

# Contents

<b>Series Preface</b>	<b>ix</b>
<b>Preface</b>	<b>xi</b>
<b>1 Introduction to Propulsion Systems</b>	<b>1</b>
1.1 Conservation of Momentum	7
1.2 Conservation of Energy (the First Law of Thermodynamics) and Other Thermodynamic Relationships	10
1.3 One-Dimensional Gas Dynamics	13
1.4 Heat Transfer	14
1.5 Standard Atmospheric Air Properties	15
1.6 Unit Conversion	17
1.7 Problems	20
Bibliography	20
<b>2 Principle of Thrust</b>	<b>21</b>
2.1 Thrust Configurations	21
2.2 Thrust Equation	23
2.3 Basic Engine Performance Parameters	28
2.4 Propulsion and Aircraft Performance	34
2.5 Propeller Propulsion	38
2.6 MATLAB <sup>®</sup> Program	39
2.7 Problems	40
Bibliography	42
<b>3 Basic Analyses of Gas-Turbine Engines</b>	<b>43</b>
3.1 Introduction	43
3.2 Gas-Turbine Engine as a Power Cycle (Brayton Cycle)	43
3.3 Ideal-Cycle Analysis for Turbofan Engines	49
3.4 Turbojets, Afterburners and Ramjets	61
3.4.1 Turbojet	61
3.4.2 Turbojets with Afterburners	64
3.4.3 Turbofan Engines with Afterburning ( <i>Mixed Stream</i> )	68
3.4.4 Ramjets	70

3.5	Further Uses of Basic Engine Analysis	73
3.6	MATLAB <sup>®</sup> Program	76
3.7	Problems	77
	Bibliography	79
<b>4</b>	<b>Gas-Turbine Components: Inlets and Nozzles</b>	<b>81</b>
4.1	Gas-Turbine Inlets	81
4.2	Subsonic Diffuser Operation	82
4.3	Supersonic Inlet Operation	91
4.4	Gas-Turbine Nozzles	95
4.5	Problems	98
	Bibliography	99
<b>5</b>	<b>Compressors and Turbines</b>	<b>101</b>
5.1	Introduction	101
5.2	Basic Compressor Aero-Thermodynamics	103
5.2.1	<i>Compressor Stage Performance</i>	107
5.2.2	<i>Pressure Coefficient and Boundary Layer Separation</i>	109
5.2.3	<i>de Haller Number and the Diffusion Factor</i>	110
5.2.4	<i>Mach Number Effect</i>	111
5.2.5	<i>Degree of Reaction</i>	112
5.3	Radial Variations in Compressors	115
5.3.1	<i>Stage Work and Degree of Reaction for Free-Vortex Swirl Distribution</i>	118
5.4	Preliminary Compressor Analysis/Design	119
5.5	Centrifugal Compressors	120
5.6	Turbine	123
5.6.1	<i>Estimation of the Blade Stagnation Temperature</i>	126
5.6.2	<i>Turbine Blade and Disk Stresses</i>	128
5.7	MATLAB <sup>®</sup> Programs	129
5.8	Problems	131
	Bibliography	133
<b>6</b>	<b>Combustors and Afterburners</b>	<b>135</b>
6.1	Combustion Chambers	135
6.2	Jet Fuels and Heating Values	137
6.3	Fluid Mixing in the Combustor	141
6.4	Afterburners	149
6.5	Combustor Heat Transfer	152
6.6	Stagnation Pressure Loss in Combustors	153
6.7	Problems	155
	Bibliography	157
<b>7</b>	<b>Gas-Turbine Analysis with Efficiency Terms</b>	<b>159</b>
7.1	Introduction	159
7.2	Turbofan Engine Analysis with Efficiency Terms	160

---

7.2.1	<i>Polytropic Factor</i>	162
7.2.2	<i>Diffuser</i>	164
7.2.3	<i>Compressor and Fan</i>	164
7.2.4	<i>Combustor</i>	165
7.2.5	<i>Turbine Power Balance</i>	165
7.2.6	<i>Nozzle Exit Pressure</i>	165
7.2.7	<i>Output Parameters</i>	166
7.3	MATLAB <sup>®</sup> Program	172
7.4	Problems	174
	Bibliography	175
<b>8</b>	<b>Basics of Rocket Propulsion</b>	<b>177</b>
8.1	Introduction	177
8.2	Basic Rocketry	182
8.2.1	<i>Specific Impulse</i>	182
8.2.2	<i>Vehicle Acceleration</i>	183
8.2.3	<i>Staging</i>	184
8.2.4	<i>Propulsion and Overall Efficiencies</i>	188
8.3	MATLAB <sup>®</sup> Programs	189
8.4	Problems	190
	Bibliography	191
<b>9</b>	<b>Rocket Propulsion and Mission Analysis</b>	<b>193</b>
9.1	Introduction	193
9.2	Trajectory Calculations	195
9.3	Rocket Maneuvers	203
9.3.1	<i>Coplanar Orbit Change</i>	205
9.3.2	<i>Hohmann Transfer</i>	206
9.3.3	<i>Plane Change</i>	207
9.3.4	<i>Attitude Adjustments</i>	208
9.4	Missile Pursuit Algorithms and Thrust Requirements	209
9.4.1	<i>Velocity Pursuit</i>	210
9.4.2	<i>Proportional Navigation</i>	211
9.4.3	<i>Command-to-Line-of-Sight (CLOS)</i>	212
9.5	Problems	213
	Bibliography	215
<b>10</b>	<b>Chemical Rockets</b>	<b>217</b>
10.1	Rocket Thrust	217
10.1.1	<i>Ideal Rocket Thrust</i>	217
10.1.2	<i>Thrust Coefficient and Characteristic Velocity</i>	218
10.2	Liquid Propellant Rocket Engines	220
10.2.1	<i>Liquid Propellants and Their Chemistry</i>	222
10.2.2	<i>Chemical Equilibrium</i>	225
10.2.3	<i>Liquid Propellants Combustion Chambers</i>	232
10.3	Solid Propellant Combustion	244

10.3.1	<i>Burning Rate Analysis</i>	247
10.4	Rocket Nozzles	252
10.4.1	<i>Thrust Vector Control</i>	254
10.4.2	<i>Nozzle and Combustion Chamber Heat Transfer</i>	254
10.5	MATLAB <sup>®</sup> Program	256
10.6	Problems	256
	Bibliography	258
<b>11</b>	<b>Non-Chemical Rockets</b>	<b>259</b>
11.1	Electrothermal Devices	261
11.2	Ion Thrusters	265
11.2.1	<i>Ion Generation</i>	266
11.2.2	<i>Acceleration of Ions</i>	271
11.2.3	<i>Electromagnetic Thrusters</i>	275
11.3	Problems	280
	Bibliography	282
<b>Appendices</b>		<b>283</b>
	Appendix A: Standard Atmospheric Air Properties	283
	Appendix B: Specific Heats for Air as a Function of Temperature	286
	Appendix C: Normal Shock Properties	287
	Appendix D: Oblique Shock Angle Chart	291
	Appendix E: Polynomial Coefficients for Specific Heat of Selected Gases	292
	Appendix F: Standard state Gibbs free energy ( $T=298.15\text{K}$ , $P=1\text{ atm}$ )	
	$\bar{g}_f^o(T)$ [ $\text{kJ}/\text{kmol}$ ]	293
<b>Index</b>		<b>295</b>