

Contents

Preface *xiii*

1	Thermodynamic Cycles	1
1.1	Introduction to Thermodynamic Cycles	1
1.2	Rankine Cycle	1
1.2.1	Introduction	1
1.2.2	Thermodynamic Diagrams	2
1.2.3	The Carnot Cycle	10
1.2.4	Ideal and Actual Rankine Cycles	12
1.2.4.1	Ideal Cycle	13
1.2.4.2	Superheated Rankine Cycle	15
1.2.4.3	Actual Rankine Cycle	17
1.2.4.4	Improvements to the Rankine Cycle	19
1.2.4.5	Regenerative Rankine Cycles	22
1.2.4.6	Cogeneration	26
1.2.5	Other Configurations of the Rankine Cycle	29
1.2.5.1	Supercritical Rankine Cycles	29
1.2.5.2	Reverse Rankine Cycles	30
1.2.6	Rankine Cycles in Power Plants	31
1.2.6.1	Fossil Fuel Power Plants	31
1.2.6.2	Nuclear Power Plants	32
1.2.6.3	Overall Efficiency of a Power Plant	32
1.2.6.4	Case Studies	33
1.3	Organic Rankine Cycle	34
1.3.1	Configurations of ORC	35
1.3.1.1	Basic ORC Configuration	35
1.3.1.2	ORC with Preheating	36
1.3.1.3	Recuperative ORC	38
1.3.1.4	Recuperative ORC with Preheating	39
1.3.2	Organic Working Fluids	40
1.3.3	Organic Working Fluid Selection	42
1.3.4	Applications of the ORC	45
1.3.4.1	Waste Heat Recovery	45

1.4	Kalina Cycle	46
1.4.1	Cycle Fundamentals	46
1.4.1.1	Why Use Ammonia–Water Solution in Kalina Cycle?	48
1.4.2	Advantages and Drawbacks	49
1.4.2.1	Advantages	49
1.4.2.2	Drawbacks	50
1.4.3	Applications of the Kalina Cycle	50
1.4.3.1	The Different Configurations of the Cycle	51
1.4.4	Case Studies	53
1.5	Brayton Cycle	53
1.5.1	Regenerative Brayton Cycle (Regenerator)	57
1.5.1.1	Compressor Analysis	58
1.5.1.2	Turbine Analysis	58
1.5.1.3	Heat Supplied to the Cycle	59
1.5.2	Regenerative Brayton Cycle (Reheater and Intercooler)	59
1.5.2.1	Intercooling	60
1.5.2.2	Reheating	60
1.6	Chapter Summary	61
	References	62
2	Waste Heat Recovery	67
2.1	Burner and Air Preheaters	67
2.1.1	Recuperators	67
2.1.1.1	Recuperative Burners	68
2.1.1.2	Classifying Recuperative Burners	71
2.1.1.3	Efficiency Improvement and Fuel Savings	72
2.1.2	Regenerators	74
2.1.2.1	Rotary Regenerators	74
2.1.2.2	Static Regenerators	75
2.1.2.3	Regenerative Burners	75
2.1.3	Burner Technology Comparison	76
2.1.4	NO _x Formation	77
2.1.5	Run-Around Coil	78
2.2	Heat Exchangers	79
2.2.1	Shell and Tube HEXs	79
2.2.1.1	Construction	80
2.2.1.2	Applications and Limitations	82
2.2.2	Plate Heat Exchanger	82
2.2.2.1	Spiral Plate Heat Exchanger	83
2.2.3	Heat Pipe Heat Exchanger	83
2.2.4	Compact HEX	85
2.3	Waste Heat Boilers	86
2.3.1	Different WHB Designs	87
2.3.2	WHB Methodologies	88
2.3.2.1	Feed Water Preheating Effect	88

2.3.2.2	Optimising Thermodynamic Cycles	89
2.3.2.3	Heat Recovery Boiler with Water Spray Systems	91
2.3.3	Failure Modes	92
2.3.3.1	Failure Modes Analysis	92
2.4	Heat Recovery Steam Generators	93
2.4.1	Construction of Waste HRSG	94
2.4.1.1	HRSG Design and Construction	95
2.4.1.2	Evaporator	95
2.4.1.3	Superheater	96
2.4.1.4	Economiser	96
2.4.1.5	Steam Drum	96
2.4.1.6	Evaporator Types	96
2.4.1.7	Horizontal Tube HEXs	98
2.4.1.8	Natural Circulation HRSGs	98
2.4.1.9	Assisted (or Forced) Circulation HRSGs	99
2.4.1.10	Tube Materials	99
2.4.1.11	The 'Pinch Point' and Other Effects	100
2.5	Heat Pumps	100
2.5.1	Fundamental Principles of Heat Pumps	100
2.5.1.1	Cooling Mode	101
2.5.1.2	Heating Mode	101
2.5.2	Variation of Heat Pump System	102
2.5.2.1	Air Source Heat Pump System	103
2.5.2.2	Ground Source Heat Pump System	103
2.5.2.3	Water Source Heat Pump System	105
2.5.2.4	Water Loop Heat Pump System	105
2.5.2.5	Exhaust Air System	106
2.5.2.6	Hybrid Heat Pump	106
2.5.2.7	Solar-Assisted Heat Pumps	106
2.6	Direct Electrical Conversion Device	107
2.6.1	TEG – Working Principle	108
2.6.2	The Seebeck Effect	109
2.6.3	The Peltier Effect	109
2.6.3.1	Applications of the Peltier Effect	110
2.6.4	Thomson Effect	110
2.6.5	Joule Heating	111
2.6.6	Theoretical Principle	112
2.6.7	Figure of Merit	112
2.6.8	Fermi Level	113
2.6.9	Nano-Sizing	114
2.6.10	Efficiency of TEG	115
2.7	Thermal Storage	116
2.7.1	Sensible Heat Storage	117
2.7.2	Latent Heat Storage	120
2.7.3	Thermochemical Storage	123

2.7.4	Phase Change Materials	123
2.7.5	Organic Material	125
2.7.6	Inorganic PCMs	128
2.7.7	Eutectic PCMs	128
2.7.8	PCM Methodologies	129
2.7.8.1	Encapsulation of PCMs	129
2.7.8.2	Microencapsulated PCMs	129
2.7.8.3	Macroencapsulation of the PCMs	132
2.7.8.4	Nanomaterial PCMs	132
2.7.8.5	Shape Stabilisation	135
2.8	Design Development Methods	135
2.8.1	Introduction	135
2.8.2	Heat Exchangers	140
2.8.2.1	Local Heat Transfer	140
2.8.2.2	LMTD Method	147
2.8.2.3	Effectiveness-Number of Transfer Units (ϵ -NTU) Method	151
2.8.3	Regenerative and Recuperative Burners	152
2.8.3.1	Regenerative Burners	154
2.8.3.2	Recuperative Burners	156
2.8.4	Waste Heat Boilers	157
2.8.5	Air Preheaters	160
2.8.6	Heat Recovery Steam Generator	166
2.8.7	Heat Pumps	170
2.8.8	Direct Electrical Conversion Device	173
2.8.9	Thermal Storage	176
	References	178
3	Low-Temperature Applications	191
3.1	Refrigeration	191
3.2	Cryogenics	198
3.2.1	Loop Heat Pipe	199
3.3	HVAC	204
	References	209
4	Medium-Temperature Applications	213
4.1	Food Industry	213
4.1.1	Energy Use in the Industry	213
4.1.2	Case Study 1: Heat Recovery Potential of the Crisps Manufacturing Process	214
4.1.3	Case Study 2: Temperature and Energy Performance of Open Refrigerated Display Cabinets Using Heat Pipe Shelves	215
4.2	Ventilation	221
4.2.1	Applications	221
4.3	Solar Energy	223
4.4	Geothermal Energy	230

4.5	Automotive Industry	233
4.5.1	Industrial Processes	235
4.6	Aviation	237
	References	239
5	High-Temperature Applications	245
5.1	Steel Industry	245
5.1.1	TEG Modules	246
5.1.2	Heat Exchangers	246
5.1.2.1	Application 1: Slag Particles Blast Furnace Retrofit	246
5.1.2.2	Application 2: Flat Heat Pipe Heat Exchanger	247
5.1.3	Recuperators	249
5.1.3.1	Application 1: Heat Recuperator for Steel Slag	249
5.2	Ceramic Industry	251
5.2.1	Introduction	251
5.2.2	Heat Exchangers	251
5.2.2.1	Application 1: Radiative Heat Pipe	251
5.2.2.2	Application 2: Multi-Pass Heat Pipe	252
5.2.2.3	Application 3: Forced Convection Heat Pipe	253
5.3	Cement Industry	254
5.3.1	Gas Suspension Preheaters	255
5.3.1.1	Application 1	255
5.3.1.2	Application 2	256
5.3.2	Heat Pipe Thermoelectric Generator	256
5.4	Aluminium Industry	258
5.4.1	Rotary Regenerator	258
5.4.2	Heat Exchangers	258
5.4.3	Heat Pumps	258
5.4.4	Recuperators	260
5.4.4.1	Radiative Recuperator	260
5.4.4.2	Convective Recuperator	261
5.4.4.3	Hybrid Recuperator	262
5.4.5	Thermoelectric Device	262
5.4.6	Regenerative Burner	262
5.4.7	Preheating Scrap	264
5.4.8	De-coating	265
	References	265
	Index	269

