

# **Heat Transfer Applications for the Practicing Engineer**

# Heat Transfer Applications for the Practicing Engineer

Louis Theodore



A JOHN WILEY & SONS, INC., PUBLICATION

Copyright © 2011 by John Wiley & Sons, Inc. All rights reserved

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

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, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at [www.copyright.com](http://www.copyright.com). Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permission>.

**Limit of Liability/Disclaimer of Warranty:** While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at [www.wiley.com](http://www.wiley.com).

***Library of Congress Cataloging-in-Publication Data:***

Theodore, Louis.

Heat transfer applications for the practicing engineer/Louis Theodore.

p. cm. -- (Essential engineering calculations series; 4)

Includes index.

ISBN 978-0-470-64372-3 (hardback)

1. Heat exchangers. 2. Heat--Transmission. I. Title.

TJ263.T46 2011

621.402'2--dc23

2011016265

Printed in the United States of America

oBook ISBN: 9780470937228

ePDF ISBN: 9780470937211

ePub ISBN: 9781118002100

10 9 8 7 6 5 4 3 2 1

To  
Jack Powers

My friend,  
a future basketball Hall-of-Famer,  
and  
a true quality individual

# Contents

---

Preface xv

Introductory Comments xvii

## Part One Introduction

---

### 1. History of Heat Transfer 3

Introduction 3  
Peripheral Equipment 4  
Recent History 5  
References 6

---

### 2. History of Chemical Engineering: Transport Phenomena vs Unit Operations 7

Introduction 7  
History of Chemical Engineering 8  
Transport Phenomena vs Unit Operations 10  
What is Engineering? 12  
References 13

---

### 3. Process Variables 15

Introduction 15  
Units and Dimensional Consistency 16  
Key Terms and Definitions 19  
    Fluids 19  
    Temperature 19  
    Pressure 20  
    Moles and Molecular Weights 22  
    Mass and Volume 23  
    Viscosity 25  
    Heat Capacity 27  
    Thermal Conductivity 28  
    Thermal Diffusivity 30  
    Reynolds Number 30

**viii** Contents

Kinetic Energy	31
Potential Energy	32
Determination of Dimensionless Groups	33
References	36

**4. Conservation Laws** **37**

---

Introduction	37
The Conservation Laws	38
The Conservation Law for Momentum	38
The Conservation Law for Mass	40
The Conservation Law for Energy	45
References	54

**5. Gas Laws** **55**

---

Introduction	55
Boyle's and Charles' Laws	56
The Ideal Gas Law	57
Standard Conditions	60
Partial Pressure and Partial Volume	63
Non-Ideal Gas Behavior	65
References	65

**6. Heat Exchanger Pipes and Tubes** **67**

---

Introduction	67
Pipes	67
Tubes	73
Valves and Fittings	75
Valves	75
Fittings	77
Noncircular Conduits	78
Flow Considerations	80
References	83

Part Two Principles

**7. Steady-State Heat Conduction** **87**

---

Introduction	87
Fourier's Law	87
Conductivity Resistances	90
Microscopic Approach	99

Applications	102
References	114

## **8. Unsteady-State Heat Conduction** **115**

---

Introduction	115
Classification of Unsteady-State Heat Conduction Processes	116
Microscopic Equations	117
Applications	118
References	130

## **9. Forced Convection** **131**

---

Introduction	131
Convective Resistances	134
Heat Transfer Coefficients: Qualitative Information	137
Heat Transfer Coefficients: Quantitative Information	138
Flow Past a Flat Plate	141
Flow in a Circular Tube	146
Liquid Metal Flow in a Circular Tube	147
Convection Across Cylinders	148
Microscopic Approach	155
References	159

## **10. Free Convection** **161**

---

Introduction	161
Key Dimensionless Numbers	162
Describing Equations	164
Environmental Applications	171
Lapse Rates	171
Plume Rise	173
References	176

## **11. Radiation** **177**

---

Introduction	177
Energy and Intensity	180
Radiant Exchange	183
Kirchoff's Law	184
Emissivity Factors	189
View Factors	196
References	200

**12. Condensation and Boiling** **201**


---

Introduction	201
Condensation Fundamentals	203
Phase Equilibrium	205
Psychrometric Chart	207
Steam Tables	208
Condensation Principles	209
Boiling Fundamentals	215
Boiling Principles	218
References	225

**13. Refrigeration and Cryogenics** **227**


---

Introduction	227
Background Material	228
Refrigeration	228
Cryogenics	230
Liquefaction	231
Cryogens	232
Equipment	234
Typical Heat Exchangers	234
Materials of Construction	235
Insulation and Heat Loss	236
Storage and Transportation	240
Hazards, Risks, and Safety	241
Physiological Hazards	241
Physical Hazards	242
Chemical Hazards	244
Basic Principles and Applications	244
Coefficient of Performance	246
Thermal Efficiency	248
Entropy and Heat	252
References	253

**Part Three Heat Transfer Equipment Design Procedures and Applications****14. Introduction to Heat Exchangers** **257**


---

Introduction	257
Energy Relationships	258
Heat Exchange Equipment Classification	260



The Log Mean Temperature Difference (LMTD) Driving Force	262
Temperature Profiles	265
Overall Heat Transfer Coefficients	268
Fouling Factors	271
The Controlling Resistance	272
Varying Overall Heat Transfer Coefficients	276
The Heat Transfer Equation	278
References	279
<b>15. Double Pipe Heat Exchangers</b>	<b>281</b>
<hr/>	
Introduction	281
Equipment Description	282
Describing Equations	286
Calculation of Exit Temperatures	298
Effectiveness Factor and Number of Transfer Units	304
Wilson's Method	309
References	313
<b>16. Shell and Tube Heat Exchangers</b>	<b>315</b>
<hr/>	
Introduction	315
Equipment Description	316
Describing Equations	322
The "F" Factor	328
Effectiveness Factor and Number of Transfer Units	344
References	356
<b>17. Fins and Extended Surfaces</b>	<b>357</b>
<hr/>	
Introduction	357
Fin Types	358
Describing Equations	360
Fin Effectiveness and Performance	371
Fin Considerations	380
References	380
<b>18. Other Heat Exchange Equipment</b>	<b>381</b>
<hr/>	
Introduction	381
Evaporators	382
Mixing Effects	384
Waste Heat Boilers	392
Describing Equations	394

**xii** Contents

Condensers	401
Quenchers	404
Dilution with Ambient Air	405
Quenching with Liquids	405
Contact with High Heat Capacity Solids	405
Natural Convection and Radiation	406
Forced-Draft Cooling	406
References	410

**19. Insulation and Refractory** **411**

---

Introduction	411
Describing Equations	411
Insulation	430
Critical Insulation Thickness	431
Refractory	435
References	442

**20. Operation, Maintenance, and Inspection (OM&I)** **443**

---

Introduction	443
Installation Procedures	443
Clearance Provisions	444
Foundations	444
Leveling	444
Piping Considerations	444
Operation	445
Startup	446
Shut Down	446
Maintenance and Inspection	446
Cleaning	446
Testing	447
Improving Operation and Performance	448
References	449

**21. Entropy Considerations and Analysis** **451**

---

Introduction	451
Qualitative Review of the Second Law	452
Describing Equations	453
The Heat Exchanger Dilemma	455
Applications	460
References	463

**22. Design Principles and Industrial Applications** **465**

---

Introduction	465
--------------	-----

General Design Procedures	466
Process Schematics	467
Purchasing a Heat Exchanger	468
Applications	470
References	490

**Part Four Special Topics**

**23. Environmental Management 493**

---

Introduction	493
Environmental Management History	493
Environmental Management Topics	495
Applications	496
References	503

**24. Accident and Emergency Management 505**

---

Introduction	505
Legislation	506
Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)	506
Superfund Amendments and Reauthorization Act of 1986 (SARA)	507
Occupational Safety and Health Act (OSHA)	508
USEPA's Risk Management Program (RMP)	509
Hazard Risk Assessment	510
Applications	513
References	531

**25. Ethics 533**

---

Introduction	533
Teaching Ethics	534
The Case Study Approach	535
Applications	537
References	540

**26. Numerical Methods 541**

---

Introduction	541
History	542
Partial Differential Equations (PDE)	544
Parabolic PDE	545
Elliptical PDE	546
Regression Analysis	554
Correlation Coefficient	557

**xiv** Contents

Optimization 560  
    Perturbation Studies in Optimization 560  
References 562

---

**27. Economics and Finance** **563**

---

Introduction 563  
The Need for Economic Analyses 563  
Definitions 565  
    Simple Interest 565  
    Compound Interest 565  
    Present Worth 566  
    Evaluation of Sums of Money 566  
    Depreciation 567  
    Fabricated Equipment Cost Index 567  
    Capital Recovery Factor 567  
    Present Net Worth 568  
    Perpetual Life 568  
    Break-Even Point 569  
    Approximate Rate of Return 569  
    Exact Rate of Return 569  
    Bonds 570  
    Incremental Cost 570  
    Optimization 570  
Principles of Accounting 571  
Applications 573  
References 588

---

**28. Open-Ended Problems** **589**

---

Introduction 589  
Developing Students' Power of Critical Thinking 592  
Creativity 592  
Brainstorming 593  
Inquiring Minds 594  
Applications 594  
References 602

---

**Appendix A. Units** **603**

---

**Appendix B. Tables** **613**

---

**Appendix C. Figures** **627**

---

**Appendix D. Steam Tables** **631**

---

**Index** 639

# Preface

---

We should be careful to get out of an experience only the wisdom that is in it—and stop there; lest we be like the cat that sits down on a hot stove-lid. She will never sit down on a hot stove-lid again—and that is well; but also she will never sit down on a cold one anymore.

Mark Twain (Samuel Langhorne Clemens 1835–1910),  
*Pudd'nhead Wilson, Chapter 19*

This project was a rather unique undertaking. Heat transfer is one of the three basic tenants of chemical engineering and engineering science, and contains many basic and practical concepts that are utilized in countless industrial applications. The author therefore considered writing a practical text. The text would hopefully serve as a training tool for those individuals in industry and academia involved directly, or indirectly, with heat transfer applications. Although the literature is inundated with texts emphasizing theory and theoretical derivations, the goal of this text is to present the subject of heat transfer from a strictly pragmatic point-of-view.

The book is divided into four Parts: Introduction, Principles, Equipment Design Procedures and Applications, and ABET-related Topics. The first Part provides a series of chapters concerned with introductory topics that are required when solving most engineering problems, including those in heat transfer. The second Part of the book is concerned with heat transfer principles. Topics that receive treatment include steady-state heat conduction, unsteady-state heat conduction, forced convection, free convection, radiation, boiling and condensation, and cryogenics. Part Three—considered by the author to be the “meat” of the book—addresses heat transfer equipment design procedures and applications. In addition to providing a detailed treatment of the various types of heat exchangers, this part also examines the impact of entropy calculations on exchanger design, operation, maintenance and inspection (OM&I), plus refractory and insulation effects. The concluding Part of the text examines ABET (Accreditation Board for Engineering and Technology)-related topics of concern, including environmental management, safety and accident management, ethics, numerical methods, economics and finance, and open-ended problems. An appendix is also included. An outline of the topics covered can be found in the Table of Contents.

The author cannot claim sole authorship to all of the problems and material in this text. The present book has evolved from a host of sources, including: notes, homework problems and exam problems prepared by several faculty for a required one-semester, three-credit, “Principles II: Heat Transfer” undergraduate course offered at Manhattan College; I. Farag and J. Reynolds, “Heat Transfer”, A Theodore Tutorial, East Williston, N.Y., 1994; J. Reynolds, J. Jeris, and L. Theodore, “Handbook of

Chemical and Environmental Engineering Calculations”, John Wiley & Sons 2004, and J. Santoleri, J. Reynolds, and L. Theodore’s “Introduction to Hazardous Waste Incineration”, 2nd edition, John Wiley & Sons, 2000. Although the bulk of the problems are original and/or taken from sources that the author has been directly involved with, every effort has been made to acknowledge material drawn from other sources.

It is hoped that this writing will place in the hands of industrial, academic, and government personnel, a book covering the principles and applications of heat transfer in a thorough and clear manner. Upon completion of the text, the reader should have acquired not only a working knowledge of the principles of heat transfer operations, but also experience in their application; and, the reader should find himself/herself approaching advanced texts, engineering literature, and industrial applications (even unique ones) with more confidence. The author strongly believes that, while understanding the basic concepts is of paramount importance, this knowledge may be rendered virtually useless to an engineer if he/she cannot apply these concepts to real-world situations. This is the essence of engineering.

Last, but not least, I believe that this modest work will help the majority of individuals working and/or studying in the field of engineering to obtain a more complete understanding of heat transfer. If you have come this far, and read through most of the Preface, you have more than just a passing interest in this subject. I strongly suggest that you try this text; I think you will like it.

My sincere thanks are extended to Dr. Jerry Maffia and Karen Tschinkel at Manhattan College for their help in solving some of the problems and proofing the manuscript, and to the ever reliable Shannon O’Brien for her valuable assistance.

LOUIS THEODORE

# Introductory Comments

---

**P**rior to undertaking the writing of this text, the author (recently) co-authored a text entitled “Thermodynamics for the Practicing Engineer”. It soon became apparent that some overlap existed between thermodynamic and heat transfer (the subject of this text). Even though the former topic is broadly viewed as a science, heat transfer is one of the unit operations and can justifiably be classified as an engineering subject. But what are the similarities and what are the differences?

The similarities that exist between thermodynamics and heat transfer are grounded in the three conservation laws: mass, energy, and momentum. Both are primarily concerned with energy-related subject matter and both, in a very real sense, supplement each other. However, thermodynamics deals with the transfer of energy and the conversion of energy into other forms of energy (e.g., heat into work), with consideration generally limited to systems in equilibrium. The topic of heat transfer deals with the transfer of energy in the form of heat; the applications almost exclusively occur with heat exchangers that are employed in the chemical, petrochemical, petroleum (refinery), and engineering processes.

The aforementioned transfer of heat occurs between a hot and a cold body, normally referred to as the source and receiver, respectively. (The only exception is in cryogenic applications.) When this transfer occurs in a heat exchanger, some or all of the following 10 topics/subjects can come into play:

1. The class of heat exchanger
2. The physical surface arrangement of the exchanger
3. The quantity or rate of heat transferred
4. The quantity or rate of heat “lost” in the application
5. The temperature difference between the source and receiver
6. The prime mover(s) required in the application (e.g., pump, fan, etc.)
7. The entropy gain (i.e., the quality energy lost in the application)
8. The cost to design, construct, and start up a new application
9. The cost to operate the exchanger
10. The cost to maintain the exchanger

Each of the above topics receive treatment once or several times in this text.