

Contents

1 Introduction to Gas Turbine Engines	1
1.1 Definition	1
1.2 Advantages of Gas Turbine Engines	1
1.3 Applications of Gas Turbine Engines	2
1.4 The Gas Generator	4
1.5 Air Intake and Inlet Flow Passage	4
1.6 Engine Exhaust Component	5
1.7 Multispool Engine Arrangements	5
1.8 Thermodynamic Cycle in a Single-Combustor Engine	6
1.9 Importance of Metallurgical Progress	7
2 Overview of Turbomachinery Nomenclature	8
2.1 Definition of a Turbomachine	8
2.2 General Classification of Turbomachines	9
2.3 Stage Definition	12
2.4 Coordinate System	15
2.5 Velocity Diagrams	16
2.6 Multiple Staging	20
2.7 Viscosity and Compressibility Factors	21
2.8 Stator/Rotor Interaction	23
Reference	24
3 Aerothermodynamics of Turbomachines and Design-Related Topics	25
3.1 Assumptions and Limitations	25
3.2 Energy-Conservation Law	27
3.3 Introduction of Total Properties	28
3.4 Ideal Gas as a Working Medium	28
3.5 Entropy-Based Loss Coefficient	34
3.6 Comments	38
3.7 Compressibility of the Working Medium	39
3.8 Sonic Speed in Ideal Gases	40
3.9 Mach Number and Compressibility of a Flow Field	40
3.10 Total Properties in Terms of the Mach Number	41

x	Contents	
	3.11 Definition of the Critical Mach Number	41
	3.12 Total Properties in Terms of the Critical Mach Number	43
	3.13 Definition of the Pitch Line in Turbomachines	44
	3.14 Continuity Equation in Terms of Total Properties	45
	3.15 Isentropic Flow in Varying-Area Passages	47
	3.16 The Sonic State	50
	3.17 Nozzle and Diffuser-Like Airfoil Cascades	51
	3.18 Bernoulli's Equation: Applicability and Limitations	52
	3.19 Favorable and Unfavorable Pressure Gradients	57
	3.20 Design Point and Off-Design Operation Modes	62
	3.21 Choice of the Design Point	63
	3.22 Variable-Geometry Turbomachines	64
	3.23 Means of Assessing Turbomachinery Performance	68
	3.24 Total-Relative Flow Properties	73
	3.25 Introduction to the Relative Critical Mach Number	74
	3.26 Losses in Constant-Area Annular Ducts (Fanno Process)	75
	3.27 Fanno Flow Relationships	78
	3.28 Exhaust Diffusers	94
	3.29 Definition of the Momentum Thickness	97
	Problems	105
	References	111
	4 Energy Transfer between a Fluid and a Rotor	112
	4.1 Axial Momentum Equation	112
	4.2 Radial Momentum Equation	113
	4.3 Tangential Momentum Equation	114
	4.4 Stationary and Rotating Frames of Reference	115
	4.5 Flow and Airfoil Angles	119
	4.6 Components of Energy Transfer	120
	4.7 Definition of the Stage Reaction	121
	4.8 Reaction of Axial-Flow Stages	122
	4.9 Introduction of the Utilization Factor	124
	4.10 Impulse Turbines	125
	4.11 Reaction Turbines	126
	4.12 Fifty Percent Reaction Turbines	126
	4.13 Reaction-Alternative Option	127
	4.14 Reaction-Related Topic Summary	128
	4.15 Invariant Thermophysical Properties	129
	4.16 Importance of the Invariant Properties	131
	4.17 Total-Relative Properties	132
	4.18 Incidence and Deviation Angles	134

	Contents	xi
4.19	Comments	140
4.20	Remark	142
4.21	Flow in Vaneless Passages	166
4.22	Flow across Bends	170
4.23	Flat Plate Parallel to the Flow	172
4.24	Flat Plate Normal to the Flow Direction	174
4.25	Flow over Airfoil Sections	174
4.26	Pressure Distribution	175
4.27	Effect of Compressibility	178
4.28	Blade Terminology	180
4.29	Fluid Angles	182
4.30	Cascades of Blades	184
4.31	Theoretical Methods	189
4.32	Flow Deviation	191
4.33	Energy Transfer and Loss in Terms of Lift and Drag	193
4.34	Arrangement of Blades	196
4.35	Optimum Performance of a Stagger: Degree of Reaction	199
4.36	Optimum Stage Performance: Effect of Blade Spacing	201
4.37	Free- versus Forced-Vortex Flows	205
4.38	Discussion of Vortex Flow	207
4.39	Effects of Vortex Flows on Design	208
4.40	Blade-to-Blade Hub-to-Casing Drag Coefficients	209
4.41	Wall (or Annulus) Friction Loss	210
4.42	Secondary Flow Loss	211
	Problems	217
	References	230
5	Dimensional Analysis, Maps, and Specific Speed	231
5.1	Introduction	231
5.2	Geometrical Similarity	231
5.3	Dynamic Similarity	231
5.4	Buckingham's π Theorem: Incompressible Flows	232
5.5	Application to Compressible-Flow Turbomachines	233
5.6	Compressor and Turbine Maps	234
5.7	Choking of Compressors and Turbines	237
5.8	Specific Speed	239
5.9	Application to Incompressible-Flow Turbomachines	240
5.10	Application to Compressible-Flow Turbomachines	241
5.11	Design Role of the Specific Speed	243
5.12	Traditional Specific-Speed Approximations	245
	Problems	260

xii	Contents	
	6 Radial Equilibrium Theory	269
	6.1 Assumptions	269
	6.2 Implications	269
	6.3 Derivation of the Radial Equilibrium Equation	271
	6.4 Special Forms of the Radial Equilibrium Equation	274
	6.5 Further Simplifications	275
	Problems	290
	7 Polytropic (Small-Stage) Efficiency	298
	7.1 Derivation of the Polytropic Efficiency	298
	7.2 Multistage Compressors and Turbines	302
	Problems	308
	8 Axial-Flow Turbines	314
	8.1 Stage Definition	314
	8.2 The Preliminary Design Process	315
	8.3 First Step: Investigate a Single-Stage Configuration	317
	8.4 Second Step: Define the Stage-to-Stage Work Split	318
	8.5 Third Step: Stage-by-Stage Turbine Design	318
	8.6 Stage Design: A Simplified Approach	319
	8.7 Definition of the Incidence and Deviation Angles	344
	8.8 Detailed Design of Airfoil Cascades	346
	8.9 Airfoil Cascade Geometry Variables	349
	8.10 Airfoil Aerodynamic Loading	351
	8.11 Geometrical Discontinuities	354
	8.12 Performance-Controlling Variables	355
	8.13 Aspect Ratio	355
	8.14 Tip Clearance Effects	356
	8.15 Reynolds Number Effect	358
	8.16 Incidence Angle Effect	360
	8.17 Suction-Side Flow Diffusion	362
	8.18 Location of the Front Stagnation Point	364
	8.19 Trailing-Edge Thickness	365
	8.20 Design-Oriented Empirical Correlations	366
	8.21 Stacking of the Vane and Blade Airfoil Sections	369
	8.22 Shaft-Work Extraction in Low Aspect-Ratio Blades	370
	8.23 The Supersonic Stator Option	370
	8.24 Comment	375
	8.25 Shape of the Stagnation Streamlines	376

	Contents	xiii
8.26 Simple Component Adaptation Means		377
8.27 Hot-to-Cold Dimensions Conversion		379
8.28 Cooling Flow Extraction and Path of Delivery		379
8.29 Comment		399
Problems		399
References		410
9 Axial-Flow Compressors		412
9.1 Introduction		412
9.2 Comparison with Axial-Flow Turbines		412
9.3 Stage Definition and Multiple Staging		415
9.4 Normal Stage Definition		417
9.5 Standard Airfoil Profiles		418
9.6 Real Flow Effects: Effect of the Incidence Angle		421
9.7 Effect of the Reynolds Number		422
9.8 Effect of the Mach Number		423
9.9 Tip Clearance Effect		424
9.10 Compressor Off-Design Characteristics		424
9.11 Rotating Stall and Total Surge		425
9.12 Compressor Behavior during Starting		428
9.13 Means of Suppressing Startup Problems		429
Problems		455
Reference		466
10 Radial-Inflow Turbines		467
10.1 Introduction		467
10.2 Components of Energy Transfer		467
10.3 Flow Angles		469
10.4 Stage Reaction		469
10.5 Other Performance-Related Dimensionless Variables		469
10.6 Total-Relative Properties and Critical Mach Number		470
10.7 Conventional-Stage Geometrical Configurations		472
10.8 Compressibility Effects		478
10.9 Stage Design Approach		485
10.10 Closed-Form Loss Correlations		488
10.11 Effect of the “Scallop” Radius and Backface Clearance		495
10.12 Stage Placement in a Multistage Turbine		532
10.13 Cooling Techniques		532
Problems		535
References		547

xiv Contents

11 Centrifugal Compressors	548
11.1 Component Identification	549
11.2 Impeller Inlet System	552
11.3 Inlet-Duct Total-Pressure Loss	552
11.4 Compressor Thermodynamics	553
11.5 Impeller Blading Options	554
11.6 Components of Energy Transfer and Stage Reaction	558
11.7 Performance Consequences of the Static Head	559
11.8 Performance Consequences of the Dynamic Head	562
11.9 Acceleration Components within the Impeller	563
11.10 Slip Phenomenon	565
11.11 Slip Factor	565
11.12 Stage Total-to-Total Efficiency	566
11.13 Volute Flow Field	566
11.14 One-Dimensional Approach to Volute Design	570
11.15 Total-to-Static Efficiency	571
11.16 Tip Clearance Effect	571
11.17 Multiple Staging	573
11.18 Impeller–Stator Unsteady Flow Interaction	573
Problems	597
References	608
12 Turbine–Compressor Matching	609
12.1 Problem Category 1	612
12.2 Problem Category 2	616
12.3 Performance-Related Variables in Propulsion Systems	618
12.4 Mechanism of Shaft-Speed Setting	620
12.5 Gas Generator Operating Lines on Compressor Maps: Constant T_{t4}/T_{t2} Lines	622
12.6 Outer Loop	623
12.7 Inner Loop	624
12.8 Required Postprocessing Work	625
Problems	643
Index	654