

# contents

Overview	xi
Introduction	xiii

## CHAPTER 1

<b>High Temperature Turbine Design Considerations</b>	<b>1</b>
Material Properties	2
Manufacturing Processes	3
Cooling Techniques	5
Cooling Flow	8
Cooling Air Temperature	8
Mixing Losses	11
Aerodynamic Losses	12
Mechanical Design	14
Mechanical and Thermal Life	14
Metallurgical Stability	20
Coatings	20
Coating Interactions	22
Summary	23
Nomenclature	24
Acknowledgments	24
References	24

## CHAPTER 2

<b>Summary of NASA Aerodynamic and Heat Transfer Studies in Turbine Vanes and Blades</b>	<b>27</b>
<b>Aerodynamic Studies</b>	<b>28</b>
Cascade Tests	28
Coolant Hole Angle Orientation	28
Single and Multirow Coolant Ejection	28
Full-Film-Cooled Vane	30

Varying Primary-to-Coolant Temperature Ratio	30
Effect of Ceramic Coating on Vane Efficiency	31
Rotating Stage Tests	31
Description of Turbines	32
Test Results	34
<b>Cooling Studies</b>	<b>34</b>
Flat-Plate Heat Transfer Investigations	35
Cascade and Engine Investigations	39
<b>Summary of Major Results</b>	<b>43</b>
<b>Current Programs</b>	<b>44</b>
Film Cooling	44
Endwall Cooling	46
Impingement Cooling	46
Thermal Barrier Coatings	46
<b>References</b>	<b>46</b>
<b>Symbols</b>	<b>52</b>
Subscripts	52

### CHAPTER 3

<b>Cooling Modern Aero Engine Turbine Blades and Vanes</b>	<b>53</b>
<b>Part I by Arthur Hare</b>	<b>53</b>
Extent of Application of Cooling	53
Purposes of Cooling	54
Degree of Cooling	55
Some Effects on Engine Functioning	56
Some Effects on Design	57
Some Effects on Engine Development	59
Effect on Manufacturing Cost	60
Summary	61
<b>Part II by H.H. Malley</b>	<b>61</b>
<b>Turbine Entry Temperature</b>	<b>61</b>
Blade Cooling Level	61
Material Creep Strength	63
<b>Cooling Air Feed System</b>	<b>63</b>
<b>Combustion-Chamber Exit Temperature Traverse</b>	<b>63</b>
<b>Nozzle Guide Vane Cooling</b>	<b>65</b>
Early Standard of Vane	65
Vane with “Jet Cooled” Leading Edge	66
Vane with “Tube Cooling”	67

<b>Turbine Blade Cooling</b>	<b>68</b>
“Triple Pass” Cooling	68
“Double Pass” Cooling	69
“Single Pass” Cooling	71
<b>Turbine Blade Problems</b>	<b>72</b>
Thermal Fatigue	72
Oxidation and Corrosion	73
Creep	74
<b>Future Trends</b>	<b>77</b>

#### CHAPTER 4

### An Investigation of Convective Cooling of Gas Turbine Blades Using Intermittent Cooling Air **79**

<b>Introduction</b>	<b>79</b>
<b>Results of Prior Investigations</b>	<b>81</b>
<b>Experimental Results</b>	<b>86</b>
<b>Analysis and Correlation</b>	<b>86</b>
<b>Conclusions</b>	<b>90</b>
<b>Summary</b>	<b>91</b>
<b>References</b>	<b>91</b>

#### CHAPTER 5

### The Prospects of Liquid Cooling for Turbines **95**

<b>History of Liquid Cooling</b>	<b>95</b>
Possibilities for Turbine Liquid Cooling	95
A Critique of Demonstrated Liquid-Cooled Turbines	99
<b>Prospects for Turbine Liquid Cooling</b>	<b>104</b>
<b>A Case Study: The Cooled Radial Turbine</b>	<b>105</b>
Cycle Impact of Turbine Cooling	105
Turbine Aerodynamic Design	108
Turbine Cooling	108
<b>Summary</b>	<b>111</b>
<b>References</b>	<b>112</b>
<b>Appendix A Cycle Performance Data for Small Gas Turbine Components</b>	<b>113</b>
<b>Appendix B Typical Turbine Design Calculations</b>	<b>116</b>
Turbine Aerodynamic Design	116
<b>Turbine Cooling Design</b>	<b>117</b>
<b>Nomenclature</b>	<b>117</b>
Subscripts	118

## CHAPTER 6

<b>Feasibility Demonstration of a Small Fluid-Cooled Turbine at 2300°F</b>	<b>119</b>
<b>Aero-Thermodynamic Performance</b>	<b>122</b>
Turbine	122
Correction Factor Analysis	124
Turbine Analysis	126
<b>Heat Transfer</b>	<b>128</b>
Discussion	128
Turbine Disc and Blade	129
Turbine Inlet Nozzle	131
<b>Combustor</b>	<b>133</b>
<b>Mechanical-Structural Integrity</b>	<b>133</b>
Summary	133
Mechanical Assembly	134
Turbine Rotor	134
Gearbox	135
Turbine Blades	135
Airfoil Stress Analysis	136
Blade/Disc Pin Attachment	137
Blade/Disc Seal	137
Disc Stress Analysis	137
Fuel Deposits	137
Turbine Shroud	137
Turbine Nozzle and Combustor Assemblies	138
<b>Manufacturing Technology</b>	<b>138</b>
Turbine Disc	138
Disc Process	138
Turbine Blade	139
Blade Process	139
Nondestructive Testing (NDT)	140
<b>Summary</b>	<b>140</b>
<b>References</b>	<b>143</b>

## CHAPTER 7

<b>Design and Fabrication Aspects of Transpiration Air-Cooled Turbine Blades for 2500°F Turbine Operation</b>	<b>145</b>
<b>Synopsis</b>	<b>145</b>
<b>General</b>	<b>145</b>

Turbine Blade Design Aspects	150
Porous Metal Fabrication	153
Mechanical Properties of Porous Metals	154
Forming of Porous Airfoils	155
Brazing of Porous Material	156
Inspection of Brazed Blades	158
Engine Test Program	159
Summary and Conclusions	162
Acknowledgments	162
References	162

## CHAPTER 8

### Design and Test of a Small Turbine at 2500°F with Transpiration-Cooled Blading 165

Transpiration Cooling	167
Program Objectives	168
Turbine Design Problems	169
Aerodynamic	169
Thermal	169
Mechanical	172
Turbine Fabrication	174
Turbine Test Program	177
Combustor	177
Cascade	179
Full Stage Turbine Durability Test	180
Conclusions	183
Acknowledgments	183
Reference	183

## CHAPTER 9

### The Role of the Turbulent Prandtl Number in Turbine Blade Heat Transfer Prediction 185

Introduction	185
Code Selection	186
Turbulent Prandtl Number Models	187
Experimental Data	188
Results	189

<b>Conclusions</b>	<b>193</b>
<b>Acknowledgments</b>	<b>193</b>
<b>References</b>	<b>193</b>

## CHAPTER 10

<b>Parametric Analysis of Aero-Derivative Gas Turbine: Effect of Radiative Heat Transfer on Blade Coolant Requirement</b>	<b>195</b>
<b>Introduction</b>	<b>196</b>
<b>System Configuration</b>	<b>197</b>
<b>Modeling and Governing Equations</b>	<b>198</b>
Air/Gas Property Model	198
Compressor	199
Combustion Chamber	199
<b>Cooled Gas Turbine Model</b>	<b>200</b>
Air-Film Blade Cooling Scheme	201
Horlock et al. [8] Model for Blade Coolant Mass Fraction	201
Sanjay et al. [13] Model for Coolant Mass Fraction	202
Horlock and Torbidoni Model [12] for Blade Coolant Mass Fraction	202
Proposed Model for Blade Coolant Mass Fraction	202
Assumptions	203
Calculation of Gas Turbine Work	203
<b>Results and Discussion</b>	<b>205</b>
Effect of TIT on Blade Coolant Mass Fraction	205
Effect of Compressor Pressure Ratio on Coolant Mass Fraction	206
Effect of Advancement in Blade Material Technology	206
Effect of Improvement in Blade Material Temperature	206
Effect of Adoption of Single-Crystal Blades	207
Effect of TBC Coatings	207
Variation in Gas Turbine Efficiency with $r_{pc}$	208
Performance Map for Proposed Model	208
<b>Conclusions</b>	<b>210</b>
<b>References</b>	<b>210</b>
<b>Contact Information</b>	<b>212</b>
<b>Greek Symbols</b>	<b>212</b>
<b>Nomenclature</b>	<b>212</b>
Subscript	213
<b>Abbreviations</b>	<b>213</b>
About the Author	215