

First Revised Edition

SOLAR ENERGY

Fundamentals and Applications

H P Garg

J Prakash

CONTENTS

Preface to the First Revised Edition

Preface to the First Edition

Acknowledgements

v

vii

ix

Chapter 1. Solar Radiation

1

- 1.1 Introduction 1
- 1.2 The Sun as the Source of Radiation 2
- 1.3 The Earth and Solar Constant 2
- 1.4 Spectral Distribution of Extraterrestrial Radiation 4
- 1.5 Variation of Extraterrestrial Radiation 5
- 1.6 Basic Earth-Sun Angles 7
- 1.7 Solar Time and the Equation of Time 11
- 1.8 Depletion of Solar Radiation by the Atmosphere 11
- 1.9 Diffuse Radiation at the Ground 15
- 1.10 Empirical Equations for Predicting the Availability of Solar Radiation 16
 - 1.10.1 Average Daily Global Radiation 16
 - 1.10.2 Average Daily Diffuse Radiation 18
 - 1.10.3 Estimation of Hourly Global and Diffuse Solar Radiation 19
 - 1.10.4 Angle of Incidence on Horizontal and Inclined Planes 20
- 1.11 Computation of Radiation on Inclined Surfaces 22
- 1.12 Angstrom's Turbidity 25
- 1.13 Solar Charts 26
- 1.14 Measurement of Diffuse, Global and Direct Solar Radiation 26
 - 1.14.1 Standard Radiation Scale and Radiation Measuring Instruments 28
 - 1.14.2 Abbot Silver Disc Pyrheliometer 29
 - 1.14.3 Linke-Feussner Pyrheliometer (Actinometer) 30
 - 1.14.4 Eppley Normal Incidence (NI) Pyrheliometer 31
 - 1.14.5 The Moll-Gorezynski Pyranometer 31
 - 1.14.6 The Eppley 180° pyranometer 32
 - 1.14.7 Photovoltaic Silicon Pyranometer 35
- 1.15 Measurement of Diffuse Radiation 35
- 1.16 Spectral Measurements 36
- 1.17 Calibration and Standardization 37
- 1.18 Duration of Sunshine Hours 40
- 1.19 Solar Radiation Data 40
 - References* 45

Chapter 2. Flat Plate Collectors

- 2.1 Introduction 46
- 2.2 The Liquid Flat Plate Collector 47
- 2.3 Materials for Flat Plate Collectors 49
 - 2.3.1 Absorber Plate 50
 - 2.3.2 Insulation 50
 - 2.3.3 Cover Plate 50
- 2.4 Efficiency of Flat Plate Collectors 52
- 2.5 Overall Heat Loss Coefficient 59
 - 2.5.1 Heat loss from the Top of Collector Plate 60
 - 2.5.2 Heat Transfer between Enclosed Parallel Surfaces 61
 - 2.5.3 Forced Convective Heat Transfer from top cover 62
 - 2.5.4 Sky Temperature (T_{sky}) 63
 - 2.5.5 Bottom Loss Coefficient 63
 - 2.5.6 Side (Edge) loss coefficient (U_e) 64
 - 2.5.7 Top loss coefficient (U_t) 64
 - 2.5.8 Improving Efficiency of a Flat-Plate Collector 66
 - 2.5.9 Selective Surfaces 66
- 2.6 Long-Term Average Performance of Flat-Plate Collectors 75
 - 2.6.1 Liu and Jordan's Method of Hourly Utilizability 75
 - 2.6.2 Klein's and Collares-Pereira and Rabl's Method of Daily Utilizability 81
- 2.7 Flat Plate Air-Heating Collectors 83
 - 2.7.1 Types of Air Heating Collectors 84
 - 2.7.2 Performance Analysis of Conventional Air Heater 85
 - 2.7.3 Heat Transfer and Pressure Drop in a Parallel Plate Duct 89
- 2.8 Other Types of Solar Air Heaters 89
 - 2.8.1 Air Heater with Air Flow Above the Absorber Plate 89
 - 2.8.2 Conventional Air Heater with Fins 90
 - 2.8.3 Two-Pass Solar Air Heater 91
- 2.9 Some Novel Designs of Solar Air Heaters 92
 - 2.9.1 Overlapped Glass Plate Solar Air Heater 92
 - 2.9.2 Matrix Air Heater 93
 - 2.9.3 Honeycomb Porous-bed Air Heater 94
- 2.10 Solar Ponds 94
 - 2.10.1 Salt Gradient or Non-Convective Solar Ponds 94
 - 2.10.2 Temperatures and Efficiencies of Solar Ponds 97
- 2.11 Tubular Solar Energy Collectors 97
 - 2.11.1 Analysis of the Concentric-Tube Collector (CTC) 99
- 2.12 Testing of Solar Collectors 101
 - 2.12.1 ASHRAE Standard 93-77 103
 - 2.12.2 Collector Time Constant 109
 - 2.12.3 Collector Incident Angle Modifier 110
 - 2.12.4 Calculation of All-day Solar Efficiency from the Test Data of ASHRAE Standard 93-77 112

Chapter 3. Solar Concentrating Collectors

- 3.1 Introduction 116
- 3.2 Parameters Characterizing Solar Concentrators 116
- 3.3 Classification of Solar Concentrators 118
- 3.4 Thermodynamic Limits to Concentration 119
- 3.5 Solar Concentrator Mountings 121
- 3.6 Solar Incident Angle for Different Concentrator Mountings 124
- 3.7 Performance Analysis of Cylindrical Parabolic Collector 125
- 3.8 Compound Parabolic Collector 128
 - 3.8.1 Tracking Requirements of a Compound Parabolic Concentrating Collector (CPC) 130
 - 3.8.2 Performance Analysis of a Compound Parabolic Concentrating Collector (CPC) 130
- 3.9 Point Focusing Solar Concentrators 131
 - 3.9.1 Paraboloid of Revolution 132
 - 3.9.2 Central Power Receiver Systems 132
 - 3.9.3 Analysis of a Central Receiver System 136
- 3.10 Materials for Solar Concentrators 137
 - 3.10.1 Materials for the Reflecting and Refracting Surfaces 137
 - 3.10.2 Materials for the Absorber 138
 - 3.10.3 Absorber Cover (Envelope) Materials 138
 - 3.10.4 Absorber Surface Coating Materials 139
 - 3.10.5 Heat Transfer Fluids 139
 - 3.10.6 Insulation on the Non-irradiated Portion of the Absorber 140

References 140

Chapter 4. Solar Water Heating

141

- 4.1 Introduction 141
 - 4.2 Swimming Pool Heating 142
 - 4.3 Built-in-storage type-storage Solar Water Heaters (Integrated Collector Storage System) 143
 - 4.4 Separate Collector and Storage Type Solar Water Heater 148
 - 4.4.1 Natural Circulation Type Systems 149
 - 4.4.2 Forced-Circulation or Pumped Systems 151
 - 4.5 Performance Prediction of Solar Water Heaters 152
 - 4.5.1 Mathematical Model for Natural Circulation Type Solar Water Heater 152
 - 4.5.2 Mathematical Model for Performance Predictions of Forced Circulation Type Solar Water Heater 156
- References* 163

Chapter 5. Solar Cookers

166

- 5.1 Introduction 166
 - 5.2 Types of Solar Cookers 168
 - 5.3 Performance of Box Type Solar Cooker 172
 - 5.4 Testing of a Solar Cooker 173
- References* 175

Chapter 6. Solar Desalination	176
6.1 Introduction	176
6.2 Simple Solar Still	178
6.3 Basics of Solar Still	180
6.4 Material Problems in Solar Stills	181
6.5 Performance Prediction of Basin-Type Still	182
6.6 Experiments on Solar Stills	185
6.6.1 Wick Type Solar Still	186
6.6.2 Regenerative Type Solar Still	188
6.7 Solar Disinfection	189
References	190
Chapter 7. Solar Drying of Food	191
7.1 Introduction	191
7.2 Basics of Solar Drying	192
7.3 Types of Solar Dryers	197
7.3.1 Natural Convection or Direct Type Solar Dryers	197
7.3.2 Mixed Mode Type Solar Dryer	199
7.4 Forced Circulation Type Dryers	200
7.4.1 Hybrid Dryer	200
7.4.2 Bin Type Grain Dryers	200
7.4.3 Solar Timber Drying	203
7.5 Simulation Models of Drying	205
7.5.1 Thin layer drying	205
7.5.2 Deep Bed Drying	210
7.5.3 Continuous Flow Dryers	212
References	214
Chapter 8. Passive Solar House Heating and Cooling	215
8.1 Introduction	215
8.2 Passive Heating of Buildings	217
8.2.1 Direct gain	217
8.2.2 Thermal Storage Wall	218
8.2.3 Attached Greenhouse (Sunspace)	220
8.2.4 Thermal Storage Roof	220
8.2.5 Convective Loop	222
8.3 Passive Cooling of Building	223
8.3.1 Shading	223
8.3.2 Ventilation	224
8.3.3 Evaporation	224
8.3.4 Radiation Cooling	225
8.3.5 Ground Coupling	226
8.3.6 Dehumidification	226
References	227

Chapter 9. Solar Energy for Industrial Process Heat

- 9.1 Introduction 228
- 9.2 Industrial Energy Use 229
- 9.3 Industrial Process Heat System 231
 - 9.3.1 Hot Water Industrial Process Heat System 232
 - 9.3.2 Hot Air Industrial Process Heat System 234
 - 9.3.3 Steam Industrial Process Heat System 235
- 9.4 Problems with SIPH Systems 239
- References* 240

Chapter 10. Solar Heating of Buildings: Active Systems

242

- 10.1 Introduction 242
- 10.2 Building Form and Functions 243
- 10.3 General Aspects of Solar Active Heating of Buildings 244
- 10.4 Components of Solar Heating Systems 246
 - 10.4.1 Solar Collector 246
 - 10.4.2 Thermal Storage System 247
 - 10.4.3 Auxiliary Heat Supply System 248
 - 10.4.4 Control Systems 249
- 10.5 Three Ways of Solar Space Heating 253
 - 10.5.1 Solar Air Systems 253
 - 10.5.2 Solar Liquid Systems 254
 - 10.5.3 Solar Heat Pump Systems 255
- 10.6 Prediction of Heating Loads 257
- 10.7 Sizing of Active Solar Space Heating Systems 260
- References* 264

Chapter 11. Solar Greenhouses

265

- 11.1 Introduction 265
- 11.2 Basics of Plant Growth 266
 - 11.2.1 Light Intensity 266
 - 11.2.2 Temperature 268
 - 11.2.3 Humidity 268
 - 11.2.4 Air Movement 268
 - 11.2.5 Carbon dioxide 269
 - 11.2.6 Nutrients 270
 - 11.2.7 Watering 270
- 11.3 Greenhouse Design 271
 - 11.3.1 Orientation and Tilt 271
 - 11.3.2 Modes of Heat Transfer 271
 - 11.3.3 Glass or Plastic Greenhouse 274
- 11.4 Typical Greenhouse Designs 277
 - 11.4.1 The Brace Greenhouse Design 277
 - 11.4.2 The KISR Greenhouse for Warm Climates 279
- 11.5 Performance Prediction of Thermal Environment and Crop Yield in Greenhouse 279
- References* 280

Chapter 12. Solar Refrigeration and Air Conditioning	282
12.1 Introduction	282
12.2 Carnot Refrigeration Cycle	284
12.3 Absorption Cooling	285
12.3.1 Principle of Absorption Cooling	286
12.3.2 Basics of Absorption Cooling	287
12.3.3 Lithium Bromide-Water Absorption System	290
12.3.4 Aqua-ammonia Absorption System	293
12.3.5 Intermittent Absorption Refrigeration System	295
12.4 Vapour Compression Refrigeration	296
12.5 Desiccant Cooling	298
References	302
Chapter 13. Solar Furnaces	304
13.1 Introduction	304
13.2 Types of Solar Furnaces	305
13.3 Components of Solar Furnace	306
13.3.1 Concentrator	306
13.3.2 Heliostat	307
13.3.3 Sun Tracking	308
13.4 Typical Solar Furnace Designs	308
13.4.1 Single Concentrator Furnace	308
13.4.2 Single Heliostat Solar Furnace	308
13.4.3 Multiple Heliostats Solar Furnace	310
13.5 Measuring Instruments in Solar Furnace	311
References	312
Chapter 14. Solar Thermo-Mechanical Power	314
14.1 Introduction	314
14.2 Principles of Solar Engines	316
14.3 Limitations of Solar Mechanical Power Conversion	319
14.4 Solar Heat Engines	319
14.5 Steam Engines	320
14.6 Turbines	322
14.7 Stirling Engines	324
14.8 Brayton Engines	325
14.9 Solar Power Plants	328
14.9.1 Solar Thermal Electric Generation Plant of 500 kW _e at Almeria, Spain	328
14.9.2 Central Receiver Electric Plant of 1 MW _e Capacity (Eurelios)	331
14.9.3 The White Cliffs (Australia) Solar Power Station	335
14.9.4 Parabolic-Trough Power Plants	338
References	341

Chapter 15 Solar Powered Thermal Water Pump**342**

- 15.1 Introduction 342
- 15.2 Typical Solar Pump Systems 344
 - 15.2.1 Coolidge, Arizona 150 kW Solar Irrigation Pump 345
 - 15.2.2 Gila Band, Phoenix, Arizona, 37 kW Solar Powered Irrigation Pump 347
 - 15.2.3 Sofretes Solar Pump 348
 - 15.2.4 Special Solar Pumps 349
- References 350*

Chapter 16 Solar Thermal Energy Storage**351**

- 16.1 Introduction 351
- 16.2 Need of Thermal Energy Storage 351
- 16.3 Size and Duration of Storage 353
- 16.4 Thermal Energy Storage 354
 - 16.4.1 Sensible heat storage 357
 - 16.4.2 Storage in phase change materials (PCM) 362
- 16.5 Storage in Reversible Chemical Reactions 367
- References 369*

Chapter 17 Solar Photovoltaics**370**

- 17.1 Introduction 370
- 17.2 Fundamentals of Photovoltaic Conversion 371
 - 17.2.1 Semiconductor materials 371
 - 17.2.2 Photon energy 373
 - 17.2.3 Electron-hole concentration and Fermi level 374
 - 17.2.4 A p-n junction 377
 - 17.2.5 Light absorption in a semiconductor 383
 - 17.2.6 Solar cell materials 385
- 17.3 Efficiency of Solar Cells 388
- 17.4 Silicon Solar Cell 391
 - 17.4.1 Purification of silicon 391
 - 17.4.2 Methods of growing crystal 393
 - 17.4.3 Silicon wafer to silicon solar cell Fabrication 393
 - 17.4.4 Module design 395
 - 17.4.5 Polycrystalline silicon cells 396
 - 17.4.6 Amorphous silicon cells 397
- 17.5 Balance of System (BOS) 401
 - 17.5.1 Structure and installation 401
 - 17.5.2 Power conditioning and control 402
 - 17.5.3 Storage batteries 403
- 17.6 PV Systems 404
 - 17.6.1 Stand-alone PV systems 404
 - 17.6.2 Grid-connected system 404
 - 17.6.3 Solar power satellite 405
- 17.7 Photovoltaic Applications 405
 - 17.7.1 Industrial applications 405

17.7.2	Social applications	407
17.7.3	Consumer applications	409
	<i>References</i>	410

Chapter 18 Economic Analysis 412

18.1	Introduction	412
18.2	Net Present Value Concept	412
18.2.1	Investment with money from hand	412
18.2.2	Investment with money on loan	413
18.3	Life-cycle Cost Method	414
18.3.1	Residential systems	415
18.3.2	Commercial systems	415
18.4	Cost-Benefit Comparison Method	416
18.5	Pay-back Period Method	416
	<i>References</i>	417

Appendix Heat Transfer 418

Conduction	418
Convection	420
Radiation	423
<i>References</i>	425

Author Index 426

Subject Index 430