

Fluid Mechanics and Thermodynamics of Turbomachinery

Fourth Edition, in SI/Metric units

S. L. Dixon, B.Eng., Ph.D

Senior Fellow at the University of Liverpool

BUTTERWORTH
HEINEMANN

Boston Oxford Johannesburg
Melbourne New Delhi Singapore

Contents

PREFACE TO FOURTH EDITION ix

PREFACE TO THIRD EDITION xi

ACKNOWLEDGEMENTS xiii

LIST OF SYMBOLS xv

1. Introduction: Dimensional Analysis: Similitude 1

<i>Definition of a turbomachine</i>	1
<i>Units and dimensions</i>	3
<i>Dimensional analysis and performance laws</i>	4
<i>Incompressible fluid analysis</i>	6
<i>Performance characteristics</i>	7
<i>Variable geometry turbomachines</i>	9
<i>Specific speed</i>	10
<i>Cavitation</i>	12
<i>Compressible gas flow relations</i>	15
<i>Compressible fluid analysis</i>	16
<i>The inherent unsteadiness of the flow within turbomachines</i>	20
<i>References</i>	21
<i>Problems</i>	22

2. Basic Thermodynamics, Fluid Mechanics: Definitions of Efficiency 23

<i>Introduction</i>	23
<i>The equation of continuity</i>	23
<i>The first law of thermodynamics – internal energy</i>	24
<i>The momentum equation – Newton's second law of motion</i>	25
<i>The second law of thermodynamics – entropy</i>	29
<i>Definitions of efficiency</i>	30
<i>Small stage or polytropic efficiency</i>	35
<i>Nozzle efficiency</i>	41
<i>Diffusers</i>	43
<i>References</i>	53
<i>Problems</i>	53

3. Two-dimensional Cascades 55

Introduction 55
Cascade nomenclature 56
Analysis of cascade forces 57
Energy losses 59
Lift and drag 59
Circulation and lift 61
Efficiency of a compressor cascade 62
Performance of two-dimensional cascades 63
The cascade wind tunnel 63
Cascade test results 65
Compressor cascade performance 68
Turbine cascade performance 70
Compressor cascade correlations 71
Fan blade design (McKenzie) 80
Turbine cascade correlation (Ainley) 81
Comparison of the profile loss in a cascade and in a turbine stage 86
Optimum space-chord ratio of turbine blades (Zweifel) 87
References 88
Problems 90

4. Axial-flow Turbines: Two-dimensional Theory 93

Introduction 93
Velocity diagrams of the axial turbine stage 93
Thermodynamics of the axial turbine stage 94
Stage losses and efficiency 96
Soderberg's correlation 97
Types of axial turbine design 99
Stage reaction 101
Diffusion within blade rows 103
Choice of reaction and effect on efficiency 107
Design point efficiency of a turbine stage 108
Maximum total-to-static efficiency of a reversible turbine stage 112
Stresses in turbine rotor blades 114
Turbine flow characteristics 120
Flow characteristics of a multistage turbine 122
The Wells turbine 124
References 132
Problems 133

5. Axial-flow Compressors and Fans 137

Introduction 137
Two-dimensional analysis of the compressor stage 138
Velocity diagrams of the compressor stage 140
Thermodynamics of the compressor stage 141

<i>Stage loss relationships and efficiency</i>	142
<i>Reaction ratio</i>	143
<i>Choice of reaction</i>	143
<i>Stage loading</i>	144
<i>Simplified off-design performance</i>	145
<i>Stage pressure rise</i>	147
<i>Pressure ratio of a multistage compressor</i>	148
<i>Estimation of compressor stage efficiency</i>	149
<i>Stall and surge phenomena in compressors</i>	154
<i>Control of flow instabilities</i>	159
<i>Axial-flow ducted fans</i>	160
<i>Blade element theory</i>	162
<i>Blade element efficiency</i>	163
<i>Lift coefficient of a fan aerofoil</i>	164
<i>References</i>	165
<i>Problems</i>	166

6. Three-dimensional Flows in Axial Turbomachines 169

<i>Introduction</i>	169
<i>Theory of radial equilibrium</i>	169
<i>The indirect problem</i>	171
<i>The direct problem</i>	179
<i>Compressible flow through a fixed blade row</i>	180
<i>Constant specific mass flow</i>	181
<i>Off-design performance of a stage</i>	183
<i>Free-vortex turbine stage</i>	184
<i>Actuator disc approach</i>	186
<i>Blade row interaction effects</i>	190
<i>Computer-aided methods of solving the through-flow problem</i>	191
<i>Secondary flows</i>	193
<i>References</i>	195
<i>Problems</i>	196

7. Centrifugal Pumps, Fans and Compressors 199

<i>Introduction</i>	199
<i>Some definitions</i>	200
<i>Theoretical analysis of a centrifugal compressor</i>	202
<i>Inlet casing</i>	203
<i>Impeller</i>	203
<i>Conservation of rothalpy</i>	204
<i>Diffuser</i>	205
<i>Inlet velocity limitations</i>	205
<i>Optimum design of a pump inlet</i>	206
<i>Optimum design of a centrifugal compressor inlet</i>	208
<i>Slip factor</i>	213
<i>Head increase of a centrifugal pump</i>	218

viii **Contents**

Performance of centrifugal compressors 219
The diffuser system 227
Choking in a compressor stage 230
References 232
Problems 233

8. Radial Flow Gas Turbines 236

Introduction 236
Types of inward flow radial turbine 237
Thermodynamics of the 90 deg IFR turbine 239
Basic design of the rotor 241
Nominal design point efficiency 242
Mach number relations 246
Loss coefficients in 90 deg IFR turbines 247
Optimum efficiency considerations 248
Criterion for minimum number of blades 253
Design considerations for rotor exit 256
Incidence losses 260
Significance and application of specific speed 263
Optimum design selection of 90 deg IFR turbines 266
Clearance and windage losses 269
Pressure ratio limits of the 90 deg IFR turbine 269
Cooled 90 deg IFR turbines 271
References 272
Problems 273

9. Hydraulic Turbines 277

Introduction 277
Hydraulic turbines 278
The Pelton turbine 281
Reaction turbines 290
The Francis turbine 290
The Kaplan turbine 296
Effect of size on turbomachine efficiency 299
Cavitation 301
References 305
Problems 306

Bibliography 309

Appendix 1. Conversion of British and US Units to SI Units 310

Appendix 2. Answers to Problems 311

Index 315