Design of Solar Thermal Systems

Moustafa M. Elsayed
Mechanical Engineering Department,
King Abdulaziz University, Jeddah, Saudi Arabia

Ibrahim S. Taha
Mechanical Engineering Department,
Assuit University, Assiut, Egypt

Jaffar A. Sabbagh
Mechanical Engineering Department,
King Abdulaziz University
Jeddah, Saudi Arabia

Scientific Publishing Centre
King Abdulaziz University
P.O. Box 1540, Jeddah 21441
Saudi Arabia.
Preface

This book presents the design of solar thermal systems using mathematical modeling. The importance of mathematical modeling is continuously increasing because of the rapid spread in the use of computers as design tools. The book is thus prepared for those who are involved in the design, optimization, or evaluation of the performance of solar thermal systems.

The book is based on teaching notes for undergraduate and first year graduate courses for thermal engineering students. It is recommended as a text for senior undergraduate students or first year graduate students, and also as a reference book for engineers working in various solar thermal applications.

The book consists of 10 chapters. The first chapter reviews the world resources of energy and their classification and relation to solar energy. The second chapter reviews important topics in thermal radiation which are relevant to the subject of the book. The third chapter is concerned with the estimation of solar angles and the hourly, daily, and monthly average daily solar radiation. Mathematical equations are given to enable the designer of a solar thermal system to estimate the beam, diffuse, or total radiation on horizontal or tilted surfaces.

The transmission of solar radiation through transparent sheets of different material is treated in Chapter 4. This chapter gives mathematical equations to predict the radiation properties of multi-layer partially transparent sheets with or without an absorber plate. A computer program is included to enable the designer to estimate the radiation properties for several geometries of a stack of similar or nonsimilar transparent sheets with or without an absorber plate at any incidence angle. The program is useful in the design and optimization of flat plate collectors and solar concentrators, and can also be utilized by air conditioning engineers to estimate solar heat gain through transparent windows and doors.

Chapter 5 gives the design of flat plate collectors, and presents various types. Complete simulation of the collectors is given, and the various factors affecting their performance are discussed. A computer program is given to design and optimize the design parameters of the flat plate collectors. This program can also be used to evaluate the performance of flat plate collectors in off-design conditions.
Chapter 6 deals with solar desalination. The chapter will be helpful to those designing either roof-type or diffusion-type solar desalination systems, since it includes a more detailed description of these systems than most other solar energy textbooks. Analysis are given to predict the transient performance of the roof-type still. A computer program is given to assist the designer in predicting the effect of various design and operating conditions on the performance of the still. Various novel designs of roof-types stills are presented with the advantages and disadvantages of each. The chapter also gives the analysis of both the single effect and the multiple-effect diffusion-type still together with a brief presentation of the mass diffusion theory. Other methods of solar desalination are also discussed in the chapter.

The collection of solar energy at medium and high temperatures by solar concentrators is discussed in Chapter 7. Various types of concentrators are presented. Thermal analyses are given to show the important factors affecting the performance of solar concentrators. Different tracking modes are given. The material in this chapter will help the reader to select the type of solar concentrator most suitable for a particular application together with the adequate tracking mode. Details of the designing of intermittent tracking are given in the chapter. Readers interested in continuous tracking will find ample material in section 10.8 of Chapter 10.

In Chapter 8, the design of solar energy storage is considered. The first part of the chapter deals with storage methods, characteristics, location, and the evaluation of the storage process. Mathematical simulations of various types of sensible heat storage are carried out for low, intermediate, and high temperature applications. In particular, mathematical simulations are presented for the transient performance of the mixed liquid storage, underground liquid storage, and stratified liquid storage. With these simulations the reader of the chapter should be able to size the liquid storage tank required for a certain application. Designers of solid storage tanks will also find that the mathematical simulation of rock bed storage and its sizing are covered in the chapter. In addition, other techniques of solar energy storage such as low, intermediate, and high temperature phase change and chemical and mechanical storages are considered. The user of the simulation models given in this chapter should have a reasonable background in the finite difference numerical technique.

The solar-operated absorption cooling system is treated in Chapter 9. Both H$_2$O-LiBr and NH$_3$-H$_2$O absorption systems are considered. Different arrangements of solar-operated absorption cooling systems are given, together with the criteria to evaluate and compare these systems. Alternative combinations of absorption cooling systems, such as the dual series connected system and the two stage absorption cooling system, are presented. Mathematical simulations of both the H$_2$O-LiBr and NH$_3$-H$_2$O absorption machines are considered. A computer program is included to predict the performance of the absorption cooling machine in various design and operating conditions. An optimization procedure is given for the determination of the design parameters of the absorption cooling machine. The chapter also contains a brief description of the intermittent absorption cooling system.

Chapter 10 deals with solar power generation. The chapter includes the charac-
teristics required for the working fluids of the solar-operated Rankine cycle. Mathematical simulation is given for the Rankine cycle and selection of the various design parameters of the system is presented. The chapter also includes the performance of the solar-operated Rankine cycle (SORC) in various operating conditions. In addition, the engineering considerations for the selection of the various components of SORC are given. Analyses are also presented to select the optimum collector temperature for solar-operated power cycles. A sizeable section of the chapter is devoted to power tower technology, including material for the determination of the heliostat field layout, the determination of the tilt and orientation angle of each heliostat, and the sizing of the receiver.

The book adds considerably to engineering expertise in the design of solar thermal systems. Chapters 5 and 8 are relevant to the design of solar water heaters, swimming pool heating systems, and space heating. Chapter 6 will also assist in the design of solar desalination systems. Those involved in the design of solar operated absorption cooling systems should read Chapter 9 in addition to Chapter 8 and Chapters 5 or 7. Information on solar power generation is given in Chapter 10 and also in Chapters 7 and 8.

Authors

Jeddah
May 1986
# Contents

## Chapter 1: The World Energy Resources

1.1 The Sun ................................................................. 1  
1.2 The World Energy Resources .............................................. 2  
1.2.1 Coal ........................................................................ 2  
1.2.2 Petroleum Oil and Natural Gas ................................. 3  
1.2.3 Shale Oil and Tar Sand ............................................. 4  
1.2.4 Nuclear Fission .......................................................... 4  
1.2.5 Fast Breeder Reactor .................................................. 4  
1.2.6 Nuclear Fusion Energy .............................................. 5  
1.2.7 Hydraulic Power ........................................................ 5  
1.2.8 Wind Power ............................................................... 6  
1.2.9 Geothermal Energy ................................................... 6  
1.2.10 Hydrogen Fuel .......................................................... 6  
1.3 Solar Energy ............................................................... 6  
References .................................................................... 10  

## Chapter 2: Thermal Radiation

2.1 Introduction ............................................................... 13  
2.2 Radiation Properties .................................................... 13  
2.3 Opaque and Non-Opaque Materials .................................. 17  
2.4 Selective Surfaces ......................................................... 19  
2.5 Net Radiation Leaving a Gray Surface .......................... 24  
2.6 Intensity of Radiation Leaving a Gray Surface ................ 25  
2.7 Radiation Exchange between Gray Surfaces .................. 26  
2.7.1 Exchange between Two Surfaces ............................ 26  
2.7.2 Example: Four Surface Enclosures ......................... 28  
2.7.3 Estimation of Shape Factor ...................................... 28  
2.7.4 Special Cases ........................................................... 29  
2.8 Absorption and Emission of Radiation by Gases .......... 34  
2.9 Radiation Exchange between Two Gray Surfaces Through Absorbing and Transmitting Mediums ............................. 35  
2.9.1 One Absorbing and Transmitting Medium ................ 35  
2.9.2 Two Absorbing and Transmitting Medium ................. 37
Chapter 3: Solar Radiation

3.1 Introduction .......................................................... 41
3.2 Solar Angles .......................................................... 41
3.3 Extraterrestrial Solar Radiation ................................... 48
3.4 Depletion of Solar Radiation ..................................... 51
3.5 Estimation of Solar Radiation Received by a Horizontal Surface ........... 54
  3.5.1 Clear Sky Models ................................................ 57
    3.5.1.1 ASHRAE Model (clear sky) .............................. 57
    3.5.1.2 Hottel Model ............................................ 58
  3.5.2 Models Dependent on Local Solar Measurements ................. 62
    3.5.2.1 Hourly Radiation ........................................ 62
    3.5.2.2 Models to Estimate Daily Radiation .................... 66
    3.5.2.3 Models to Estimate the Monthly-Average Daily Radiation .......... 68
3.6 Estimation of Solar Radiation on a Tilted Surface .................. 69
3.7 Atmospheric Radiation ........................................... 74
3.8 Measurements of Solar Radiation ................................ 75
Nomenclature .................................................................. 76
Problems ...................................................................... 77
References .................................................................... 80

Chapter 4: Optical Properties of Materials and Radiation Characteristics of Surfaces

4.1 Introduction .......................................................... 83
4.2 Reflectances and Transmittances of Interfaces and Plates ........... 84
  4.2.1 Interface and Material Properties ............................ 84
  4.2.2 Effective Properties for a Plate ............................... 86
4.3 Effective Properties of a Stack of Plates .......................... 89
  4.3.1 Incident Radiation on the Outer Surface of the Stack ....... 89
  4.3.2 Incident Radiation on the Inner Surface of the Stack ...... 91
4.4 Effective Properties of an Absorber Plate with N-Cover: Incident Radiation on the Absorber Plate .......... 96
  4.4.1 An Absorber with One Cover Plate ....................... 96
  4.4.2 An Absorber Plate with N-Covers ........................... 97
4.5 Effective Properties of an Absorber Plate with N-Cover: Incident Radiation on the Top Cover ........... 99
4.6 Computer Programming ............................................. 104
Nomenclature ................................................................ 116
Problems .................................................................. 117
References .................................................................. 117
Chapter 5: Flat Plate Collectors

5.1 Introduction .................................................................................. 119
5.2 Types of Flat Plate Collectors ......................................................... 120
  5.2.1 Liquid Flat Plate Collectors ...................................................... 120
  5.2.2 Gas Flat Plate Collectors ......................................................... 121
5.3 Thermal Analysis of Flat Plate Collectors ........................................ 122
  5.3.1 Introduction ............................................................................ 122
  5.3.2 Specifications of the Collector and the Meteorological Parameters ............................................................................. 124
  5.3.3 Radiation Processes in the Collector .......................................... 126
  5.3.4 Energy Balance of Different Elements of Collector ................. 130
  5.3.5 Analytical Method of Solution ............................................... 135
  5.3.6 Empirical Formula for Top Loss Coefficient ......................... 144
  5.3.7 Total Loss Coefficient .......................................................... 145
  5.3.8 Local Temperature Across the Plate ....................................... 146
  5.3.9 Collector Efficiency Factor .................................................... 148
  5.3.10 Fluid Temperatures and Heat Removal Factor .................... 149
  5.3.11 Average Plate Temperature ................................................ 151
  5.3.12 Outlet Fluid Temperature .................................................... 151
5.4 Factors Affecting the Performance of FPC ....................................... 154
  5.4.1 Introduction ............................................................................ 154
  5.4.2 Cover .................................................................................... 154
  5.4.3 Absorber Plate ..................................................................... 156
  5.4.4 Liquid Tubes ........................................................................ 156
  5.4.5 Operating Conditions .......................................................... 156
  5.4.6 Conclusions .......................................................................... 157
5.5 Simulation, Design, and Optimization of FPC ................................... 157
5.6 Simulation and Algorithm of Solution for Liquid FPC ...................... 158
  5.6.1 Nomenclature ...................................................................... 159
  5.6.2 Data ...................................................................................... 161
  5.6.3 Steps of Calculation ............................................................ 161
  5.6.4 Algorithm for Assisting Subroutines ..................................... 162
  5.6.5 Checked Program List in Basic Language .............................. 165
  5.6.6 Sample Output ..................................................................... 177
5.7 Analysis of Solar Air Heaters .......................................................... 178

Problems ............................................................................................ 181
References .......................................................................................... 184

Chapter 6: Solar Desalination

6.1 Introduction .................................................................................. 187
6.2 Definitions .................................................................................... 188
6.3 Roof-Type Solar Stills (Basin-Type) ........................................... 189
   6.3.1 Construction .............................................................. 189
   6.3.2 Thermal Analysis of the Still ........................................... 193
6.4 Performance Prediction of Roof-Type Stills ............................................. 198
   6.4.1 Generalized Procedure .................................................... 199
   6.4.2 Morse-Read Chart ............................................................ 209
   6.4.3 Approximate Solution ...................................................... 211
6.5 The Maximum Efficiency of The Still .................................................... 213
6.6 Effect of Various Parameters on the Performance of Roof-Type Stills ............... 215
   6.6.1 Effect of Solar Radiation .................................................. 215
   6.6.2 Effect of Ambient Temperature ............................................ 215
   6.6.3 Effect of Wind Velocity .................................................... 215
   6.6.4 Effect of Edge and Base Loss Coefficient .................................. 216
   6.6.5 Brine Depth ....................................................................... 216
   6.6.6 Vapor Tightness .................................................................. 216
   6.6.7 Condensate Leakage ............................................................ 216
   6.6.8 Effect of Cover Slope ........................................................... 216
   6.6.9 Effect of Gap Distance between Water Surface and Cover ................. 216
   6.6.10 Effect of Build-up of Reflecting Layers of Salt on Water Surface and Basin Linear .............................................................. 217
6.7 Novel Designs of Roof-Type Stills ............................................................. 217
   6.7.1 Double-Basin Still ............................................................... 217
   6.7.2 Basin-Type Stepped Solar Still .................................................. 217
   6.7.3 Wick-Type Collector-Evaporator Still ........................................... 219
   6.7.4 Vertical Microporous Evaporator Solar Still ................................... 220
   6.7.5 Cascade Solar Still ............................................................... 221
   6.7.6 Roof-Type Still with Treated Cover Surface .................................... 221
   6.7.7 Roof-Type Still with Cover Cooling ............................................ 222
   6.7.8 Double-Effect Tilted Solar Still ............................................... 222
6.8 Diffusion Stills ............................................................................. 224
   6.8.1 Introduction to Mass Diffusion ............................................... 224
   6.8.2 Thermal Analysis of Diffusion Stills ........................................... 227
6.9 Multiple-Effect Diffusion Stills ............................................................... 231
6.10 Comparison of Transient Performance Predictions of a Single-Effect Diffusion Still with a Roof-Type Still .............................................................. 237
6.11 Economics of Solar Stills .................................................................... 243
6.12 Other Types of Solar Desalination Systems .............................................. 246
   6.12.1 Forced Convection Stills .......................................................... 246
   6.12.2 Multiple Effect Humidification-Dehumidification ................................ 246
   6.12.3 Solar Water Recovery from Air .................................................. 247
Nomenclature ......................................................................................... 248
Problems ............................................................................................... 249
References ............................................................................................. 253
**Chapter 7: Concentrating Collectors**

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1</td>
<td>Introduction</td>
<td>255</td>
</tr>
<tr>
<td>7.2</td>
<td>Types of Concentrating Collectors</td>
<td>255</td>
</tr>
<tr>
<td>7.2.1</td>
<td>Planar Reflector</td>
<td>259</td>
</tr>
<tr>
<td>7.2.2</td>
<td>V-Trough Reflector</td>
<td>259</td>
</tr>
<tr>
<td>7.2.3</td>
<td>Parabolic Reflector</td>
<td>259</td>
</tr>
<tr>
<td>7.2.4</td>
<td>Compound Parabolic Concentrator</td>
<td>259</td>
</tr>
<tr>
<td>7.2.5</td>
<td>Dish Reflector</td>
<td>261</td>
</tr>
<tr>
<td>7.2.6</td>
<td>Heliostat Reflectors</td>
<td>262</td>
</tr>
<tr>
<td>7.2.7</td>
<td>Lens Refractor</td>
<td>263</td>
</tr>
<tr>
<td>7.2.8</td>
<td>Fresnel Lens Refractor</td>
<td>263</td>
</tr>
<tr>
<td>7.3</td>
<td>Important Factors</td>
<td>263</td>
</tr>
<tr>
<td>7.4</td>
<td>Concentration Ratio</td>
<td>263</td>
</tr>
<tr>
<td>7.4.1</td>
<td>Definitions</td>
<td>263</td>
</tr>
<tr>
<td>7.4.1.1</td>
<td>Aperture Area ($A_{ap}$)</td>
<td>264</td>
</tr>
<tr>
<td>7.4.1.2</td>
<td>Absorber Area ($A_{abs}$)</td>
<td>264</td>
</tr>
<tr>
<td>7.4.1.3</td>
<td>Acceptance Angle and Acceptance Half Angle</td>
<td>264</td>
</tr>
<tr>
<td>7.4.1.4</td>
<td>Theoretical Concentration Ratio $C$</td>
<td>264</td>
</tr>
<tr>
<td>7.4.1.5</td>
<td>Actual Concentration Ratio $C_a$</td>
<td>265</td>
</tr>
<tr>
<td>7.4.2</td>
<td>Maximum Theoretical Concentration Ratio</td>
<td>265</td>
</tr>
<tr>
<td>7.4.3</td>
<td>Ideal Concentrators</td>
<td>268</td>
</tr>
<tr>
<td>7.4.4</td>
<td>Actual Concentrators</td>
<td>268</td>
</tr>
<tr>
<td>7.5</td>
<td>Tracking Modes</td>
<td>268</td>
</tr>
<tr>
<td>7.5.1</td>
<td>Solar Profile Angle</td>
<td>270</td>
</tr>
<tr>
<td>7.5.2</td>
<td>No Tracking Mode</td>
<td>270</td>
</tr>
<tr>
<td>7.5.3</td>
<td>Intermittent Adjustment of Tilt Angle</td>
<td>272</td>
</tr>
<tr>
<td>7.5.4</td>
<td>Continuous Tracking About One Axis</td>
<td>276</td>
</tr>
<tr>
<td>7.5.5</td>
<td>Continuous Tracking About Two Axes</td>
<td>277</td>
</tr>
<tr>
<td>7.6</td>
<td>Thermal Analysis</td>
<td>277</td>
</tr>
</tbody>
</table>

**Nomenclature** | 280
**Problems** | 281
**References** | 284

**Chapter 8: Solar Energy Storage**

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1</td>
<td>General Concepts</td>
<td>285</td>
</tr>
<tr>
<td>8.1.1</td>
<td>Storage Methods</td>
<td>285</td>
</tr>
<tr>
<td>8.1.2</td>
<td>Storage Characteristics</td>
<td>287</td>
</tr>
<tr>
<td>8.1.3</td>
<td>Storage Location</td>
<td>287</td>
</tr>
<tr>
<td>8.1.4</td>
<td>Storage Efficiency</td>
<td>288</td>
</tr>
<tr>
<td>8.2</td>
<td>Low Temperature Sensible Storage</td>
<td>288</td>
</tr>
<tr>
<td>8.2.1</td>
<td>Introduction</td>
<td>288</td>
</tr>
<tr>
<td>8.2.2</td>
<td>Storage in Liquids</td>
<td>290</td>
</tr>
<tr>
<td>8.2.2.1</td>
<td>Above Ground Liquid Storage</td>
<td>290</td>
</tr>
</tbody>
</table>
Chapter 9: Solar Operated Absorption Cooling Systems

9.1 Introduction ......................................................... 329
9.2 Basic Absorption Cooling Cycle .................................. 329
  9.2.1 Description of the Cycle .................................... 329
  9.2.2 Upper and Lower Limits for COP of Irreversible Absorption
        Cooling Cycle .................................................. 332
  9.2.3 Desirable Characteristics of Refrigerant-Absorbent Solution ... 333
  9.2.4 Selection of Working Fluids for Solar Operated Absorption
        Cooling Cycle .................................................. 336
  9.2.5 The H₂O-LiBr and NH₃-H₂O Absorption Cooling Machines ... 336
9.3 Different Arrangements of Solar-Operated Absorption Cooling Sys-
    tems ............................................................. 341
9.4 Evaluation of Solar-Operated Absorption Cooling System ............ 345
  9.4.1 System Thermal Ratio ....................................... 345
  9.4.2 Specific Collector Area ..................................... 348
9.5 Some Alternative Absorption Cooling Systems ........................ 348
  9.5.1 Dual Series-Connected System ............................... 351
Chapter 10: Solar Power Generation

10.1 Introduction ......................................................... 387
10.2 Thermodynamic Power Cycles ........................................ 388
  10.2.1 Ideal Rankine and Reheat Cycles .......................... 388
  10.2.2 Ideal Air-Standard Otto and Diesel Cycles ............. 389
  10.2.3 Ideal Air-Standard Stirling and Ericson Cycles ....... 390
  10.2.4 Ideal Air-Standard Brayton Cycle ....................... 391
10.3 Solar-Operated Rankine Cycle .................................... 393
  10.3.1 Selection of Working Fluid ................................. 393
  10.3.2 Simulation of Solar Operated Rankine Cycle ........... 395
  10.3.3 Design Parameters of Solar Operated Rankine Cycle ... 398
    10.3.3.1 Overall Fluid-to-Fluid Conductance of the Heat Trans-
             fer Elements .............................................. 398
    10.3.3.2 Thermal Capacity of External Flows .................. 399
    10.3.3.3 Efficiency of Rotating or Moving Elements .......... 400
    10.3.3.4 External Temperatures ................................. 400
  10.3.4 Performance of Solar Operated Rankine Cycle .......... 401
  10.3.5 Engineering Consideration for the Selection of the Various
        Components of Rankine Cycle ................................ 401
    10.3.5.1 Expanders and Pumps .................................. 401
    10.3.5.2 Heat Exchangers ...................................... 403
10.4 Power Generation Using Hybrid Heating of Rankine Cycle ........ 404
10.5 Power Generation Using Organic Rankine Cycle Coupled to a Solar
        Pond .......................................................... 406
10.6 Power Generation Using the Brayton Cycle ....................... 406
10.7 Optimum Collector Temperature for the Solar-Operated Power Cycle .. 407
10.7.1 Low Temperature Solar Collectors ................................................. 407
10.7.2 High Temperature Solar Collectors ................................................. 408
10.7.3 Various Types of Solar Collectors .................................................. 409
10.8 Power Tower Technology .................................................................... 409
   10.8.1 Concept .................................................................................. 409
   10.8.2 Heliostat Field Layout ................................................................. 412
   10.8.3 Tilt Angles and Orientations of Heliostats .................................... 420
   10.8.4 Sizing of Receiver ...................................................................... 424
   10.8.5 Types of Receivers .................................................................... 429
   10.8.6 Review of Some Central Receiver Systems ................................... 429
Nomenclature ............................................................................................. 429
Problems .................................................................................................... 432
References ................................................................................................. 433

Appendices

A. Hooke and Jeeves Pattern Search Optimization Technique .................. 435
B. Equilibrium Property Data Equations for NH₃-H₂O Solution .............. 439
C. Values of Latitude and Longitude Angles of Some Major Cities Around the World .................................................................................. 441
Solar thermal collectors are a special kind of heat exchangers that convert solar radiation into thermal energy through a transport medium or a heat transfer fluid (HTF). From: Solar Heating and Cooling Systems, 2017. Related terms: More details on the design of such systems can also be found in the book Solar Energy Engineering, published by the author [30]. The interested reader can refer to this publication where details of the various collectors available are described together with their possible applications, including desalination.