

CONTENTS

Preface	xiii
Notation	xvii
 Chapter 1. A brief review of power generation thermodynamics.	 1
1.1. Introduction	1
1.2. Criteria for the performance of power plants	4
1.2.1. Efficiency of a closed circuit gas turbine plant	4
1.2.2. Efficiency of an open circuit gas turbine plant	6
1.2.3. Heat rate	7
1.2.4. Energy utilisation factor	7
1.3. Ideal (Carnot) power plant performance	7
1.4. Limitations of other cycles	8
1.5. Modifications of gas turbine cycles to achieve higher thermal efficiency	9
References	11
 Chapter 2. Reversibility and availability.	 13
2.1. Introduction	13
2.2. Reversibility, availability and exergy	14
2.2.1. Flow in the presence of an environment at T_0 (not involving chemical reaction)	14
2.2.2. Flow with heat transfer at temperature T	16
2.3. Exergy flux.	19
2.3.1. Application of the exergy flux equation to a closed cycle.	20
2.3.2. The relationships between ξ , σ and I^{CR} , I^{Q}	20
2.4. The maximum work output in a chemical reaction at T_0	22
2.5. The adiabatic combustion process.	23
2.6. The work output and rational efficiency of an open circuit gas turbine	24
2.7. A final comment on the use of exergy.	26
References	26
 Chapter 3 Basic gas turbine cycles	 27
3.1. Introduction	27

3.2.	Air standard cycles (uncooled)	28
3.2.1.	Reversible cycles	28
3.2.1.1.	The reversible simple (Joule–Brayton) cycle, $[\text{CHT}]_R$	28
3.2.1.2.	The reversible recuperative cycle $[\text{CHTX}]_R$	29
3.2.1.3.	The reversible reheat cycle $[\text{CHTHT}]_R$	30
3.2.1.4.	The reversible intercooled cycle $[\text{CICHT}]_R$	32
3.2.1.5.	The ‘ultimate’ gas turbine cycle	32
3.2.2.	Irreversible air standard cycles	33
3.2.2.1.	Component performance	33
3.2.2.2.	The irreversible simple cycle $[\text{CHT}]_I$	34
3.2.2.3.	The irreversible recuperative cycle $[\text{CHTX}]_I$	37
3.2.3.	Discussion	39
3.3.	The $[\text{CBT}]_I$ open circuit plant—a general approach	39
3.4.	Computer calculations for open circuit gas turbines	43
3.4.1.	The $[\text{CBT}]_{IG}$ plant.	43
3.4.2.	Comparison of several types of gas turbine plants.	44
3.5.	Discussion	45
	References	46
Chapter 4.	Cycle efficiency with turbine cooling (cooling flow rates specified).	47
4.1.	Introduction	47
4.2.	Air-standard cooled cycles	48
4.2.1.	Cooling of internally reversible cycles	49
4.2.1.1.	Cycle $[\text{CHT}]_{RC1}$ with single step cooling	49
4.2.1.2.	Cycle $[\text{CHT}]_{RC2}$ with two step cooling	51
4.2.1.3.	Cycle $[\text{CHT}]_{RCM}$ with multi-step cooling	52
4.2.1.4.	The turbine exit condition (for reversible cooled cycles)	54
4.2.2.	Cooling of irreversible cycles	55
4.2.2.1.	Cycle with single-step cooling $[\text{CHT}]_{IC1}$	55
4.2.2.2.	Efficiency as a function of combustion temperature or rotor inlet temperature (for single-step cooling)	56
4.2.2.3.	Cycle with two step cooling $[\text{CHT}]_{IC2}$	58
4.2.2.4.	Cycle with multi-step cooling $[\text{CHT}]_{ICM}$	59
4.2.2.5.	Comment.	59
4.3.	Open cooling of turbine blade rows—detailed fluid mechanics and thermodynamics.	59
4.3.1.	Introduction	59
4.3.2.	The simple approach	61
4.3.2.1.	Change in stagnation enthalpy (or temperature) through an open cooled blade row	61
4.3.2.2.	Change of total pressure through an open cooled blade row	62
4.3.3.	Breakdown of losses in the cooling process	64

4.4.	Cycle calculations with turbine cooling	65
4.5.	Conclusions	68
	References	69
Chapter 5.	Full calculations of plant efficiency	71
5.1.	Introduction	71
5.2.	Cooling flow requirements	71
5.2.1.	Convective cooling	71
5.2.2.	Film cooling	72
5.2.3.	Assumptions for cycle calculations	73
5.3.	Estimates of cooling flow fraction	73
5.4.	Single step cooling	75
5.5.	Multi-stage cooling	75
5.6.	A note on real gas effects	82
5.7.	Other studies of gas turbine plants with turbine cooling	82
5.8.	Exergy calculations	82
5.9.	Conclusions	84
	References	84
Chapter 6.	'Wet' gas turbine plants	85
6.1.	Introduction	85
6.2.	Simple analyses of STIG type plants.	85
6.2.1.	The basic STIG plant	85
6.2.2.	The recuperative STIG plant	90
6.3.	Simple analyses of EGT type plants	91
6.3.1.	A discussion of dry recuperative plants with ideal heat exchangers	91
6.3.2.	The simple EGT plant with water injection	93
6.4.	Recent developments	97
6.4.1.	Developments of the STIG cycle	97
6.4.1.1.	The ISTIG cycle	97
6.4.1.2.	The combined STIG cycle.	99
6.4.1.3.	The FAST cycle	99
6.4.2.	Developments of the EGT cycle.	99
6.4.2.1.	The RWI cycle	100
6.4.2.2.	The HAT cycle	100
6.4.2.3.	The REVAP cycle	100
6.4.2.4.	The CHAT cycle	101
6.4.2.5.	The TOPHAT cycle	101
6.4.3.	Simpler direct water injection cycles.	103

6.5.	A discussion of the basic thermodynamics of these developments	103
6.6.	Some detailed parametric studies of wet cycles	105
6.7.	Conclusions	107
	References	107
Chapter 7.	The combined cycle gas turbine (CCGT)	109
7.1.	Introduction	109
7.2.	An ideal combination of cyclic plants.	109
7.3.	A combined plant with heat loss between two cyclic plants in series	110
7.4.	The combined cycle gas turbine plant (CCGT).	111
7.4.1.	The exhaust heated (unfired) CCGT	112
7.4.2.	The integrated coal gasification combined cycle plant (IGCC)	114
7.4.3.	The exhaust heated (supplementary fired) CCGT	116
7.5.	The efficiency of an exhaust heated CCGT plant	117
7.5.1.	A parametric calculation	118
7.5.2.	Regenerative feed heating.	122
7.6.	The optimum pressure ratio for a CCGT plant	123
7.7.	Reheating in the upper gas turbine cycle.	126
7.8.	Discussion and conclusions.	128
	References	129
Chapter 8.	Novel gas turbine cycles	131
8.1.	Introduction	131
8.2.	Classification of gas-fired plants using novel cycles	132
8.2.1.	Plants (A) with addition of equipment to remove the carbon dioxide produced in combustion	132
8.2.2.	Plants (B) with modification of the fuel in combustion—chemically reformed gas turbine (CRGT) cycles	133
8.2.3.	Plants (C) using non-carbon fuel (hydrogen)	133
8.2.4.	Plants (D) with modification of the oxidant in combustion	135
8.2.5.	Outline of discussion of novel cycles	135
8.3.	CO ₂ removal equipment.	136
8.3.1.	The chemical absorption process	136
8.3.2.	The physical absorption process	136
8.4.	Semi-closure	139
8.5.	The chemical reactions involved in various cycles	140
8.5.1.	Complete combustion in a conventional open circuit plant	140
8.5.2.	Thermo-chemical recuperation using steam (steam-TCR).	141
8.5.3.	Partial oxidation	143

8.5.4.	Thermo-chemical recuperation using flue gases (flue gas/TCR)	143
8.5.5.	Combustion with recycled flue gas as a carrier	144
8.6.	Descriptions of cycles	144
8.6.1.	Cycles A with additional removal equipment for carbon dioxide sequestration	144
8.6.1.1.	Direct removal of CO ₂ from an existing plant	144
8.6.1.2.	Modifications of the cycles of conventional plants using the semi-closed gas turbine cycle concept	146
8.6.2.	Cycles B with modification of the fuel in combustion through thermo-chemical recuperation (TCR)	147
8.6.2.1.	The steam/TCR cycle	149
8.6.2.2.	The flue gas thermo-chemically recuperated (FG/TCR) cycle	150
8.6.3.	Cycles C burning non-carbon fuel (hydrogen)	152
8.6.4.	Cycles D with modification of the oxidant in combustion	154
8.6.4.1.	Partial oxidation cycles	155
8.6.4.2.	Plants with combustion modification (full oxidation)	158
8.7.	IGCC cycles with CO ₂ removal (Cycles E)	160
8.8.	Summary	162
	References	164
CHAPTER 9.	The gas turbine as a cogeneration (combined heat and power) plant.	167
9.1.	Introduction	167
9.2.	Performance criteria for CHP plants	168
9.2.1.	Energy utilisation factor	168
9.2.2.	Artificial thermal efficiency	170
9.2.3.	Fuel energy saving ratio	170
9.3.	The unmatched gas turbine CHP plant	173
9.4.	Range of operation for a gas turbine CHP plant	174
9.5.	Design of gas turbines as cogeneration (CHP) plants	177
9.6.	Some practical gas turbine cogeneration plants	177
9.6.1.	The Beilen CHP plant	177
9.6.2.	The Liverpool University CHP plant	180
	References	181
APPENDIX A.	Derivation of required cooling flows.	183
A.1.	Introduction	183
A.2.	Convective cooling only	183
A.3.	Film cooling	185
A.4.	The cooling efficiency	186

A.5.	Summary	186
	References	187
APPENDIX B. Economics of gas turbine plants		189
B.1.	Introduction	189
B.2.	Electricity pricing	189
B.3.	The capital charge factor	190
B.4.	Examples of electricity pricing	191
B.5.	Carbon dioxide production and the effects of a carbon tax	192
	References	194
Index		195