HEAT TRANSFER

A problem solving approach

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and Thomas Grassie

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Taylor & Francis
Taylor & Francis Group
NEW YORK AND LONDON

First published 2003
by Taylor & Francis
11 New Fetter Lane, London EC4P 4EE

Simultaneously published in the USA and Canada
by Taylor & Francis
29 West 35th Street, New York, NY 10001

Taylor & Francis is an imprint of the Taylor & Francis Group

Typeset in Sabon by
Newgen Imaging Systems (P) Ltd, Chennai, India
Printed and bound in Great Britain by
MPG Books Ltd, Bodmin, Cornwall

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

Library of Congress Cataloging in Publication Data
A catalog record for this book has been requested

ISBN 0–415–24169–3

To Jameela, Amanda, and Gillean

Thank you for your forbearance!

Highlights of the book

Modern books on most engineering subjects are increasingly being written for a computer literate audience. Hence, nowadays, it is a common practice to use a hard–soft publishing format. This book uses the MS-Excel medium for the development of workbooks that are available on the companion CD-ROM. A sample of the workbooks is also available from the website: http://www.napierengineering.org.uk/research/heatxfer/heatxfer.html

The highlights of this book are:

(i) Clear and concise text that presents the physical theories for selected topics in thermal conduction, convection, and radiation.
(ii) Mathematical rigour maintained throughout the book.
(iii) Latest available regression models for convection heat transfer.
(iv) Use of a standard spreadsheet package for solving involved problems.
(v) Extensive use of numerical experimentation which enables the reader to develop the understanding of the critical parameters.
(vi) Thermophysical properties of common substances made available as digital files.
(vii) A comprehensive thermodynamic software package, 'Allprops' provided, courtesy of the University of Idaho.

Some of the key features of the accompanying workbooks are:

- Rapid, step-wise computations with dynamically linked graphs that enable numerical experimentation.
- All matrix operations handled with ease.
- Solution of non-linear system of equations experienced in multi-mode heat transfer.
- Solution to linear and non-linear optimisation problems.
- Electronic look-up tables for transport and thermodynamic properties.
- Facility for user-developed T–s and p–h charts for visualisation of thermodynamic property change.
- Conjoining of thermodynamic and thermal transfer regimes for heat exchanger design problems.

- Finite element approach to obtain radiation view factors.
- Use of in-built Visual Basic for Applications (VBA) language for handling complex iterative tasks.
- Use of Graphical User Interface (GUI) for solving one- and two-dimensional (Cartesian) conduction problems, producing temperature raster plots and exploring accuracy dependence on mesh size.

Preface

The main purpose of this book is to give a lucid account of the theoretical developments in the field of Heat Transfer while attempting to present the latest available computational methods, particularly within the convection heat transfer discipline. The text would be suitable for an undergraduate as well as postgraduate course.

It is fair to say that while thermal conduction and thermal radiation heat transfer disciplines have reached a plateau in terms of their evolution, convection transfer, due to its empirical nature, still enjoys an ongoing development phase with regression models being added within the forced- and free-convection domains. In all fairness to conduction and radiation disciplines their development under physical laws has helped them acquire rapid maturity. As a matter of fact even fifty years ago thermal radiation development was considered 'dead', the space exploration programme being instrumental in its brief revival. On the other hand, following the explosion of activity within solid mechanics finite element techniques, convection in particular has gained prominence with the use of Computational Fluid Dynamics (CFD) development. This has led not only to solution of convection problems for complex geometries, but also, it has been responsible for new, more involved regression models that offer ease of application and enhanced accuracy.

The new generations of engineering students need new type of working textbooks that enable their training to be completed at a faster pace without compromising the quality of education. The emphasis has therefore shifted from a teaching to a learning mode. The authors hope that by taking away the tedium of repetitive calculation, by providing general-purpose software, the reader will be able to concentrate more on the learning and numerical experimentation part.

The origins of this book lie in the work previously undertaken at Napier University. Pedagogical experiments have been devised at this institution with control groups of engineering students' with- and without access to software. In each case their performance was monitored. It was found that a significant improvement in a student's learning and problem-solving capability results with the use of software that is not too demanding in terms of its own training.

Due to its very nature engineering heat transfer poses problems that often require iterative solution. With this in view the book has a numerical solution slant. The book covers the fundamental and constituent areas of engineering heat transfer – conduction, convection, and thermal radiation. The necessary rigour for understanding the physical principles and analysis is backed up with a number of computer workbooks, each respectively dealing with a given computational aspect and catering the solution of a particular problem type. The accompanying software also allows the reader to perform numerical experimentation – changes may be made to independent variables and their effects seen readily via numerical and graphical outputs. Furthermore, identification of strong and weak variables is possible.

A contributing factor for the present development is the emerging use of computer spreadsheet environment for engineering computation. To quote E. M. Forster, 'The only books that influence us are those for which we are ready, and have gone a little farther down our particular path than we have yet gone ourselves'. The simplicity of data entry and its manipulation afforded by spreadsheets makes it an ideal design and analysis tool. Modern spreadsheet software offers very powerful numerical and decision making facilities. Almost every engineering student and professional has a spreadsheet loaded on his or her computer. This book exploits this situation to fill the gap between the ability to perform involved calculations and the desire to do so without going to the tedium of writing one's own software.

Another advantage offered by the spreadsheet medium is that each formula is readable, and fits in its appropriate position, that is, the spreadsheet cell. This enables the user to easily follow the algorithmic chain. On the other hand commercially available software, while powerful, does not allow the user the facility to examine or alter the computer code. In many cases such commercial or shareware software, due to its very design, may take several weeks and months of training. Owing to their widespread use and user-friendly layout, spreadsheets require only a few minutes training before the user is fully in charge of the situation. This point shall be demonstrated in Chapter 2 where more sophisticated features of Microsoft Excel shall be introduced.

The production of text has also provided the authors with an opportunity to explore the frontiers of the MS-Excel medium to handle quite involved problems. In this respect the authors are indeed grateful to the publishers for providing such an opportunity. Highlights of the present text are presented in a companion section.

The authors would like their readers to feel that they are participating in a hands-on seminar rather than attending a lecture. In this context it is to be emphasised that the present book is inter-active. The hard-soft combination of material presented here is, we hope, 'just the beginning'. In due course there is bound to be much more activity for this type of presentation where the boundary between the author and the reader starts to become blurred. The reader may then be able to take the book onward to a different plane! Indeed we hope that the readers will communicate with the authors and suggest ways of further improving text, particularly the material related to numerical computation and convection regression modelling part. In this respect the authors are looking forward to learning from the readers.

The solution techniques presented herein are of such a nature that they may easily be incorporated in the solution of other thermophysical problems, that is, fluid mechanics, thermodynamics, refrigeration, and air-conditioning.

The greatest problem in the preparation of this book has been to avoid the unnecessary repetition of what has been said elsewhere, while at the same time making each individual chapter comprehensive. Topics, which demand more extensive reading for complete understanding, have therefore been treated in sufficient detail, even if referenced elsewhere in a prior chapter.

Acknowledgements are gratefully made here to colleagues and others whose work has been drawn upon when preparing the text. Additional and express acknowledgement is further made to those works that have been extensively used via references and bibliography.

The authors welcome suggestions for additions or improvements.

Acknowledgements

The authors are indebted to a number of individuals for their support. Professor Steve Penoncello of the University of Idaho for furnishing the 'Allprops' thermodynamic property software for inclusion in our book's companion CD. Dr David Kinghorn prepared the first drafts of Chapters 7 and 8. Dr Nasser Abodahab and Ms Alison Murdoch furnished some elementary material and their contribution is acknowledged. Our research students Muhammad Asif and Xiaodong Zhang undertook the task of checking all Microsoft Excel workbooks. Steven Paterson efficiently prepared all drawings. The publishers Tony Moore and Sarah Kramer have been very patient with us, we owe them our heartfelt thanks.

The completion of this book was made possible due to a generous grant from Napier University. We have also been influenced by a number of concurrent heat transfer publications and it is only fair to cite those key references: Heat Transfer by J P Holman, McGraw-Hill; Fundamentals of Heat and Mass Transfer by F P Incropera and D P DeWitt, Wiley; Engineering Heat Transfer by N V Suryanarayana, West Publishing Company; Heat Transmission by W H McAdams, McGraw-Hill; Conduction Heat Transfer by Carslaw and Jaeger, Oxford University Press; Thermal Radiation Heat Transfer by R Seigel and J R Howell, Taylor & Francis.

The following references were the basis for generation of thermophysical tables that have been used within numerous Excel workbooks in this publication, the authors remain grateful to the respective sources: ASHRAE Handbook of Fundamentals (1977), American Society of Heating, Refrigerating, and Air-Conditioning Engineers; Fundamentals of Heat and Mass Transfer (2002), F P Incropera and D P DeWitt, Wiley (for properties of saturated water, based on the work P E Liley: Steam tables in SI units, Purdue University (1978); NBS/NRC Steam tables: Thermodynamic and transport properties and computer programs for vapor and liquid states of water in SI units (1984), L Haar, J Gallagher and S Kell, Hemisphere Publishing Corporation; and CRC Handbook of tables for applied engineering science (1977), R E Boltz and G E Tuve, CRC Press.

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Contents of companion CD-ROM

There are two sub-folders within the main 'HT_MKG' folder: 'HT_Workbooks' and 'Allprops'. The former contains Excel workbooks that enable the user to go through the examples given in the hardcopy as well as solve the problems given at the end of each chapter. The latter folder 'Allprops' contains a special software tool for thermodynamic properties, provided by the University of Idaho.

Microsoft Excel Workbooks on CD-ROM sub-folder 'HT_Workbooks'

List of Workbooks (unless mentioned otherwise, all files have a '.xls' extension

Ex02-04-01	Sequential computation for pressure drop calculation
Ex02-05-02	Lookup tables
Ex02-06-01	Three point quadratic interpolation for equally spaced data points
Ex02-06-02	Four point cubic interpolation for equally spaced data points
Ex02-07-01	Dynamic graphs
Ex02-08-01	Two dimensional lookup table for steam/water substance
Ex02-09-01	Solution of a non-linear algebraic equation via **Goal Seek**
Ex02-10-01	Solution of a non-linear algebraic equation via False Position method
Ex02-12-01	Matrix operations
Ex02-16-01	Fitting linear models via graphical means
Ex02-17-01	Multi-variable function minimisation via **Solver**
Ex02-20-01	Outlier analysis
Ex02-21-01	Weighted averages for a given data set
Ex03-05-01	Composite wall with three sections
Ex03-05-02	Complex composite wall
Ex03-07-01	Long composite axi-symmetric cylinder with three sections

Additional data files

Workbooks available from website

In due course in response to readers' request further material may be added by the authors by means of uploading files on this book's websites: http://www.napierengineering.org.uk/research/heatxfer/heatxfer.html, http://www.soe.napier.ac.uk/research/heatxfer/heatxfer.html

Presently, the following MS-Excel workbooks are available from the above website free of charge:

Ex03-07-02.xls	Critical thickness of thermal insulation
Ex04-02-01.xls	Rectangular duct with a coarse grid
Ex04-02-02.xls	Rectangular duct with a finer grid
Ex07-02-06.xls	Hot wire anemometer: Measurement of fluid velocity
Ex08-02-01.xls	Free-convection – vertical plate
Ex10-02-01.xls	Simultaneous forced-convection and radiation
Steamchart1.xls	Temperature-entropy chart for water/steam substance

Highlights of the book and text related to the above sample heat transfer problems are provided in 'Web_examples.doc' file.

Notation

A	area
Bi	finite difference form of the Biot number
C	Celsius
c	specific heat/speed of light in a medium (in a vacuum $c_0 = 2.988 \times 10^8$ m/s).
C_f	friction coefficient
c_p	specific heat capacity at constant pressure
c_v	specific heat capacity at constant volume
D	diameter
D_h	hydraulic mean diameter
E	internal thermal energy/total emissive power of a gray surface
f	friction factor/similarity variable/frequency
F_{ij}	view factor between surface area elements i and j
F_D	drag force
Fo	finite difference form of the Fourier number
G	irradiation
Gr	Grashof number
Gr*	Grashof number for constant heat flux
h	surface heat transfer coefficient/Planks constant/enthalpy
h_{fg}	enthalpy of vaporisation
I	spectral intensity
J	surface radiosity
K	Kelvin
k	thermal conductivity/Boltzmann constant
L	length/mean beam length/thickness
m	mass flow rate
$\dot{m}$	mass flow rate
N_L	number of tubes in the longitudinal plane in a tube bank
N_T	number of tubes in the transverse plane in a tube bank
Nu	Nusselt number

P	perimeter/power/length of chord between two surfaces
p	pressure
Δp	pressure differential
Pe	Peclet number
Pr	Prandtl number
q	heat flux
Q	heat transfer rate
q_g	rate of heat generation per unit volume
r	radius or radial coordinate
R	thermal resistance, gas constant
Ra	Rayleigh number
Re	Reynolds number
$R_{t,T}$	total thermal resistance
S	surface area
S_D	diagonal pitch of a tube bank
S_L	longitudinal pitch of a tube bank
St	Stanton number
S_T	transverse pitch of a tube bank
T	temperature
t	time or thickness
U	overall heat transfer coefficient
V	velocity/volume/voltage
$\dot{V}$	volume flow rate
W	width
X	distance from leading edge of a plate
x	coordinate
y	coordinate
z	coordinate
Δr	space interval
Δt	time interval
Δx	space interval
Δy	space interval
Δz	space interval

Greek letters

α	thermal diffusivity/absorptivity
β	volumetric thermal expansion coefficient
δ	hydrodynamic boundary layer thickness
δ_T	thermal boundary layer thickness
ε	emissivity, pipe roughness
η	fin efficiency