Solar Energy Engineering

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Preface

This book is intended to provide engineering and technology students with an understanding of the fundamental principles and the practical applications of solar energy. As the topic coverage of this text is sufficiently complete, it is well-suited as a reference or self-study book for those wishing to learn about how solar energy systems work and how to design such systems.

In the introductory chapter the book offers a bird's-eye view of a number of solar applications, such as domestic hot water and space heating, greenhouse and Trombe wall, central receiver thermal power, and photovoltaic conversion. Inclusion of these materials at the beginning of the book gives the reader some familiarity with the actual solar processes and, perhaps, a feel of what the book is about.

The second chapter examines solar geometry, with various solar angles defined and their relationships presented in both analytical and graphical forms. The third chapter covers the fundamentals of solar radiation, including the estimation of terrestrial insolation intercepted and absorbed by tilted surfaces. The fourth chapter deals with building heat transfer and heating-cooling load calculations.

The two principal components of a solar energy system, namely the collector and the storage, are discussed in Chapters 5 and 6. Chapter 5 is devoted to the analysis of solar collectors of both flat plate and concentrating types. Chapter 6 considers energy storage, with emphasis placed on water and packed bed units. The important subject of the economics of solar systems is explored in Chapter 7 by pursuing life cycle savings and payback time analyses.

With the basic background provided by the preceding chapters, the book goes on to inquire about the theory and design aspects of various solar energy systems. Chapter 8 is concerned with solar heating processes, utilizing the f-chart and the $\bar{\phi}$, f-chart design methods. Chapter 9 discusses some viable solar cooling methods, including absorption refrigeration and low-temperature Rankine cycles. Solar-assisted heat pumps are investigated in Chapter 10.

The reader is introduced to the concepts and methods of passive systems in Chapter 11. The book concludes with a chapter on electric power generation by means of solar thermal and photovoltaic conversions.

The appendices contain a brief review of thermodynamics, fluid dynamics, and heat transfer principles and empirical equations for quick reference and utilization. The appendices also contain an extensive collection of solar radiation and climatic data, together with tables and charts of thermophysical properties of various materials.

In short, this book is a comprehensive introduction of solar energy engineering with a strong emphasis on both fundamental principles and practical applications. Topics are covered systematically, beginning with a concise review of basic concepts prior to an in-depth presentation. A quantitative yet highly simplified approach is used throughout the book in the analysis and design of solar energy systems.

Incorporated in this book are many wide-ranging, worked-out examples which will provide the reader with a substantial learning experience. In addition, at the end of each chapter there are homework problems, some of them in the typical academic style and others as more realistic open-ended exercises.

This book has been prepared using a dual system of units, recognizing the universal adoption of the International System of units (SI) on one hand and the continued use in the United States of the English units on the other. Even though all equations are written to be dimensionally correct in either system of units, overall emphasis is placed on the SI units. Tables, figures, examples, and problems however, are given in SI and/or English units.

There is adequate material contained in this book for a two-semester junior or senior engineering course. A one-semester engineering course can be taught by proper choice of topics to meet the needs of students. By omitting the mathematical details and concentrating only on the descriptive material and example solutions, this book can be used for a one-semester technology and architecture course.

The author would like to thank Dr. E. M. Sparrow of the Mechanical Engineering Department at the University of Minnesota for his detailed review and invaluable comments on the manuscript during its preparation. The author would also like to thank Dr. S. A. Klein of the Solar Energy Laboratory at the University of Wisconsin for reading the manuscript and making valuable suggestions. Thanks are also due to Dr. H. E. Pawel of the New Jersey Institute of Technology for reading and commenting on the manuscript. The author is indebted to Dr. R. P. Kirchner also of the New Jersey Institute of Technology, who, along with the author, uses the manuscript in a solar energy course at NJIT. Finally, the author wishes to thank his daughter, Esther, for her excellent typing efforts.

J. S. Hsieh

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1 Introduction

1-1 WORLDWIDE ENERGY DEMAND

Energy is the key to industrial development for the promotion of economic and social well-being of the world population. The growth of world population, coupled with the rising material standard of living, has escalated the growth of energy usage since the turn of this century. As demonstrated in Fig. 1-1, the consumption of world fossil fuel is a pulse action of a relatively short duration in the long history of human existence. It took millions of years for the earth to fertilize and to store fossil fuels in convenient forms, but it takes people only 300 or 400 years to use them up. The rapid increase in energy usage characteristic of the past 50 to 100 years cannot continue indefinitely as the earth's finite supply exhausts. Our great-grandchildren may not even have the chance of seeing a drop of gasoline.

It is the right of the inhabitants of this planet to develop and to use natural resources. The present generation, however, does not have the right to use them wastefully. Conservation of natural resources is everybody's duty. The use of energy conservation techniques does not necessarily create a lower standard of living. Conservation methods as simple as installing more insulation in houses, turning down building thermostats in heating seasons, and getting used to public transportation and car pooling, could contribute a lot to preserving world energy reserves.

The rapid depletion of fossil-fuel resources on a worldwide basis has necessitated an urgent search for alternative energy sources to meet our demands for the immediate future and for generations to come. Of the many alternatives, nuclear fusion and solar energy stand out as the brightest long-range promises toward meeting the continually

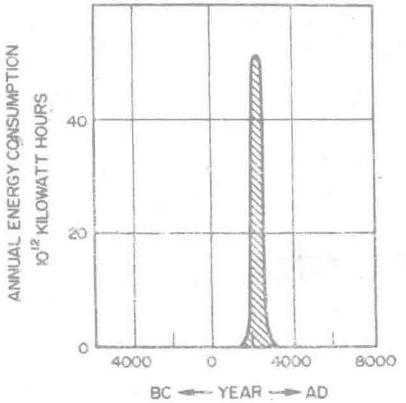

Figure 1-1 Time perspective of world fossil-fuel consumption. (Reprinted with permission from M. P. Thekaekara, "Solar Radiation Measurement: Techniques and Instrumentation," Solar Energy, vol. 18, p. 309, copyright 1976 by Pergamon Press, Ltd.)

increasing demand for energy. In a nuclear fusion process of putting light atoms together to produce power, problems associated with radiation are minimal; and the earth has an abundant supply of the required major fuels, deuterium and tritium. For these reasons, nuclear fusion can be considered as an ultimate energy solution. Unfortunately, in spite of recent progress in controlled fusion reactions, one cannot reasonably expect nuclear fusion to modify the world energy picture before the turn of the next century.

Insofar as solar energy conversion is concerned, the source is inexhaustible, the process is pollution-free, and the technology is established. The only problem that remains is how to tap and to store this energy economically to promote widespread usage. Space and hot water heating accounts for about 20% of the annual energy consumption in the United States. The technology for solar heating of space and hot water is well developed and can readily be applied to displace the conventional fuel usage. Large-scale electricity generation from solar energy is also within the reach of modern solar technology.

1-2 WORLDWIDE SOLAR ENERGY AVAILABILITY

The sun is a giant nuclear fusion reactor, converting 4 million tons of hydrogen per second to helium. Although the earth intercepts but a minute fraction of the energy released by the sun, that falling on the earth's atmosphere is at the rate of 5.4×10^{24} J per year = 170 trillion kilowatts, which is some 27,000 times the energy produced by all human-made systems in the world. Not all of this energy reaches the earth's surface, however, as a result of atmospheric attenuation. Figure 1-2 shows the worldwide annual solar radiation distribution. Some regions of the world, such as the U.S. southwestern sunbelt states, receive as much as 800 kJ of solar radiation per year per square centimeter of surface. These would be the most favorable locations for large-scale year-round solar applications.

Chapter 3 contains two maps that show the monthly-averaged daily mean total solar radiation throughout the world. Figure 3-15 is for the month of January and

ANNUAL GLOBAL RADIATION (R) IN KILOJOULES. $CM^{-2}.YEAR^{-1}$.

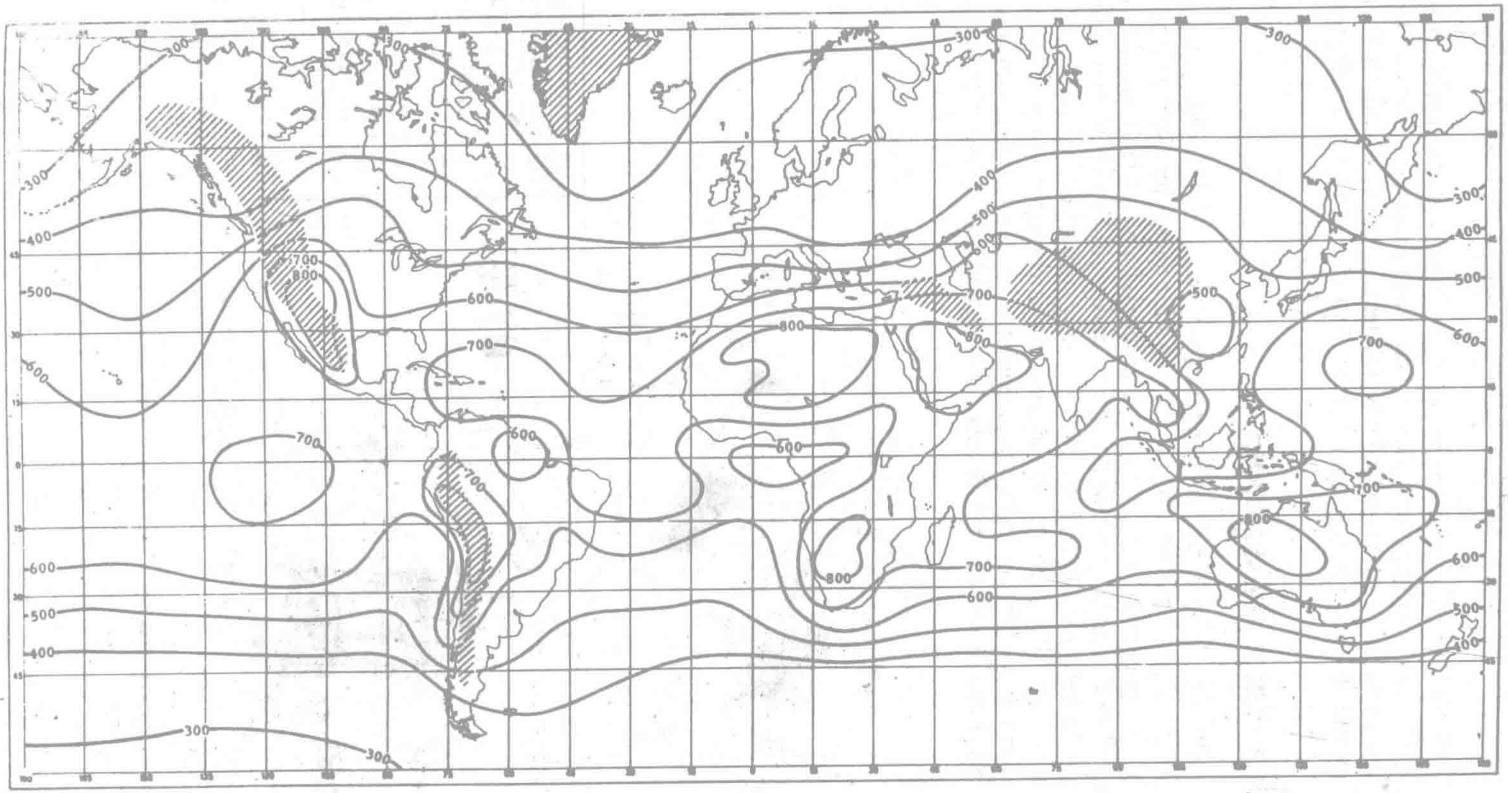

Figure 1-2 · Annual solar radiation distribution of the world. (Reprinted with permission from B. de Jong, *Net Radiation Received by a Horizontal Surface at the Earth*, Delft University Press, Delft, The Netherlands, 1973.)

Fig. 3-16 is for July. These maps can serve only as a general guide for preliminary design of solar heating and cooling systems. A complete, more accurate compilation of solar radiation data for various locations in the United States is given in Appendix B. For other parts of the world, readers should consult their local weather stations for more accurate data.

1-3 SOLAR ENERGY APPLICATIONS

Although solar energy is abundant and inexhaustive, it is thinly distributed over a wide area. Large collector areas are required to tap solar energy for useful purposes. In addition, as solar energy arriving at the earth's surface is highly variable and intermittent, the storage of solar energy is necessary to derive maximum benefits from the sun. Furthermore, it is rarely cost-effective to build an energy conversion system to meet all energy demands from solar energy alone; and economic constraints often dictate the use of some form of auxiliary energy to supplement solar in a hybrid arrangement.

Solar energy can be used for space heating and cooling, domestic hot water heat-

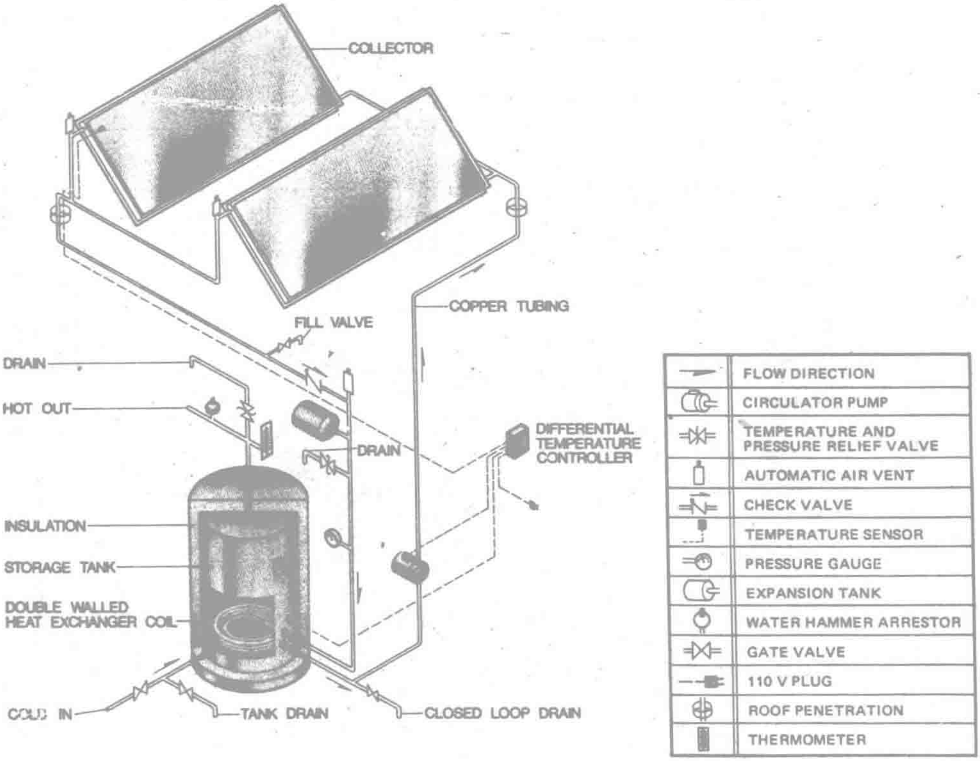

Figure 1-3 Solar domestic hot water heating system. (Courtesy of U.S. Solar Corporation.)

ing, industrial process heating, and electricity generation. We proceed now to describe briefly a few applications.

Figure 1-3 shows a domestic hot water heating system, which includes two flat-plate solar collectors, a storage tank with a double-wall heat exchanger coil and an electric backup element, a circulator pump, and a differential temperature controller (DTC). When the sun is shining, the DTC activates the circulator pump. An antifreeze solution is pumped through the collectors, where it absorbs heat, and intc the storage tank. The heat is transferred to the water inside the storage tank via the double-wall heat exchanger. The DTC automatically activates the pump only when the collectors are at a higher temperature than the tank. During inclement weather and evenings, water heating is done by the electric backup element.

Figure 1-4 shows a thermosiphon hot water heater. As water in the collector tubes is heated by solar radiation falling on the collector absorber plate, it rises, creating a thermosiphon action which draws more, cooler water into the tubes via a pipe from the bottom of the storage tank, while hot water from the collector panel is returned to the top of the storage tank. This compact heater can be installed on the roof of a house. Since there is no freeze protection, it cannot be used in cold climates where freezing is a possibility.

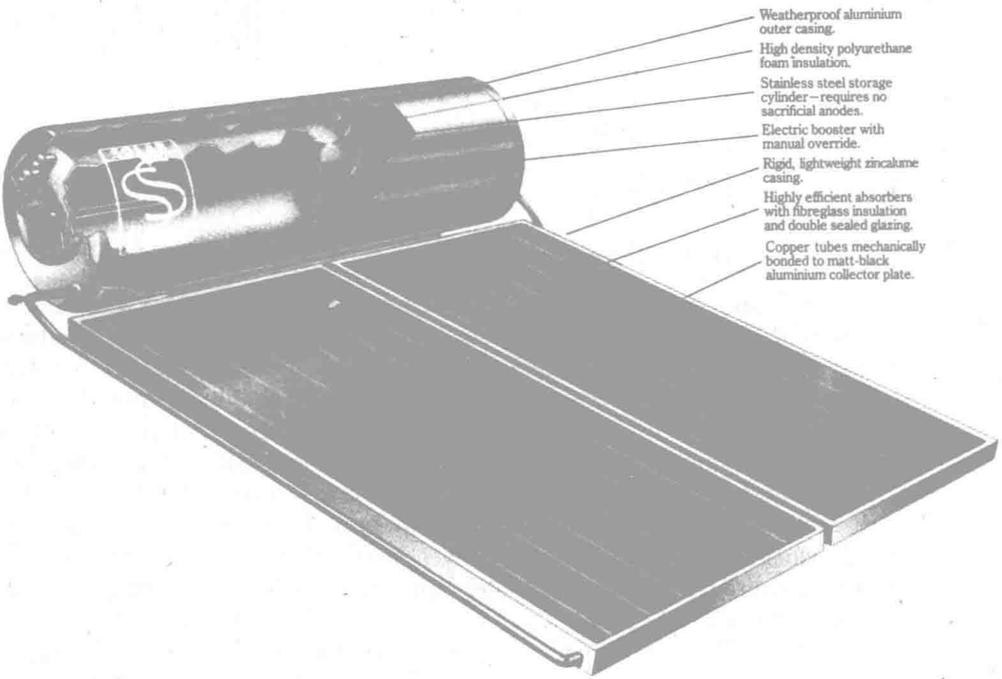

Figure 1-4 Thermosiphon hot water heater. (Courtesy of Solar Edwards USA.)