Gas Turbines: A Handbook of Air, Land, and Sea **Applications**

Claire Soares



AMSTERDAM • BOSTON • HEIDELBERG • LONDON NEW YORK • OXFORD • PARIS • SAN DIEGO SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO ELSEVIER Butterworth-Heinemann is an imprint of Elsevier



Contents

Preface xiii Introduction xv List of Acronyms xvii Notes to the Reader xix About the Author xxi

Gas Turbines: An Introduction 1 and Applications 1 Gas Turbines on Land 2 Direct Drive and Mechanical Drive 2 Applications Versatility with Land Based Gas Turbines 4 Aeroengine Gas Turbines 5 The Relations between Pressure, Volume, and Temperature 6 Changes in Velocity and Pressure 8 Airflow 8 Gas Turbines at Sea 11 Gas Turbines: Details of Individual Applications 12 Major Classes of Power Generation Application 12 Automotive Applications 17 Marine Applications 18 Aircraft Applications-Propulsion Requirements 23

2 Historical Development of the Gas Turbine 33

Early History of the Gas Turbines 34
Land Based Gas Turbine Development Perspective 34
Switzerland (& Swiss abroad) 34
Germany (& Germans abroad) 34
England (& English abroad)¹ 34
Aircraft Engine'Development: A U.S. Perspective 34
Principles of Jet Propulsion 36
Methods of Jet Propulsion 37
Appendices: The Gas Turbine Global Fleet 43

Gas Turbine Configurations and Heat Cycles 67

Gas Turbine Configurations 68
Turbojet with Afterburner and Convergent-Divergent Nozzle 68
Separate Jets Turbofan 68
Mixed Turbofan with Afterburner 68
Ramjet 69
Simple-Cycle Single-Spool Shaft-Power Engine 69
Combined Heat and Power 72
Aeroderivative and Heavyweight Gas Turbines 73 Gas Turbine Cycles: Summarized Theory and Economics 74 Power Generation Gas Turbine, Simple and Combined Cycles 74 Steam Power Plant Theory Applicable to Combined Cycles and Operating "Solo" as Competition to GTs 76 Steam Turbine Basic Components and Main Systems 79 Supercritical Systems: Targeting 700+ °C Steam Temperature 96 Case 1. Advanced Design of Mitsubishi Large Steam Turbines 99 Combined Cycles and Other GT Cycle Modifications 101 Combined Cycle Economics 105 Case 2. An End User/EPC Contractor's Experience with Some of the OEM's Latest Models 113

4 Gas Turbine Major Components and Modules 119 Economics Dictates Design 120 Primary Module Basics 122 Main Modules in a Gas Turbine 125 Compressors 125 Combustors 134

Low NO_X Combustors 154 Flameless (Catalytic) Combustors 154 Turbines 155

Cooling and Load Bearing Systems 167

Internal Air System 168 Cooling 168 Sealing 169 Control of Bearing Loads 172 Aircraft Services 172 Lubrication 172 Lubricating Systems 172 Oil System Components 174 Lubricating Oils 177 An Operator's Perspective 179

5

6

Inlets, Exhausts, and Noise Suppression183Gas Turbine Inlet Air Filtration184Inlet Air Filters for the Tropical Environment184Problems Experienced185Offshore Environment Original Design Data186The Initial Filter Designs187The Actual Offshore Environment187The Problems Encountered187Gas Turbine Exhausts189Exhaust Gas Flow189

Construction and Materials 191 Gas Turbine Noise Suppression 191 Methods of Suppressing Noise 195 Construction and Materials 196 Nonaeroengine (Land Based) Gas Turbine Noise Suppression 196 Applications of Sound Intensity Measurements to Gas Turbine Engineering 196 Fundamental Concepts 198 Instrumentation 198 Guidelines and Standards in Sound Intensity Measurements and Measurement Technique 199 Some Advantages and Limitations in Sound Intensity Measurements 201 Measuring Tonal Noise Sources 202 Case Studies of the Use of Sound Intensity 202 Acoustic Design of Lightweight Gas Turbine Enclosures 204

8

7 Gas Turbine Fuel Systems and Fuels 213

Basic Gas Turbine Fuel System 214 Manual and Automatic Control 214 Fuel Control Systems 214 Electronic Engine Control 227 Low Pressure Fuel System 228 Fuel Pumps 228 Fuel Spray Nozzles 228 Fuel Heating 230 Effect of a Change of Fuel 230 Gas Turbine Fuels 231 Fuel and Fuel Oil Properties 233 The Combustion Process and Gas Turbine Fuel Types 233 Database of Key Fuel Properties for Performance Calculations 234 Synthesis Exchange Rates for Primary Fuel Types 235 Oil Types and Database of Key Properties 237 Formulae 237 Unconventional Fuels 238 Economic Conditions that Affect Fuel Strategy 238 Physical Properties that Affect Fuel Selection and System Design 240 Liquid Fuels 244 One OEM's Success with Nonconventional Fuels 246 Fuel Treatment Hardware 250 Fuel Properties that Affect Fuel Treatment 250 Fuel Treatment 253 Methods of Separation 253 Selection of Fuel .Washing Equipment 254 Treatment of Light Crude Oil 262 Treatment of Residual Fuel 265 Case 1. A Residual "Bunker" Fuel Case Study 268 Plant Performance and Availability 276

Case 2. Autoignition Characteristics of Gaseous Fuels at Representative Gas Turbine Conditions 276 Case 3. From Concept to Commercial Operationthe Tri-Fuel Injector Used for LPG and Naphtha Applications 282 Case 4. Multi-Fuel Concept of the Siemens 3A-Gas Turbine Series 287 Fuel Changeover 291 Accessory Systems 293 Accessory Drives 294 Gearboxes and Drives 294 Construction and Materials 296 Starting and Ignition Systems 298 Methods of Starting 299 Ignition 303 Relighting 306 Ice Protection Systems 306 Hot Air System 306 Electrical System 307 Fire Protection Systems 309 Prevention of Engine Fire Ignition 309 Fire Detection 310 Fire Containment 310 Fire Extinguishing 312 Engine Overheat Detection 312 Water Injection Systems 312 Compressor Inlet Injection 313 Combustion Chamber Injection 313 Systems Unique to Aircraft Engine Applications 315 Thrust Reversal 315 Afterburning 319 Vertical/Short Take-off and Landing 326 Thrust Distribution 335 Systems Unique to Land or Marine Applications 340 Generators 340 Online Cleaning Systems 349 Expansion Joints 352

9 Controls, Instrumentation, and Diagnostics (CID) 357

(CL) Sope and Selection 358
Which Parameters on What Machine? 358
Basic Controls and Instrumentation (C&I) on GT Systems 359
A Typical Aircraft Engine C&I System 359
Typical C&I System, Land Based (Power Generation) 368
Significant Advances in CID Technology 372
Optical Pyrometry 373
Digital Telemetry 378
Pulsation Analysis: New Techniques and Their Limitations 379
Performance and C&I System Verification with Modeling 382 10 Performance, Performance Testing, and Performance Optimization 387 Performance 389 Performance Theory Summary 389 Performance Testing New Gas Turbine Engines: Parameters and Calculations 398 Parameters 398 . Analysis/Calculations on the Effects of Water as a Vapor, Liquid, or Solid 420 Case 1. The W501G Testing and Validation in the Siemens Westinghouse Advanced Turbine Systems Program 434 Performance Optimization Case Histories and Discussion 439 Case 2. A Systems Approach to Hot Section Component Life Management 440 Case 3. Augmentation of Gas Turbine Power Output by Steam Injection 445 Case 4. Integrating Gas Turbines in Power and Cogeneration Applications 455 Case 5. An Integrated Combined-Cycle Plant Design that Provides Fast Start Capability at Base-Load 459 Case 6. Challenges in the Design of High Load Cycling Operation for Combined Cycle Power Plants 462 11 Gaseous Emissions and the Environment 471 Gaseous Emissions 472 Arctic Warming Evidence 472 Emissions Legislation 473 Emission Permits 480 Carbon Dioxide: Capture, Storage, and Utilization 480 12 Maintenance, Repair, and Overhaul 493 Operating and Maintenance Strategies 494 Reactive Strategy 494 Predictive Strategy 494 Preventive Strategy 494 Evolving Strategy in Land versus Air versus Marine Applications 494 Maintenance 495 On-Wing Maintenance 496 Condition Monitoring 496 Maintenance Precautions 498 Troubleshooting 498 Adjustments 498 Ground Testing 499 Maintenance Information Systems 500 Audits of and Retrofits with GT Components and Systems 502 Aims of an Audit 503 Audit Planning 503 General Audit Procedures 504 Changing Legislative Requirements 505 Retrofits Aimed at Operational Optimization 506 Case 1. Brent Platform Retrofits for Extended Life 506

Case 2. Flotta Terminal 507 Case 3. Forties Platform Retrofits 508 Case 4. Al-Ain Flameout Problems 509 Performance Analysis 509 Case 5. Extending TBOs of Gas Turbines by Preventing Premature Turbine Disc Failure in a GE Frame 5 (Old Model) 510 Case 6. Power Addition for GT in Cogeneration Service Using Steam Injection 511 Integration of Detection, Assessment, and Planning in Audits 511 Case 7. Glass Bead Peening 516 Case 8. First-Stage Turbine Blades 516 Assessing Audit Findings 517 The Basics 517 Eliminate Obvious Problems 517 Risk and Weighting Factors Method 518 **Questionnaire to List Potential Factors and** Causes 518 Overhaul and Repair 518 Major Repair and Overhaul Case Studies 527 Case 9. Evolution of IGT "F" Class Repair Technology 527 Case 10. Liburdi Powder Metallurgy, Applications for Manufacture and Repair of Gas Turbine Components 536 Case 11. Hot-Gas-Path Life Extension Options for the V94.2 Gas Turbine ' 542

13 Installation 549

Installation of Aircraft Engines 550 Power Plant Location 550 Air Intakes 551 Engine and Jet Pipe Mountings 552 Accessories 554 Cowlings 555 Installation of Land Based and Marine Engines 555

14 The Business of Gas Turbines 557

The Contemporary Business Climate 558 Culture 559 Repair and Overhaul Shop Culture 559 End User or Operator Culture 561 OEM (Manufacturer) Culture 561 Conglomerate and Joint Venture Cultures 563 Educators and Training 563 Integration with Environmental Technology Culture 563 Risk 563 Selection and Specification Process for Gas Turbines and Gas Turbine Systems 563 Risk Factors and Their Mitigation in Gas Turbine Design and Operation 564 "Shifting Target" Data during Project Development, Negotiation, and New Model Introduction 567 Risk in Negotiating IPP Projects 568 International Negotiation 568

CONTENTS х

Market Assessment Risk 568 Plant Siting 569 Design Development and Operational Assessment by Both OEMs and End Users 569 Case 1 569 Case 2 572 Case 3 577 15 Manufacturing, Materials, and Metallurgy 585 Basic Manufacture 587 Manufacturing Strategy 587 Forging 588 Casting 589 Fabrication 589 Welding 589 Electro-Chemical Machining (E.C.M.) 592 Electro-Discharge Machining (E.D.M.) 594 Composite Materials and Sandwich Casings 595 Inspection 596 Case 1. Upgrading the Core Engine 596 Raising Serviceability Ceilings 603 Spray Forming 604 Casing Fabrication 604 Microstructure of Processed and Heat Treated RS5 604 Creep Resistance Advancements 605 Creep Resistance of Materials for Microturbine Recuperators 605 Ceramic Components 605 Case 2. Ceramic Vanes for a Model 501-K Industrial Turbine Demonstration 606 Case 3. Assessment of Ceramic and Metal Media Filters in Advanced Power Systems 611 16 Microturbines, Fuel Cells, and Hybrid

Systems 617 Microturbines 618 Fuel Cells 618 Power Generation Tubular SOFC Technology 618 Hybrids 619 Applications and Case Studies 621 Case 1. Microturbine in a CHP Application 621 Case 2. A Fuel Cell Application 622 Wide Application Fuel Cell Turbomachinery 624 Case 3. Tubular Solid Oxide Fuel Cell/Gas Turbine Hybrid Cycle Power Systems 626

Case 4. A Turbogenerator for a Fuel Cell/Gas Turbine Hybrid Power Plant 629

17 Training and Education 637

Industry Training 638 Case 1. OEM Project Application Engineer Training 638

- Training Programs within Academia 642 Case 2. Industry Supported Multimedia Aeroengine Design Case 644
 - Case 3. Theoretical Calculations Compared with Actual Cogeneration Plant 645

Case 4. Undergraduate Engine Design Program 645 Case 5. Gas Turbine University Laboratory Study 653

18 Future Trends in the Gas Turbine Industry 659

Changing Tides: Financial, Political, Legislative, and Technological 661 Politics 661 Global Deregulation in Power Generation 661 Environmental Factors 666 Environmental Legislation 666 Fuel System Variables and Versatility 666 OEM Growth and Diversification 667 OEM Acquisitions, Joint Ventures, and Licensees 667 **OEM Business Strategy Including Production** Backlogs and Vendor Alliances 668 Technology Transfer 668 Optimization of Existing Features and Support Technology 670 Transmission and Distribution Improvements 670 End-User Associations and Lobbies 670 End-User Associations 670 Lobbies 671 E-Trading 671 New and Unconventional Fuel Resources 671 Distributed Power: How Large Does a Power Plant Need to Be? 671 The Age of the Personal Turbine 671 The Power Mix 671 Case 1. Does California Need Liquefied Natural Gas? 672 California's Energy Efficiency Potential 673 California's Renewable Energy Potential 673 Is California's Renewable Energy Market Viable? 673 Additional Supplies of Natural Gas in North America 677

19 Basic Design Theory 679

Operational Envelope 680 The Environmental Envelope 680 Installation Pressure Losses 687 The Flight Envelope 689 Properties and Charts for Dry Air, Combustion Products, and Other Working Fluids 692 Description of Fundamental Gas Properties 692 Description of Key Thermodynamic Parameters 693 Composition of Dry Air and Combustion Products 693 The Use of CP and Gamma, or Specific Enthalpy and Entropy, in Calculations 694 Database for Fundamental and Thermodynamic Gas Properties 694

Formulae 699

"Design Point" Engine Design, Definitions, and Terminology 701 Design Point Performance Parameters, Definitions 702 Linearly Scaling Components and Engines 704 Design Point Exchange Rates 704 Open Shaft Power Cycles 704 Combined Heat and Power 706 Closed Cycles 706 Aircraft Engine Shaft Power Cycles 706 Aircraft Engine Thrust Cycles 706 The Engine Concept Design Process 706 Margins Required When Specifying Target Performance Levels 707 Case 1. Prediction Effects of Mass-Transfer Cooling on the Blade-Row Efficiency of Turbine Airfoils 708

One-Dimensional Methods 710 The TOTLOS Method 712 Case 2. Advanced Technology Engine Supportability: Preliminary Designer's Challenge 714 Historical Trends/Recent GEAE Experience 715 Advanced Materials 715 Engine Preliminary Design 716 Specific Examples 716

20 Additional References and Appendix for Unit Conversion 721

Additional General References 722 Some Specific References 722 Unit Conversion 722

Index 727