Hugo Hens

Applied Building Physics

Ambient Conditions, Functional Demands, and Building Part Requirements

Third Edition

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Third, revised Edition

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A Wiley Brand

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To my wife, children and grandchildren

In remembrance of Professor A. de Grave, a civil engineer who introduced building physics as a new discipline at the University of Leuven, Belgium, in 1952.

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Preface

While the first volume on Building Physics looked to the fundamentals governing the heat, air, moisture response of building parts and whole buildings, this second volume on Applied Building Physics shows how building physics may help in upgrading building and building part design and construction by applying the discipline related performance rationales, requirements and metrics to guarantee a sound building quality. How, starts with the ambient conditions out- and indoors acting as the environmental loads buildings and building parts or assemblies face. Then a move is made to the performance fields of importance at the whole building level, after which, directly linked to the book on Building Physics, the heat, air, moisture requirements and metrics actually expected when designing and realizing building parts assemblies pass the review.

This content to a large extent reflects the 38 years of teaching Building Physics and Applied Building Physics to architectural, building and civil engineering students, that, coupled to more than 36 years of experience in building and building part performance research and more than 50 years of activity in consultancy and in curing hundreds of heat, air, moisture-related damage cases. When and where needed, information from international sources and literature has been consulted, which is why all chapters end with an extended further reading list. The book uses SI units. It could be of help for undergraduate and graduate students in architectural and building engineering, although also practising building engineers, who want to refresh their knowledge, may benefit. Presumed anyhow is that the reader has a sound knowledge of the fundamentals treated in the first book, along with a background in construction materials and building design and construction.

Acknowledgements

The book reflects the work of many, not only of the author. Therefore, we thank the thousands of students we had during the 38 years of teaching. They gave us the opportunity to test the content. The book should also not have been written the way it is if not standing on the shoulders of those, who preceded it. Although we started our carrier as a structural engineer, our predecessor Professor Antoine de Grave planted the seeds that fed the interest in building physics. Bob Vos of TNO,

the Netherlands, and Helmut Künzel of the Fraunhofer Institüt für Bauphysik, Germany, showed the importance of experimental work and field testing to understand whole building and building part or assembly performance, while Lars Erik Nevander of Lund University, Sweden, taught that solving problems in building physics does not always ask complex modelling, mainly because reality in building construction is much more complex than any model can simulate.

During the four decades at the Unit of Building Physics and Sustainable Construction within the Department of Civil Engineering of the KULeuven, several researchers, then PhD-students, got involved. They all contributed by the topics chosen to the advancement of the research done at the unit. Most grateful I am to Gerrit Vermeir, my colleague from the start in 1975, now professor emeritus, to Staf Roels, Dirk Saelens, Hans Janssen and Bert Blocken, who succeeded me as professors at the unit.

The experience gained as a structural engineer and building site supervisor for a medium-sized architectural office the first 4 years of my career, as building assessor during some 50 years, as operating agent of four IEA, EXCO on Energy in Buildings and Communities Annexes forced me to rethink the engineering-based performance approach each time again. The many ideas exchanged in Canada and the United States with Kumar Kumaran of NRC, Paul Fazio of Concordia University in Montreal, Bill Brown, William B. Rose of the University of Illinois in Urbana-Champaign, Joe Lstiburek of the Building Science Corporation, Anton Ten Wolde and those participating in ASHRAE TC 1.12 'Moisture management in buildings' and TC 4.4 'Building materials and building envelope performance' were also of great value.

Finally, I thank my family, my wife Lieve, who managed living together with a busy engineering professor, our three children, our children in law and our grandchildren.

Leuven, March 2023 *Hugo S.L.C. Hens*

About the Author

Dr. Ir. Hugo S.L.C. Hens is an emeritus professor of the University of Leuven (KU Leuven), Belgium. Until 1972, he worked as a structural engineer and site supervisor at a mid-sized architectural office. After the sudden death of his predecessor and promotor Professor A. de Grave in 1975 and after defending his PhD thesis, he stepwise built up the Unit of Building Physics at the Department of Civil Engineering.

He taught Building Physics from 1975 to 2003, performance-based building design from 1975 to 2005 and building services from 1975 to 1977 and 1990 to 2008. He authored and co-authored 68 peer-reviewed journal papers and 174 conference papers about the research done, has helped to manage hundreds of building damage cases and acted as coordinator of the CIB W40 working group on Heat and Mass Transfer in Buildings from 1983 to 1993. Between 1986 and 2008, he was operating agent of the Annexes 14, 24, 32 and 41 of the IEA EXCO on Energy in Buildings and Communities. He is a fellow of the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE).

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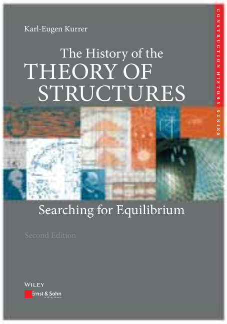

Karl-Eugen Kurrer

The History of the
THEORY OF
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Searching for Equilibrium

Second Edition

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List of Units and Symbols

Units

The book uses the SI system, internationally mandatory since 1977, with as base units the metre (m), the kilogram (kg), the second (s), the Kelvin (K), the ampere (A) and the candela. Derived units of importance when studying applied building physics are:

Unit of force	Newton (N)	$1\ \mathrm{N} = 1\ \mathrm{kg\,m/s^2}$
Unit of pressure	Pascal (Pa)	$1\ \mathrm{Pa} = 1\ \mathrm{N/m^2} = 1\ \mathrm{kg/(m\,s^2)}$
Unit of energy	Joule (J)	$1\ \mathrm{J} = 1\ \mathrm{N\,m} = 1\ \mathrm{kg\,m^2/s^2}$
Unit of power	Watt (W)	$1\ \mathrm{W} = 1\ \mathrm{J\,s^{-1}} = 1\ \mathrm{kg\,m^2/s^3}$

Symbols

For the symbols, the ISO standards (International Standardization Organization) are followed. For quantities not included, the CIB-W40 recommendations (International Council for Building Research, Studies and Documentation, Working Group ‘Heat and Moisture Transfer in Buildings’) and the list edited by Annex 24 of the IEA, EBC (International Energy Agency, Executive Committee on Energy in Buildings and Communities) apply.

Table 1 List with symbols and quantities.

Symbol	Meaning	SI units
a	Acceleration	m/s^2
a	Thermal diffusivity	m^2/s
b	Thermal effusivity	W/(m^2 K s$^{0.5}$)
c	Specific heat capacity	J/(kg K)
c	Concentration	kg/m^3, g/m^3
e	Emissivity	—
f	Specific free energy	J/kg
f_{h_i}	Temperature ratio	—
g	Specific free enthalpy	J/kg
g	Acceleration by gravity	m/s^2
g	Mass flux	kg/(m^2 s)
h	Height	m
h	Specific enthalpy	J/kg
h	Surface film coefficient for heat transfer	W/(m^2 K)
k	Mass-related permeability (mass could be moisture, air, salt, etc.)	s
l	Length	m
l	Specific enthalpy of evaporation or melting	J/kg
m	Mass	kg
n	Ventilation rate	s^{-1}, h^{-1}
p	Partial pressure	Pa
q	Heat flux	W/m^2
r	Radius	m
s	Specific entropy	J/(kg K)
t	Time	s
u	Specific latent energy	J/kg
v	Velocity	m/s
w	Moisture content	kg/m^3
x,y,z	Cartesian co-ordinates	m
A	Water sorption coefficient	kg/(m^2 s$^{0.5}$)
A	Area	m^2
B	Water penetration coefficient	m/s$^{0.5}$
D	Diffusion coefficient	m^2/s
D	Moisture diffusivity	m^2/s
E	Irradiation	W/m^2
F	Free energy	J

(Continued)

Table 1 List with symbols and quantities. (Continued)

Symbol	Meaning	SI units
G	Free enthalpy	J
G	Mass flow (mass = vapour, water, air, salt)	kg/s
H	Enthalpy	J
I	Radiation intensity	J/rad
K	Thermal moisture diffusion coefficient	kg/(m s K)
K	Mass permeance	s/m
K	Force	N
L	Luminosity	W/m^2
M	Emittance	W/m^2
P	Power	W
P	Thermal permeance	W/(m^2 K)
P	Total pressure	Pa
Q	Heat	J
R	Thermal resistance	m^2 K/W
R	Gas constant	J/(kg K)
S	Entropy, saturation degree	J/K, –
T	Absolute temperature	K
T	Period (of a vibration or a wave)	s, days, etc.
U	Latent energy	J
U	Thermal transmittance	W/(m^2 K)
V	Volume	m^3
W	Air resistance	m/s
X	Moisture ratio	kg/kg
Z	Diffusion resistance	m/s
α	Thermal expansion coefficient	K^{-1}
α	Absorptivity	—
β	Surface film coefficient for diffusion	s/m
β	Volumetric thermal expansion coefficient	K^{-1}
η	Dynamic viscosity	N s/m^2
θ	Temperature	°C
λ	Thermal conductivity	W/(m K)
μ	Vapour resistance factor	—
ν	Kinematic viscosity	m^2/s
ρ	Density	kg/m^3
ρ	Reflectivity	—

(Continued)

Table 1 List with symbols and quantities. (Continued)

Symbol	Meaning	SI units
σ	Surface tension	N/m
τ	Transmissivity	—
ϕ	Relative humidity	—
α, ϕ, Θ	Angle	rad
ξ	Specific moisture capacity	kg/kg per unit of moisture potential
Ψ	Porosity	—
Ψ	Volumetric moisture ratio	m^3/m^3
$\boldsymbol{\Phi}$	Heat flow	W

Table 2 List with suffixes and notations.

Symbol	Meaning	Symbol	Meaning
Indices			
A	Air	m	Moisture, maximal
c	Capillary, convection	o	Operative
e	Outside, outdoors	r	Radiant, radiation
h	Hygroscopic	sat	Saturation
i	Inside, indoors	s	Surface, area, suction
cr	Critical	v	Water vapour
CO_2, SO_2	Chemical symbol for gasses	w	Water
		ϕ	Relative humidity

Notation	Meaning
[], bold,	Matrix, array, value of a complex number
Dash (e.g.: $\bar{a}$)	Vector

Introduction

Subject of the Book

This is the second volume in a series of three:

- Building Physics: Heat, Air and Moisture, Fundamentals, Engineering Methods, Material Properties and Exercises
- **Applied Building Physics: Ambient Conditions, Whole Building and Building Assembly Performance**
- Performance-Based Building Design: from Below Grade over Floors, Walls, Roofs, and Windows to Finishes

The term ‘applied’ could be perceived as a pleonasm since ‘Building Physics’ is by definition referring to a body of knowledge, whose application is essential for the correct performance of new construction and renovation. Whatever, the subjects discussed in this second book offer a link between ‘Building Physics: Heat, Air and Moisture’ and the volume on ‘Performance-Based Building Design’.

Highlighted in Chapter 1 are the climate, the indoor environment and several related design approaches. Chapter 2 advances the performance concept with its hierarchical structure, from the urban environment down to whole buildings, building assemblies, the layers assemblies consist of and the materials used. In Chapter 3, several fields of importance that fix building physics-related performance requirements at the whole building level are discussed. Chapter 4 analyses the heat, air, moisture performance metrics, to which building envelopes must comply to ensure a correct behaviour. Chapter 5 advances timber frame walls as example of a construction choice with possibly a problematic heat, air, moisture response, while for the sake of completeness, the Appendix repeats lists with material property values, already discussed in ‘Building Physics: Heat, Air and Moisture, Fundamentals, Engineering Methods, Material Properties and Exercises’.

Well known is that a performance-based approach should guarantee building quality. Of course, physical integrity is not the only value of importance in the built environment. Also, functionality, spatial quality and aesthetics, all belonging to the architect’s responsibility, are, but these should never figure as arguments to neglect a correct overall structural and physical performance.

Applied Building Physics: Ambient Conditions, Functional Demands, and Building Part Requirements,
Third Edition. Hugo Hens.

Further Reading

CIB-W40 (1975). Quantities, Symbols and Units for the description of heat and moisture transfer in Buildings: Conversion factors, IBBC-TNP, report no. BI-75-59/03.8.12, Rijs-wijk.

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Kumaran, K. (1996). Task 3: Material Properties, Final Report IEA EBC Annex 24, ACCO, Leuven, 135 p.

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1

Ambient Conditions Out- and Indoors

1.1 Overview

The role the ambient conditions have in building physics could be compared to the role loads have in structural engineering, the reason why the term ‘ambient or environmental loads’ is often used. Their knowledge is essential to make appropriate decisions when designing building envelopes and whole buildings. The components shaping the conditions out- and indoors are:

Outdoors		**Indoors**	
Air temperature	θ_e	Air temperature	θ_i
		Radiant temperature	θ_R
Relative humidity (RH)	ϕ_e	Relative humidity (RH)	ϕ_i
(Partial water) vapour pressure	p_e	(Partial water) vapour pressure	p_i
Solar radiation	E_S		
Under-cooling	q_{rL}		
Wind	v_w	Air speed	v
Rain and snow	g_r		
Air pressure	$P_{a,e}$	Air pressure	$P_{a,i}$

In what follows, all are discussed separately. Bear in mind though that the greater the difference between the out- and indoor temperature and relative humidity is, the stricter the envelope and HVAC performance requirements become. If not, maintaining thermally comfortable and environmentally healthy conditions indoors will among other things require more energy than acceptable.

Predicting the future climate outdoors remains a guess. Not only are most components not measured everywhere, but the future is never a copy of the past and does not obey the paradigm ‘the longer the data chain available, the better the

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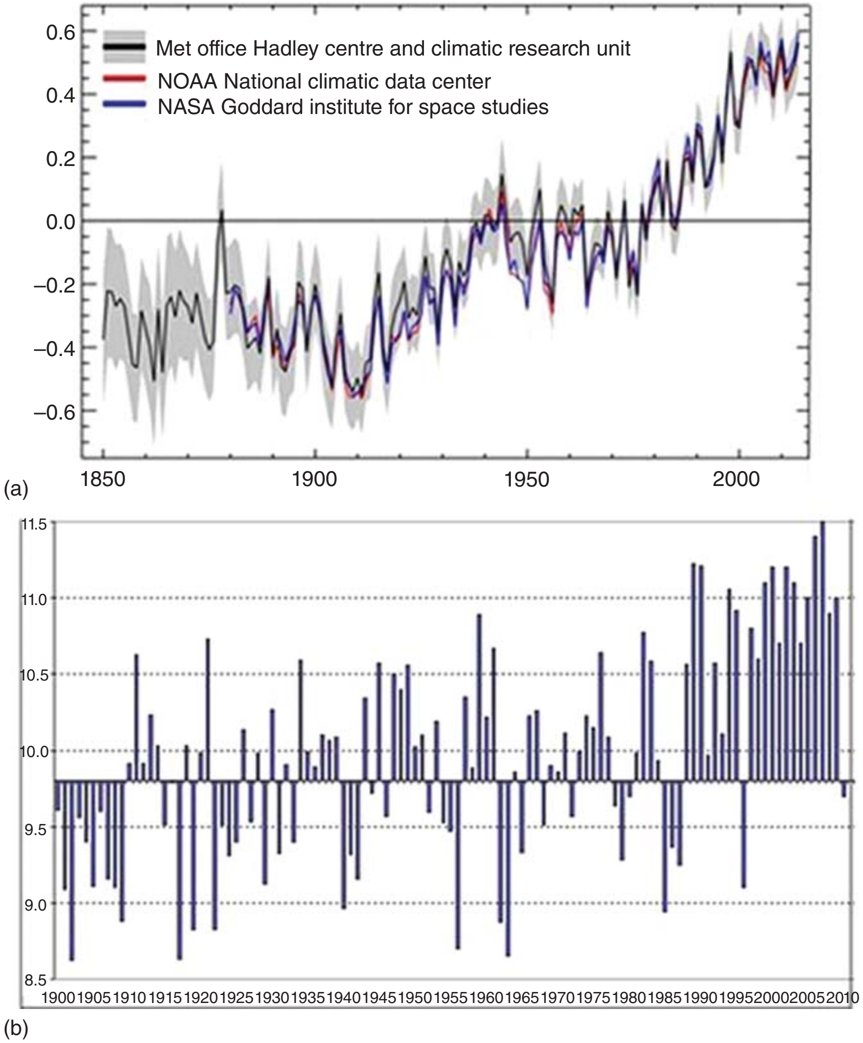

Figure 1.1 Global warming, (a) increase in the world's average annual temperature from 1850 to 2014; (b) the same for Uccle, Belgium.

forecast'. Moreover, global warming combined with the actual measures taken and future measures that will be taken to minimize the emission of global warming gasses, is loading any long-term prediction with uncertainty, see Figure 1.1.

A way to bypass that uncertainty is by using reference values and reference years for any performance check requiring climate data. Many of the facts and trends illustrating this in the book come from the weather station at Uccle, Belgium (50° 51′ north, 4° 21′ east). The large number of observations available there allowed to synthetize what happened over the last century.

1.2 Outdoors

1.2.1 In General

The geographic location is what largely determines the climate: northern or southern latitude, proximity of the sea, presence of a warm or cold sea current, and height above sea level. Of course, also microclimatic factors play. In city centres, the air temperature is on average 4–6 °C higher than at the countryside, while the relative humidity (RH) is lower and the solar radiation less intense, a reality called the urban heat island effect. To illustrate, Table 1.1 lists the monthly mean dry bulb temperatures measured at Uccle and Sint Joost for the period 1901–1930, both weather stations in the Brussels region, with the Uccle one situated in a green area and the Sint Joost one in the city centre.

From the annual down to the daily fluctuations, all are linked to the earth's elliptic orbit around the sun, the earth's inclination, the rotation around its axis and at its surface, more locally, the sequence of low- and high-pressure days. As a consequence, outside the equatorial band with its wet and dry seasons, each year sees a winter, springtime, summer and autumn passing. In addition, each 24 hours, day- and night-time alternate. In temperate and cold climates, high pressure brings warmth in summer and cold in winter, while low pressure cares for more moderate but often wet weather in summer and fresh but wet weather in winter. Anyhow, the last decennia, global warming is changing these patterns. New are more heat waves in summer, sequences of days showing excessive rain fall and warmer winters.

The data needed should focus on the annual cycle, the daily cycle and the daily averages. From a meteorological point of view, the 30-year averages, for the twentieth to twenty-first century 1901–1930, 1931–1960, 1961–1990, 1991–2020, 2021–2050, figure as the annual reference. Due to long-term climate changes induced by solar activity and global warming, the consequence of a still increasing imbalance between GW-gasses released and removed from the atmosphere, the trend to warmer, just mentioned, is real. Relocation of weather stations, more accurate measuring and the way averages are calculated also impact the data. Up to 1930, as daily mean was used the average between the daily minimum and maximum temperature logged by a minimum/maximum mercury thermometer. Today, the air temperature is logged each 10′ and the daily mean is calculated as the average of the 144 values so obtained.

Table 1.1 Monthly average dry bulb temperature at Uccle and Sint Joost, Brussels (°C).

Month	J	F	M	A	M	J	J	A	S	O	N	D
Uccle	2.7	3.1	5.5	8.2	12.8	14.9	16.8	16.4	14.0	10.0	5.2	3.7
Sint Joost	3.8	4.2	6.8	9.4	14.6	16.7	18.7	18.0	15.4	11.2	6.4	4.7

1.2.2 Air Temperature

Calculating the heating and cooling load and estimating related annual end energy use requires knowledge of the outside air temperature, while the loads so quantified fix the size and the investment in the HVAC installation and the energy use as annual cost. From day to day, the air temperature further impacts the heat, air, moisture stress building enclosures endure, while high hourly values increase overheating risk indoors. As imposed by the World Meteorological Organization (WMO), the measuring accuracy in the open field, 1.5 m above grade in a thermometer hut (Figure 1.2) should be ±0.5 °C. Table 1.2 gives the 30-year monthly averages for several weather stations across Europe and North America.

An annual average with one harmonic reflects the table data quite well, although two harmonics, the second on a half a year basis, do better:

$$\textit{Single harmonic}:\ \theta_\mathrm{e} = \bar{\theta}_\mathrm{e} + A_{1,1}\sin\left(\frac{2\pi t}{365.25}\right) + B_{1,1}\cos\left(\frac{2\pi t}{365.25}\right) \tag{1.1}$$

$$\textit{Two harmonics}:\ \begin{aligned}\theta_\mathrm{e} &= \bar{\theta}_\mathrm{e} + A_{2,1}\sin\left(\frac{2\pi t}{365.25}\right) + B_{2,1}\cos\left(\frac{2\pi t}{365.25}\right)\\ &+ A_{2,2}\sin\left(\frac{4\pi t}{365.25}\right) + B_{2,2}\cos\left(\frac{4\pi t}{365.25}\right)\end{aligned} \tag{1.2}$$

In both $\bar{\theta}_\mathrm{e}$ is the annual average and t time.

For three locations, the two harmonics gave as a result (°C, also see Figure 1.3):

	$\bar{\theta}_\mathrm{e}$	$A_{2,1}$	$B_{2,1}$	$A_{2,2}$	$B_{2,2}$
Uccle	9.8	−2.4	−7.4	0.45	−0.1
Kiruna	−1.2	−4.2	−11.6	1.2	0.5
Catania	17.2	−4.1	−6.6	0.8	0.2

Figure 1.2 Thermometer hut.