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Shyam

Handbook of Solar Energy

Theory, Analysis and Applications

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*Our respected teacher and guruji, Padmashri
Prof. M.S. Sodha, FNA, on his 84th birthday
(February 08, 2016)*

Preface

Solar energy is clean, environmentally friendly and freely available over the planet earth. Life on earth also owes its existence to solar energy. Solar energy is used to produce thermal as well as electrical power. If fossil fuels continue to be depleted at the present rate, they will be exhausted soon. The use of fossil fuels is also largely responsible for increasing pollution and resulting climate change. Solar energy and other renewable sources, enable us to meet the demand for energy, while offering a cleaner and greener footprint.

In the recent past, there has been rapid development in solar thermal technologies and photovoltaic (PV) materials. This development brought cost effectiveness to solar devices. Based on the developments in the field of solar technology, we decided to compose a handbook of solar energy, which goes beyond the usual and brings together a myriad of current topics such as Day-lighting, Solar cell materials, Photovoltaic thermal (PVT) systems, Energy conservation, Solar power generation, Thermodynamics, Solar cooling of houses, Energy and exergy analysis, CO₂ credit, Energy Matrices, Life Cycle analysis with and without CO₂ credit.

The main objective of writing this book is to create a comprehensive and easy-to-understand source of information on the advances in this rapidly growing research area. This book includes enough information on the basics to be used as a textbook undergraduate coursework in for engineering and the sciences. The inclusion of advanced concepts and research trends will also make it useful as a reference for scientists and professionals. An attempt has also been made to give solved examples and exercise problems with hint and objective questions at appropriate place in each chapter for better understanding of solar energy applications.

This book consists of twenty chapters. The basics of hourly, daily, monthly solar radiation on horizontal and inclined surfaces and sun-earth angles have been discussed briefly in Chap. 1. The various natural day lighting system with examples have been discussed in Chap. 2. Chapter 3 deals with the basic elements of heat transfer mechanisms, laws of thermodynamics and exergy which have been used

throughout text. Effects of nano-particles with water as a base fluid have also been discussed briefly. Chapter 4 discusses different solar cell materials, PV modules, PV arrays and its applications in various sectors. Solar fluid collectors namely conventional flat plate collectors (FPC's), solar concentrators and evacuated tubular collectors (ETC's) are dealt with in Chaps. 5–7. Chapter 8 discusses industrial solar water heating systems for different modes of operation. The modeling of PVT solar air heaters and their applications are reported in Chap. 9. The various passive concepts of heating/cooling of a house with approximate methods and solar cooling houses have been briefly discussed in Chaps. 10 and 11, respectively. Chapters 12 and 13 cover other solar thermal applications namely solar crop drying and solar distillation systems with basic heat transfer, thermal modeling and examples. Energy analyses of solar thermal and PV systems have been covered in Chap. 14. Solar energy storage in different modes is discussed in Chap. 15. Solar power generation by means of photovoltaic (grid and off-grid) and solar concentrating have been considered in Chap. 16. Chapters 17 and 18 report applications of solar thermal energy, which has not been covered in preceding chapters and cover energy conservation in different sectors. Study of exergy, CO₂ mitigation, carbon credit, and life cycle cost analysis of some solar thermal and PV system, which is the backbone of its success, is included in Chaps. 19 and 20, respectively.

SI units are used throughout the book. Some conversion units, various physical and chemical properties of water, air, metals and non-metals are also given as appendices.

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Approximate Values of Various Constants in Solar Energy

S.No	Constants	Actual value	Approximate value
1	Diameter of the Sun	$1.39 \times 10^9 \text{ m}$	$1.50 \times 10^9 \text{ m}$
2	Distance of the Sun from the Earth	$1.5 \times 10^{11} \text{ m}$	$150 \times 10^9 \text{ m}$
3	Black-body temperature of the Sun	5777 K	6000 K
4	Centre core temperature of the Sun	$8-40 \times 10^6 \text{ K}$	$9-30 \times 10^6 \text{ K}$
5	Energy generated in the Sun's centre core	90 %	90 %
6	Diameter of the Earth	1300 km	$1.5 \times 10^6 \text{ m}$
7	Solar constant	1367 W/m^2	1500 W/m^2
8	Short-wavelength radiation	$0.23-2.6 \text{ }\mu\text{m}$	$0.3-3.0 \text{ }\mu\text{m}$
9	Average temperature of the Earth	298 K	300 K
10	Stefan-Boltzmann constant	$5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$	$60 \times 10^{-9} \text{ W/m}^2 \text{ K}^4$
11	Wein's displacement law (λT)	$2897.6 \text{ }\mu\text{mK}$	$3000 \text{ }\mu\text{mK}$
12	Long-wavelength radiation from the Earth	$10 \text{ }\mu\text{m}$	$9 \text{ }\mu\text{m}$
13	Wavelength radiation from the Earth	$0 - 30 \text{ }\mu\text{m}$	$0 - 30 \text{ }\mu\text{m}$
14	Sunshine hour at the equator	12 h	12 h
15	Sunshine hour at the North Pole	24 h	24 h
16	Optimum tilt angle for maximum solar radiation	$\phi \pm 15$	$\phi \pm 15$
17	Convective heat-transfer coefficient for air	$2.8 + 3 \text{ V}$	$3(1 + \text{V})$
18	Sky temperature (T_{sky})		$(T_a - 12)$
19	Long-wavelength radiation exchange between the ambient air and the sky	60 W/m^2	60 W/m^2
20	Order of the radiative heat-transfer coefficient	$6 \text{ W/m}^2 \text{ K}$	$6 \text{ W/m}^2 \text{ K}$

(continued)

(continued)

S.No	Constants	Actual value	Approximate value
21	Convective and radiative heat-transfer coefficient for air	$5.7 + 3.8 \text{ VW}/m^2 K$	$3(2 + v) \text{ W}/m^2 K$
22	Order of the convective heat-transfer coefficient between a hot plate and water		$90 - 300 \text{ W}/m^2 K$
23	Overall heat-transfer coefficient for a single glazed FPC		$6 \text{ W}/m^2 K$
24	FPC-efficiency factor(F')		0.9
25	Insulation thickness	0.10 m	0.09 m
26	Fin efficiency (F)		0.9
27	Flow-rate factor		< 0.9
28	Transmittivity of window glass		0.9
29	Threshold intensity		$> 300 \text{ W}/m^2$
30	FPC connected in series		≤ 3
31	Thermal conductivity of an insulating material	$0.03 - 0.04 \text{ W}/mK$	$0.03 \text{ W}/mK$
32	Maximum temperature in a concentrating collector		3000 °C
33	Ideal efficiency of solar efficiency	60 %	60 %
34	Optimum depth of a basin of water	$0.02 - 0.03 \text{ m}$	0.03 m
35	Effect of the climatic parameter on solar-still yield		9 – 12 %
36	Emissivity of a surface	0.9	0.9
37	Optimum water depth in a collection-cum-storage water heater	0.10 m	0.09 m
38	Optimum temperature for the fermentation of slurry for biogas production	25–27 °C	27 °C
39	Cooking time by solar cooker	2 – 3 h	3 h
40	Latent heat of vaporization	$2.3 \times 10^6 \text{ J}/kg$	$3.0 \times 10^6 \text{ J}/kg$
41	Band gap for silicon	1.16 eV	1.2 eV
42	Boltzmann's constant (k)	$1.38 \times 10^{-23} \text{ J}/K$	$12 \times 10^{-24} \text{ J}/K$
43	V-group impurity concentration	10^{15} cm^3	10^{15} cm^3
44	Effective density of states in the conduction band	$2.82 \times 10^{19} \text{ cm}^3$	$28 \times 10^{18} \text{ cm}^3$
45	Saturation current in reverse bias	10^{-8} A	10^{-8} A
46	Thickness of an n-type semiconductor in a solar cell	0.2 μm	0.3 μm
47	Thickness of a p-type semiconductor in a solar cell	0.5 μm	0.6 μm
48	Diffusion path length	50 – 100 μm	60 – 90 μm

(continued)

(continued)

S.No	Constants	Actual value	Approximate value
49	Junction near an n-type semiconductor in Si	$0.15 \mu m$	$0.15 \mu m$
50	Solar intensity in the terrestrial region		$\approx 900 W/m^2$
51	Efficiency of a solar cell under standard conditions	15 %	15 %
52	Efficiency of a PV module with an Si- solar cell	12 %	12 %
53	Specific heat of water	$4190 J/kgK$	$4200 J/kgK$
54	Specific heat of air	$1000 J/kgK$	$1000 J/kgK$
55	Density of air	$1.2 kg/m^3$	$1.2 kg/m^3$
56	Absorptivity of a bare surface		≈ 0.3
57	Absorptivity of a blackened surface		> 0.9
58	Heating value of coal	$29000 kJ/kg$	$30000 kJ/kg$
59	Heating value of biogas	$20000 kJ/kg$	$21000 kJ/kg$
60	Heating value of wood/straw	$15000 kJ/kg$	$15000 kJ/kg$
61	Heating value of gasoline/kerosene	$42000 kJ/kg$	$42000 kJ/kg$
62	Heating value of methane	$50000 kJ/kg$	$51000 kJ/kg$
63	Energy contained in an infrared region	51.02 %	51 %
64	Energy contained in a visible region	36.76 %	36 %
65	Energy contained in an ultraviolet (UV) region	12.22 %	12 %