

Introduction to Heat Transfer

WIT*PRESS*

WIT Press publishes leading books in Science and Technology.

Visit our website for the current list of titles.

www.witpress.com

WIT*eLibrary*

Home of the Transactions of the Wessex Institute, the WIT electronic-library provides the international scientific community with immediate and permanent access to individual papers presented at WIT conferences.

Visit the WIT eLibrary at <http://library.witpress.com>

Introduction to Heat Transfer

Bengt Sundén
Lund University, Sweden

WIT*PRESS* Southampton, Boston



Bengt Sundén

Lund University, Sweden

Published by

WIT Press

Ashurst Lodge, Ashurst, Southampton, SO40 7AA, UK

Tel: 44 (0) 238 029 3223; Fax: 44 (0) 238 029 2853

E-Mail: witpress@witpress.com

<http://www.witpress.com>

For USA, Canada and Mexico

WIT Press

25 Bridge Street, Billerica, MA 01821, USA

Tel: 978 667 5841; Fax: 978 667 7582

E-Mail: infousa@witpress.com

<http://www.witpress.com>

British Library Cataloguing-in-Publication Data

A Catalogue record for this book is available
from the British Library

ISBN (hardback): 978-1-84564-656-1

ISBN (paperback): 978-1-84564-

eISBN: 978-1-84564-657-8

Library of Congress Catalog Card Number: 2011939411

*The texts of the papers in this volume were set
individually by the authors or under their supervision.*

No responsibility is assumed by the Publisher, the Editors and Authors for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions or ideas contained in the material herein. The Publisher does not necessarily endorse the ideas held, or views expressed by the Editors or Authors of the material contained in its publications.

© WIT Press 2012

Printed in Great Britain by Lightning Source, UK.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of the Publisher.

Contents

Nomenclature	xi
Preface	xv
Introduction	1
1 Heat conduction	3
1.1 General theory	3
1.2 Analogy with electric current	4
1.3 Heat conduction equation for an isotropic material	5
1.4 Heat conduction equation in cylindrical coordinates	7
1.5 Heat conduction equation in spherical coordinates	7
1.6 Boundary conditions for heat conduction problems	8
1.7 Anisotropic material	9
References	9
2 Thermal conductivity	11
2.1 Introduction	11
2.2 Gases	13
2.3 Solid substances	15
2.4 Liquids	20
2.5 Influence of pressure on the thermal conductivity	21
References	22
Further reading	22
3 Steady heat conduction	23
3.1 Introduction	23
3.2 Heat conduction across a plane wall	23
3.3 Heat conduction across circular tubes and layers	25
3.4 Heat conduction in a spherical layer	26
3.5 Critical insulation thickness	27
3.6 Plane wall with heat sources (internal heat generation)	29
3.7 Circular rod (or wire) with internal heat generation	30

3.8	Finned heat transfer surfaces	31
3.9	Application of the fin efficiency ϕ in engineering calculations	45
3.10	Limitations in the presented fin theory	46
3.11	Buried electrical cables and hot water pipes	46
	References	52
	Further reading	53
4	Unsteady heat conduction	55
4.1	Introduction	55
4.2	Bodies with very high thermal conductivity	55
4.3	Infinite plate with moderate thermal conductivity	56
4.4	Infinite long circular cylinder or cylinder with insulated end surfaces	64
4.5	Transient radial heat conduction in a sphere	67
4.6	Graphical representation of the amount of heat flow	67
4.7	Two- and three-dimensional solutions	67
4.8	Semi-infinite bodies	73
	References	76
5	Heat conduction with moving boundaries	77
5.1	Introduction	77
5.2	Solidification process where the solid phase has negligible heat capacity	77
5.3	Melting and solidification taking heat capacity into account.	78
	References	81
6	Convection—general theory	83
6.1	Introduction	83
6.2	Continuity equation (mass conservation equation)	84
6.3	Navier–Stokes’ equations	85
6.4	Derivation of the temperature field equation	88
6.5	Basic equations in cylindrical coordinates	90
6.6	Boundary layer equations for the laminar case	91
6.7	Dimensionless groups and rules of similarity	94
	References	96
7	Similarity solutions for laminar boundary layer flow	97
7.1	Introduction	97
7.2	Derivation of flow and temperature distribution equations	97
7.3	Results for the flow and temperature fields	101
7.4	The wall shear stress and the heat transfer coefficient	104

7.5	Analytical expressions for the influence of the Prandtl number.....	106
7.6	The Stanton number.....	108
7.7	The constant c in $U = cx^m$	108
7.8	Linear superposition.....	109
7.9	Blowing and suction at the surface.....	110
7.10	Temperature distribution and heat transfer coefficient when blowing or suction occur at the surface.....	111
7.11	Physical properties.....	113
7.12	Local similarity.....	114
	References.....	114

8 Forced convection in channels—laminar case 117

8.1	Introduction.....	117
8.2	Flow conditions at the entrance region of channels.....	117
8.3	Transition to turbulent flow.....	118
8.4	Circular pipes or tubes.....	119
8.5	Entrance length in circular pipes (tubes).....	119
8.6	The pressure drop over the entrance length.....	119
8.7	The pressure drop for fully developed flow.....	119
8.8	Heat transfer for a circular pipe (tube).....	121
8.9	Heat transfer for noncircular channels.....	130
8.10	Heat transfer when the velocity field is not fully developed.....	130
8.11	Final remarks.....	131
	References.....	131

9 Forced convection—turbulent flow 133

9.1	Introduction.....	133
9.2	Properties of turbulence.....	133
9.3	Methods of analysis.....	134
9.4	About length scales in a turbulent flow.....	134
9.5	The origin of turbulence.....	135
9.6	Equations of motion for turbulent flow.....	135
9.7	Temperature field equation for turbulent flow.....	140
9.8	Boundary layer equations for turbulent flow.....	141
9.9	Turbulent viscosity and turbulent diffusivity.....	142
9.10	Reynolds' analogy.....	143
9.11	The velocity profile in a turbulent boundary layer and in pipe flow.....	144
9.12	Determination of the shear stress coefficient.....	150
9.13	Improvements of Reynolds' analogy.....	155
9.14	Formulas for determination of the heat transfer coefficient for turbulent flow.....	155
9.15	Stanton number for pipe flow.....	157

9.16	Dimensionless or universal temperature profile	158
9.17	Turbulence modeling	160
	References	161
10	Natural convection	163
10.1	Introduction	163
10.2	Natural convection along vertical surfaces	163
10.3	Horizontal circular cylinders	174
10.4	Natural convection for vertical surfaces when the wall heat flux is prescribed	176
10.5	Reference temperature	176
10.6	Natural convection in enclosures	176
10.7	More than two layers	180
10.8	Summary	181
	References	182
11	Forced convective heat transfer for bodies in external flow	183
11.1	Introduction	183
11.2	Flow field around a circular cylinder (tube) in cross flow	183
11.3	Convective heat transfer from a circular cylinder (tube).....	188
11.4	Tube bundles	191
11.5	Pressure drop calculations for a tube bundle in cross flow	193
11.6	Heat transfer from spheres	194
	References	195
12	Thermal radiation	197
12.1	Introduction	197
12.2	Physical mechanism	197
12.3	Properties of thermal radiation	198
12.4	Blackbody radiation	199
12.5	Radiation from nonblackbodies	203
12.6	Radiation intensity	205
12.7	Angle factor, view factor, or shape factor	207
12.8	Radiative exchange between blackbodies	211
12.9	Radiative exchange between nonblackbodies	212
12.10	Simple example	213
12.11	Gas radiation	214
12.12	Mean beam length, equivalent beam length	216
12.13	Radiative heat exchange between a gas and a room with black walls	217
	References	220

13	Condensation	221
13.1	Introduction	221
13.2	General statements	221
13.3	Film condensation along a vertical surface	221
13.4	The Reynolds number	225
13.5	Improvements of the Nusselt film theory for condensation	226
13.6	Film condensation on the outer surface of a horizontal tube and horizontal tube bundles	226
13.7	Condensation inside tubes	227
13.8	Influence of noncondensable gases	229
13.9	Dropwise condensation	229
	References	230
	Further reading	231
14	Boiling and evaporation	233
14.1	Introduction	233
14.2	General	233
14.3	Nukiyama's experiment and the so-called boiling curve	234
14.4	Description of the boiling curve	235
14.5	Temperature distribution in the liquid phase for saturated pool boiling	237
14.6	Nucleate boiling	238
14.7	Film boiling	247
14.8	Minimum heat flux, q_{\min}	248
14.9	Influence of various parameters on the boiling curve	248
14.10	Forced convective boiling for immersed bodies	249
14.11	Forced convective boiling in tubes	250
14.12	Some definitions and relations for two-phase flows	253
14.13	Pressure drop for two-phase flow	254
14.14	Heat transfer and temperature distributions	256
14.15	Additional correlations	260
14.16	Maximum heat flux	261
	References	261
	Further reading	262
15	Heat exchangers	263
15.1	Introduction	263
15.2	Classification of heat exchangers	263
15.3	The overall heat transfer coefficient	271
15.4	The LMTD method for analysis of heat exchangers	272
15.5	The ε -NTU method for analysis of heat exchangers	278

15.6	Condensers and evaporators (boilers).....	283
15.7	Compact heat exchangers.....	283
15.8	Shell-and-tube heat exchangers.....	287
15.9	Plate heat exchangers.....	292
15.10	Regenerative heat exchangers.....	294
	References.....	297
	Further reading.....	298
Addendum 1	Derivation regarding unsteady heat conduction for semi-infinite bodies	299
Addendum 2	Derivation of the complete temperature field equation	303
Addendum 3	Heat transfer at high velocities	309
Addendum 4	Collection of problems in heat transfer	315
Index		341

Nomenclature

A	area [m ²]
a	thermal diffusivity [m ² /s], (eq. (4.5))
a_λ	monochromatic absorption coefficient [-], (eq. (12.48))
Bi	Biot number [-], (eq. (4.5))
Bo	boiling number [-], (eq. (14.69))
b	length, thickness [m]
C	heat capacity flow rate [W/K], (eq. (15.4))
C_D	drag coefficient [-], (eq. (11.1))
C_F	shear stress coefficient [-], (eq. (7.30))
C_p	pressure coefficient [-], Fig. 11.3
c	specific heat [J/(kg K)]
c	propagation velocity for electromagnetic wave motion [m/s]
c_p	specific heat at constant pressure [J/(kg K)]
D	diameter [m]
D_h	hydraulic diameter [m], (eq. (8.8))
d_{ij}	deviatic stress tensor [N/m ²], (eq. (6.12))
E	energy [J]
\dot{E}	energy per time unit [W]
E	emitted radiation energy, emissive power [W/m ²]
E	voltage [V]
E_B	emitted black body radiation [W/m ²], (eq. (12.10))
E_λ	emitted monochromatic radiation emissive power [W/(m ² m)]
e	specific energy [J/kg]
e_{ij}	rate of strain tensor [1/s], (eq. (6.15))
F	force [N]
F	correction factor [-]
F_{ij}	angle factor, view or shape factor [-], (eq. (12.26))
Fo	Fourier number [-], (eq. (4.5))
Fr	Froude number [-], (eq. (14.56))
f	Darcy friction factor [-], (eq. (8.6))
f_s	vortex frequency [s ⁻¹], (eq. (11.2))
G	incident radiation [W/m ²], (eq. (12.5))
G	average mass velocity [kg/(m ² s)]
Gr	Grashof number [-], (eq. (10.4))

Gr^*	modified Grashof number [-], (eq. (10.51))
g	gravity constant [m/s^2]
H	enthalpy [J]
\dot{H}	enthalpy per time unit [W]
h	specific enthalpy [J/kg]
h	Planck's constant [J s], (eq. (12.2))
h_{fg}	latent heat [J/kg]
I	radiation intensity [W/m^2 sr], (eq. (12.20))
I	current [A]
I	momentum [kg m/s]
i, j, k	unit vectors
J	radiosity [W/m^2], (eq. (12.5))
Ja	Jakob number, (eq. (13.26))
j	Colburn factor [-], $St \cdot Pr^{2/3}$
K_c	contraction coefficient [-], (eq. (15.37))
K_e	expansion coefficient [-], (eq. (15.37))
L	length, thickness [m]
L_i	entrance length [m], (eq. (8.4))
$LMTD$	logarithmic mean temperature difference [K], [$^{\circ}C$], (eq. (15.9))
l_m	mixing length [m], (eq. (9.51))
M	molecular weight [kg/kmol]
m	mass [kg]
\dot{m}	mass flow rate [kg/s]
N	number of tube rows
NTU	number of transfer units [-], (eq. (15.17))
Nu	Nusselt number [-], (eq. (6.62))
n	number of molecules per unit volume
P	efficiency parameter [-], (eq. (15.12))
P_R	reduced pressure [-]
Pr	Prandtl number [-], (eq. (6.50))
Pr_t	turbulent Prandtl number, [-], (eq. (9.33))
p	pressure [Pa]
p'	fluctuating pressure [Pa]
\bar{p}	time averaged pressure [Pa]
Q	heat [J]
\dot{Q}	heat transfer rate [W]
q	heat flux [W/m^2]
R	radius [m]
R	gas constant [J/(kg K)]
R	heat capacity flow rate ratio [-], (eq. (15.13))
R_p	surface roughness [μm]
Re	Reynolds number [-], (eq. (6.60))
r	radius [m]
r_s	latent heat melting [J/kg]
S_L	lateral tube pitch [m]

S_T	longitudinal tube pitch [m]
Sr	Strouhal number [-], (eq. (11.2))
St	Stanton number [-], (eq. (7.42))
T	absolute temperature [K]
T^+	dimensionless temperature [-], (eq. (9.82))
TR	thermal resistance [K/W], (eq. (15.1))
t	temperature [°C]
t'	fluctuating temperature [°C]
\bar{t}	time averaged temperature [°C]
U	internal energy [J]
\dot{U}	internal energy per time unit (effekt) [W]
U	(mean) velocity [m/s]
U_∞	freestream velocity [m/s]
U	overall heat transfer coefficient [W/(m ² K)], (eq. (15.1))
u, v, w	local velocity [m/s]
u', v', w'	fluctuating velocity [m/s]
$\bar{u}, \bar{v}, \bar{w}$	time averaged velocity [m/s], (eq. (9.4))
u^+	dimensionless velocity [-]
u_{fS}	fictitious liquid velocity [m/s], (eq. (14.43))
u_{gS}	fictitious gas velocity [m/s], (eq. (14.44))
u_m	mean velocity [m/s]
u_τ, u^*	friction velocity [m/s]
V	volume [m ³]
X	coordinate [m]
X	Martinelli parameter [-], (eq. (14.52))
X_F	flowing mass fraction [-], (eq. (14.40))
X_S	static mass fraction [-], (eq. (14.41))
x, y, z	coordinates [m]
y^+	dimensionless coordinate perpendicular to a solid surface [-], (eq. (9.45))
W	work [J]
\dot{W}	work per time unit [W]
We	Weber number [-], (eq. (14.23))
Z	width, length [m]
α	heat transfer coefficient [W/(m ² K)], (eq. (1.23))
α	absorptance [-], (eq. (12.3))
β	thermal expansion coefficient [1/K]
β	angle [rad]
γ	ratio of specific heats, c_p/c_v [-]
δ	angle [rad]
δ	boundary layer thickness [m]
δ_{ij}	Kronecker's delta [-], (eq. (6.12))
ε	emissivity [-], (eq. (12.11))
ε	void [-], (eq. (14.39))
ε	efficiency [-], (eq. (15.14))

ε_m	turbulent kinematic viscosity [m^2/s], (eq. (9.31))
ε_q	turbulent diffusivity [m^2/s], (eq. (9.32))
η	dimensionless coordinate [-]
η	fin effectiveness [-], (eq. (3.48))
θ	dimensionless temperature [-]
θ	angle [rad]
θ	thermal length [-], (eq. (15.43))
ϑ	temperature [$^{\circ}\text{C}$]
κ	von Karmans constant [-], (eq. (9.51))
λ	parameter [-]
λ	thermal conductivity [$\text{W}/(\text{m K})$], (eq. (1.1))
λ	wavelength [m]
λ_1	mean free path for molecular motion [m]
μ	dynamic viscosity [$\text{kg}/(\text{m s})$]
ν	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
ρ	reflectance [-], (eq. (12.3))
ρ	resistivity [$\Omega \text{ m}$]
σ	Stefan-Boltzmann constant [$\text{W}/(\text{m}^2 \text{ K}^4)$], (eq. (12.10))
σ	shear stress [N/m^2]
σ	surface tension [N/m]
σ	electric conductivity [$1/(\Omega \text{ m})$]
σ	area ratio [-], (eq. (15.35))
τ	time [s]
τ	transmittance [-], (eq. (12.3))
ϕ	angle [rad]
φ	fin efficiency [-], (eq. (3.49))
Φ	radiation energy [W/m^2], (eq. (12.21))
ψ	stream function [s^{-1}], (eq. (10.21))
ω	solid angle [sr], (eq. (12.16))

Index

B	bulk, blackbody
C	convective boiling
f	at film temperature, fluid
g	gas
i	inner
KK	nucleate boiling
m	mean
o	outer
TF	two-phase
w	wall
λ	monochromatic
∞	freestream

Preface

This book aims as an introduction of heat transfer at undergraduate and graduate levels. Compared to other similar textbooks it differs significantly as it is much more comprehensive in describing the thermal conductivity of various substances, providing deeper analysis of fin heat transfer, and it includes buried pipes. For convective heat transfer the relation to fluid mechanics is much more highlighted. The turbulent convection, evaporation and heat exchanger chapters are all more comprehensive than other general heat transfer textbooks available. The textbook has been used for exchange students and PhD students for several years. The text has been developed and improved over the years.

At the end of the book a number of problems in heat transfer can be found. These can be solved by the methods presented in the various chapters.

Lund in September 2011

Bengt Sundén
Professor in Heat Transfer
Department of Energy Sciences
Lund University

