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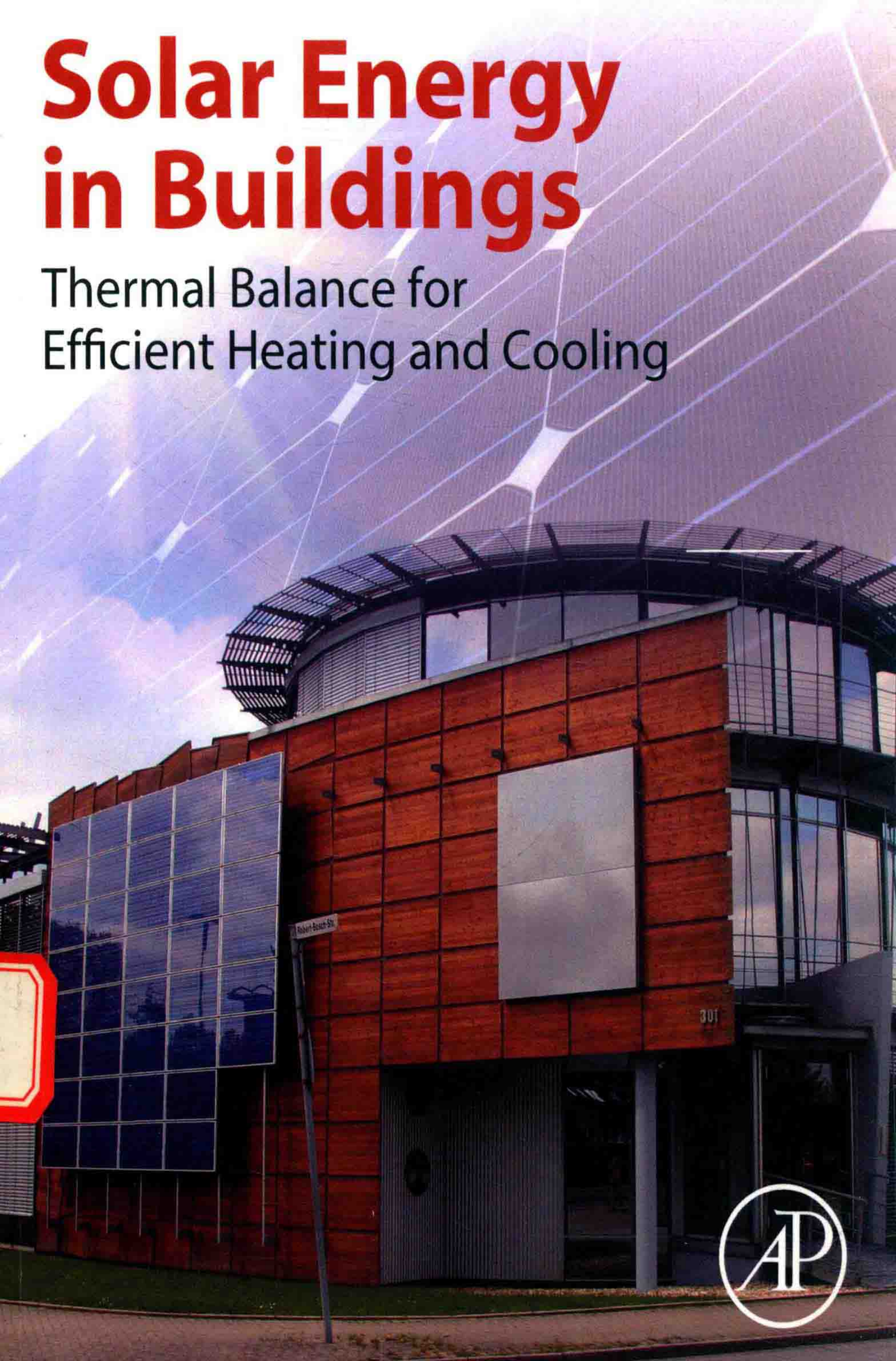

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Thermal Balance for Efficient Heating and Cooling

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Introduction

The main aim of this publication is to present fundamentals of solar energy for buildings and show what modern solar energy technologies may offer to the building sector applications. The book demonstrates that a modern building is not only a construction structure, but also an integrated and complex energy system.

Solar energy reaches the Earth by various ways, depending on geographical location and local terrain features. Each building is affected by solar radiation. Therefore it is important to plan and manage this interaction. The book presents certain recommendations for shaping building envelopes in the context of solar radiation availability, and shows how passive and active technologies can be integrated with a building structure. A method for determining influence of solar radiation on the building heat balance as well as quantitative energy input in selected cases is shown as well. Moreover possibilities for utilizing solar radiation in the construction technology by implementation of active systems involving photothermal and photovoltaic conversion are analyzed.

It may be expected that incorporation of active and passive solar energy systems will enable rapid decrease of energy consumption in buildings. Adopting improved technologies for collecting solar energy and converting it into useful heat and electrical power, as well as coupling those achievements to other renewable energy technologies and efficiency solutions, will soon result with practical realization of nearly zero-energy buildings, then followed by structures independent from energy supplies or even energy-plus ones.

Thanks to well-designed envelopes and structures, correct choice of materials and suitable siting (including orientation in reference to cardinal directions as well as neighboring structures) combined with a thought-through concept for utilizing specific zones and rooms, the buildings will soon considerably decrease their energy needs. Moreover, thanks to implementing highly efficient and reliable equipment and systems, the final energy demand will also drop considerably. Then if the final energy demand can be covered by renewable energy—solar energy in particular—the fossil fuel primary energy consumption will be significantly reduced or even totally nullified. A building structure of the future will be one, which generates energy for its own needs, and sells a surplus to an external grid. Nowadays a building is not just a structure anymore, it is also an energy system which links anticipated behavior of the structure and utilized materials to the energy systems and related equipment. Energy management in a building no longer boils down to supplying power from external networks. Now it is also about local energy generation following actual demand, where key role is played by solar systems which are the focus of this publication.

The Directive *2010/31/EC* of the European Parliament and of the Council *on the energy performance of buildings (a recast* of the earlier Directive *2002/91/EC)* obliges member states to carry out analyses related to determining energy characteristics of buildings. The Directive creates a general framework for a methodology of calculation of the integrated energy performance of buildings and specifies certification of compliance with minimum requirements on the energy performance of new and existing buildings. Article 1 of Section 1 stipulates that the Directive promotes the improvement of the energy performance of buildings, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness. Another notable stipulation of the Directive is its article on "nearly zero-energy buildings" (Article 9). According to this article, from the year 2021 all new buildings will have to be nearly zero-energy buildings, and in case of public utility buildings the rule will come into force already in 2019. EU Member States are obliged to draw up and implement national plans for introducing nearly zero-energy buildings.

Therefore adopting rules of nearly zero-energy construction technology, including solar energy utilization in building structures, is no longer just a concept for implementing general energy conservation principles and minimizing environmental footprint, but also a legal necessity. This publication is intended to—at least partially—assist in implementation of new EU requirements.

The main aim of this book is to systematically present knowledge on phenomena related to collecting, converting, storing, and utilizing solar energy radiation occurring in a building, i.e., in elements of its envelope and interior, as well as within integral systems. Issues, which rarely come into focus of publications on both construction technology and solar energy systems, are covered in detail.

Special attention was given to the issue of solar radiation availability at the building envelope in reference to individual components, especially transparent envelope elements—windows, and then also opaque elements. Detailed discussion based on simulation analyses performed by the author are presented and graphically illustrated. Developed results may become an important and interesting source of information for specialists designing buildings and solar energy systems, as well as those willing to participate in conceptual planning of their own building structures.

Much attention is given to the issue of energy balance of a building and its rooms, with focus on solar energy interactions. Energy balances of sample rooms in different locations within a building are analyzed basing on own simulation calculations. In particular their heating and cooling needs are compared. Obtained results are extensively illustrated with figures and followed by qualitative and quantitative conclusions concerning influence of solar radiation on room energy balances. It is shown, how significant role in such a balance may be played by solar energy, stressing the importance of its planned utilization, including interaction blockades whenever necessary. Presented data may be a source of information for all building users, they may also be used as a base for detailed architectural and structural engineering works. It may also serve as a foundation for further analysis on shaping building envelopes, planning their material structure, as well as internal and external layouts, especially for optimization studies.

Except for author's own theoretical and computational studies on availability, collection, conversion, and utilization of solar energy in active and passive ways, the book also contains a review of fundamentals of solar energy systems for buildings and presents some application examples. Those examples are real-life structures utilizing solar energy as well as selected information on state-of-the-art solar energy systems and their further development prospects.

Chapter 1 gives the terminology utilized in reference to the solar energy use. The chapter also covers physical fundamentals of selected phenomena related to solar radiation, its travel to the Earth's surface including transmission through the atmosphere and the greenhouse effect. The final section presents classification of key technologies that utilize in direct or indirect way solar energy.

Chapter 2 covers the issue of solar radiation availability on the Earth, nature of the solar radiation and its properties, as well as conditions enabling practical utilization of solar energy. It describes fundamentals of the spherical geometry for Sun–Earth relations and methods for measuring solar radiation. Key astronomical and geographical parameters used to describe the Earth position and movement in reference to the Sun are described together with methods for determining irradiation of arbitrarily defined reception surfaces. Various solar radiation models, including isotropic and anisotropic diffuse models, are presented. The chapter also discusses questions of shading and presents sun charts, which describe position of the Sun over the horizon and may be used as a practical aid when determining solar radiation attenuation due to shading.

Chapter 3 discusses ability to shape building envelope in reference to incident solar radiation. This chapter compares results of irradiation simulations for variously oriented surfaces in a selected location (higher latitudes) when using isotropic and anisotropic models. Recommendations for designing building envelopes in the context of solar energy availability are given.

Chapter 4 discusses fundamentals of the phenomena occurring during collecting and converting solar energy into useful heat, as well as during storage and utilization of that heat. Fundamentals of optics related to the solar radiation going through transparent media, including radiation transmission, absorption, emission, reflection, and refraction are discussed. Phenomena occurring in solar energy receivers are analyzed. Energy balance for a generic solar energy receiver is presented. Thermal resistance method, which may be used for modeling phenomena occurring in solar energy receivers, is described. Also optical and thermal phenomena occurring in transparent glass panes (glazing) and in a composite system of a transparent body and absorbing surface are described in detail. Impact of the absorbing surface type on solar energy gained is analyzed, including discussion of selective surfaces. Heat exchange between the solar energy receiver and its surroundings, including interaction between surrounding and covered or uncovered receiver, is discussed. Solar energy collection and conversion into heat in a receiver in form of a solar collector implemented in both active and passive solar systems is described. Solutions for storage of gained heat are analyzed. Also thermodiffusion phenomena occurring in thermosiphon (natural gravity) installations are presented.

Chapter 5 concerns passive solar energy utilization in a building. Solutions for reducing energy demand of a building are presented. Passive solar systems classification is given and selected solar technologies for building applications are described together with experimental research of phenomena occurring in passive solar systems. Particular attention is given to the selected glazing technologies, transparent insulations, and natural daylighting systems—applications that are still not commonly used, but at the same time enable considerable decrease of building's electricity demand. Also utilization of phase-change materials (PCMs) integrated with the building structure in various manners and used for storage of heat, including heat gained from solar radiation, is investigated.

Chapter 6 provides various forms of a heat balance equation for a room within a building. General form of a balance equation is presented together with simplifications for steady and quasi-steady states. Steady state heat transfer through building envelope is described with particular attention given to its thermal resistance and building's heat capacity. Phenomena occurring inside envelope structure and its surrounding are described using the thermal resistance method. This is followed by a description of unsteady processes occurring in the envelope and its surroundings, taking into account solar radiation influence, both for transparent and opaque elements. Energy transfer through glazing, heat exchange with external and internal surrounding, and heat exchange in the gas cavity between glass panes are discussed in detail. Solar energy and heat flow through the central part and edges of glazing as well as its frame are described in a spatially diverse way. Solar energy passing via building's envelope is investigated. More complex forms of the energy equation for unsteady states are given together with solutions and exemplary results of simulation calculations for opaque and transparent elements, with special attention given to solar radiation influence on the thermal balance. Solutions for exemplary energy equations are presented. Heating and cooling needs for room examples are analyzed and the results are graphically illustrated. Energy consumption parameters describing annual heat demand for space heating and cooling in exemplary rooms differently situated within a building are compared. It is highlighted that the cooling needs during summer season is considerably higher at certain room locations, which results primarily from the role of windows in the building thermal balance.

Chapter 7 describes active solar heating systems utilized in buildings. State-of-the-art solutions are presented together with development directions. Basic configurations of active solar heating systems are presented together with their functional description and operation in various energy supply and demand conditions. Structure and operation of main components of active solar heating systems, namely collectors and storage systems, are discussed too. Roles of key solar collector components are presented and so are different collector types, primarily flat and vacuum collectors, together with scopes of application. Thermal characteristics for selected solar collectors are presented. The focus is on liquid-based systems, which are primary application arrangements for active solar heating in construction industry. Modern integrated heating systems are discussed, where a solar subsystem is just one component of a more complex solution for heating (space heating and domestic hot water) and possibly also cooling (air-conditioning). Various methods of cooperation with other conventional and renewable energy systems are described.

Chapter 7 also covers photovoltaics (PV) and its applications in buildings. It describes physical fundamentals of the internal photovoltaic effect. Key PV technologies and application examples in buildings are presented. Also, solar cooling technologies and their possible applications are presented, giving an idea of solar combi-systems very perspective for future energy efficient solutions. An important observation made in this chapter, and at the same time an important conclusion concerning solar energy applications in a building, is that implementation of solar systems in a building should be taken into account already at the stage of architectural and construction concept, allowing to integrate components of solar systems with the building's envelope and its internal structure, creating a coherent complex system. This is significant for both technical and aesthetic purposes.

The author would like to show what the modern solar engineering, which integrates solutions developed by energy engineering, architecture, and civil engineering, is really about. Solar engineering understood in such a way covers the very concept of building's shape and siting, its structural design and materials selection for both transparent and opaque elements. It may be expected that transparent envelope elements will prevail in the envelopes of future buildings, and it is those very elements that are particularly sensitive to the solar radiation influence. Solar engineering is also about utilizing natural lighting and planning ambient surrounding to influence availability of solar radiation, including light. Finally solar engineering includes integration of building's internal systems with its envelope, combined or alternating utilization of different energy sources, collecting energy available in the environment, storing it and utilizing in an efficient manner, as well as waste energy recovery. Therefore solar engineering in a building is a complex problem of its structure with regard to energy conservation and environment protection.

This publication is intended for architects, engineers, and other experts in areas like construction, energy, civil, and environmental engineering, as well as students pursuing degrees in science and engineering, and all other individuals interested in solar energy systems in general and possibilities of utilizing them in buildings in particular. This book may become a source of information for those who touch its subject for the first time, as well as readers who already have some knowledge on solar energy and its applications in buildings. It contains information on both scientific fundamentals and practical applications.

Contents

Chapter 1

Solar Radiation—Fundamentals

1.1 TERMINOLOGY

Solar energy terminology is systematized in the standard ISO 9488 "Solar energy—Vocabulary" [1]. This section describes certain selected terms related to solar energy, which will be used throughout this publication. Vocabulary used in this book is consistent with the above-mentioned standard.

Solar radiation is characterized by various parameters. Certain vocabulary incompatibilities may be observed in publications on solar energy and civil engineering. Vocabulary related to the description of solar energy quantities was proposed in the 1980s by Duffie, Beckman, and Klein in one of the best known publications on solar energy fundamentals [2]. In numerous later publications, vocabulary varied, depending on the research center involved. In 1999, standard EN ISO 9488:1999 [1] concerning solar energy vocabulary was published in order for it to be standardized. Vocabulary given below is defined according to this standard.

Solar radiation is radiation emitted by the Sun, whereas solar energy is the energy emitted by the Sun in the form of electromagnetic waves. According to the EN ISO 9488 standard, solar energy may also be understood as any energy available thanks to collecting and converting solar radiation.

Global solar radiation is the solar radiation incident on the horizontal Earth's surface. According to the EN ISO 9488 standard, the global radiation term may only be applied to a horizontal surface. In case of any tilted surface, the term hemispherical radiation should be used instead. In fact, the global radiation is a case of hemispherical radiation too, but only that which reaches the horizontal Earth's surface. Hemispherical solar radiation incident on a horizontal surface consists of beam radiation (also known as direct radiation) and radiation scattered by the atmosphere. Beam radiation is incident at small solid angle starting from the Sun's disk.

Hemispherical radiation is radiation received from the entire hemisphere above (i.e., solid angle 2π sr). Hemispherical solar radiation incident on a tilted surface consists of direct and scattered radiation, as well as radiation reflected by the ground. Scattered and reflected components form diffuse radiation that reaches any tilted surface. Diffuse radiation may be determined as hemispheric radiation minus beam radiation.

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Radiant energy is the amount of energy carried by radiation. The radiation itself is energy emission or transfer in the form of electromagnetic waves. Radiant energy flux (radiant flux, flux of radiation) is the total power emitted, transferred, or received in the form of radiation. Then, irradiance is a power density of radiation incident on a surface (i.e., the amount of incident energy in the time unit-per-unit area of the given surface).

Spectral solar irradiance is irradiance for a specific wavelength (i.e., irradiance of monochromatic solar radiation). Solar spectrum is presented as a spectral solar irradiance function of radiation wavelength.

Radiant exitance is the radiant flux leaving a unit area of a surface in the form of emission, reflection, or transmission. Then, radiant self-exitance is the radiant flux density of the surface's own emission, meaning that it refers to the flux leaving the surface only by means of emission.

A parameter that is very extensively used to describe radiation quantity is irradiation (radiation exposure). It is defined as the incident energy per unit area of a surface, and found by integration of irradiance over a certain time interval, often in a single hour or day. Meteorology also uses descriptions like hourly or daily sum of radiation per unit area of a surface. Hourly sum is found by integration of irradiance over a time interval of 1 h. Daily sum, in turn, is obtained by integration of irradiance over a time interval limited by the times of sunrise and sunset. Another term used in meteorology is diurnal sum, which refers to the radiation balance during a 24-h period, thus also including longwave Earth radiation. The term "insolation" currently is not recommended for use, although it may be often encountered in literature on solar energy. Insolation should be considered a colloquial term, which generally describes conditions of solar radiation availability.

Another term often used in solar energy science and applications is "sunshine duration" (solar hours). It is a sum of hours during which the Sun's disk is directly visible over a specified time interval.

Table 1.1 compiles key characteristic parameters describing solar radiation as per the EN ISO 9488 standard. The names and symbols as shown in the table will be utilized throughout this book.

Other terms used when discussing solar energy, not listed in Table 1.1, are explained below.

Total radiation is defined as a sum of shortwave solar radiation with wavelengths between 0.28 and 3 μm, and thermal longwave radiation with wavelengths above 3 μm. Longwave radiation is usually emitted by sources of terrestrial temperature, like clouds, atmosphere, ground, and other terrestrial objects. Atmospheric radiation is longwave radiation emitted by the atmosphere and dispersing in it.

Discussions of solar energy problems also take into account radiation that reaches the outer boundary of the Earth's atmosphere, so-called extraterrestrial radiation. Then, in the atmosphere itself, atmospheric attenuation of solar

TABLE 1.1 Key Characteristic Parameters Describing Solar Radiation

Key Parameters of Solar Radiation	Symbol	Unit
Solar radiation Solar energy		
Global solar radiation • Beam (direct) solar radiation • Diffuse solar radiation	E E_b E_d	(J)
Hemispherical solar radiation • Beam solar radiation • Diffuse solar radiation ◦ Scattered ◦ Reflected	E E_b E_d E_r	(J)
Radiant energy	E	(J)
Radiant energy flux Radiant power Flux of radiation	ϕ	(W)
Irradiance • Solar irradiance • Hemispheric solar irradiance • Global solar irradiance • Beam solar irradiance • Diffuse solar irradiance	 G G_b G_d	(W/m^2)
Spectral solar irradiance	E_λ	(W/m^2/µm)
Radiant exitance		(W/m^2)
Radiant self-exitance Specific emission	 M	(W/m^2)
Irradiation (radiance exposure) • For a day • For an hour or determined period of time	 H I	(J/m^2)
Solar hours ≡ sunshine duration	U_s	(h)

radiation is observed. This attenuation is defined as a loss of flux of beam radiation during transfer through the atmosphere, attributable to absorption and scattering by the atmosphere's components.

Another significant parameter not shown in Table 1.1 is the sky temperature. It is the temperature of longwave radiation of sky (considered to be a black body) incident on the horizontal surface of the Earth.

Further sections of this chapter provide definitions and descriptions (both physical and mathematical) of more parameters used in solar engineering, which are not listed above.