Thermal Design & Optimization

Adrian Bejan George Tsatsaronis Michael Moran

CONTENTS

1	Introduction to Thermal System Design			
	1.1	Preliminaries / 2		
	1.2	Workable, Optimal, and Nearly Optimal Designs / 3		
	1.3	Life-Cycle Design / 6 1.3.1 Overview of the Design Process / 6 1.3.2 Understanding the Problem: "What?" not "How?" / 9 1.3.3 Project Management / 11 1.3.4 Project Documentation / 12		
	1.4	Thermal System Design Aspects / 15 1.4.1 Environmental Aspects / 16 1.4.2 Safety and Reliability / 17 1.4.3 Background Information and Data Sources / 19 1.4.4 Performance and Cost Data / 20		
	1.5	Concept Creation and Assessment / 21 1.5.1 Concept Generation: "How?" not "What?" / 21 1.5.2 Concept Screening / 22 1.5.3 Concept Development / 25 1.5.4 Sample Problem Base-Case Design / 29		
	1.6	Computer-Aided Thermal System Design / 31 1.6.1 Preliminaries / 31 1.6.2 Process Synthesis Software / 32 1.6.3 Analysis and Optimization: Flowsheeting Software / 32		
1.7 Closure / 33		Closure / 33		
References / 34				
	Problems / 36			

2 Thermodynamics, Modeling, and Design Analysis			39	
	2.1	Basic 2.1.1 2.1.2 2.1.3 2.1.4	The First Law of Thermodynamics, Energy / 42 The Second Law of Thermodynamics / 46	
	2.2	Contro	ol Volume Concepts / 55	
		2.2.1 2.2.2 2.2.3		
	2.3	Proper	ty Relations / 64	
		2.3.1 2.3.2	Basic Relations for Pure Substances / 64 Multicomponent Systems / 76	
	2.4	2.4.1 2.4.2 2.4.3	ng Mixtures and Combustion / 78 Combustion / 78 Enthalpy of Formation / 78 Absolute Entropy / 80 Ancillary Concepts / 81	
	2.5	Therm	odynamic Model—Cogeneration System / 84	
	2.6	Model 2.6.1 2.6.2 2.6.3 2.6.4	Estimation of Head Loss / 99	
	2.7	Closur	e / 107	
	References / 108			
	Problems / 108			
3	3 Exergy Analysis		alysis	113
	3.1	Exergy 3.1.1 3.1.2 3.1.3 3.1.4	Preliminaries / 113 Defining Exergy / 114 Environment and Dead States / 115 Exergy Components / 116	
	3.2	3.2.1	al Exergy / 117 Derivation / 117 Discussion / 120	

3.3	Exergy	Balance / 121		
	3.3.1 Closed System Exergy Balance / 121 3.3.2 Control Volume Exergy Balance / 123			
3.4	Chemical Exergy / 131			
	3.4.1	Standard Chemical Exergy / 131 Standard Chemical Exergy of Gases and Gas Mixtures / 132		
	3.4.3	Standard Chemical Exergy of Fuels / 134		
3.5	Applications / 138			
	3.5.1 3.5.2 3.5.3	Cogeneration System Exergy Analysis / 139 Exergy Destruction and Exergy Loss / 143 Exergetic Efficiency / 150 Chemical Exergy of Coal, Char, and Fuel Oil / 156		
3.6	Guidelines for Evaluating and Improving Thermodynamic Effectiveness / 159			
3.7	Closur	e / 162		
Refe	rences	/ 162		
Prob	lems /	163		
Heat	Trans	fer, Modeling, and Design Analysis		
4.1	The Objective of Heat Transfer / 167			
4.2	Conduction / 170			
		Steady Conduction / 170 Unsteady Conduction / 176		
4.3	Convection / 184			
	4.3.2 4.3.3 4.3.4	External Forced Convection / 184 Internal Forced Convection / 190 Natural Convection / 195 Condensation / 199 Boiling / 202		
4.4	Radiation / 207			
	4.4.1 4.4.2 4.4.3 4.4.4 4.4.5 4.4.6	Blackbody Radiation / 208 Geometric View Factors / 209 Diffuse-Gray Surface Model / 213 Two-Surface Enclosures / 214 Enclosures with More Than Two Surfaces / 220 Gray Medium Surrounded by Two Diffuse-Gray		
		Surfaces / 221		

4.5 Closure / 225					
References / 225					
Prob	olems /	227			
App	lication	ns with Heat and Fluid Flow	237		
5.1	Thermal Insulation / 237				
5.2	Fins /	241			
		Known Fin Width / 241 Known Fin Thickness / 244			
5.3	Electro	onic Packages / 247			
		Natural Convection Cooling / 247			
		Forced Convection Cooling / 251 Cooling of a Heat-Generating Board Inside a			
		Parallel-Plate Channel / 256			
5.4	Closui	re / 265			
Refe	erences	/ 265			
Prob	olems /	266			
	Applications with Thermodynamics and Heat and Fluid Flow 273				
6.1	Heat I	Exchangers / 273			
6.2	The Trade-off Between Thermal and Fluid Flow Irreversibilities / 281				
		Local Rate of Entropy Generation / 282			
		Internal Flows / 283			
	6.2.4	External Flows / 287 Nearly Ideal Balanced Counterflow Heat			
		Exchangers / 290			
		Unbalanced Heat Exchangers / 296			
6.3		reheater Preliminary Design / 297			
	6.3.1 6.3.2	Shell-and-Tube Counterflow Heat Exchanger / 298 Plate-Fin Crossflow Heat Exchanger / 305			
	6.3.3	Closure / 310			
6.4		onal Applications / 311			
	6.4.1 6.4.2	Refrigeration / 311 Power Generation / 315			

		6.4.3 Exergy Storage by Sensible Heating / 3206.4.4 Concluding Comment / 325	
	6.5 Closure / 326		
	Refe	rences / 326	
	Prob	lems / 327	
7	Eco	nomic Analysis	
	7.1	Estimation of Total Capital Investment / 334 7.1.1 Cost Estimates of Purchased Equipment / 337 7.1.2 Estimation of the Remaining FCI Direct Costs / 344 7.1.3 Indirect Costs of FCI / 346 7.1.4 Other Outlays / 347 7.1.5 Simplified Relationships / 348 7.1.6 Cogeneration System Case Study / 351	
	7.2	Principles of Economic Evaluation / 353 7.2.1 Time Value of Money / 353 7.2.2 Inflation, Escalation, and Levelization / 359 7.2.3 Current versus Constant Dollars / 361 7.2.4 Time Assumptions / 363 7.2.5 Depreciation / 364 7.2.6 Financing and Required Returns on Capital / 366 7.2.7 Fuel, Operating, and Maintenance Costs / 367 7.2.8 Taxes and Insurance / 367 7.2.9 Cogeneration System Case Study / 369	
	7.3	Calculation of Revenue Requirements / 374 7.3.1 Total Capital Recovery / 376 7.3.2 Returns on Equity and Debt / 379 7.3.3 Taxes and Insurance / 382 7.3.4 Fuel, Operating, and Maintenance Costs / 383 7.3.5 Total Revenue Requirement / 383	
7.4 Levelized Costs and Cost of the Main Product / 383		Levelized Costs and Cost of the Main Product / 383	
	7.5	Profitability Evaluation and Comparison of Alternative Investments / 388 7.5.1 Average Rate of Return and Payback Period / 389 7.5.2 Methods Using Discounted Cash Flows / 392 7.5.3 Different Economic Lives / 396 7.5.4 Discussion of Profitability–Evaluation Methods / 399	

	7.6	7.6 Closure / 399			
	Refe	References / 400			
	Problems / 401				
8	Thermoeconomic Analysis and Evaluation 40				
	8.1	Funda 8.1.1 8.1.2 8.1.3 8.1.4 8.1.5 8.1.6	Aggregation Level for Applying Exergy Costing / 417 Cost Rates, Auxiliary Relations, and Average Costs Associated with Fuel and Product / 420 Costing of Exergy Loss Streams / 425		
	8.2	Therm 8.2.1 8.2.2 8.2.3	6,		
	8.3	8.3.1	Design Evaluation / 439 Performance Evaluation / 445		
	8.4	Additi 8.4.1 8.4.2 8.4.3 8.4.4	Costing Reactive and Nonreactive Exergy / 453		
8.5 Closure / 458		re / 458			
	Refe	rences	/ 459		
Problems / 460					
9	The	moeco	onomic Optimization	463	
9.1 Introduction		Introdu	action to Optimization / 463		
	9.2	O.2 Cost-Optimal Exergetic Efficiency for an Isolated System Component / 466			
	9.3	Optimi 9.3.1 9.3.2 9.3.3	Temperature–Enthalpy Rate Difference Diagram / 474 Composite Curves and Process Pinch / 477 Maximum Energy Recovery / 481		

		9.3.5 9.3.6 9.3.7 9.3.8	Grand Compo Estimation of Surface Area HEN Design Integration of	/ 490 a HEN with Other Components / 495
	9.4	9.4.1 9.4.2 9.4.3	ical and Nume Functions of Unconstrained Linear Progra Nonlinear Pro	erical Optimization Techniques / 498 a Single Variable / 499 d Multivariable Optimization / 500 amming Techniques / 500 ogramming with Constraints / 501
	9.5	Case S 9.5.1 9.5.2 9.5.3	Study / 502 Preliminaries Thermodynan	nic Optimization / 503 otimization / 506
	9.6	Therm	oeconomic Op	otimization of Complex Systems / 506
	9.7 Closure / 509			
	References / 510 Problems / 512			
	App	endix A	Variational	Calculus / 515
	App	endix B	Economic N	Model of the Cogeneration System / 517
	App	endix C		roperty Data / 519 Variation of Specific Heat, Enthalpy, Absolute Entropy, and Gibbs Function with Temperature at 1 bar for Various Substances 519
			Table C.2	Standard Molar Chemical Exergy, $\overline{e}^{\rm CH}$ (kJ/kmol), of Various Substances at 298.15 K and p_0 / 521
	App	endix D	Symbols /	523
	App	endix E	Conversion	Factors / 531

Index / 533