

Contents

List of contributors	xi
Woodhead Publishing Series in Energy	xiii
Part One Introduction to Organic Rankine Cycle power systems	1
1 Theoretical basis of the Organic Rankine Cycle	3
<i>E. Macchi</i>	
1.1 Introduction	3
1.2 The unique features of Organic Rankine Cycles	6
1.3 Why air (or any other gas) is not an appropriate working fluid for a power cycle operating with low-medium temperature heat sources	6
1.4 Why water is not the right working fluid for power cycles fed by energy sources of limited capacity	14
1.5 Thermodynamic issues related to the choice of working fluid	15
1.6 Criteria for the selection of the working fluid	22
2 History of Organic Rankine Cycle systems	25
<i>L.Y. Bronicki</i>	
2.1 Introduction	25
2.2 Learning by doing: from steam engine to thermodynamics	25
2.3 From steam engine to ORC, progress based on practical engineering and not on theory	27
2.4 Rebirth of the ORC: integrating thermodynamics and system design	31
2.5 Early commercial plants	40
2.6 Commercialization of ORC systems, present status	45
2.7 Software development	63
2.8 Summary	63
References	63

3	Technical options for Organic Rankine Cycle systems	67
	<i>M. Astolfi</i>	
3.1	Equipment list	67
3.2	Plant layouts	75
3.3	Use of mixtures versus pure fluids	86
	References	87
4	Organic fluids for Organic Rankine Cycle systems: classification and calculation of thermodynamic and transport properties	91
	<i>I.H. Bell, E.W. Lemmon</i>	
4.1	Overview of thermophysical properties of fluids and their application to Organic Rankine Cycle systems	91
4.2	Classification of fluids	92
4.3	Thermodynamic properties of pure fluids	92
4.4	Thermodynamic properties of mixtures	101
4.5	Transport properties of pure fluids	106
4.6	Transport properties of mixtures	110
4.7	Surface tension	111
4.8	Interpolation methods	112
4.9	Libraries available	115
	Acknowledgments	116
	References	116
5	Thermal stability of organic fluids for Organic Rankine Cycle systems	121
	<i>C.M. Invernizzi, D. Bonalumi</i>	
5.1	Introduction	121
5.2	The thermal and the thermochemical stability of working fluids	124
5.3	The evaluation of thermal stability	126
5.4	A system for the measurement of thermal stability	131
5.5	Conclusions	143
	Nomenclature	147
	References	148
6	Dynamic modeling and control of Organic Rankine Cycle plants	153
	<i>F. Casella</i>	
6.1	Introduction	153
6.2	Dynamic modeling and simulation for control design	155
6.3	Control design work-flow	166
6.4	Conclusions	170
	References	170

7	Thermodynamic and technoeconomic optimization of Organic Rankine Cycle systems	173
	<i>M. Astolfi, E. Martelli, L. Pierobon</i>	
7.1	Design of Organic Rankine Cycles and their optimization	173
7.2	System optimization	184
7.3	Numerical examples	220
	Acronyms	242
	Nomenclature	243
	Subscripts	244
	References	245
 Part Two Organic Rankine Cycle plant components and system optimization		 251
8	Fluid dynamic design of Organic Rankine Cycle turbines	253
	<i>G. Persico, M. Pini</i>	
8.1	Introduction	253
8.2	Review of Organic Rankine Cycle turbine architectures	255
8.3	Mean-line preliminary design	259
8.4	Bridge between preliminary and aerodynamic design: throughflow model	265
8.5	Aerodynamic design	272
8.6	Conclusions	292
	References	293
9	Axial flow turbines for Organic Rankine Cycle applications	299
	<i>E. Macchi, M. Astolfi</i>	
9.1	The role of axial-flow turbines in the power generation sector	299
9.2	The peculiarities of the design procedures of Organic Rankine Cycle turbines	301
9.3	Methodology	302
9.4	The proposed efficiency correlation	306
9.5	Model validation	313
9.6	Conclusions	316
	Nomenclature	317
	References	318
10	Radial inflow turbines for Organic Rankine Cycle systems	321
	<i>P. Valdimarsson</i>	
10.1	Radial inflow turbines: what are they?	321
10.2	Radial inflow turbines: who makes them?	321
10.3	Thermodynamic fundamentals	322

10.4	Variable geometry nozzle guide vanes in the radial inflow turbine	326
10.5	Gearbox and integral gear technology	329
10.6	Advantages of radial turbines compared to axial or impulse turbines in Organic Rankine Cycle-based waste heat recovery processes	329
10.7	Radial turbines support higher pressure ratios and broader areas of application	330
10.8	Large turbines	330
10.9	Sturdiness and reliability	331
10.10	Advantages of gas-lubricated mechanical face seals: optimal turbine efficiency	331
10.11	Advantages of oil-lubricated mechanical face seals: maximum leakproofness	332
10.12	The track records	332
	References	333
11	Radial outflow turbines for Organic Rankine Cycle expanders	335
	<i>C. Spadacini, D. Rizzi</i>	
11.1	Introduction	335
11.2	The history of the radial outflow configuration	336
11.3	Radial outflow configuration: considerations about particular features and comparison with the most traditional alternative	339
11.4	Other configurations of the radial outflow turbine in Organic Rankine Cycles	354
11.5	Conclusion	357
	References	358
12	Positive displacement expanders for Organic Rankine Cycle systems	361
	<i>V. Lemort, A. Legros</i>	
12.1	General introduction	361
12.2	Description of major types of displacement expanders	363
12.3	Thermodynamics of displacement expanders	377
12.4	Performance of displacement expanders	387
12.5	Integration of displacement expanders into Organic Rankine Cycle systems	390
12.6	Conclusions	394
	Acknowledgments	394
	References	394
13	Heat transfer and heat exchangers	397
	<i>A. Cavallini</i>	
13.1	Heat transfer in exchangers	397
13.2	Heat exchanger basics	407

13.3	Heat transfer and pressure drop in pipe flow	420
13.4	Heat transfer and pressure drop in external flow through banks of plain and finned tubes	424
13.5	Evaporation and boiling heat transfer	430
13.6	Condensation heat transfer	439
13.7	Pressure drop in two-phase flow	448
13.8	Shell-and-tube heat exchangers	451
13.9	Air-cooled heat exchangers	455
13.10	Gasketed and brazed plate heat exchangers	458
	Nomenclature	463
	References	467
Part Three Fields of application		471
14	Geothermal energy exploitation with Organic Rankine Cycle technologies	473
	<i>C. Spadacini, L.G. Xodo, M. Quaia</i>	
14.1	Introduction: geothermal resource exploitation	473
14.2	Geothermal ORC binary plants	495
14.3	Geothermal-specific features and case studies	512
	References	524
15	Biomass-fired Organic Rankine Cycle combined heat and power systems	527
	<i>A. Guercio, R. Bini</i>	
15.1	Introduction	527
15.2	State of the art of biomass-fired Organic Rankine Cycle combined heat and power plant	529
15.3	Applications and references	549
15.4	Current market overview and European policy: economic and environmental considerations	556
15.5	Economic feasibility and sensitivity	558
15.6	Conclusions and final considerations	565
	Further reading	566
16	Solar thermal powered Organic Rankine Cycles	569
	<i>M. Orosz, R. Dickes</i>	
16.1	Introduction to solar Organic Rankine Cycle systems	569
16.2	Solar Organic Rankine Cycle components and architecture	578
16.3	Solar Organic Rankine Cycle systems	596
	References	609

17 Organic Rankine Cycle systems for large-scale waste heat recovery to produce electricity	613
<i>H. Tian, G.Q. Shu</i>	
17.1 The comparison between Organic Rankine Cycles and steam Rankine Cycles	613
17.2 The application of Organic Rankine Cycles for industrial waste heat recovery	616
17.3 The application of Organic Rankine Cycles for waste heat recovery on ships	619
17.4 The application of Organic Rankine Cycles for waste heat recovery from Distributed Energy Systems	623
17.5 The application of Organic Rankine Cycles for waste heat recovery from recompression stations along pipelines	628
References	634
18 Micro-Organic Rankine Cycle systems for domestic cogeneration	637
<i>R. Bracco, D. Micheli, R. Petrella, M. Reini, R. Taccani, G. Toniato</i>	
18.1 Requirements and main features of domestic Organic Rankine Cycle systems	637
18.2 Existing models and prototypes and comparison with solutions based on Stirling engines	642
18.3 Main technical features of domestic Organic Rankine Cycle components	644
18.4 System integration	660
18.5 Conclusions	665
References	666
Index	669