4th edition, 2013).

As in the first edition, the most important feature of this book is that many of the topics and problems came from my own research. These problems recommended themselves as interesting and beautiful, i.e., worthy of study. They represent my argument in favor of practicing *laissez faire* in engineering research, and against the *dirigiste* policy advocated by others.

ADRIAN BEJAN

Durham, North Carolina
June 1994

PREFACE TO THE FIRST EDITION

My main reason for writing a convection textbook is to place the field's past 100 years of growth in perspective. This book is intended for the educator who wants to present his students with more than a review of the generally accepted ‘‘classical’’ methods and conclusions. Through this book I hope to encourage the convection student to question what is known and to think freely and creatively about what is unknown.

There is no such thing as ‘‘unanimous agreement’’ on any topic. The history of scientific progress shows clearly that our present knowledge and understanding—contents of today's textbooks—are the direct result of conflict and controversy. By encouraging our students to question authority, we encourage them to make discoveries on their own. We can all only benefit from the scientific progress that results.

In writing this book, I sought to make available a textbook alternative that offers something new on two other fronts: (1) content, or the selection of topics, and (2) method, or the approach to solving problems in convection heat transfer.

Regarding content, this textbook reflects the relative change in the priorities set by our technological society over the past two decades. Historically, the field of convective heat transfer grew out of great engineering pursuits such as energy conversion (power plant technology), the aircraft, and the exploration of extraterrestrial space. Today, we are forced to face additional challenges, primarily in the areas of ‘‘energy’’ and ‘‘ecology.’’ Briefly stated, engineering education today places a strong emphasis on man's need to coexist with the environment. This new emphasis is reflected in the topics assembled in this book. Important areas covered for the first time in a convection textbook are: (1) natural convection on *an equal footing* with forced convection, with application to energy conservation in buildings and to geophysical dynamics, (2) convection through porous media saturated with fluid, with application to geothermal and thermal insulation engineering, and (3) turbulent mixing in free-stream flow, with application to the dispersion of pollutants in the atmosphere and the hydrosphere.

Regarding method, in this book I made a consistent effort to teach problem solving (a *Solutions Manual* is available from the publisher or from me). This book is a textbook to be used for teaching a course, not a handbook. Of course, important engineering results are listed; however, the emphasis is placed on the thinking that leads to these results. A unique feature of this book is that it stresses the importance of correct scale analysis as an eligible and cost-effective method of solution, and as a precondition for more refined methods of solution. It also stresses the need for correct scaling in the graphic reporting of more refined analytical results and of experimental and numerical data. The cost and the ‘‘return on investment’’ associated with a possible method of solution are issues that each student-researcher should examine critically: these issues are stressed throughout the text.

I wrote this book during the academic year 1982–1983, in our mountain-side house on the greenbelt of North Boulder. This project turned out to be a highly rewarding intellectual experience for me, because it forced upon me the rare opportunity to think about an entire field, while continuing my own research on special topics in convection and other areas (specialization usually inhibits the ability to enjoy a bird’s-eye-view of anything). It is a cliché in education and research for the author of a new book to end the preface by thanking his family for the ‘‘sacrifice’’ that allowed completion of the work. My experience with writing *Convection Heat Transfer* has been totally different (i.e., much more enjoyable!), to the point that I must thank this book for making me work at home and for triggering so many inspiring conversations with Mary. Convection can be entertaining.

ADRIAN BEJAN

Boulder, Colorado
July 1984

LIST OF SYMBOLS

a, b	dimensions of rectangular duct cross section (Fig. 3.5)
A	area
A_c	cross-sectional area
A, B	constants in the logarithmic law of the wall [eqs. (7.41) and (7.42)]
Ar	Archimedes number [eq. (10.80)]
b	empirical constant, Forchheimer flow [eq. (12.15)]
b	natural convection parameter [eq. (5.117)]
b	radial length scale of round velocity jet [eq. (9.40)]
b	stratification parameter [eq. (12.116)]
b	taper parameter [eq. (2.140)]
b	thermal stratification number [eq. (4.81)]
b_T	radial length scale of round thermal jet [eq. (9.43)]
$\tilde{b}_{1,2}$	empirical factors (Table 11.6)
B	condensation driving parameter [eq. (10.26)]
B	cross-sectional shape number (Fig. 3.7)
B	dimensionless group [eq. (2.147)]
B	dimensionless group [eq. (12.107)]
Be_L	Bejan number, pressure drop number [eq. (3.120′)]
Be_p	Bejan number for a porous medium [eq. (12.113)]
Bo_H	Boussinesq number [eq. (4.35)]
c	specific heat of incompressible substance
c_v	specific heat at constant volume
c_P	specific heat at constant pressure
$c_{1,2}$	constants
C	compressive impulse or reaction [eq. (6.7)]
C	concentration [eq. (11.1)]
C	constant
$C_{f,x}$	local skin friction coefficient [eqs. (2.57) and (7.52)]
C_n	factor (Fig. 7.11)
C_1, C_2, C_μ	constants [eq. (8.61)]
C_D	drag coefficient [eq. (7.103)]
C_{sf}	constant (Table 10.1)
d, D	diameter
D	mass diffusivity [eq. (11.24), Tables 11.1 and 11.2]
D	plate-to-plate spacing (Fig. 3.1)
D	stream transversal length scale
D_h	hydraulic diameter [eq. (3.26)]
D_{k-k}	knee-to-knee thickness of time-averaged turbulent shear layer (Fig. 9.3)

D_T	distance of maximum thermal penetration in the y direction, in the vicinity of a direct contact spot [eq. (7.94)]
e	specific energy (labeled u in Table 1.1)
f	Blasius streamfunction similarity profile [eq. (2.80)]
f	factor [eq. (7.113)]
f	friction factor [eq. (3.24)]
f	porous medium friction factor [eq. (12.12)]
f	roll thickness [eq. (5.92)]
f_u	curve fit for the velocity profile [eq. (7.53)]
f_v	frequency of vortex shedding [eq. (7.102)]
F	force
F	streamfunction similarity profile [eqs. (4.60) and (12.139)]
Fo	Fourier number [eq. (10.104)]
F_D	drag force
F_n	normal force
F_t	tangential force
g	gravitational acceleration
Gr_H	Grashof number [eq. (4.38)]
Gr_*	Grashof number based on heat flux (Table 6.1)
Gz	Graetz number [eq. (3.107)]
$G_{\pounds}$	constant (Table 4.3)
h	heat transfer coefficient [eq. (2.4)]; local heat transfer coefficient [eq. (2.100)]
h	specific enthalpy
h_{fg}	latent heat of condensation or evaporation (Table 10.2)
h'_{fg}	augmented latent heat [eq. (10.10)]
h''_{fg}	augmented latent heat [eq. (10.41)]
h_m	mass transfer coefficient [eq. (11.46)]
h_{sf}	latent heat of melting
H	enthalpy flow rate [eq. (10.5)]
H	heatfunction [defined via eqs. (1.68) and (1.69)]
H	height
H	Henry's constant [eq. (11.35) and Table 11.3]
I	area moment of inertia
I	integral [eq. (3.135)]
j	diffusion flux [eq. (11.20)]
j_{app}	apparent mass flux [eq. (11.102)]
J	dimensionless thickness parameter [eq. (2.139)]
Ja	Jakob number [eq. (10.19)]
k	thermal conductivity
k	wave number
$k''_n,\ k'''_n$	reaction rates [eqs. (11.135) and (11.136)]
k_s	sand grain size [eq. (8.16)]

K	jet strength [eq. (9.33)]
K	permeability [eq. (12.9)]
$K_{1,2}$	constants
l	effective length [eq. (4.127)]
l	mixing length [eq. (7.27)]
L	length
L	length of direct viscous contact [eq. (7.92)]
L_c	characteristic length
ℓ	equivalent length [eq. (10.86)]
L_m	length of direct thermal contact [eq. (7.95)]
£	effective length [eq. (4.128)]
Le	Lewis number [eq. (11.93)]
m	exponent in flow over a wedge [eq. (2.124)]
m	function [eq. (6.27)]
m	profile shape function for integral analysis [eq. (2.54)]
$\dot{m}$	mass flow rate
$\dot{m}'$	mass transfer rate per unit length [eq. (11.52)]
$\dot{m}'''$	volumetric mass generation rate [eq. (11.15)]
M	bending moment [eq. (6.8)]
M	function [eq. (8.22)]
M	impulse or reaction force due to fluid flow into or out of a control volume (Fig. 2.3)
M	mass
M	massfunction [eqs. (11.133)–(11.134)]
M	material constraint [eq. (3.132)]
M	molar mass [eq. (11.4)]
n	dimensionless coordinate across the velocity boundary layer (y/δ) [eq. (2.54)]
n	number of cylinders
n	number of heat-generating boards
n	number of moles [eq. (11.4)]
n_l	number of rows
N_B	buckling number [eq. (6.14)]
N_{tu}	number of heat transfer units [eq. (8.56)]
Nu	local Nusselt number [eq. (2.101)]
Nu	Nusselt number in the fully developed region [eq. (3.52)]
$\overline{\mathrm{Nu}}$	overall Nusselt number
$\overline{\mathrm{Nu}}_L^0$	constant (Table 4.3)
Nu_{0-x}	overall Nusselt number [eq. (3.91)]
Nu_x	local Nusselt number in the developing (entrance) region [eq. (3.90)]
p	dimensionless coordinate across the thermal boundary layer (y/δ_T) [eq. (2.58)]
p	even function (eq. (5.37)]

p	wetted perimeter
P	pressure
P_∞	pressure in the free stream
Pe_D	Péclet number (UD/α)
Pe_L	Péclet number ($U_\infty L/\alpha$)
Po	Poiseuille number ($f\,\mathrm{Re}_{Dh}$)
Pr	Prandtl number (ν/α)
Pr_p	porous medium Prandtl number [eq. (12.215)]
Pr_t	turbulent Prandtl number [eq. (7.66)]
q	heat transfer rate (W)
q	odd function [eq. (5.37)]
q'	heat transfer rate per unit length (W/m)
q''	heat flux (W/m^2)
q''_{app}	apparent heat flux [eq. (7.24)]
$q''_{0,\max}$	maximum heat flux, under a direct thermal contact spot [eq. (7.86)]
q'''	rate of internal heat generation (W/m^3)
$\dot{Q}$	heat transfer rate (W)
Q	flow rate (m^2/s) [eq. (10.69)]
r	radial coordinate
r_0	tube radius
r_h	hydraulic radius [eq. (3.26)]
r, θ, z	cylindrical coordinates (Fig. 1.1)
r, ϕ, θ	spherical coordinates (Fig. 1.1)
R	ideal gas constant
$\overline{R}$	universal gas constant
R	radius
R	thermal resistance
Ra_H	Rayleigh number [eq. (4.25)]
Ra_y	Darcy modified Rayleigh number [eq. (12.89)]
$\mathrm{Ra}_{m,y}$	mass transfer Rayleigh number [eq. (11.86)]
Ra_q	Rayleigh number based on source strength [eq. (6.6)]
Ra_{*H}	Rayleigh number based on heat flux [eq. (4.70)]
Ra_{*y}	Darcy modified Rayleigh number based on heat flux [eq. (12.99)]
Re_D	Reynolds number (UD/ν)
Re_{Dh}	Reynolds number based on hydraulic diameter (UD_h/ν)
Re_l	local Reynolds number [eq. (6.15)]
Re_L	Reynolds number ($U_\infty L/\nu$)
Re_t	terminal Reynolds number [eq. (10.37)]
s	constant (Table 10.1)
s	specific entropy
s	thickness of liquid zone (Fig. 10.24)
S	entropy (J/K)