GAS TURBINE HEAT TRANSFER AND COOLING TECHNOLOGY

Je-Chin Han, Sc.D.
HTRI Professor, Texas A&M University,
Department of Mechanical Engineering,
College Station, Texas

Sandip Dutta, Ph.D.
Assistant Professor, University of South Carolina,
Department of Mechanical Engineering,
Columbia, South Carolina

Srinath Ekkad, Ph.D.
Assistant Professor, Louisiana State University,
Department of Mechanical Engineering,
Baton Rouge, Louisiana

Taylor & Francis
Taylor & Francis Group
New York London

Taylor & Francis is an imprint of the
Taylor & Francis Group, an **informa** business

Contents

Preface xv

CHAPTER 1
FUNDAMENTALS 1
1.1 NEED FOR TURBINE BLADE COOLING 1
1.1.1 Recent Development in Aircraft Engines 1
1.1.2 Recent Development in Land-Based Gas Turbines 4
1.2 TURBINE-COOLING TECHNOLOGY 5
1.2.1 Concept of Turbine Blade Cooling 5
1.2.2 Typical Turbine Cooling System 7
1.3 TURBINE HEAT-TRANSFER AND COOLING ISSUES 13
1.3.1 Turbine Blade Heat Transfer 13
1.3.2 Turbine Blade Internal Cooling 17
1.3.3 Turbine Blade Film Cooling 21
1.3.4 Thermal Barrier Coating and Heat Transfer 21
1.4 STRUCTURE OF THE BOOK 22
1.5 REVIEW ARTICLES AND BOOK CHAPTERS ON TURBINE COOLING AND HEAT TRANSFER 23

CHAPTER 2
TURBINE HEAT TRANSFER 27
2.1 INTRODUCTION 27
2.1.1 Combustor Outlet Velocity and Temperature Profiles 27
2.2 TURBINE-STAGE HEAT TRANSFER 31
2.2.1 Introduction 31
2.2.2 Real Engine Turbine Stage 32
2.2.3 Simulated Turbine Stage 38
2.2.4 Time-Resolved Heat-Transfer Measurements on a Rotor Blade 44

2.3 CASCADE VANE HEAT-TRANSFER EXPERIMENTS **47**
2.3.1 Introduction 47
2.3.2 Effect of Exit Mach Number and Reynolds Number 48
2.3.3 Effect of Free-Stream Turbulence 52
2.3.4 Effect of Surface Roughness 54
2.3.5 Annular Cascade Vane Heat Transfer 57
2.4 CASCADE BLADE HEAT TRANSFER **60**
2.4.1 Introduction 60
2.4.2 Unsteady Wake-Simulation Experiments 62
2.4.3 Wake-Affected Heat-Transfer Predictions 69
2.4.4 Combined Effects of Unsteady-Wake and Free-Stream Turbulence 73
2.5 AIRFOIL ENDWALL HEAT TRANSFER **77**
2.5.1 Introduction 77
2.5.2 Description of the Flow Field 77
2.5.3 Endwall Heat Transfer 79
2.5.4 Near-Endwall Heat Transfer 83
2.5.5 Engine Condition Experiments 83
2.5.6 Effect of Surface Roughness 85
2.6 TURBINE ROTOR BLADE TIP HEAT TRANSFER **88**
2.6.1 Introduction 88
2.6.2 Blade Tip Region Flow Field and Heat Transfer 88
2.6.3 Flat-Blade Tip Heat Transfer 92
2.6.4 Squealer- or Grooved-Blade Tip Heat Transfer 93
2.7 LEADING-EDGE REGION HEAT TRANSFER **100**
2.7.1 Introduction 100
2.7.2 Effect of Free-Stream Turbulence 101
2.7.3 Effect of Leading-Edge Shape 106
2.7.4 Effect of Unsteady Wake 107
2.8 FLAT-SURFACE HEAT TRANSFER **110**
2.8.1 Introduction 110
2.8.2 Effect of Free-Stream Turbulence 111
2.8.3 Effect of Pressure Gradient 115
2.8.4 Effect of Streamwise Curvature 116
2.8.5 Surface Roughness Effects 117
2.9 CLOSURE **119**

CHAPTER 3
TURBINE FILM COOLING 129
3.1 INTRODUCTION 129
3.1.1 Fundamentals of Film Cooling 129
3.2 FILM COOLING ON ROTATING TURBINE BLADES 133
3.3 FILM COOLING ON CASCADE VANE SIMULATIONS 140
3.3.1 Introduction 140
3.3.2 Effect of Film Cooling 140
3.3.3 Effect of Free-Stream Turbulence 150
3.4 FILM COOLING ON CASCADE BLADE SIMULATIONS 151
3.4.1 Introduction 151
3.4.2 Effect of Film Cooling 151
3.4.3 Effect of Free-Stream Turbulence 154
3.4.4 Effect of Unsteady Wake 156
3.4.5 Combined Effect of Free-Stream Turbulence and Unsteady Wakes 162
3.5 FILM COOLING ON AIRFOIL ENDWALLS 162
3.5.1 Introduction 162
3.5.2 Low-Speed Simulation Experiments 162
3.5.3 Engine Condition Experiments 169
3.5.4 Near-Endwall Film Cooling 171
3.6 TURBINE BLADE TIP FILM COOLING 173
3.6.1 Introduction 173
3.6.2 Heat-Transfer Coefficient 175
3.6.3 Film Effectiveness 175
3.7 LEADING-EDGE REGION FILM COOLING 179
3.7.1 Introduction 179
3.7.2 Effect of Coolant-to-Mainstream Blowing Ratio 180
3.7.3 Effect of Free-Stream Turbulence 183
3.7.4 Effect of Unsteady Wake 186
3.7.5 Effect of Coolant-to-Mainstream Density Ratio 186
3.7.6 Effect of Film Hole Geometry 192
3.7.7 Effect of Leading-Edge Shape 193
3.8 FLAT-SURFACE FILM COOLING 194
3.8.1 Introduction 194
3.8.2 Film-Cooled, Heat-Transfer Coefficient 195

3.8.2.1 Effect of Blowing Ratio 196
3.8.2.2 Effect of Coolant-to-Mainstream Density Ratio 197
3.8.2.3 Effect of Mainstream Acceleration 198
3.8.2.4 Effect of Hole Geometry 201
3.8.3 Film-Cooling Effectiveness 206
3.8.3.1 Effect of Blowing Ratio 208
3.8.3.2 Effect of Coolant-to-Mainstream Density Ratio 209
3.8.3.3 Film Effectiveness Correlations 210
3.8.3.4 Effect of Streamwise Curvature and Pressure Gradient 215
3.8.3.5 Effect of High Free-Stream Turbulence 220
3.8.3.6 Effect of Film Hole Geometry 223
3.8.3.7 Effect of Coolant Supply Geometry 225
3.8.3.8 Effect of Surface Roughness 228
3.8.3.9 Effect of Gap Leakage 230
3.8.3.10 Effect of Bulk Flow Pulsations 234
3.8.3.11 Full-Coverage Film Cooling 235
3.9 DISCHARGE COEFFICIENTS OF TURBINE COOLING HOLES 235
3.10 FILM-COOLING EFFECTS ON AERODYNAMIC LOSSES 239
3.11 CLOSURE 243

CHAPTER 4
TURBINE INTERNAL COOLING 251
4.1 JET IMPINGEMENT COOLING 251
4.1.1 Introduction 251
4.1.2 Heat-Transfer Enhancement by a Single Jet 25
4.1.2.1 Effect of Jet-to-Target-Plate Spacing 25
4.1.2.2 Correlation for Single Jet Impingement Heat Transfer 25
4.1.2.3 Effectiveness of Impinging Jets 25
4.1.2.4 Comparison of Circular to Slot Jets 25
4.1.3 Impingement Heat Transfer in the Midchord Region by Jet Array 2

4.1.3.1 Jets with Large Jet-to-Jet Spacing 259
4.1.3.2 Effect of Wall-to-Jet-Array Spacing 260
4.1.3.3 Cross-Flow Effect and Heat-Transfer Correlation 260
4.1.3.4 Effect of Initial Cross-Flow 266
4.1.3.5 Effect of Cross-Flow Direction on Impingement Heat Transfer 267
4.1.3.6 Effect of Coolant Extraction on Impingement Heat Transfer 270
4.1.3.7 Effect of Inclined Jets on Heat Transfer 276
4.1.4 Impingement Cooling of the Leading Edge 278
4.1.4.1 Impingement on a Curved Surface 278
4.1.4.2 Impingement Heat Transfer in the Leading Edge 279

4.2 RIB-TURBULATED COOLING 287

4.2.1 Introduction 287
4.2.1.1 Typical Test Facility 290
4.2.2 Effects of Rib Layouts and Flow Parameters on Ribbed-Channel Heat Transfer 291
4.2.2.1 Effect of Rib Spacing on the Ribbed and Adjacent Smooth Sidewalls 291
4.2.2.2 Angled Ribs 292
4.2.2.3 Effect of Channel Aspect Ratio with Angled Ribs 295
4.2.2.4 Comparison of Different Angled Ribs 296
4.2.3 Heat-Transfer Coefficient and Friction Factor Correlation 297
4.2.4 High-Performance Ribs 301
4.2.4.1 V-Shaped Rib 301
4.2.4.2 V-Shaped Broken Rib 304
4.2.4.3 Wedge- and Delta-Shaped Rib 306
4.2.5 Effect of Surface-Heating Condition 309
4.2.6 Nonrectangular Cross Section Channels 313
4.2.7 Effect of High-Blockage–Ratio Ribs 325
4.2.8 Effect of Rib Profile 327
4.2.9 Effect of Number of Ribbed Walls 333
4.2.10 Effect of a 180° Sharp Turn 343

4.2.11 Detailed Heat-Transfer Coefficient Measurements in a Ribbed Channel 355
4.2.12 Effect of Film-Cooling Hole on Ribbed-Channel Heat Transfer 366
4.3 PIN-FIN COOLING 371
4.3.1 Introduction 371
4.3.2 Flow and Heat-Transfer Analysis with Single Pin 373
4.3.3 Pin Array and Correlation 377
4.3.4 Effect of Pin Shape on Heat Transfer 385
4.3.5 Effect of Nonuniform Array and Flow Convergence 390
4.3.6 Effect of Skewed Pin Array 391
4.3.7 Partial Pin Arrangements 395
4.3.8 Effect of Turning Flow 398
4.3.9 Pin-Fin Cooling with Ejection 399
4.3.10 Effect of Missing Pin on Heat-Transfer Coefficient 404
4.4 COMPOUND AND NEW COOLING TECHNIQUES 406
4.4.1 Introduction 406
4.4.2 Impingement on Ribbed Walls 406
4.4.3 Impingement on Pinned and Dimpled Walls 411
4.4.4 Combined Effect of Ribbed Wall with Grooves 414
4.4.5 Combined Effect of Ribbed Wall with Pins and Impingement Inlet Conditions 420
4.4.6 Combined Effect of Swirl Flow and Ribs 421
4.4.7 Impingement Heat Transfer with Perforated Baffles 425
4.4.8 Combined Effect of Swirl and Impingement 431
4.4.9 Concept of Heat Pipe for Turbine Cooling 43?
4.4.10 New Cooling Concepts 43?

CHAPTER 5
TURBINE INTERNAL COOLING WITH ROTATION 43?
5.1 ROTATIONAL EFFECTS ON COOLING 43
5.2 SMOOTH-WALL COOLANT PASSAGE 43
5.2.1 Effect of Rotation on Flow Field 4?
5.2.2 Effect of Rotation on Heat Transfer 4?
5.2.2.1 Effect of Rotation Number 4?
5.2.2.2 Effect of Density Ratio 4?
5.2.2.3 Combined Effects of Rotation Number and Density Ratio 4

CHAPTER 6
EXPERIMENTAL METHODS 531
6.1 INTRODUCTION 531
6.2 HEAT-TRANSFER MEASUREMENT TECHNIQUES 531
6.2.1 Introduction 531
6.2.2 Heat Flux Gauges 532
6.2.3 Thin-Foil Heaters with Thermocouples 535
6.2.4 Copper Plate Heaters with Thermocouples 538
6.2.5 Transient Technique 539
6.3 MASS-TRANSFER ANALOGY TECHNIQUES 540
6.3.1 Introduction 540
6.3.2 Naphthalene Sublimation Technique 540
6.3.3 Foreign-Gas Concentration Sampling Technique 543
6.3.4 Swollen-Polymer Technique 545
6.3.5 Ammonia-Diazo Technique 546
6.3.6 Pressure-Sensitive Paint (PSP) Techniques 547
6.4 OPTICAL TECHNIQUES 548
6.4.1 Introduction 548
6.4.2 Infrared Thermography 54
6.4.3 Thermographic Phosphors 55
6.5 LIQUID CRYSTAL THERMOGRAPHY 55
6.5.1 Steady-State Yellow-Band Tracking Technique 55
6.5.2 Steady-State HSI Technique 55
6.5.3 Transient HSI Technique 55
6.5.4 Transient Single-Color Capturing Technique 55
6.6 FLOW AND THERMAL FIELD MEASUREMENT TECHNIQUES 5
6.6.1 Introduction 5
6.6.2 Five-Hole Probe/Thermocouples 5
6.6.3 Hot-Wire/Cold-Wire Anemometry 5
6.6.4 Laser Doppler Velocimetry (LDV) 5
6.6.5 Particle Image Velocimetry
6.6.6 Laser Holographic Interferometry
6.6.7 Surface Visualization
6.7 CLOSURE

CHAPTER 8
FINAL REMARKS 637
8.1 TURBINE HEAT TRANSFER AND FILM COOLING 637
8.2 TURBINE INTERNAL COOLING WITH ROTATION 637
8.3 TURBINE EDGE HEAT TRANSFER AND COOLING 638
8.4 CLOSURE 638

INDEX 639