

Contents

Preface	xv
Nomenclature	xix
1 Classification of Heat Exchangers	1
1.1 Introduction	1
1.2 Classification According to Transfer Processes	3
1.2.1 Indirect-Contact Heat Exchangers	3
1.2.2 Direct-Contact Heat Exchangers	7
1.3 Classification According to Number of Fluids	8
1.4 Classification According to Surface Compactness	8
1.4.1 Gas-to-Fluid Exchangers	11
1.4.2 Liquid-to-Liquid and Phase-Change Exchangers	12
1.5 Classification According to Construction Features	12
1.5.1 Tubular Heat Exchangers	13
1.5.2 Plate-Type Heat Exchangers	22
1.5.3 Extended Surface Heat Exchangers	36
1.5.4 Regenerators	47
1.6 Classification According to Flow Arrangements	56
1.6.1 Single-Pass Exchangers	57
1.6.2 Multipass Exchangers	64
1.7 Classification According to Heat Transfer Mechanisms	73
Summary	73
References	73
Review Questions	74
2 Overview of Heat Exchanger Design Methodology	78
2.1 Heat Exchanger Design Methodology	78
2.1.1 Process and Design Specifications	79
2.1.2 Thermal and Hydraulic Design	83
2.1.3 Mechanical Design	87
2.1.4 Manufacturing Considerations and Cost Estimates	90
2.1.5 Trade-off Factors	92
2.1.6 Optimum Design	93
2.1.7 Other Considerations	93

2.2	Interactions Among Design Considerations	93
	Summary	94
	References	94
	Review Questions	95
	Problems	95
3	Basic Thermal Design Theory for Recuperators	97
3.1	Formal Analogy between Thermal and Electrical Entities	98
3.2	Heat Exchanger Variables and Thermal Circuit	100
3.2.1	Assumptions for Heat Transfer Analysis	100
3.2.2	Problem Formulation	102
3.2.3	Basic Definitions	104
3.2.4	Thermal Circuit and UA	107
3.3	The ε -NTU Method	114
3.3.1	Heat Exchanger Effectiveness ε	114
3.3.2	Heat Capacity Rate Ratio C^*	118
3.3.3	Number of Transfer Units NTU	119
3.4	Effectiveness – Number of Transfer Unit Relationships	121
3.4.1	Single-Pass Exchangers	122
3.5	The P -NTU Method	139
3.5.1	Temperature Effectiveness P	140
3.5.2	Number of Transfer Units, NTU	140
3.5.3	Heat Capacity Rate Ratio R	141
3.5.4	General P -NTU Functional Relationship	141
3.6	P -NTU Relationships	142
3.6.1	Parallel Counterflow Exchanger, Shell Fluid Mixed, 1–2 TEMA E Shell	142
3.6.2	Multipass Exchangers	164
3.7	The Mean Temperature Difference Method	186
3.7.1	Log-Mean Temperature Difference, LMTD	186
3.7.2	Log-Mean Temperature Difference Correction Factor F	187
3.8	F Factors for Various Flow Arrangements	190
3.8.1	Counterflow Exchanger	190
3.8.2	Parallelfow Exchanger	191
3.8.3	Other Basic Flow Arrangements	192
3.8.4	Heat Exchanger Arrays and Multipassing	201
3.9	Comparison of the ε -NTU, P -NTU, and MTD Methods	207
3.9.1	Solutions to the Sizing and Rating Problems	207
3.9.2	The ε -NTU Method	208
3.9.3	The P -NTU Method	209
3.9.4	The MTD Method	209
3.10	The ψ - P and $P_1 - P_2$ Methods	210
3.10.1	The ψ - P Method	210
3.10.2	The $P_1 - P_2$ Method	211

3.11	Solution Methods for Determining Exchanger Effectiveness	212
3.11.1	Exact Analytical Methods	213
3.11.2	Approximate Methods	213
3.11.3	Numerical Methods	213
3.11.4	Matrix Formalism	214
3.11.5	Chain Rule Methodology	214
3.11.6	Flow-Reversal Symmetry	215
3.11.7	Rules for the Determination of Exchanger Effectiveness with One Fluid Mixed	216
3.12	Heat Exchanger Design Problems	216
	Summary	219
	References	219
	Review Questions	220
	Problems	227
4	Additional Considerations for Thermal Design of Recuperators	232
4.1	Longitudinal Wall Heat Conduction Effects	232
4.1.1	Exchangers with $C^* = 0$	236
4.1.2	Single-Pass Counterflow Exchanger	236
4.1.3	Single-Pass Parallelflow Exchanger	239
4.1.4	Single-Pass Unmixed–Unmixed Crossflow Exchanger	239
4.1.5	Other Single-Pass Exchangers	239
4.1.6	Multipass Exchangers	239
4.2	Nonuniform Overall Heat Transfer Coefficients	244
4.2.1	Temperature Effect	248
4.2.2	Length Effect	249
4.2.3	Combined Effect	251
4.3	Additional Considerations for Extended Surface Exchangers	258
4.3.1	Thin Fin Analysis	259
4.3.2	Fin Efficiency	272
4.3.3	Fin Effectiveness	288
4.3.4	Extended Surface Efficiency	289
4.4	Additional Considerations for Shell-and-Tube Exchangers	291
4.4.1	Shell Fluid Bypassing and Leakage	291
4.4.2	Unequal Heat Transfer Area in Individual Exchanger Passes	296
4.4.3	Finite Number of Baffles	297
	Summary	298
	References	298
	Review Questions	299
	Problems	302
5	Thermal Design Theory for Regenerators	308
5.1	Heat Transfer Analysis	308
5.1.1	Assumptions for Regenerator Heat Transfer Analysis	308
5.1.2	Definitions and Description of Important Parameters	310
5.1.3	Governing Equations	312

5.2	The ε -NTU _o Method	316
5.2.1	Dimensionless Groups	316
5.2.2	Influence of Core Rotation and Valve Switching Frequency	320
5.2.3	Convection Conductance Ratio (hA) [*]	320
5.2.4	ε -NTU _o Results for a Counterflow Regenerator	321
5.2.5	ε -NTU _o Results for a Parallelflow Regenerator	326
5.3	The Λ - Π Method	337
5.3.1	Comparison of the ε -NTU _o and Λ - Π Methods	341
5.3.2	Solutions for a Counterflow Regenerator	344
5.3.3	Solution for a Parallelflow Regenerator	345
5.4	Influence of Longitudinal Wall Heat Conduction	348
5.5	Influence of Transverse Wall Heat Conduction	355
5.5.1	Simplified Theory	355
5.6	Influence of Pressure and Carryover Leakages	360
5.6.1	Modeling of Pressure and Carryover Leakages for a Rotary Regenerator	360
5.7	Influence of Matrix Material, Size, and Arrangement	366
	Summary	371
	References	372
	Review Questions	373
	Problems	376
6	Heat Exchanger Pressure Drop Analysis	378
6.1	Introduction	378
6.1.1	Importance of Pressure Drop	378
6.1.2	Fluid Pumping Devices	380
6.1.3	Major Contributions to the Heat Exchanger Pressure Drop	380
6.1.4	Assumptions for Pressure Drop Analysis	381
6.2	Extended Surface Heat Exchanger Pressure Drop	381
6.2.1	Plate-Fin Heat Exchangers	382
6.2.2	Tube-Fin Heat Exchangers	391
6.3	Regenerator Pressure Drop	392
6.4	Tubular Heat Exchanger Pressure Drop	393
6.4.1	Tube Banks	393
6.4.2	Shell-and-Tube Exchangers	393
6.5	Plate Heat Exchanger Pressure Drop	397
6.6	Pressure Drop Associated with Fluid Distribution Elements	399
6.6.1	Pipe Losses	399
6.6.2	Sudden Expansion and Contraction Losses	399
6.6.3	Bend Losses	403
6.7	Pressure Drop Presentation	412
6.7.1	Nondimensional Presentation of Pressure Drop Data	413
6.7.2	Dimensional Presentation of Pressure Drop Data	414

6.8	Pressure Drop Dependence on Geometry and Fluid Properties	418
	Summary	419
	References	420
	Review Questions	420
	Problems	422
7	Surface Basic Heat Transfer and Flow Friction Characteristics	425
7.1	Basic Concepts	426
7.1.1	Boundary Layers	426
7.1.2	Types of Flows	429
7.1.3	Free and Forced Convection	438
7.1.4	Basic Definitions	439
7.2	Dimensionless Groups	441
7.2.1	Fluid Flow	443
7.2.2	Heat Transfer	446
7.2.3	Dimensionless Surface Characteristics as a Function of the Reynolds Number	449
7.3	Experimental Techniques for Determining Surface Characteristics	450
7.3.1	Steady-State Kays and London Technique	451
7.3.2	Wilson Plot Technique	460
7.3.3	Transient Test Techniques	467
7.3.4	Friction Factor Determination	471
7.4	Analytical and Semiempirical Heat Transfer and Friction Factor Correlations for Simple Geometries	473
7.4.1	Fully Developed Flows	475
7.4.2	Hydrodynamically Developing Flows	499
7.4.3	Thermally Developing Flows	502
7.4.4	Simultaneously Developing Flows	507
7.4.5	Extended Reynolds Analogy	508
7.4.6	Limitations of j vs. Re Plot	510
7.5	Experimental Heat Transfer and Friction Factor Correlations for Complex Geometries	511
7.5.1	Tube Bundles	512
7.5.2	Plate Heat Exchanger Surfaces	514
7.5.3	Plate-Fin Extended Surfaces	515
7.5.4	Tube-Fin Extended Surfaces	519
7.5.5	Regenerator Surfaces	523
7.6	Influence of Temperature-Dependent Fluid Properties	529
7.6.1	Correction Schemes for Temperature-Dependent Fluid Properties	530
7.7	Influence of Superimposed Free Convection	532
7.7.1	Horizontal Circular Tubes	533
7.7.2	Vertical Circular Tubes	535
7.8	Influence of Superimposed Radiation	537
7.8.1	Liquids as Participating Media	538

7.8.2	Gases as Participating Media	538
	Summary	542
	References	544
	Review Questions	548
	Problems	553
8	Heat Exchanger Surface Geometrical Characteristics	563
8.1	Tubular Heat Exchangers	563
8.1.1	Inline Arrangement	563
8.1.2	Staggered Arrangement	566
8.2	Tube-Fin Heat Exchangers	569
8.2.1	Circular Fins on Circular Tubes	569
8.2.2	Plain Flat Fins on Circular Tubes	572
8.2.3	General Geometric Relationships for Tube-Fin Exchangers	574
8.3	Plate-Fin Heat Exchangers	574
8.3.1	Offset Strip Fin Exchanger	574
8.3.2	Corrugated Louver Fin Exchanger	580
8.3.3	General Geometric Relationships for Plate-Fin Surfaces	584
8.4	Regenerators with Continuous Cylindrical Passages	585
8.4.1	Triangular Passage Regenerator	585
8.5	Shell-and-Tube Exchangers with Segmental Baffles	587
8.5.1	Tube Count	587
8.5.2	Window and Crossflow Section Geometry	589
8.5.3	Bypass and Leakage Flow Areas	592
8.6	Gasketed Plate Heat Exchangers	597
	Summary	598
	References	598
	Review Questions	599
9	Heat Exchanger Design Procedures	601
9.1	Fluid Mean Temperatures	601
9.1.1	Heat Exchangers with $C^* \approx 0$	603
9.1.2	Counterflow and Crossflow Heat Exchangers	604
9.1.3	Multipass Heat Exchangers	604
9.2	Plate-Fin Heat Exchangers	605
9.2.1	Rating Problem	605
9.2.2	Sizing Problem	617
9.3	Tube-Fin Heat Exchangers	631
9.3.1	Surface Geometries	631
9.3.2	Heat Transfer Calculations	631
9.3.3	Pressure Drop Calculations	632
9.3.4	Core Mass Velocity Equation	632
9.4	Plate Heat Exchangers	632
9.4.1	Limiting Cases for the Design	633
9.4.2	Uniqueness of a PHE for Rating and Sizing	635

9.4.3	Rating a PHE	637
9.4.4	Sizing a PHE	645
9.5	Shell-and-Tube Heat Exchangers	646
9.5.1	Heat Transfer and Pressure Drop Calculations	646
9.5.2	Rating Procedure	650
9.5.3	Approximate Design Method	658
9.5.4	More Rigorous Thermal Design Method	663
9.6	Heat Exchanger Optimization	664
	Summary	667
	References	667
	Review Questions	668
	Problems	669
10	Selection of Heat Exchangers and Their Components	673
10.1	Selection Criteria Based on Operating Parameters	674
10.1.1	Operating Pressures and Temperatures	674
10.1.2	Cost	675
10.1.3	Fouling and Cleanability	675
10.1.4	Fluid Leakage and Contamination	678
10.1.5	Fluids and Material Compatibility	678
10.1.6	Fluid Type	678
10.2	General Selection Guidelines for Major Exchanger Types	680
10.2.1	Shell-and-Tube Exchangers	680
10.2.2	Plate Heat Exchangers	693
10.2.3	Extended-Surface Exchangers	694
10.2.4	Regenerator Surfaces	699
10.3	Some Quantitative Considerations	699
10.3.1	Screening Methods	700
10.3.2	Performance Evaluation Criteria	713
10.3.3	Evaluation Criteria Based on the Second Law of Thermodynamics	723
10.3.4	Selection Criterion Based on Cost Evaluation	724
	Summary	726
	References	726
	Review Questions	727
	Problems	732
11	Thermodynamic Modeling and Analysis	735
11.1	Introduction	735
11.1.1	Heat Exchanger as a Part of a System	737
11.1.2	Heat Exchanger as a Component	738
11.2	Modeling a Heat Exchanger Based on the First Law of Thermodynamics	738
11.2.1	Temperature Distributions in Counterflow and Parallelflow Exchangers	739
11.2.2	True Meaning of the Heat Exchanger Effectiveness	745

11.2.3	Temperature Difference Distributions for Parallelflow and Counterflow Exchangers	748
11.2.4	Temperature Distributions in Crossflow Exchangers	749
11.3	Irreversibilities in Heat Exchangers	755
11.3.1	Entropy Generation Caused by Finite Temperature Differences	756
11.3.2	Entropy Generation Associated with Fluid Mixing	759
11.3.3	Entropy Generation Caused by Fluid Friction	762
11.4	Thermodynamic Irreversibility and Temperature Cross Phenomena	763
11.4.1	Maximum Entropy Generation	763
11.4.2	External Temperature Cross and Fluid Mixing Analogy	765
11.4.3	Thermodynamic Analysis for 1–2 TEMA J Shell-and-Tube Heat Exchanger	766
11.5	A Heuristic Approach to an Assessment of Heat Exchanger Effectiveness	771
11.6	Energy, Exergy, and Cost Balances in the Analysis and Optimization of Heat Exchangers	775
11.6.1	Temperature–Enthalpy Rate Change Diagram	776
11.6.2	Analysis Based on an Energy Rate Balance	779
11.6.3	Analysis Based on Energy/Enthalpy and Cost Rate Balancing	783
11.6.4	Analysis Based on an Exergy Rate Balance	786
11.6.5	Thermodynamic Figure of Merit for Assessing Heat Exchanger Performance	787
11.6.6	Accounting for the Costs of Exergy Losses in a Heat Exchanger	791
11.7	Performance Evaluation Criteria Based on the Second Law of Thermodynamics	796
	Summary	800
	References	801
	Review Questions	802
	Problems	804
12	Flow Maldistribution and Header Design	809
12.1	Geometry-Induced Flow Maldistribution	809
12.1.1	Gross Flow Maldistribution	810
12.1.2	Passage-to-Passage Flow Maldistribution	821
12.1.3	Manifold-Induced Flow Maldistribution	834
12.2	Operating Condition-Induced Flow Maldistribution	837
12.2.1	Viscosity-Induced Flow Maldistribution	837
12.3	Mitigation of Flow Maldistribution	844
12.4	Header and Manifold Design	845
12.4.1	Oblique-Flow Headers	848
12.4.2	Normal-Flow Headers	852
12.4.3	Manifolds	852
	Summary	853
	References	853

Review Questions	855
Problems	859
13 Fouling and Corrosion	863
13.1 Fouling and its Effect on Exchanger Heat Transfer and Pressure Drop	863
13.2 Phenomenological Considerations of Fouling	866
13.2.1 Fouling Mechanisms	867
13.2.2 Single-Phase Liquid-Side Fouling	870
13.2.3 Single-Phase Gas-Side Fouling	871
13.2.4 Fouling in Compact Exchangers	871
13.2.5 Sequential Events in Fouling	872
13.2.6 Modeling of a Fouling Process	875
13.3 Fouling Resistance Design Approach	881
13.3.1 Fouling Resistance and Overall Heat Transfer Coefficient Calculation	881
13.3.2 Impact of Fouling on Exchanger Heat Transfer Performance	882
13.3.3 Empirical Data for Fouling Resistances	886
13.4 Prevention and Mitigation of Fouling	890
13.4.1 Prevention and Control of Liquid-Side Fouling	890
13.4.2 Prevention and Reduction of Gas-Side Fouling	891
13.4.3 Cleaning Strategies	892
13.5 Corrosion in Heat Exchangers	893
13.5.1 Corrosion Types	895
13.5.2 Corrosion Locations in Heat Exchangers	895
13.5.3 Corrosion Control	897
Summary	898
References	898
Review Questions	899
Problems	903
Appendix A: Thermophysical Properties	906
Appendix B: ε -NTU Relationships for Liquid-Coupled Exchangers	911
Appendix C: Two-Phase Heat Transfer and Pressure Drop Correlations	913
C.1 Two-Phase Pressure Drop Correlations	913
C.2 Heat Transfer Correlations for Condensation	916
C.3 Heat Transfer Correlations for Boiling	917
Appendix D: U and C_{UA} Values for Various Heat Exchangers	920
General References on or Related to Heat Exchangers	926
Index	931