



# INTRODUCTION TO THERMO-FLUIDS SYSTEMS DESIGN

ANDRÉ G. McDONALD | HUGH L. MAGANDE

 WILEY



# **Introduction to Thermo-Fluids Systems Design**



# Introduction to Thermo-Fluids Systems Design

**André G. McDonald, Ph.D., P.ENG.**

*University of Alberta, Canada*

**Hugh L. Magande, M.B.A., M.S.E.M.**

*Rinnai America Corporation, USA*



A John Wiley & Sons, Ltd., Publication

This edition first published 2012.  
© 2012 André G. McDonald and Hugh L. Magande.

*Registered office*

John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at [www.wiley.com](http://www.wiley.com).

The right of the author to be identified as the author of this work has been asserted in accordance with the Copyright, Designs and Patents Act 1988.

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, except as permitted by the UK Copyright, Designs and Patents Act 1988, without the prior permission of the publisher.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The publisher is not associated with any product or vendor mentioned in this book. This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

**DISCLAIMER**

The contents of this textbook are meant to supply information on the design of thermo-fluids systems. The book is not meant to be the sole resource used in any design project. The examples and solutions presented are not to be construed as complete engineered design solutions for any particular problem or project. The authors and publisher are not attempting to render any type of engineering or other professional services. Should these services be required, an appropriate professional engineer should be consulted. The authors and publisher assume no liability or responsibility for any uses made of the material contained and described herein.

*Library of Congress Cataloging-in-Publication Data*

McDonald, Andre G.

Introduction to thermo-fluids systems design / Andre G. McDonald, Ph. D., P. Eng., Hugh L. Magande, M.B.A., M.S.E.M.

pages cm

Includes bibliographical references and index.

ISBN 978-1-118-31363-3 (cloth)

1. Heat exchangers—Fluid dynamics. 2. Fluids—Thermal properties. I. Magande, Hugh L. II. Title.

TJ263.M38 2013

621.402'2—dc23

2012023753

A catalogue record for this book is available from the British Library.

ISBN: 9781118313633

Set in 10/12.5pt Palatino by Aptara Inc., New Delhi, India.

# Contents

<b>Preface</b>	<b>xi</b>
<b>List of Figures</b>	<b>xv</b>
<b>List of Tables</b>	<b>xix</b>
<b>List of Practical Notes</b>	<b>xxi</b>
<b>List of Conversion Factors</b>	<b>xxiii</b>
<b>1 Design of Thermo-Fluids Systems</b>	<b>1</b>
1.1 Engineering Design—Definition	1
1.2 Types of Design in Thermo-Fluid Science	1
1.3 Difference between Design and Analysis	2
1.4 Classification of Design	2
1.5 General Steps in Design	2
1.6 Abridged Steps in the Design Process	2
<b>2 Air Distribution Systems</b>	<b>5</b>
2.1 Fluid Mechanics—A Brief Review	5
2.1.1 Internal Flow	5
2.2 Air Duct Sizing—Special Design Considerations	12
2.2.1 General Considerations	12
2.2.2 Sizing Straight Rectangular Air Ducts	13
2.2.3 Use of an Air Duct Calculator to Size Rectangular Air Ducts	18
2.3 Minor Head Loss in a Run of Pipe or Duct	18
2.4 Minor Losses in the Design of Air Duct Systems—Equal Friction Method	20

2.5	Fans—Brief Overview and Selection Procedures	44
2.5.1	Classification and Terminology	44
2.5.2	Types of Fans	44
2.5.3	Fan Performance	46
2.5.4	Fan Selection from Manufacturer's Data or Performance Curves	48
2.5.5	Fan Laws	51
2.6	Design for Advanced Technology—Small Duct High-Velocity (SDHV) Air Distribution Systems	54
	Problems	66
	References and Further Reading	72
<b>3</b>	<b>Liquid Piping Systems</b>	<b>73</b>
3.1	Liquid Piping Systems	73
3.2	Minor Losses: Fittings and Valves in Liquid Piping Systems	73
3.2.1	Fittings	73
3.2.2	Valves	73
3.2.3	A Typical Piping System—A Closed-Loop Fuel Oil Piping System	75
3.3	Sizing Liquid Piping Systems	75
3.3.1	General Design Considerations	75
3.3.2	Pipe Data for Building Water Systems	77
3.4	Fluid Machines (Pumps) and Pump–Pipe Matching	83
3.4.1	Classifications and Terminology	83
3.4.2	Types of Pumps	83
3.4.3	Pump Fundamentals	83
3.4.4	Pump Performance and System Curves	86
3.4.5	Pump Performance Curves for a Family of Pumps	88
3.4.6	A Manufacturer's Performance Plot for a Family of Centrifugal Pumps	89
3.4.7	Cavitation and Net Positive Suction Head	92
3.4.8	Pump Scaling Laws: Nondimensional Pump Parameters	97
3.4.9	Application of the Nondimensional Pump Parameters—Affinity Laws	98
3.4.10	Nondimensional Form of the Pump Efficiency	99
3.5	Design of Piping Systems Complete with In-Line or Base-Mounted Pumps	103
3.5.1	Open-Loop Piping System	103
3.5.2	Closed-Loop Piping System	111
	Problems	121
	References and Further Reading	126
<b>4</b>	<b>Fundamentals of Heat Exchanger Design</b>	<b>127</b>
4.1	Definition and Requirements	127



4.2	Types of Heat Exchangers	127
4.2.1	Double-Pipe Heat Exchangers	127
4.2.2	Compact Heat Exchangers	129
4.2.3	Shell-and-Tube Heat Exchangers	129
4.3	The Overall Heat Transfer Coefficient	130
4.3.1	The Thermal Resistance Network for Plane Walls— Brief Review	132
4.3.2	Thermal Resistance from Fouling—The Fouling Factor	136
4.4	The Convection Heat Transfer Coefficients—Forced Convection	138
4.4.1	Nusselt Number—Fully Developed Internal Laminar Flows	139
4.4.2	Nusselt Number—Developing Internal Laminar Flows— Correlation Equation	139
4.4.3	Nusselt Number—Turbulent Flows in Smooth Tubes: Dittus–Boelter Equation	141
4.4.4	Nusselt Number—Turbulent Flows in Smooth Tubes: Gnielinski’s Equation	141
4.5	Heat Exchanger Analysis	142
4.5.1	Preliminary Considerations	142
4.5.2	Axial Temperature Variation in the Working Fluids—Single Phase Flow	143
4.6	Heat Exchanger Design and Performance Analysis: Part 1	147
4.6.1	The Log-Mean Temperature Difference Method	147
4.6.2	The Effectiveness-Number of Transfer Units Method: Introduction	148
4.6.3	The Effectiveness-Number of Transfer Units Method: $\varepsilon$ -NTU Relations	149
4.6.4	Comments on the Number of Transfer Units and the Capacity Ratio (c)	151
4.6.5	Procedures for the $\varepsilon$ -NTU Method	156
4.6.6	Heat Exchanger Design Considerations	157
4.7	Heat Exchanger Design and Performance Analysis: Part 2	157
4.7.1	External Flow over Bare Tubes in Cross Flow—Equations and Charts	157
4.7.2	External Flow over Tube Banks—Pressure Drop	162
4.7.3	External Flow over Finned-Tubes in Cross Flow—Equations and Charts	175
4.8	Manufacturer’s Catalog Sheets for Heat Exchanger Selection	202
	Problems	208
	References and Further Reading	211
<b>5</b>	<b>Applications of Heat Exchangers in Systems</b>	<b>213</b>
5.1	Operation of a Heat Exchanger in a Plasma Spraying System	213
5.2	Components and General Operation of a Hot Water Heating System	216

5.3	Boilers for Water	217
5.3.1	Types of Boilers	217
5.3.2	Operation and Components of a Typical Boiler	218
5.3.3	Water Boiler Sizing	220
5.3.4	Boiler Capacity Ratings	224
5.3.5	Burner Fuels	226
5.4	Design of Hydronic Heating Systems c/w Baseboards or Finned-Tube Heaters	227
5.4.1	Zoning and Types of Systems	227
5.4.2	One-Pipe Series Loop System	227
5.4.3	Two-Pipe Systems	229
5.4.4	Baseboard and Finned-Tube Heaters	233
5.5	Design Considerations for Hot Water Heating Systems	236
	Problems	258
	References and Further Reading	265
<b>6</b>	<b>Performance Analysis of Power Plant Systems</b>	<b>267</b>
6.1	Thermodynamic Cycles for Power Generation—Brief Review	267
6.1.1	Types of Power Cycles	267
6.1.2	Vapor Power Cycles—Ideal Carnot Cycle	268
6.1.3	Vapor Power Cycles—Ideal Rankine Cycle for Steam Power Plants	268
6.1.4	Vapor Power Cycles—Ideal Regenerative Rankine Cycle for Steam Power Plants	269
6.2	Real Steam Power Plants—General Considerations	271
6.3	Steam-Turbine Internal Efficiency and Expansion Lines	272
6.4	Closed Feedwater Heaters (Surface Heaters)	280
6.5	The Steam Turbine	282
6.5.1	Steam-Turbine Internal Efficiency and Exhaust End Losses	282
6.5.2	Casing and Shaft Arrangements of Large Steam Turbines	284
6.6	Turbine-Cycle Heat Balance and Heat and Mass Balance Diagrams	286
6.7	Steam-Turbine Power Plant System Performance Analysis Considerations	288
6.8	Second-Law Analysis of Steam-Turbine Power Plants	300
6.9	Gas-Turbine Power Plant Systems	307
6.9.1	The Ideal Brayton Cycle for Gas-Turbine Power Plant Systems	307
6.9.2	Real Gas-Turbine Power Plant Systems	309
6.9.3	Regenerative Gas-Turbine Power Plant Systems	312
6.9.4	Operation and Performance of Gas-Turbine Power Plants—Practical Considerations	313
6.10	Combined-Cycle Power Plant Systems	324
6.10.1	The Waste Heat Recovery Boiler	325
	Problems	332
	References and Further Reading	338

---

<b>Appendix A: Pipe and Duct Systems</b>	<b>339</b>
<b>Appendix B: Symbols for Drawings</b>	<b>365</b>
<b>Appendix C: Heat Exchanger Design</b>	<b>373</b>
<b>Appendix D: Design Project— Possible Solution</b>	<b>383</b>
D.1 Fuel Oil Piping System Design	383
<b>Appendix E: Applicable Standards and Codes</b>	<b>413</b>
<b>Appendix F: Equipment Manufacturers</b>	<b>415</b>
<b>Appendix G: General Design Checklists</b>	<b>417</b>
G.1 Air and Exhaust Duct Systems	417
G.2 Liquid Piping Systems	418
G.3 Heat Exchangers, Boilers, and Water Heaters	419
<b>Index</b>	<b>421</b>



# Preface

Design courses and projects in contemporary undergraduate curricula have focused mainly on topics in solid mechanics. This has left graduating junior engineers with limited knowledge and experience in the design of components and systems in the thermo-fluids sciences. ABB Automation in their handbook on *Energy Efficient Design of Auxiliary Systems in Fossil-Fuel Power Plants* has mentioned that this lack of training in thermo-fluids systems design will limit our ability to produce high-performance systems. This deficiency in contemporary undergraduate curricula has resulted in an urgent need for course materials that underline the application of fundamental concepts in the design of thermo-fluids components and systems.

Owing to the urgent need for course materials in this area, this textbook has been developed to bridge the gap between the fundamental concepts of fluid mechanics, heat transfer, and thermodynamics and the practical design of thermo-fluids components and systems. To achieve this goal, this textbook is focused on the design of internal fluid flow systems, coiled heat exchangers, and performance analysis of power plant systems. This requires prerequisite knowledge of internal fluid flow, conduction heat transfer, convection heat transfer with emphasis on forced convection in tubes and over cylinders, analysis of constant area fins, and thermodynamic power cycles, in particular, the Rankine and Brayton cycles. The fundamental concepts are used as tools in an exhaustive design process to solve various practical problems presented in the examples. For junior design engineers with limited practical experience, use of fundamental concepts of which they have previous knowledge will help them to increase their confidence and decision-making capabilities.

The complete design or modification of modern equipment and systems will require knowledge of current industry practices. While relying on and demonstrating the application of fundamental principles, this textbook highlights the use of manufacturers' catalogs to select equipment and practical rules to guide decision-making in the design process. Some of these practical rules are included in the text as *Practical Notes*, to underline their importance in current practice and provide additional information. While great emphasis is placed upon the use of these rules, an effort was made to ensure that the reader understands the fundamental

concepts that support these guidelines. It is strongly believed that this will also enable the design engineer to make quick and accurate decisions in situations where the guidelines may not be applicable.

The topics covered in the text are arranged so that each topic builds on the previous concepts. It is important to convey to the reader that, in the design process, topics are not stand-alone items and they must come together to produce a successful design. There are three main topical areas, arranged in six chapters.

Introductory material on the design process is presented in *Chapter 1*. Since the book focuses on the detailed, technical design of thermo-fluids components and systems, the chapter ends with an abridged version of the full design process.

*Chapters 2 and 3* deal with the design of air duct and liquid piping systems, respectively. It is in these initial chapters that a brief review of internal fluid flow is presented. System layout, component sizing, and equipment selection are also covered.

An introduction to heat exchanger design and analysis is presented in *Chapter 4*. This chapter presents the most fundamental material in the textbook. Extensive charts are used to design and analyze the performance of bare-tube and finned-tube coiled heat exchangers. The chapter ends with a description of excerpts from a manufacturer's catalog used to select heating coil models that are used in high-velocity duct systems.

*Chapter 5* continues the discussion of heat exchangers by focusing on the sizing and selection of various heat exchangers such as boilers, water heaters, and finned-tube baseboard heaters. Various rules and data are presented to guide the selection and design process.

*Chapter 6* focuses on the analysis of power plant systems. Here, the reader is introduced to a review of thermodynamic power cycles and various practical considerations in the analysis of steam-turbine and gas-turbine power generation systems. Combined-cycle systems and waste heat recovery boilers are also presented.

There are seven *Appendices* at the end of this book. They contain a wide variety of charts, tables, and catalog sheets that the design engineer will find useful during practice. Also included in the appendices are: a possible solution of a design project, the names of organizations that provide applicable codes and standards, and the names of some manufacturers and suppliers of equipment used in thermo-fluids systems.

The writing of this textbook was inspired, in part, by the difficulty to find appropriate textbooks that presented a detailed practical approach to the design of thermo-fluids components and systems in industrial environments. It is hoped that the readers and design engineers, in particular, will find it useful in practice as a reference during design projects and analysis.

The authors have made no effort to claim complete originality of the text. We have been motivated by the work of many others that have been appropriately referenced throughout the textbook.

While we feel that this textbook will be a valuable resource for design engineers in industry, it is offered as a guide, and as such, judgement is required when using the text to design systems or for application to specific installations. The authors and the publisher are not responsible for any uses made of this text.

---

We express our deepest gratitude to and acknowledge the advice, critiques, and suggestions that we received from, our advisory committee of professors, professional engineers, and students. These individuals include Dr. Roger Toogood, P. Eng.; Mr. Mark Ackerman, P. Eng.; Mr. Curt Stout, P. Eng.; Dr. Larry Kostiuk, P. Eng.; Mr. Dave DeJong, P. Eng.; Mr. Michael Ross; and Mr. David Therrien.

A.G. McDonald  
H.L. Magande





# List of Figures

1.1	General steps in the design process	3
2.1	Duct shapes and aspect ratios	13
2.2	Photo of a typical air duct calculator	19
2.3	A ductwork system to transport air ( <i>ASHRAE Handbook, Fundamentals Volume, 2005</i> ; reprinted with permission)	21
2.4	Axial fans	45
2.5	Centrifugal fans	45
2.6	Classification of centrifugal fans based on blade types	46
2.7	Typical performance curves of centrifugal fans	47
2.8	Forward-curved centrifugal fan performance curves (Morrison Products, Inc.; reprinted with permission)	49
3.1	Some typical industrial valves	74
3.2	A typical fuel oil piping system complete with a pump set ( <i>ASHRAE Handbook, Fundamentals Volume, 2005</i> ; reprinted with permission)	75
3.3	Plastic pipe (Schedule 80) friction loss chart ( <i>ASHRAE Handbook, Fundamentals Volume, 2005</i> ; reprinted with permission)	79
3.4	Pipes supported on hangers	79
3.5	Pipes and an in-line pump mounted on brackets	81
3.6	Types of industrial pumps: (a) three-lobe rotary pump; (b) two-screw pump; (c) in-line centrifugal pump; (d) vertical multistage submersible pump (Hydraulic Institute, Parsippany, NJ, <a href="http://www.pumps.org">www.pumps.org</a> ; reprinted with permission)	84
3.7	Schematic of a $H_{\text{pump}}$ versus $\dot{V}$ curve for a centrifugal pump	86
3.8	Schematic of a $\eta_{\text{pump}}$ versus $\dot{V}$ curve	87
3.9	Schematic of a system curve intersecting a pump performance curve	88
3.10	Performance curves for a family of geometrically similar pumps	89
3.11	Pump performance plot (Taco, Inc.; reprinted with permission)	89
3.12	A typical open-loop condenser piping system for water	104
3.13	Diagrams of closed-loop piping systems	112

4.1	Temperature profiles and schematics of (a) parallel and (b) counter flow double-pipe heat exchangers	128
4.2	Cross-flow heat exchangers	129
4.3	Picture of a continuous plate-fin-tube type cross-flow heat exchanger	130
4.4	Schematics of shell-and-tube heat exchangers	131
4.5	Temperature distribution around and through a 1D plane wall	132
4.6	Thermal resistance network around a plane wall	135
4.7	Axial temperature variation in parallel flow heat exchanger	144
4.8	Axial temperature variation in counter flow heat exchanger	145
4.9	Axial temperature variation in a balanced heat exchanger	145
4.10	Axial temperature variation in a heat exchanger with condensation	146
4.11	Axial temperature variation in a heat exchanger with boiling	146
4.12	Effectiveness charts for some heat exchangers (Kays and London [2])	153
4.13	(a) Finned tube and (b) bare tube bank bundles	158
4.14	Flow pattern for an in-line tube bank (Çengel [3], reprinted with permission)	159
4.15	Data for flow normal to an in-line tube bank (Kays and London [2])	160
4.16	Flow pattern for a staggered tube bank (Çengel [3], reprinted with permission)	161
4.17	Data for flow normal to a staggered tube bank (Kays and London [2])	162
4.18	Schematic drawing of tube bank showing the total length, $L_{total}$	163
4.19	Examples of finned heat exchangers	176
4.20	General constant area, straight fins attached to a surface	177
4.21	Staggered tube bank with a hexangular finned-tube array	178
4.22	Data for flow normal to a finned staggered tube bank ( <i>ASHRAE Transactions</i> , Vol. 79, Part II, 1973; reprinted with permission)	179
4.23	Data for flow normal to staggered tube banks: multiple tube rows ( <i>ASHRAE Transactions</i> , Vol. 81, Part I, 1975; reprinted with permission)	180
4.24	M series heating coil from Unico, Inc. (a) Page 1 of the M series heating coil from Unico, Inc. (Unico, Inc., reprinted with permission) (b) Page 2 of the M series heating coil from Unico, Inc. (Unico, Inc.; reprinted with permission) (c) Page 3 of the M series heating coil from Unico, Inc. (Unico, Inc., reprinted with permission) Page 4 of the M series heating coil from Unico, Inc. (Unico, Inc.; reprinted with permission)	203
5.1	A Praxair SG-100 plasma spray torch in operation	214
5.2	The Sulzer Metco Climet-HE <sup>TM</sup> -200 heat exchanger (Sulzer Metco, Product Manual MAN 41292 EN 05; reprinted with permission)	214
5.3	Functional diagram for the Sulzer Metco Climet-HE <sup>TM</sup> -200 (Sulzer Metco, Product Manual MAN 41292 EN 05; reprinted with permission)	215
5.4	Flow diagram for cooling a typical plasma torch (modified from Sulzer Metco, Product Manual MAN 41292 EN 05; reprinted with permission)	216
5.5	Schematic of a closed-loop hydronic heating system c/w a boiler	217
5.6	A typical gas-fired hot water boiler	218
5.7	Schematic of the internal section of typical water heaters	220

---

5.8	(a) A Rinnai noncondensing tankless water heater. (b) Schematic of Rinnai noncondensing tankless water heater (reprinted with permission)	221
5.9	Brochure showing specifications for a line of gas-fired boilers (Smith Cast Iron Boilers, GB100 series technical brochure; reprinted with permission)	225
5.10	Schematic diagram of a one-pipe series loop system	227
5.11	Schematic diagram of a split series loop system	228
5.12	Schematic of a one-pipe “monoflow” series loop system	229
5.13	Schematic diagram of a multizone system of one-pipe series loops	230
5.14	Schematic of a two-pipe direct return system	230
5.15	Schematic of a two-pipe reverse return system	231
5.16	Unbalanced flow in a two-pipe direct return system	232
5.17	Improved balance in a two-pipe direct return system	232
5.18	Diagrams of baseboard heaters. (a) 1-tiered baseboard heater; (b) 2-tiered finned-tube heater	233
6.1	Ideal Carnot cycle	268
6.2	Ideal Rankine cycle	269
6.3	Ideal regenerative Rankine cycles. (a) Single-stage feedwater heating; (b) four-stage feedwater heating	270
6.4	Mollier diagram for water	273
6.5	Mollier diagram for water showing an expansion line	274
6.6	Drain disposals for closed feedwater heaters (surface heaters)	281
6.7	Turbine operation	283
6.8	Exhaust diffuser of a LP turbine	284
6.9	Casing and shaft arrangements for large condensing turbines. (a) Tandem-compound 2 flows from 150 to 400 MW; (b) Tandem-compound 4 flows from 300 to 800 MW; (c) Cross-compound 2 flows from 300 to 800 MW; (d) Cross-compound 4 flows from 800 to 1200 MW	285
6.10	Heat-and-mass balance diagram for a fossil-fuel power plant (Li and Priddy [1]; reprinted with permission)	287
6.11	Ideal Brayton cycle	308
6.12	Real Brayton cycle	309
6.13	Regenerative Brayton cycle	313
6.14	Regenerative Brayton cycle with intercooling	313
6.15	Schematic of a combined-cycle power plant	324
6.16	Piping schematic of a single-pressure waste heat recovery boiler	325
6.17	Temperature profile in a single-pressure waste heat recovery boiler	326
A.1	Friction Loss in Round (Straight) Ducts. <i>Source: System Design Manual, Part 2: Air Distribution, Carrier Air Conditioning Co., Syracuse, NY, 1974 (Reprinted with permission)</i>	351
A.2	Schematics elbows in ducts	352

A.3	Copper tubing friction loss (open and closed piping systems) (Carrier Corp.; reprinted with permission)	353
A.4	Commercial steel pipe (Schedule 40) friction loss. (a) <i>Open piping systems</i> (Carrier Corp.; reprinted with permission); (b) <i>closed piping systems</i> (Carrier Corp.; reprinted with permission)	354
A.5	Bell & Gosset pump catalog (ITT Bell & Gossett; reprinted with permission)	356
C.1	$j$ -factor versus $Re_G$ charts for in-line tube banks. Transient tests (2 charts): (a) For $X_t = 1.50$ and $X_L = 1.25$ ; (b) For $X_t = 1.25$ and $X_L = 1.25$ . (Kays, W. and London, A. (1964) <i>Compact Heat Exchangers</i> , 2nd edn, McGraw-Hill, Inc., New York)	375
C.2	$j$ -factor versus $Re_G$ charts for staggered tube banks. Transient tests (6 charts): (a) For $X_t = 1.50$ and $X_L = 1.25$ ; (b) For $X_t = 1.25$ and $X_L = 1.25$ ; (c) For $X_t = 1.50$ and $X_L = 1.0$ ; (d) For $X_t = 1.5$ and $X_L = 1.5$ ; (e) For $X_t = 2$ and $X_L = 1$ ; (f) For $X_t = 2.5$ and $X_L = 0.75$ . (Kays, W. and London, A. (1964) <i>Compact Heat Exchangers</i> , 2nd edn, McGraw-Hill, Inc., New York)	376
C.3	$j$ -factor versus $Re_{x_L}$ charts for staggered tube banks (finned tubes): (a) five rows of tubes ( <i>ASHRAE Transactions</i> , vol. 79, Part II, 1973; reprinted with permission); (b) multiple rows of tubes ( <i>ASHRAE Transactions</i> , vol. 81, Part I, 1975; reprinted with permission)	380
C.4	$j$ -factor versus $Re_G$ charts for staggered tube banks (finned tubes). (a) Tube outer diameter = 0.402 in.; (b) tube outer diameter = 0.676 in. (Kays, W. and London, A. (1964) <i>Compact Heat Exchangers</i> , 2nd edn, McGraw-Hill, Inc., New York)	381

# List of Tables

2.1	Maximum duct velocities	14
2.2	Typical values of component pressure losses [9]	21
2.3	Maximum supply duct velocities	54
2.4	Sound data during airflow through a rectangular elbow	55
2.5	Maximum main duct air velocities for acoustic design criteria	56
2.6	Acoustic design criteria for unoccupied spaces [21]	57
3.1	Typical average velocities for selected pipe flows	76
3.2	Pipe data for copper and steel	78
3.3	Hanger spacing for straight stationary pipes and tubes [1]	80
3.4	Minimum hanger rod size for straight stationary pipes and tubes [1]	80
4.1	Values of the overall heat transfer coefficient (US)	136
4.2	Values of the overall heat transfer coefficient (SI)	137
4.3	Representative fouling factors in heat exchangers	138
4.4	Nusselt numbers and friction factors for fully developed laminar flow in tubes of various cross sections: constant surface temperature and surface heat flux [3]	140
4.5	Effectiveness relations for heat exchangers	152
5.1	Minimum recovery rates and minimum usable storage capacities	224
5.2	Approximate heating value of fuels	226
5.3	Baseboard heater rated outputs at 1 gpm water flow rate	233
5.4	“Front outlet” finned-tube heater ratings for Trane heaters	234
5.5	Flow rate correction factors for water velocities less than 3 fps	235
5.6	Temperature correction factors for hot water ratings	236
6.1	Pressure drops at the gas-turbine plant inlet and exhaust [1]	315
6.2	Common steam conditions for waste heat recovery boilers [1]	327
A.1	Average roughness of commercial pipes	339
A.2	Correlation equations for friction factors	340
A.3	Circular equivalents of rectangular ducts for equal friction and capacity	341
A.4	Approximate equivalent lengths for selected fittings in circular Ducts	342
A.5	Approximate equivalent lengths for elbows in ducts	342

---

A.6	Data for copper pipes	343
A.7	Data for schedule 40 steel pipes	344
A.8	Data for schedule 80 steel pipes	345
A.9	Data for class 150 cast iron pipes	346
A.10	Data for glass pipes	346
A.11	Data for PVC plastic pipes	347
A.12	Typical average velocities for selected pipe flows <sup>a</sup>	348
A.13	Erosion limits: maximum design fluid velocities for water flow in small tubes	348
A.14	Loss coefficients for pipe fittings	349
A.15	Typical pipe data format	350
A.16	Typical pump schedule format	350
B.1	Airmoving devices and ductwork symbols	365
B.2	Piping symbols	367
B.3	Symbols for piping specialities	368
B.4	Additional/alternate valve symbols	369
B.5	Fittings	370
B.6	Radiant Panel Symbols	372
C.1	Representative values of the overall heat transfer coefficients (US)	373
C.2	Representative values of the overall heat transfer coefficients (SI)	374
C.3	Representative fouling factors in heat exchangers	374

# List of Practical Notes

2.1	Total Static Pressure Available at a Plenum or Produced by a Fan	20
2.2	Diffuser Discharge Air Volume Flow Rates in SDHV Systems	56
3.1	Link Seals	75
3.2	Piping Systems Containing Air	76
3.3	Higher Pipe Friction Losses and Velocities	77
3.4	Piping System Supported by Brackets	81
3.5	Manufacturers' Pump Performance Curves	88
3.6	"To-the-point" Design	90
3.7	Oversizing Pumps	90
3.8	NPSH	93
3.9	Bypass Lines	104
3.10	Regulation and Control of Flow Rate across a Pump	104
3.11	In-Line and Base-Mounted Pumps	105
3.12	Flanged or Screwed Pipe Fittings?	113
4.1	Industrial Flows	142
4.2	Flow in Rough Pipes	142
4.3	Condensers and Boilers	147
4.4	Real Heat Exchangers	149
4.5	Heat Transfer from Staggered Tube Banks	161
4.6	Coil Arrangement in Air-to-Water Heat Exchangers	164
4.7	Pressure Drop Over Tube Banks	164
4.8	$L$ and $M$ values	179
5.1	Condensing Boilers	219
5.2	Typical OSF Values	222
5.3	Domestic Water Data for Edmonton, Alberta, Canada	223
5.4	Hot Water Temperatures from Faucets	223
5.5	Temperature Data for Sizing Finned-Tube Heaters	235

6.1	Optimizing the Number of Feedwater Heaters	271
6.2	<i>DCA</i> and <i>TTD</i> Values	281
6.3	Stages of a Steam Turbine	282
6.4	Exhaust End Loss	284
6.5	Units of the Net Heat Rate (NHR)	288
6.6	How Does One Initiate Operation of a Power Plant System?	289
6.7	Reference Pressure and Temperature for Availability Analysis	302
6.8	Combustion Air and Cracking in a Burner	309



# List of Conversion Factors

Dimension	Conversion
Energy	$1 \text{ Btu} = 778.28 \text{ lbf ft}$ $1 \text{ kWh} = 3412.14 \text{ Btu}$ $1 \text{ hp h} = 2545 \text{ Btu}$ $1 \text{ therm} = 10^5 \text{ Btu (natural gas)}$
Force	$1 \text{ lbf} = 32.2 \text{ lbm ft/s}^2 = 16 \text{ ozf}$ $1 \text{ dyne} = 2.248 \times 10^{-6} \text{ lbf}$
Length	$1 \text{ ft} = 12 \text{ in.}$ $1 \text{ yard} = 3 \text{ ft}$ $1 \text{ in.} = 25.4 \text{ mm}$ $1 \text{ mile} = 5280 \text{ ft}$
Mass	$1 \text{ slug} = 32.2 \text{ lbm}$ $1 \text{ lbm} = 16 \text{ ounces (oz)}$ $1 \text{ ton mass} = 2000 \text{ lbm}$
Power	$1 \text{ kW} = 3412.14 \text{ Btu/h}$ $1 \text{ hp} = 550 \text{ lbf ft/s}$ $1 \text{ hp (boiler)} = 33475 \text{ Btu/h}$ $1 \text{ ton refrigeration} = 12000 \text{ Btu/h}$
Pressure	$1 \text{ atm} = 14.7 \text{ psia}$ $1 \text{ psia} = 2.0 \text{ in Hg at } 32^\circ\text{F}$
Temperature	$T(\text{R}) = T(^{\circ}\text{F}) + 460$ $T(^{\circ}\text{F}) = 1.8T(^{\circ}\text{C}) + 32$
Viscosity (dynamic)	$1 \text{ lbm}/(\text{ft s}) = 1488 \text{ centipoises (cp)}$
Viscosity (kinematic)	$1 \text{ ft}^2/\text{s} = 929 \text{ stokes (St)}$
Volume	$1 \text{ British gallon} = 1.2 \text{ US gallon}$ $1 \text{ ft}^3 = 7.48 \text{ US gallons}$ $1 \text{ US gallon} = 128 \text{ fluid ounces}$
Volume Flow Rate	$35.315 \text{ ft}^3/\text{s} = 15850 \text{ gal/min (gpm)} = 2118.9 \text{ ft}^3/\text{min (cfm)}$



# 1

## Design of Thermo-Fluids Systems

### 1.1 Engineering Design—Definition

Process of devising a system, subsystem, component, or process to meet desired needs.

### 1.2 Types of Design in Thermo-Fluid Science

- (i) *Process Design*: The manipulation of physical and/or chemical processes to meet desired needs.  
Example: (a) Introduce boiling or condensation to increase heat transfer rates.
- (ii) *System Design*: The process of defining the components and their assembly to function to meet a specified requirement.  
Examples: (a) Steam turbine power plant system consisting of turbines, pumps, pipes, and heat exchangers.  
(b) Hot water heating system, complete with boilers.
- (iii) *Subsystem Design*: The process of defining and assembling a small group of components to do a specified function.  
Example: Pump/piping system of a large power plant. The pump/piping system is a subsystem of the larger power plant system used to transport water to and from the boiler or steam generator.
- (iv) *Component Design*: Development of a piece of equipment or device.

### 1.3 Difference between Design and Analysis

**Analysis:** Application of fundamental principles to a well-defined problem. All supporting information is normally provided, and one closed-ended solution is possible.

**Design:** Application of fundamental principles to an undefined, open problem. All supporting information may not be available and assumptions may need to be made. Several alternatives may be possible. No single correct answer exists.

### 1.4 Classification of Design

- (i) Modification of an existing device for
  - (a) cost reduction;
  - (b) improved performance and/or efficiency;
  - (c) reduced mean time between “breakdowns”;
  - (d) satisfy government codes and standards;
  - (e) satisfy customer/client preferences.
- (ii) Selection of existing components for the design of a subsystem or a complete system.
- (iii) Creation of a new device or system.

### 1.5 General Steps in Design

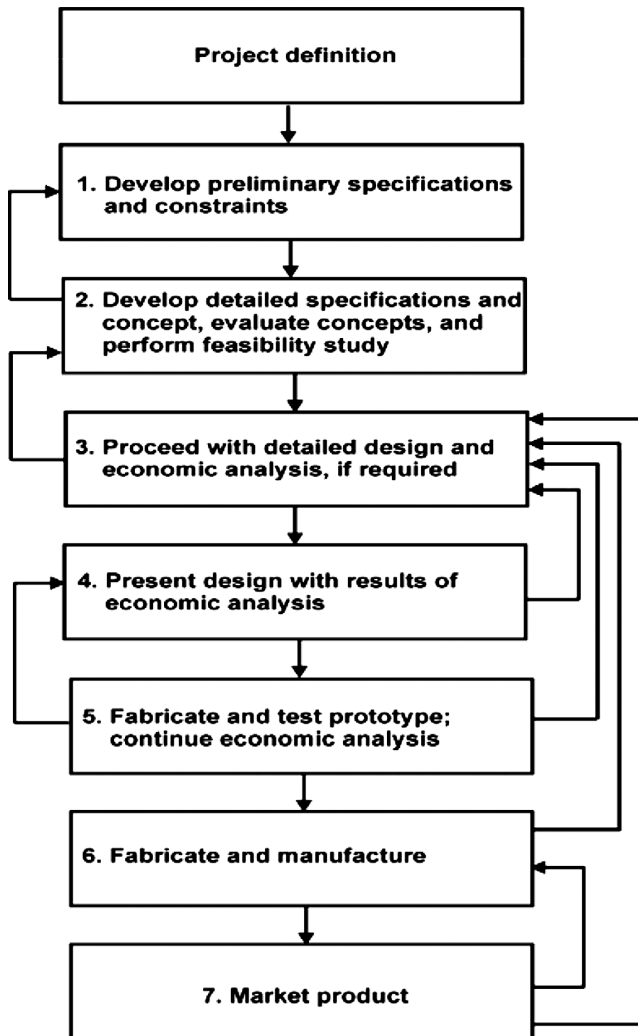
The general steps in the design process are shown schematically in Fig. 1.1.

### 1.6 Abridged Steps in the Design Process

1. *Project Definition:* One or two sentences describing the system or component to be designed. Check the problem statement for information.
2. *Preliminary Specifications and Constraints:* List the requirements that the design should satisfy. Requirements could come from the problem statement provided by the client or from the end users' preferences.

At this point, develop detailed, quantifiable specifications. For example, the client wants a fan-duct system that is quiet. What does “quiet” mean? What are the maximum and minimum noise levels for this “quiet” range? 60 dB may be satisfactory. Could the maximum noise level be 70 dB?

Detailed specifications or requirements could originate from the client (“client desired”), could be internally imposed by the designer to proceed with the design, or could be externally imposed by international/federal/provincial/municipal/industry standards or codes.



**Figure 1.1** General steps in the design process

### 3. Detailed Design and Calculations

- (i) Objective
- (ii) Data Given or Known
- (iii) Assumptions/Limitations/Constraints
- (iv) Sketches (where appropriate)
- (v) Analysis
- (vi) Drawings (where appropriate) or other documentation such as manufacturer's catalog sheets and Specifications.
- (vii) Conclusions

