

Contents

	<i>Credits</i>	page xii
	<i>Introduction</i>	xiii
	<i>Preface</i>	xvii
	<i>Acknowledgements</i>	xix
	<i>Conventions and Nomenclature</i>	xxi
1	Introduction to Radial Flow Turbocompressors	1
	1.1 Overview	1
	1.2 Definition of Turbomachinery	2
	1.3 Classification of Turbomachines	9
	1.4 Short History of Thermal Turbomachines	14
	1.5 Components of Radial Flow Turbocompressors	15
	1.6 Applications of Centrifugal Turbocompressors	24
	1.7 Some Other Publications	40
2	Energy Transfer	44
	2.1 Overview	44
	2.2 The Euler Turbine Equation	45
	2.3 The First Law of Thermodynamics	55
	2.4 The Steady Flow Energy Equation	61
	2.5 The Second Law of Thermodynamics	66
	2.6 Energy Transfer in Radial Turbocompressors	69
	2.7 Different Ideal Compression Processes	74
	2.8 The Aerodynamic Work	81
	2.9 The Compressor Stage as the Sum of Its Components	85
3	Equations of State	87
	3.1 Overview	87
	3.2 Equations of State for Perfect Fluids	88
	3.3 Equations of State for Real Gases	92
	3.4 The Aungier–Redlich–Kwong Cubic Equation of State	99
	3.5 Isentropic and Polytropic Processes with Real Gases	101
	3.6 The Aerodynamic Work with Real Gases	103

4	Efficiency Definitions for Compressors	106
	4.1 Overview	106
	4.2 Compressor Efficiency	107
	4.3 Isentropic Efficiency	111
	4.4 Polytropic Efficiency	118
	4.5 The Impeller Wheel Efficiency	129
	4.6 External Losses and Sideloads	130
	4.7 Efficiency in Diabatic Processes	130
	4.8 Efficiency Definitions for Real Gases	134
5	Fluid Mechanics	135
	5.1 Overview	135
	5.2 The Laws of Fluid Mechanics	136
	5.3 Pressure Gradients in Fluid Flows	142
	5.4 Coriolis and Centrifugal Forces in Impellers	148
	5.5 Boundary Layers and End-Wall Flows	155
	5.6 Secondary Flows	171
	5.7 Tip Clearance Flows	176
	5.8 Jet-Wake Flow in Impellers	180
6	Gas Dynamics	191
	6.1 Overview	191
	6.2 Gas Dynamics of Ideal Gases	191
	6.3 Shock and Expansion Waves	199
	6.4 Shock Structure in Transonic Compressors	203
	6.5 Gas Dynamics of Real Gases	206
7	Aerodynamic Loading	210
	7.1 Overview	210
	7.2 Isolated Aerofoils	211
	7.3 Profiles in Cascade	219
	7.4 Diffusers	226
	7.5 Blade Loading Parameters	236
8	Similarity	247
	8.1 Overview	247
	8.2 Similarity of Fluid Flows	248
	8.3 Geometric Similarity	252
	8.4 Fluid Dynamic Similarity	253
	8.5 Thermodynamic Similarity	261
	8.6 Applications of Similarity Parameters	265
	8.7 Performance Corrections for Deviation from Similarity	278

9	Specific Speed	284
	9.1 Overview	284
	9.2 Specific Speed and Specific Diameter	284
	9.3 The Cordier Diagram	290
10	Losses and Performance	297
	10.1 Overview	297
	10.2 The Definition of Losses	298
	10.3 Viscous Loss Mechanisms	303
	10.4 Other Aerodynamic Losses	313
	10.5 Loss Correlations in Centrifugal Stages	318
	10.6 Parasitic Losses	320
	10.7 Global Estimate for Aerodynamic Efficiency at the Design Point	325
	10.8 Mean-Line Calculation of the Flow Conditions through the Stage	330
11	Impeller Design	338
	11.1 Overview	338
	11.2 Impeller Design	339
	11.3 Impeller Types	340
	11.4 Flow Conditions at the Impeller Inlet	343
	11.5 Flow Conditions at the Impeller Throat	355
	11.6 Flow Conditions at Impeller Outlet	358
	11.7 The Compressor Characteristic as Influenced by Losses and Work	376
	11.8 Guidelines to Detailed Impeller Design	378
	11.9 Three-Dimensional Features	387
	11.10 Impeller Families	390
	11.11 Impeller Trim	393
	11.12 Comparison with Rotors of Other Machine Types	397
12	Diffuser Design	405
	12.1 Overview	405
	12.2 Effect of the Flow at the Impeller Outlet	406
	12.3 Vaneless Diffusers	412
	12.4 Vaned Diffusers	417
	12.5 Ideal Pressure Recovery in a Vaned Diffuser	423
	12.6 Zones of Pressure Recovery in a Vaned Diffuser	424
	12.7 Vaneless Space and Semivaneless Space	426
	12.8 Blockage at the Throat in Diffuser Channels	428
	12.9 Matching the Diffuser Throat with the Impeller	430
	12.10 Wedge Diffuser Channels	433
	12.11 Cascade Diffuser Channels	435
	12.12 Pipe Diffusers	440
	12.13 Downstream Semivaneless Space and Vaneless Space	441
	12.14 Special Cases	441

x	Contents	
13	Casing Component Design	443
	13.1 Overview	443
	13.2 Casing and Rotor Configurations	444
	13.3 Inlet or Suction Nozzle	446
	13.4 Intermediate Inlet Nozzles	447
	13.5 Inlet Guide Vanes	448
	13.6 Outlet Volute	449
	13.7 Return Channel System	455
	13.8 Deswirl Vanes	459
	13.9 Axial Thrust	461
14	Geometry Definition	466
	14.1 Overview	466
	14.2 Coordinate Systems for Turbomachinery	466
	14.3 Axisymmetric and Blade-to-Blade Stream Surfaces in Radial Compressors	468
	14.4 Geometry Definition of Flow Channels	470
	14.5 Geometry Definition of Blades and Vanes	478
15	Throughflow Code for Radial Compressors	480
	15.1 Overview	480
	15.2 A Preliminary Overview of the Throughflow Method	481
	15.3 Notation for the Blade Angles of the Velocity Gradient Equation	489
	15.4 The Throughflow Equation of Motion	492
	15.5 Streamline Curvature Velocity Gradient Equation	497
	15.6 The Iterative Scheme	504
	15.7 Empirical Modifications	506
	15.8 Spanwise Mixing	508
	15.9 Pressure Gradient from Blade Force	513
	15.10 Choking	515
	15.11 Use of Throughflow in Design	526
16	Computational Fluid Dynamics	528
	16.1 Overview	528
	16.2 Historical Background to Turbomachinery CFD	529
	16.3 The Governing Equations	536
	16.4 The Modern Numerical Method	537
	16.5 Stage Calculations with Interface Planes	546
	16.6 Turbulence Models	550
	16.7 Quality and Trust	554
	16.8 Checklists for the Design Process with CFD	560
17	Compressor Instability and Control	565
	17.1 Overview	565
	17.2 Instabilities in Compressors	566

	17.3 Off-Design Operation of Radial Compressors	584
	17.4 Typical Operating Range of Single-Stage Radial Turbocompressors	587
	17.5 Stability Control and Enhancement	590
18	Maps and Matching	601
	18.1 Overview	601
	18.2 Methods of Map Prediction	602
	18.3 Map Prediction for Single Stages	605
	18.4 Apparent Efficiency Due to Heat Transfer Effects	619
	18.5 Extrapolation of a Measured Map	620
	18.6 Map Prediction for Multiple Stages	624
	18.7 Matching of the Diffuser with the Impeller	628
	18.8 Matching in Multistage Compressors	629
	18.9 Matching of the Compressor to a Turbine in a Gas Turbine	631
	18.10 Matching Issues of a Compressor in a Turbocharger	634
19	Structural Integrity	643
	19.1 Overview	643
	19.2 Open or Closed Impellers	644
	19.3 Impeller Manufacturing and Materials	645
	19.4 Introduction to Static Blade Loading of Impellers	649
	19.5 Introduction to Dynamic Blade Loading of Impellers	652
	19.6 Computational Methods	660
	19.7 Design Data for Mechanical Analysis	661
	19.8 Assessment of Fatigue	665
	19.9 Vibrational Considerations	666
	19.10 Disc Design	673
	19.11 Assembly Designs	675
	19.12 Rotordynamics	677
	19.13 Rotor Modelling	684
20	Development and Testing	688
	20.1 Overview	688
	20.2 Design and Development for Centrifugal Compressors	688
	20.3 Compressor Testing	698
	20.4 Basic Research and Development Tests	702
	20.5 Instrumentation and Measurements	708
	20.6 Determination of Stall and Surge	714
	<i>References</i>	715
	<i>Index</i>	752