Solar Engineering of Thermal Processes

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Preface

When we started to revise our earlier book, *Solar Energy Thermal Processes,* it quickly became evident that the years since 1974 had brought many significant developments in our knowledge of solar processes. What started out to be a second edition of the 1974 book quickly grew into a new work, with new analysis and design tools, new insights into solar process operation, new industrial developments, and new ideas on how solar energy can be used. The result is a new book, substantially broader in scope and more detailed than the earlier one. Perhaps less than 20 percent of this book is taken directly from *Solar Energy Thermal Processes,* although many diagrams have been reused and the general outline of the work is similar. Our aim in preparing this volume has been to provide both a reference book and a text. Throughout it we have endeavored to present quantitative methods for estimating solar process performance.

In the first two chapters we treat solar radiation, radiation data, and the processing of the data to get it in forms needed for calculation of process performance. The next set of three chapters is a review of some heat transfer principles that are particularly useful and a treatment of the radiation properties of opaque and transparent materials. Chapters 6 through 9 go into detail on collectors and storage, as without an understanding of these essential components in a solar process system it is not possible to understand how systems operate. Chapters 10 and 11 are on system concepts and economics. They serve as an introduction to the balance of the book, which is concerned with applications and design methods.

Some of the topics we cover are very well established and well understood. Others are clearly matters of research, and the methods we have presented can be expected to be outdated and replaced by better methods. An example of this situation is found in Chapter 2; the methods for estimating the fractions of total radiation which are beam and diffuse are topics of current research, and procedures better than those we suggest will probably become available. In these situations we have included in the text extensive literature citations so the interested reader can easily go to the references for further background.

Collectors are at the heart of solar processes, and for those who are starting a study of solar energy without any previous background in the subject, we suggest reading Sections 6.1 and 6.2 for a general description of these unique heat transfer devices. The first half of the book is aimed entirely at development of the ability to calculate how collectors work, and a reading of the description will make clearer the reasons for the treatment of the first set of chapters.

Our emphasis is on solar applications to buildings, as they are the applications developing most rapidly and are the basis of a small but growing industry. The same ideas that are the basis of applications to buildings also underlie applications to industrial process heat, thermal conversion to electrical energy generation, and evaporative processes, which are all discussed briefly. Chapter 15 is a discussion of passive heating, and uses many of the same concepts and calculation methods for estimating solar gains that are developed and used in active heating systems. The principles are the same; the first half of the book develops these principles, and the second half is concerned with their application to active, passive, and nonbuilding processes.

New methods of simulation of transient processes have been developed in recent years, in our laboratory and in others. These are powerful tools in the development of understanding of solar processes and in their design, and in the chapters on applications the results of simulation studies are used to illustrate the sensitivity of long-term performance to design variables. Simulations are the basis of the design procedures described in Chapters 14 and 18. Experimental measurements of system performance are still scarce, but in several cases we have made comparisons of predicted and measured performance.

Since the future of solar applications depends on the costs of solar energy systems, we have included a discussion of life cycle economic analysis, and concluded it with a way of combining the many economic parameters in a life cycle savings analysis into just two numbers which can readily be used in system optimization studies. We find the method to be highly useful, but we make no claims for the worth of any of the numbers used in illustrating the method, and each user must pick his own economic parameters.

In order to make the book useful, we have wherever possible given useful relationships in equation, graphical and tabular form. We have used the recommended standard nomenclature of the *Journal of Solar Energy* (**21**, 69, 1978), except for a few cases where additional symbols have been needed for clarity. For example, G is used for irradiance (a rate, W/m^2), H is used for irradiation for a day (an integrated quantity, MJ/m^2), and I is used for irradiation for an hour (MJ/m^2), which can also be thought of as an average rate for an hour. A listing of nomenclature appears in Appendix B, and includes page references to discussions of the meaning of symbols where there might be confusion. SI units are used throughout, and Appendix C provides useful conversion tables.

Numerous sources have been used in writing this book. The *Journal of Solar Energy*, a publication of the International Solar Energy Society, is very useful, and contains a variety of papers on radiation data, collectors of various types, heating and cooling processes, and other topics. Publications of ASME and ASHRAE have provided additional sources. In addition to these journals, there exists a very large and growing body of literature in the form of reports to and by government agencies which are not reviewed in the usual sense but which contain useful information not readily available elsewhere. These materials are not as readily available as journals, but they are referenced where we have not found the material in journals. We also call the reader's attention to *Gelio-*

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tekhnika (Applied Solar Energy), a journal published by the Academy of Sciences of the UZSSR which is available in English and the *Revue Internationale d'Heliotechnique*, published by COMPLES in Marseille.

Many have contributed to the growing body of solar energy literature on which we have drawn. Here we note only a few of the most important of them. The work of H. C. Hottel and his colleagues at MIT, that of A. Whillier at MIT and McGill University, and that of B. Y. H. Liu and R. C. Jordan at Minnesota continues to be of basic importance. In space heating, the publications of G. O. G. Löf, S. Karaki and their colleagues at Colorado State University provide much of the quantitative information we have on that application.

Individuals who have helped us with the preparation of this book are many. Our graduate students and staff at the Solar Energy Laboratory have provided us with ideas, useful information and reviews of parts of the manuscript. Their constructive comments have been invaluable, and references to their work are included in the appropriate chapters. The help of students in our course on Solar Energy Technology is also acknowledged; the number of errors in the manuscript is substantially lower as a result of their good-natured criticisms.

Critical reviews are imperative, and we are indebted to S. A. Klein for his reading of the manuscript. He has been a source of ideas, a sounding board for a wide range of concepts, the author of many publications on which we have drawn, and a constructive critic of the best kind.

High on any list of acknowledgements for support of this work must be the College of Engineering and the Graduate School of the University of Wisconsin–Madison. The College has provided us with support while the manuscript was in preparation, and the Graduate School made it possible for each of us to spend a half year at the Division of Mechanical Engineering of the Commonwealth Scientific and Industrial Research Organization, Australia, where we made good use of their library and developed some of the concepts of this book. Our Laboratory at Wisconsin has been supported by the National Science Foundation, the Energy Research and Development Administration, and now the Department of Energy, and the research of the Laboratory has provided ideas for the book.

It is again appropriate to acknowledge the inspiration of the late Farrington Daniels. He kept interest in solar energy alive in the 1960s and so helped to prepare for the new activity in the field during the 1970s.

Generous permissions have been provided by many publishers and authors for the use of their tables, drawings and other materials in this book. The inclusion of these materials makes the book more complete and useful, and their cooperation is deeply appreciated.

A book such as this takes more than authors and critics to bring it into being. Typing and drafting help are essential and we are pleased to note the help of Shirley Quamme and her co-workers in preparing the manuscript. We have been through several drafts of the book which have been typed by our student helpers at the laboratory; it has often been difficult work, and their persistence, skill and good humor have been tremendous.

Not the least, we thank our patient families for their forbearance during the lengthly process of putting this book together.

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CHAPTER 1

Solar Radiation

The sun's structure and characteristics determine the nature of the energy it radiates into space. This chapter notes the characteristics of this energy outside of the earth's atmosphere and the effects of the atmosphere in attenuating the radiation. Then the characteristics of the resulting energy resource available at the earth's surface are outlined, that is, its intensity, spectral distribution, and its directional characteristics. We are concerned primarily with radiation in a wavelength range of 0.3 to 3.0 μm, the portion of the spectrum that includes most of the energy radiated by the sun.

In general, it is not practical to start from knowledge of extraterrestrial radiation and predict the intensity and spectral distribution to be expected on the ground. Adequate meteorological data for such calculations are seldom available, and recourse usually is made to measurements. However, an understanding of the nature of extraterrestrial radiation, atmospheric attenuation, and the effects of orienting a receiving surface is important in understanding and using solar radiation data.

1.1 THE SUN

The sun is a sphere of intensely hot gaseous matter with a diameter of 1.39×10^9 m and is, on the average, 1.5×10^{11} m from the earth. As seen from the earth, the sun rotates on its axis about once every four weeks. However, it does not rotate as a solid body; the equator takes about 27 days and the polar regions take about 30 days for each rotation.

The sun has an effective blackbody temperature of 5762 K.* The temperature in the central interior regions is variously estimated at 8×10^6 to 40×10^6 K and the density at about 100 times that of water. The sun is, in effect, a continuous fusion reactor with its constituent gases as the "containing vessel" retained by gravitational forces. Several fusion reactions have been suggested to supply the

* This effective blackbody temperature of 5762 K is the temperature of a blackbody radiating the same amount of energy as does the sun. Other effective temperatures can be defined, for example, that corresponding to the blackbody temperature giving the same wavelength of maximum radiation as solar radiation (about 6300 K).

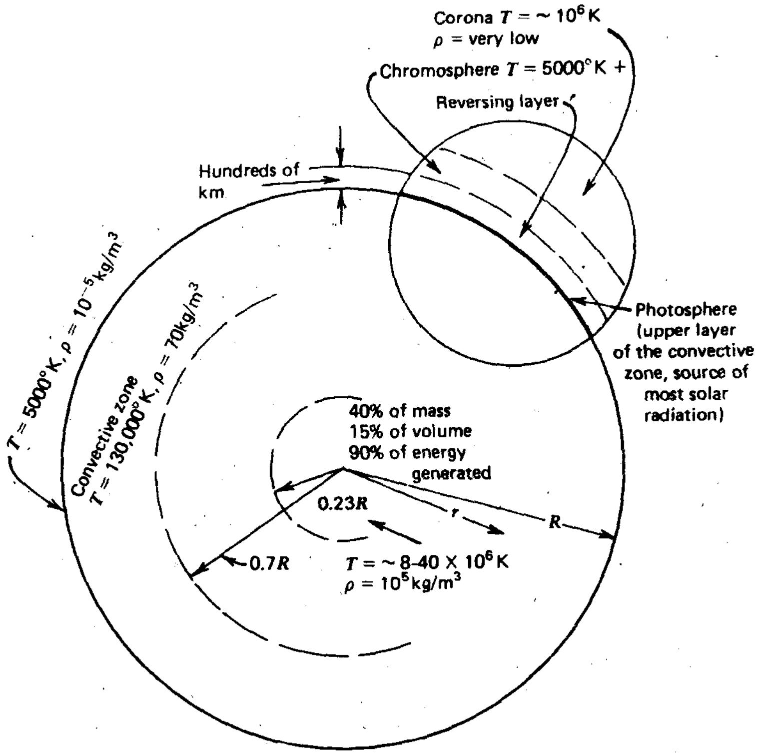

Figure 1.1.1 The structure of the sun.

energy radiated by the sun; the one considered the most important is a process in which hydrogen (i.e., four protons) combines to form helium (i.e., one helium nucleus); the mass of the helium nucleus is less than that of the four protons, mass having been lost in the reaction and converted to energy.

This energy is produced in the interior of the solar sphere, at temperatures of many millions of degrees. It must be transferred out to the surface and then be radiated into space. A succession of radiative and convective processes must occur, with successive emission, absorption, and reradiation; the radiation in the sun's core must be in the x-ray and gamma-ray parts of the spectrum with the wavelengths of the radiation increasing as the temperature drops at larger radial distances.

A schematic of the structure of the sun is shown in Figure 1.1.1. It is estimated that 90% of the energy is generated in the region of 0 to 0.23*R* (where *R* is the radius of the sun), which contains 40% of the mass of the sun. At a distance 0.7*R* from the center, the temperature has dropped to about 130,000 K and the density has dropped to 70 kg/m^3; here convection processes begin to become important and the zone from 0.7 to 1.0*R* is known as the *convective zone*. Within this zone, the temperature drops to about 5000 K and the density to about 10^{-5} kg/m^3.

The sun's surface appears to be composed of granules (irregular convection cells), with dimensions of cells from 1000 to 3000 km and with cell lifetime of a few minutes. Other features of the solar surface are small dark areas called pores, which are of the same order of magnitude as the convective cells, and larger dark areas called sunspots, which vary in size. The outer layer of the convective zone is called the *photosphere*. The edge of the photosphere is sharply defined, even though it is of low density (about 10^{-4} that of air at sea level). It is essentially opaque, as the gases of which it is composed are strongly ionized and able to absorb and emit a continuous spectrum of radiation. The photosphere is the source of most solar radiation.

Outside of the photosphere is a more or less transparent solar atmosphere, which is observable during total solar eclipse or by instruments that occult the solar disk. Above the photosphere is a layer of cooler gases several hundred kilometers deep called the *reversing layer*. Outside of that is a layer referred to as the *chromosphere*, with a depth of about 10,000 km. This is a gaseous layer with temperatures somewhat higher than that of the photosphere and with lower density. Still further out is the *corona*, of very low density and of very high (10^6 K) temperature. For further information on the sun's structure see Thomas (1958) or Robinson (1966).

This simplified picture of the sun, its physical structure, and its temperature and density gradients, will serve as a basis for appreciating that the sun does not, in fact, function as a blackbody radiator at a fixed temperature. Rather, the emitted solar radiation is the composite result of the several layers that emit and absorb radiation of various wavelengths. The resulting extraterrestrial solar radiation and its spectral distribution have now been measured by various methods in several experiments; the results are noted in the following two sections.

1.2 THE SOLAR CONSTANT

Figure 1.2.1 shows schematically the geometry of the sun-earth relationships. The eccentricity of the earth's orbit is such that the distance between the sun and the earth varies by 1.7%. At a distance of one astronomical unit, 1.495×10^{11} m, the mean earth-sun distance, the sun subtends an angle of 32′. The radiation emitted by the sun and its spatial relationship to the earth result in a nearly fixed intensity of solar radiation outside of the earth's atmosphere. The *solar constant*, G_{sc}, is the energy from the sun, per unit time, received on a unit area of surface perpendicular to the direction of propagation of the radiation, at the earth's mean distance from the sun, outside of the atmosphere.

Until recently, estimates of the solar constant had to be made from ground-based measurements of solar radiation after it had been transmitted through the atmosphere, and thus in part absorbed and scattered by components of the atmosphere. Extrapolations from the terrestrial measurements, which were

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