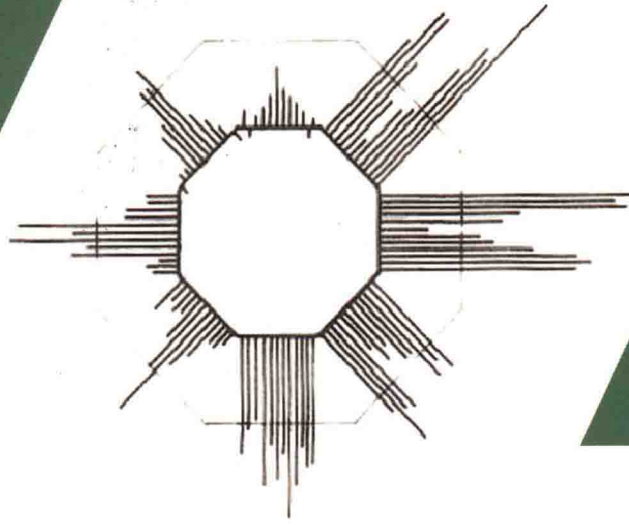
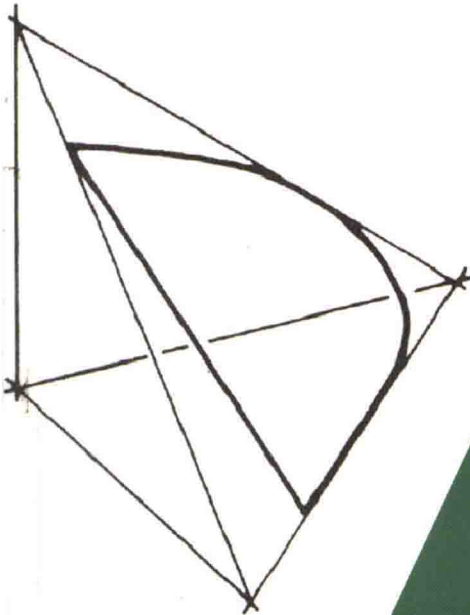


Second edition



# Introduction to Architectural Science

The Basis of Sustainable Design



Steven V Szokolay



Architectural  
Press

# Introduction to

# ARCHITECTURAL SCIENCE

## The Basis of Sustainable Design

---

Steven V. Szokolay

Second edition



ELSEVIER

AMSTERDAM • BOSTON • HEIDELBERG • LONDON • NEW YORK • OXFORD  
PARIS • SAN DIEGO • SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

Architectural Press is an imprint of Elsevier



Architectural Press is an imprint of Elsevier  
Linacre House, Jordan Hill, Oxford OX2 8DP, UK  
30 Corporate Drive, Suite 400, Burlington, MA 01803, USA

Second edition 2008

Copyright © 2008, Steven Szokolay. Published by Elsevier Ltd. All rights reserved

The right of Steven Szokolay to be identified as the author of this work has been asserted in accordance with the Copyright, Designs and Patents Act 1988

No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means electronic, mechanical, photocopying, recording or otherwise without the prior written permission of the publisher

Permissions may be sought directly from Elsevier's Science & Technology Rights Department in Oxford, UK: phone (+44) (0) 1865 843830; fax (+44) (0) 1865 853333; e-mail: [permissions@elsevier.com](mailto:permissions@elsevier.com). Alternatively you can submit your request online by visiting the Elsevier web site at <http://elsevier.com/locate/permissions>, and selecting *Obtaining Permissions to use Elsevier material*

#### Notice

No responsibility is assumed by the publisher for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions or ideas contained in the material herein

#### British Library Cataloguing in Publication Data

Szokolay, S. V.

Introduction to architectural science : the basis of sustainable design. – 2nd ed.

1. Architectural design 2. Buildings – Environmental engineering 3. Sustainable architecture

I. Title

721'.046

**Library of Congress Catalog Number:** 2008924601

ISBN: 978-0-7506-8704-1

For information on all Architectural Press publications  
visit our website at: [www.architecturalpress.com](http://www.architecturalpress.com)

Typeset by Charon Tec Ltd., A Macmillan Company. ([www.macmillansolutions.com](http://www.macmillansolutions.com))

Printed and bound by Uniprint

08 09 10 11 11 10 9 8 7 6 5 4 3 2 1

Working together to grow  
libraries in developing countries

[www.elsevier.com](http://www.elsevier.com) | [www.bookaid.org](http://www.bookaid.org) | [www.sabre.org](http://www.sabre.org)

ELSEVIER

BOOK AID  
International

Sabre Foundation

Introduction to  
**ARCHITECTURAL SCIENCE**  
The Basis of Sustainable Design

---

## PREFACE TO THE SECOND EDITION

---

Much has changed in the 3 years since the first edition of this book.

The physics of heat, light, sound and energy is still the same, so there is little change in the first three parts. Apart from the correction of a few errors, a few new developments are mentioned, some new methods are included and statistics updated.

Part 4 has many new elements that reflect societal changes, especially changes in public attitudes. Three years ago there were many who denied global warming or who regarded renewable energy technologies as 'kids' stuff'. Today only a few of these survive. Global warming is recognized as a fact by politicians as well as the general public. As the general public is better informed, politicians are forced to pay at least lip service to sustainability. Some actions have also been taken, albeit rather timidly.

There is significant progress in renewable energy technologies, both at the scientific and at the practical engineering level. Real life projects are multiplying and increasing in size. Numerous large wind farms and solar power stations are already operating and many are being developed. It is most encouraging that private capital started funding large renewable energy projects. There is also a large increase in small scale, 'distributed' power generation. Architects and the building industry started moving in the direction of sustainable practice as well.

What I said in the original 'Introduction' is just as valid now, as it then was, but the importance of having a critical attitude is even greater now than it was 3 years ago. Unfortunately there are many charlatans around, many use the label of 'sustainable' without the substance, some are ignorant or downright fraudulent. Few dare to say to them that the 'emperor has no clothes'.

I can only hope that this book, besides assisting the designer or the student will also contribute to developing such a critical attitude, thus lead to a progressive improvement.

# INTRODUCTION

---

Four chains of thought lead to the idea of this book and to the definition of its content:

- 1** It can no longer be disputed that the resources of this earth are finite, that its capacity to absorb our wastes is limited, that if we (as a species) want to survive, we cannot continue our ruthless exploitation of the environment. Where our actions would affect the environment, we must act in a sustainable manner. There are many good books that deal with the need for sustainability (e.g. Vale, 1991; Farmer, 1999; Roaf, 2001; Smith, 2001; Beggs, 2002). This book assumes that the reader is in agreement with these tenets and needs no further persuasion.
- 2** Architecture is the art and science of building. There exists a large literature on architecture as an art, on the cultural and social significance of architecture – there is no need for discussing these issues here.
- 3** The term 'bioclimatic architecture' has been coined by Victor Olgyay in the early 1950s and fully explained in his book *Design with climate* (1963). He synthesized elements of human physiology, climatology and building physics, with a strong advocacy of architectural regionalism and of designing in sympathy with the environment. In many ways he can be considered as an important progenitor of what we now call 'sustainable architecture'.
- 4** Architecture, as a profession is instrumental in huge investments of money and resources. Our professional responsibility is great, not only to our clients and to society, but also for sustainable development. Many excellent books and other publications deal with sustainable development in qualitative terms. However, professional responsibility demands expertise and competence. It is this narrow area where this work intends to supplement the existing literature.

The book is intended to give an introduction to architectural science, to provide an understanding of the physical phenomena we are to deal with and to provide the tools for realizing the many good intentions. Many projects in recent times are claimed to constitute sustainable development, to be sustainable architecture. But are they really green or sustainable? Some new terms started appearing in the literature, such as 'green wash' – meaning that a conventional building is designed and then claimed to be 'green'. Or 'pure rhetoric – no substance', with the same meaning.

My hope is that after absorbing the contents of this modest work, the reader will be able to answer this question. After all, the main aim of any education is to develop a critical faculty.

Building environments affect us through our sensory organs:

- 1 The eye, i.e. vision, a condition of which is light and lighting; the aim is to ensure visual comfort but also to facilitate visual performance.
- 2 The ear, i.e. hearing, appropriate conditions for listening to wanted sound must be ensured, but also the elimination (or control) of unwanted sound, noise.
- 3 Thermal sensors, located over the whole body surface, in the skin; this is not just a sensory channel, as the body itself produces heat and has a number of adjustment mechanisms but it can function only within a fairly narrow range of temperatures and only an even narrower range would be perceived as comfortable. Thermal conditions appropriate for human well-being must be ensured.

What is important for the designer is to be able to control the indoor environmental conditions: heat, light and sound. Rayner Banham (1969) in his *Architecture of the well-tempered environment* postulated that comfortable conditions can be provided by a building (passive control) or by the use of energy (active control), and that if we had an unlimited supply of energy, we could ensure comfort even without a building. In most real cases it is a mixture (or synergy) of the two kinds of control we would be relying on.

In this day and age, when it is realized that our traditional energy sources (coal, oil, gas) are finite and their rapidly increasing use has serious environmental consequences (CO<sub>2</sub> emissions, global warming, as well as local atmospheric pollution), it should be the designer's aim to ensure the required indoor conditions with little or no use of energy, other than from ambient or renewable sources.

Therefore the designer's task is

- 1 to examine the given conditions (site conditions, climate, daylight and noise climate)
- 2 to establish the limits of desirable or acceptable conditions (temperatures, lighting and acceptable noise levels)
- 3 to attempt to control these variables (heat, light and sound) by passive means (by the building itself) as far as practicable
- 4 to provide for energy-based services (heating, cooling, electric lighting, amplification or masking sound) only for the residual control task.

The building is not just a shelter, or a barrier against unwanted influences (rain, wind, cold), but the building envelope should be considered as a selective filter: to exclude the unwanted influences, but admit the desirable and useful ones, such as daylight, solar radiation in winter or natural ventilation.

The book consists of four parts

- 1 **Heat: the thermal environment**
- 2 **Light: the luminous environment**
- 3 **Sound: the sonic environment**
- 4 **Resources**

In each part the relevant physical principles are reviewed, followed by a discussion of their relationship to humans (comfort and human requirements). Then the control functions of the building (passive controls) are examined as well as associated installations, energy-using 'active' controls. The emphasis is on how these can be considered in design. The first part (Heat) is the most substantial, as the thermal behaviour of a building has greatest effect on energy use and sustainability and its design is fully the architect's responsibility.

Each part concludes with a series of data sheets relating to that part, together with some 'methods sheets', describing some calculation and design methods



# CONTENTS

---

Preface to the second edition	vii
Introduction	ix
<b>Part 1 Heat: the thermal environment</b>	<b>1</b>
Contents and lists	1
1.1 Physics of heat	6
1.2 Thermal comfort	16
1.3 Climate	22
1.4 Thermal behaviour of buildings	35
1.5 Thermal design: passive controls	53
1.6 Active controls: HVAC	76
Data sheets and method sheets	95
<b>Part 2 Light: the luminous environment</b>	<b>135</b>
Contents and lists	135
2.1 Physics of light	138
2.2 Vision	145
2.3 Daylight and sunlight	149
2.4 Design methods	153
2.5 Electric lighting	168
Data sheets and method sheets	185
<b>Part 3 Sound: the sonic environment</b>	<b>203</b>
Contents and lists	203
3.1 Physics of sound	206
3.2 Hearing	212
3.3 Noise control	220
3.4 Room acoustics	233
Data sheets and method sheets	247
<b>Part 4 Resources</b>	<b>261</b>
Contents and lists	261
4.1 Energy	264
4.2 Renewable energy	274
4.3 Energy use	292
4.4 Water and wastes	304
4.5 Sustainability issues	310
Data sheets and method sheets	323
References	331
Further reading	333
Appendix 1: Declaration of interdependence for a sustainable future	335
Appendix 2: Environment Policy of the Royal Australian Institute of Architects	337
Index	339

# PART 1 HEAT: THE THERMAL ENVIRONMENT

---

## CONTENTS

---

<b>1.1</b>	<b>Physics of heat</b>	<b>6</b>		
1.1.1	Heat and temperature	6		
1.1.2	Heat flow	8		
1.1.2.1	conduction	9		
1.1.2.2	convection	11		
1.1.2.3	radiation	11		
1.1.3	Humid air: psychrometry	12		
1.1.4	Air flow	15		
<b>1.2</b>	<b>Thermal comfort</b>	<b>16</b>		
1.2.1	Thermal balance and comfort	16		
1.2.2	Factors of comfort	17		
1.2.3	Adjustment mechanisms	19		
1.2.4	Comfort indices, comfort zone	20		
<b>1.3</b>	<b>Climate</b>	<b>22</b>		
1.3.1	The sun	22		
1.3.1.1	sun-path diagrams	24		
1.3.1.2	solar radiation	24		
1.3.2	Global climate, greenhouse effect	26		
1.3.3	Elements of climates: data	29		
1.3.3.1	wind data	31		
1.3.3.2	derived data	32		
1.3.4	Classification of climates	33		
<b>1.4</b>	<b>Thermal behaviour of buildings</b>	<b>35</b>		
1.4.1	Solar control	36		
1.4.1.1	shading design	36		
1.4.1.2	radiation calculations	37		
1.4.1.3	solar heat gain	39		
1.4.2	Ventilation	41		
1.4.3	Steady-state heat flow	43		
1.4.3.1	conduction heat flow	43		
1.4.3.2	insulation	44		
1.4.3.3	thermal bridges	45		
1.4.4	Dynamic response of buildings	47		
1.4.4.1	thermal response simulation	51		
1.4.5	Application	52		
<b>1.5</b>	<b>Thermal design: passive controls</b>	<b>53</b>		
1.5.1	Passive control of heat flows	53		
1.5.1.1	passive solar heating	58		
1.5.1.2	the mass effect	59		
1.5.1.3	air movement	62		
1.5.1.4	evaporative cooling	63		
1.5.2	Control functions of design variables	64		
1.5.2.1	component heat flows	64		
1.5.2.2	design variables	65		
1.5.3	Climatic design archetypes	67		
1.5.3.1	in cold climates	67		
1.5.3.2	in temperate climates	68		
1.5.3.3	in hot-dry climates	69		
1.5.3.4	warm-humid climates	69		
1.5.4	Condensation and moisture control	71		
1.5.5	Microclimatic controls	73		
<b>1.6</b>	<b>Active controls: HVAC</b>	<b>76</b>		
1.6.1	Heating	76		
1.6.1.1	local heating	77		
1.6.1.2	central heating	81		
1.6.2	Hot water supply	82		
1.6.3	Ventilation and air conditioning	86		
1.6.3.1	mechanical ventilation systems	86		
1.6.3.2	air conditioning systems	88		
1.6.4	Open-cycle cooling systems	90		
1.6.5	Integration/discussion	92		
	<b>Data sheets and method sheets</b>	<b>95</b>		

**SYMBOLS AND ABBREVIATIONS**

		Units	DD	degree-days	Kd
asg	alternating solar gain factor	–			Units
<i>b</i>	breadth, thickness	m	Dh	degree-hours	Kh
clo	unit of clothing insulation		DPT	dew-point temperature	°C
dTe	sol-air excess temperature (difference)	K	DRT	dry resultant temperature	°C
er	evaporation rate	kg/h	<i>E</i>	radiant heat emission	W
<i>f</i>	response factor	–	EnvT	environmental temperature	°C
<i>g</i>	vapour quantity		Ev	evaporation heat transfer (from body)	W
<i>k</i>	linear heat loss coefficient	W/mK	ET*	new effective temperature	°C
met	unit of metabolic heat (58.2W/m <sup>2</sup> )		<i>G</i>	global irradiance	W/m <sup>2</sup>
mr	mass flow rate	kg/s	GT	globe temperature	°C
<i>p</i>	pressure	Pa	<i>H</i>	enthalpy (heat content)	kJ/kg
pt	total atmospheric pressure	Pa	HDD	heating degree-days	Kd
pv	vapour pressure	Pa	<i>H<sub>L</sub></i>	latent heat content	kJ/kg
pv <sub>s</sub>	saturation vapour pressure	Pa	<i>H<sub>S</sub></i>	sensible heat content	kJ/kg
<i>q</i>	building conductance (specific heat loss rate)	W/K	HSA	horizontal shadow angle	°
qa	total admittance	W/K	Htg	heating requirement	(kWh) Wh
qc	envelope conductance	W/K	HVAC	Heating, Ventilation and Air Conditioning	–
qv	ventilation conductance	W/K	INC	angle of incidence	°
<i>h</i>	surface conductance	W/m <sup>2</sup> K	Kd	kelvin-days	Kd
<i>h<sub>c</sub></i>	convective surface conductance	W/m <sup>2</sup> K	Kh	kelvin-hours	Kh
<i>h<sub>r</sub></i>	radiative surface conductance	W/m <sup>2</sup> K	<i>L</i>	length (linear thermal bridges)	m
sM	specific mass (per floor area)	kg/m <sup>2</sup>	LAT	geographical latitude angle	°
sQ	swing in heat flow rate (from mean)	W	<i>M</i>	metabolic heat production	W
sT	swing in temperature (from mean)	K	MRT	mean radiant temperature	°C
<i>t</i>	time	h	<i>N</i>	number of air changes per hour	–
<i>v</i>	velocity	m/s	ORI	orientation angle	°
vr	volume flow rate (ventilation rate)	m <sup>3</sup> /s, L/s	<i>Q</i>	heat flux or heat flow rate	W
vR	vapour resistance	MPa·s/m <sup>2</sup> /g	<i>Q<sub>c</sub></i>	conduction heat flow rate	W
<i>y</i>	year		<i>Q<sub>e</sub></i>	evaporative heat loss rate	W
<i>A</i>	area	m <sup>2</sup>	<i>Q<sub>i</sub></i>	internal heat gain rate	W
AH	absolute humidity	g/kg	<i>Q<sub>s</sub></i>	solar heat gain rate	W
ALT	solar altitude angle	°	<i>Q<sub>v</sub></i>	ventilation heat flow rate	W
AZI	solar azimuth angle	°	<i>R</i>	resistance	m <sup>2</sup> K/W
<i>C</i>	conductance	W/m <sup>2</sup> K	<i>R<sub>a-a</sub></i>	air-to-air resistance	m <sup>2</sup> K/W
CDD	cooling degree-days	Kd	<i>R<sub>c</sub></i>	cavity resistance	m <sup>2</sup> K/W
CoP	coefficient of performance	–	Rd	radiation, radiated heat (from body)	W
CPZ	control potential zone		RH	relative humidity	%
Cd	conduction, conducted heat (from body)	W	<i>R<sub>s</sub></i>	surface resistance	m <sup>2</sup> K/W
Cv	convection, convected heat (from body)	W	<i>R<sub>si</sub></i>	internal surface resistance	m <sup>2</sup> K/W
<i>D</i>	daily total irradiation	Wh/m <sup>2</sup> , MJ/m <sup>2</sup>	<i>R<sub>so</sub></i>	outside surface resistance	m <sup>2</sup> K/W
<i>D<sub>v</sub></i>	daily total vertical irradiation	Wh/m <sup>2</sup> , MJ/m <sup>2</sup>	SD	standard deviation	
DBT	dry-bulb temperature	°C	SET	standard effective temperature	°
DEC	solar declination angle	°	SH	saturation point humidity	g/kg
			SI	système International (of units)	
			<i>T</i>	temperature	°C
			Tb	balance point (base~)	°C
				temperature	°C
			TIL	tilt angle	°
			<i>T<sub>i</sub></i>	indoor temperature	°C
			Tn	neutrality temperature	°C

(Continued)

## SYMBOLS AND ABBREVIATIONS (Continued)

		Units			Units
$T_o$	outdoor temperature	°C	$\tau$	transmittance	
$T_s$	surface temperature	°C	$\phi$	time lag	h
$T_{s-a}$	sol-air temperature	°C	$\sigma$	stefan-Boltzmann constant	$W/m^2K^4$
$U$	air-to-air (thermal) transmittance	$W/m^2K$	$\Sigma$	sum of ...	
$V$	volume	$m^3$	$\Delta p$	pressure difference	Pa
VSA	vertical shadow angle	°	$\Delta S$	rate of change in stored heat	W
WBT	wet-bulb temperature	°C	$\Delta T$	temperature difference, interval or increment	K
$Y$	admittance	$W/m^2K$			
$\alpha$	absorptance or thermal diffusivity	–	<b>Subscripts to G and D:</b>		
$\delta$	vapour permeability	$\mu g/m s Pa$	First	b	beam~
$\epsilon$	emittance	–		d	diffuse~
$\eta$	efficiency	–		r	reflected~
$\theta$	solar gain factor	–	Second	h	horizontal
$\theta_a$	alternating solar gain factor	–		v	vertical
$\kappa$	conductivity correction factor	–		p	on plane p
$\lambda$	conductivity	$W/m K$	For G only	n	normal to radiation
$\mu$	decrement factor	–			
$\pi$	vapour permeance	$\mu g/m^2 s Pa$			
$\rho$	density or reflectance	$kg/m^3$ or –			

## LIST OF FIGURES

1.1	Temperature scale and interval.	6	1.24	Lococentric view of the sky hemisphere with sun paths for the main dates.	23
1.2	The full electromagnetic spectrum and its solar segment.	8	1.25	Stereographic projection method.	24
1.3	Example wall section: $C$ and $U$ and resistances which are additive.	9	1.26	The shift of sun-path lines on the solar chart, with latitudes.	25
1.4	Structure of the psychrometric chart.	12	1.27	A stereographic sun-path diagram for latitude 36° (e.g. Tokyo).	25
1.5	Relative humidity curves.	12	1.28	Irradiance and irradiation.	26
1.6	Psychrometric chart, with SET lines superimposed.	13	1.29	Angle of incidence.	26
1.7	Principles of an aspirated psychrometer (a) and a whirling psychrometer (b).	14	1.30	Radiation path-lengths through the atmosphere.	26
1.8	Web-bulb temperature lines.	14	1.31	Radiation balance in the atmosphere.	26
1.9	Enthalpy scales externally.	14	1.32	The global wind pattern.	27
1.10	Specific volume lines.	15	1.33	North-south shift of the ITCZ.	27
1.11	Cooling and heating: movement of the status point.	15	1.34	Development of mid-latitude cyclonic cells.	28
1.12	Cooling to reduce humidity.	15	1.35	Sectional structure of the atmosphere: changes of temperature and pressure (hPa = hectopascal = 100 Pa is used as it is the same as a millibar).	28
1.13	Evaporative cooling: humidification.	15	1.36	The Earth's heat balance: causes of the global warming.	29
1.14	Adiabatic dehumidification.	16	1.37	A precision pyranometer.	29
1.15	Stack effect in a room and in a chimney.	16	1.38	A composite climate graph (Nairobi).	30
1.16	Wind effect: cross-ventilation.	16	1.39	The simplest set of climatic data.	31
1.17	Heat exchanges of the human body.	17	1.40	A wind rose for one month.	31
1.18	Globe thermometer.	18	1.41	An annual wind rose.	31
1.19	The psycho-physiological model of thermal perception.	20	1.42	A wind frequency analysis, for January 9 a.m. and 3 p.m. (Cairns).	32
1.20	Olgay's bioclimatic chart, converted to metric, modified for warm climates.	21	1.43	Definition of degree-hours (Kh).	32
1.21	Winter (light) and summer (heavy outline) comfort zones for Budapest and Darwin.	22	1.44	The Köppen-Geiger climate zones of the world.	33
1.22	Two-dimensional section of the earth's orbit and definition of solar declination (DEC).	23	1.45	Composite (simplified) climate graphs for the four basic types.	35
1.23	Altitude and azimuth angles.	23			

(Continued)

## LIST OF FIGURES (Continued)

1.46	The shadow-angle protractor.	36	1.82	A house proposed by Socrates (cca. 400 BC) for temperate climates.	68
1.47	Plan of a pair of vertical devices (fins) and their shading mask.	36	1.83	A modern courtyard house: isometric view and plan.	69
1.48	A horizontal device (a canopy) and its shading mask.	37	1.84	A typical house for warm-humid climates.	70
1.49	Relationship of ALT and VSA.	37	1.85	Projecting building wings, vegetation screens or wing walls can be used to generate cross-ventilation.	70
1.50	An egg-crate device and its shading masks: section, plan, VSA, HSA and combined.	38	1.86	A hybrid house for warm-humid climates.	71
1.51	Equinox cut-off for summer shading and winter sun-entry (southern hemisphere, north-facing window).	38	1.87	Part of the psychrometric chart: condensation occurs when air is cooled to its DPT.	72
1.52	Design procedure for composite shading.	38	1.88	Katabatic wind: cool air flows downhill, like water.	74
1.53	Transmission through glass.	39	1.89	Wind velocity profiles.	74
1.54	Derivation of the sol-air temperature.	41	1.90	Rainfall on hills.	74
1.55	Some parallel heat loss paths from a house: the <b>conductances</b> work in parallel, therefore must be added, to get the total envelope conductance, as eq. (1.25).	43	1.91	Coastal winds.	75
1.56	Heat flow through a wall through the three material layers and a cavity: in series, thus the <b>resistances</b> must be added.	44	1.92	Urban heat island effect.	75
1.57	Heat flow through an attic space: foil is very effective when $T_{\text{roof}} > T_{\text{ceiling}}$ .	45	1.93	Local wind at one building.	75
1.58	Thermal bridge due to geometry.	46	1.94	A typical cast iron stove.	78
1.59	Thermal bridge in mixed construction.	46	1.95	A ceramic stove built <i>in situ</i> .	78
1.60	The above two effects combined.	46	1.96	A gas convector heater with a balanced flue.	78
1.61	A concrete column in a brick wall.	46	1.97	Principles of a heat pump (or cooling machine).	79
1.62	Heat flows 'downhill'.	47	1.98	Gas storage bottles. B: buckles and straps; C: changeover valve and P: pressure regulator.	81
1.63	Temperature distribution near a thermal bridge.	47	1.99	Oil storage tank room. V: vent; P: filling pipe; S: sludge valve; D: depth to contain full volume; Fi: foam inlet; M: manhole and F: fire shut-off.	81
1.64	Flow paths when column is insulated.	47	1.100	A domestic warm air system. D: radial under-floor ducts; C: alternative ceiling ducts; V: vents in doors and R = return air grill.	81
1.65	The whole area of a wall module is affected by thermal bridges.	47	1.101	Central heating ring-main system.	81
1.66	Heat flow through a real wall, compared with a wall of zero mass.	47	1.102	A two-pipe up-feed system.	82
1.67	Time lag and decrement factors for solid homogeneous walls.	48	1.103	A two-pipe down-feed system.	82
1.68	Time sequence of temperature profiles in a massive wall (in a warm climate).	49	1.104	A one-pipe down-feed system.	82
1.69	Sequence of layers in an insulated concrete roof slab.	50	1.105	Central heating radiator panels.	83
1.70	Four basic climate types vs. the local comfort zones.	54	1.106	Convector units: skirting and wall mounted types.	83
1.71	Locations of thermal bridges: linear heat loss coefficients ( $\kappa$ ).	56	1.107	Some hot water system diagrams.	84
1.72	Principles of the Trombe-Michel wall.	58	1.108	Secondary hot water circulation (for instant hot water).	85
1.73	CPZ for passive solar heating.	60	1.109	Some simple domestic solar water heater systems: (a) thermosiphon, electric booster; (b) same, with gas circulator; (c) with close-coupled tank and (d) pumped system.	86
1.74	An attic fan (or 'whole-house' fan).	61	1.110	A rotary heat exchanger for ventilation heat recovery.	87
1.75	CPZ for the mass effect and mass effect with night ventilation.	61	1.111	A ventilation heat recovery system, assisted by a heat pump.	87
1.76	CPZ for the cooling effect of air movement.	63	1.112	Schematic diagram of a packaged air conditioner unit. C: compressor; M: motor and E: evaporator.	88
1.77	Principles of a direct evaporative cooler.	63	1.113	An console type air conditioner unit.	88
1.78	CPZ for evaporative cooling.	64	1.114	An air conditioner 'split unit'.	88
1.79	Definition of 'aspect ratio' (a roof plan).	64	1.115	A typical central air-handling unit (arrangement diagram).	89
1.80	Window types by closing mechanism.	66			
1.81	Eskimo igloos (minimum surface).	67			

(Continued)

**LIST OF FIGURES (Continued)**

1.116	Four basic air conditioning systems: (a) an all-air system, (b) an induction system, (c) a dual duct system and (d) local air-handling system.	89	1.119	An indirect evaporative cooler.	91
1.117	An ammonia/water absorption chiller.	90	1.120	An open-cycle cooling system using solid sorbents.	91
1.118	The effect of structural storage on air conditioning load and required plant capacity.	90	1.121	An open-cycle system using a liquid desiccant.	91

**LIST OF TABLES**

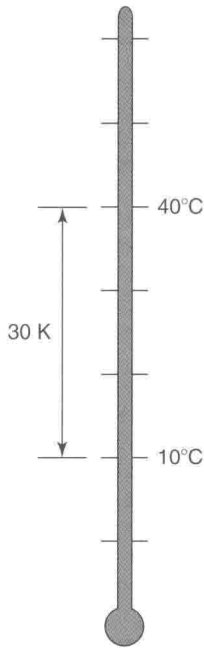
1.1	Derivation of composite SI units for thermal quantities	6	1.4	Expressions for the swing in heat flow	50
1.2	Conductivity correction factors	9	1.5	Winter design outdoor temperatures for the UK	77
1.3	Summary of steady state heat flow expressions	46	1.6	Correction factors for heating requirement	78
			1.7	Types of electric heaters	79

**LIST OF WORKED EXAMPLES**

1.1	Specific heat and temperature	7	1.6	Windows: heat loss vs. solar gain	57
1.2	Heat loss: the $U$ -value	10	1.7	CPZ: passive solar heating	59
1.3	A roof slab: position of insulation	50	1.8	CPZ: mass effect	61
1.4	$R$ -value and added insulation	55	1.9	CPZ: air movement effect	63
1.5	The effect of thermal bridges: $U_{av}$	56			

**LIST OF EQUATIONS**

1.1	Conduction heat flow rate	10	1.18	Solar heat gain	41
1.2	Air-to-air resistance	10	1.19	Ventilation conductance, volume flow rate	42
1.3	Resistance of single layer	10	1.20	Same with number of air changes per hour	42
1.4	Convection heat flow rate	11	1.21	Ventilation heat flow rate	42
1.5	Solar heat gain rate	12	1.22	Building conductance	42
1.6	Absolute humidity and vapour pressure	12	1.23	Building heat loss rate	42
1.7	Construction of a WBT line	14	1.24	Apparent cooling effect of air flow	42
1.8	The body's thermal balance	17	1.25	Envelope conductance	43
1.9	Thermal neutrality temperature	20	1.26	Conduction heat flow rate	44
1.10	Degree-days	32	1.27	Daily mean heat flow	49
1.11	Degree-hours	32	1.28	Swing in heat flow (at a time)	49
1.12	Heating requirement	33	1.29	Periodic heat flow	49
1.13	The building's thermal balance	35	1.30	Admittance	51
1.14	Solar heat gain through a window	39	1.31	Building response factor	60
1.15	Solar heat input	40	1.32	Evaporation heat loss	63
1.16	Sol-air temperature	41	1.33	Coefficient of performance (CoP), $a-b$	80
1.17	Roof sol-air temperature	41			



1.1. Temperature scale and interval.

## 1.1 PHYSICS OF HEAT

### 1.1.1 Heat and temperature

**Heat** is a form of energy, contained in substances as molecular motion or appearing as electromagnetic radiation in space. Energy is the ability or capacity for doing work and it is measured in the same units. The derivation of this unit from the basic MKS (m, kg, s) units in the SI (Système International) is quite simple and logical, as shown in Table 1.1.

**Temperature** ( $T$ ) is the symptom of the presence of heat in a substance. The Celsius scale is based on water: its freezing point taken as  $0^{\circ}\text{C}$  and its boiling point (at normal atmospheric pressure) as  $100^{\circ}\text{C}$ . The Kelvin scale starts with the 'absolute zero', the total absence of heat. Thus  $0^{\circ}\text{C} = 273.15^{\circ}\text{K}$ . The temperature interval is the same in both scales. By convention, a point on the scale is denoted  $^{\circ}\text{C}$  (degree Celsius) but the notation for a temperature difference or interval is K (Kelvin), which is a certain length of the scale, without specifying where it is on the overall scale (Fig. 1.1). Thus  $40 - 10^{\circ}\text{C} = 30\text{K}$ , and similarly  $65 - 35^{\circ}\text{C}$  is  $30\text{K}$  but  $15^{\circ}\text{C}$ , as a point on the scale, is  $288.15^{\circ}\text{K}$ .

The **specific heat** concept provides the connection between heat and temperature. This is the quantity of heat required to elevate the temperature of unit mass of a substance by one degree, thus it is measured in units of **J/kg K**. Its magnitude is different for different materials and it varies between 100 and 800 J/kg K for metals, 800–1200 J/kg K for masonry materials (brick, concrete) to water, which has the highest value of all common substances: 4176 J/kg K (see data sheet D.1.1).

**Table 1.1.** Derivation of composite SI units for thermal quantities

Length	m	(metre)
Mass	kg	(kilogram)
Time	s	(second)
Velocity, speed	<b>m/s</b>	That is unit length movement in unit time. The everyday unit is km/h, which is $1000\text{m}/3600\text{s} = 0.278\text{m/s}$ or conversely: $1\text{m/s} = 3.6\text{km/h}$
Acceleration	<b>m/s<sup>2</sup></b>	That is unit velocity increase in unit time: (m/s)/s
Force	<b>kg m/s<sup>2</sup></b>	That which gives unit acceleration to unit mass named newton ( <b>N</b> )
Work, energy	<b>kg m<sup>2</sup>/s<sup>2</sup></b>	Unit work is done when unit force is acting over unit length i.e. $\text{N} \times \text{m}$ named joule ( <b>J</b> )
Power, energy flow rate	<b>kg m<sup>2</sup>/s<sup>3</sup></b>	Unit energy flow in unit time or unit work done in unit time i.e. J/s named watt ( <b>W</b> )
Pressure, stress	<b>kg/ms<sup>2</sup></b>	Unit force acting on unit area (kgm/s <sup>2</sup> )/m <sup>2</sup> i.e. N/m <sup>2</sup> named pascal ( <b>Pa</b> )

SI unit symbols, derived from personal names, are always capitalized.

**EXAMPLE 1.1**

Given 0.5 L (=0.5 kg) of water at 20°C in an electric jug with an 800W immersion heater element (efficiency: 1.0 or 100%). How long will it take to bring it to the boil?

Requirement:  $0.5 \text{ kg} \times 4176 \text{ J/kgK} \times (100 - 20) \text{ K} = 167\,040 \text{ J}$

Heat input 800W, i.e. 800 J/s, thus the time required is

$167\,040 \text{ J}/800 \text{ J/s} = 208 \text{ s} \approx 3.5 \text{ min}$

**Latent heat** of a substance is the amount of heat (energy) absorbed by unit mass of the substance at change of state (from solid to liquid or liquid to gaseous) without any change in temperature. This is measured in J/kg, e.g. for water:

latent heat of fusion (ice to water) at 0°C = 335 kJ/kg

latent heat of evaporation at 100°C = 2261 kJ/kg

at about 18°C = 2400 kJ/kg

At a change of state in the reverse direction the same amount of heat is released.

**Thermodynamics** is the science of the flow of heat and of its relationship to mechanical work.

The **first law** of thermodynamics is the principle of conservation of energy. Energy cannot be created or destroyed (except in sub-atomic processes), but only converted from one form to another. Heat and work are interconvertible. In any system the energy output must equal the energy input, unless there is a +/− storage component.

The **second law** of thermodynamics states that heat (or energy) transfer can take place spontaneously in one direction only: from a hotter to a cooler body or generally from a higher to a lower grade state (same as water flow will take place only downhill). Only with an external energy input can a machine deliver heat in the opposite direction (water will move upwards only if it is pumped). Any machine to perform work must have an energy source and a sink, i.e. energy must flow through the machine: only part of this flow can be turned into work.

Heat flow from a high to a low temperature zone can take place in three forms: conduction, convection and radiation. The magnitude of any such flow can be measured in two ways:

- 1 as *heat flow rate* ( $Q$ ), or heat flux, i.e. the total flow in unit time through a defined area of a body or space, or within a defined system, in units of J/s, which is a watt (W) (The most persistent archaic energy flow rate or power unit is the *horsepower*, but in fully metric countries even car engines are now rated in terms of kW.)
- 2 as *heat flux density* (or density of heat flow rate), i.e. the rate of heat flow through unit area of a body or space, in  $\text{W/m}^2$ . The multiple kW (kilowatt = 1000 W) is often used for both quantities. (The term 'density' as used here is analogous with, for example, population density: i.e. people



per unit area, or with surface density: i.e. kg mass per unit area of a wall or other building element.)

A non-standard, but accepted and very convenient unit of energy is derived from this heat flux unit: the watt-hour (Wh). This is the amount of energy delivered or expended if a flow rate (flux) of 1W is maintained for an hour. As 1 h = 3600 s and

$$1W = 1 J/s$$

$$1Wh = 3600s \times 1 J/s = 3600J \quad \text{or} \quad 3.6kJ \text{ (kilojoule)}^1$$

The multiple kWh (kilowatt-hour) is often used as a practical unit of energy (e.g. in electricity accounts) 1 kWh = 3600000J or 3600kJ or 3.6MJ (megajoule).

### 1.1.2 Heat flow

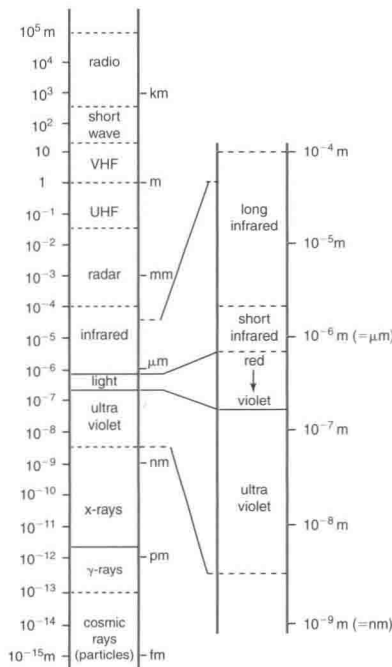
As water flows from a higher to a lower position, so heat flows from a higher temperature zone (or body) to a lower temperature one. Such heat flow can take place in three forms:

- 1 *Conduction* within a body or bodies in contact, by the 'spread' of molecular movement.
- 2 *Convection* from a solid body to a fluid (liquid or gas) or vice versa (in a broader sense it is also used to mean the transport of heat from one surface to another by a moving fluid, which, strictly speaking, is 'mass transfer'). The magnitude of convection heat flow rate depends on
  - a area of contact ( $A$ ,  $m^2$ ) between the body and the fluid
  - b the difference in temperature ( $\Delta T$ , in K) between the surface of the body and the fluid
  - c a convection coefficient ( $h_c$ ) measured in  $W/m^2K$ , which depends on the viscosity of the fluid and its flow velocity as well as on the physical configuration that will determine whether the flow is laminar or turbulent (see Section 1.1.2.2 below).
- 3 *Radiation* from a body with a warmer surface to another which is cooler. Thermal radiation is a wavelength band of electromagnetic radiation, normally taken as  $700\text{--}10\,000\text{ nm}^2\ 10\ \mu\text{m}^3$

'short infrared':  $700\text{--}2300\text{ nm}$  ( $2.3\ \mu\text{m}$ ) (see note in 1.3.1.2a) and  
 'long infrared':  $2.3\text{--}10\ \mu\text{m}$  (some suggest up to  $70\ \mu\text{m}$ )

The temperature of the emitting body determines the wavelength. The sun with its  $6000^\circ\text{C}$  surface emits short infrared (as well as visible and ultraviolet (UV)), bodies at terrestrial temperatures ( $<100^\circ\text{C}$ ) emit long infrared radiation. (Fig. 1.2 shows these bands in relation to the full electromagnetic spectrum).

In all three forms the magnitude of flux (or of flux density) depends on the temperature difference between the points (or surfaces) considered, whilst the flux (heat flow rate) in conduction also depends on the cross-sectional area of the body available.



1.2. The full electromagnetic spectrum and its solar segment.

Wave-band summary	
< 280nm	UV 'C'
280–315	UV 'B'
315–380	UV 'A'
380–780	light
Overlap with thermal:	
700–2300	short IR
2300–10000	long IR

<sup>1</sup>For all prefixes used with SI units see Table 4.1.

<sup>2</sup>1 nm (nanometre) =  $10^{-9}\text{ m}$

<sup>3</sup>1  $\mu\text{m}$  (micrometer) =  $10^{-6}\text{ m}$