



Hugo Hens

Applied Building Physics

Ambient Conditions, Building
Performance and Material Properties

Second Edition

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Ambient Conditions, Building Performance
and Material Properties

Second Edition

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Cover: Existing dwelling, retrofitted and now a low energy building

Photo: Hugo Hens

This second edition is the result of a thorough revision of the first edition, published in 2010. Where appropriate, the text was corrected, reworked and extended with new information

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To my wife, children and grandchildren

In remembrance of Professor A. de Grave who introduced Building Physics as a new discipline at the University of Leuven (KULeuven) Belgium in 1952

Preface

Until the first energy crisis of 1973, building physics was a rather dormant field within building engineering, with seemingly limited applicability. While soil mechanics, structural mechanics, building materials, building construction and HVAC were perceived as essential, designers sought advice on room acoustics, moisture tolerance, summer comfort or lighting only when really necessary or when problems arose. Energy was even not a concern, while thermal comfort and indoor environmental quality were presumed to be guaranteed thanks to infiltration, window operation and the heating and cooling system installed. The energy crises of the 1970s, persisting moisture problems, complaints about sick buildings, thermal, visual and olfactory discomfort and the move towards more sustainability changed it all. Societal pressure to diminish energy consumption in buildings without degrading usability activated the notion of performance based design and construction. As a result, today, building physics – and its potential to quantify related performance requirements – is at the forefront of building innovation.

As with all engineering sciences, building physics is orientated towards application, which is why, after the first volume on the fundamentals, this second volume examines performance metrics and requirements as the basis for sound building engineering. Choices have been made, among others to limit the text to the heat, air and moisture performances. Subjects treated are: the outdoor and indoor ambient conditions, the performance concept, performance at the building level, performance metrics at the building enclosure level and the heat-air-moisture material properties of building, insulation and finishing materials. The book reflects 38 years of teaching architectural, building and civil engineers, bolstered by close to 50 years' experience in research and consultancy. Where needed, information from international sources was used, which is why each chapter ends with an extended reading list.

The book uses SI units. Undergraduate and graduate students in architectural and building engineering should benefit, but also mechanical engineers studying HVAC and practising building engineers, who want to refresh their knowledge. The level of discussion presumes that the reader has a sound knowledge of the fundamentals treated in the first volume, along with a background in building materials and building construction.

Acknowledgements

The book reflects the work of many people, not just the author. Therefore, I would like to thank the thousands of students I have had during my 38 years of teaching. They have given me the opportunity to optimize the content. Also, were I not standing on the shoulders of those who precede me, this book would not be what it is. Although I started my career as a structural engineer, my predecessor, Professor Antoine de Grave, planted the seeds that fed my interest in building physics. The late Bob Vos of TNO, the Netherlands, and Helmut Künzl of the Fraunhofer Institut für Bauphysik, Germany, showed the importance of experimental work and field testing for understanding building performance, while Lars Erik Nevander of Lund University, Sweden, taught

that solving problems does not always require complex modelling, mainly because reality in building construction is always much more complex than any model could simulate.

During my four decades at the Laboratory of Building Physics, several researchers and PhD students have been involved. I am very grateful to Gerrit Vermeir, Staf Roels, Dirk Saelens and Hans Janssen, colleagues at the university; also to Jan Carmeliet, professor at the ETH, Zürich; Piet Standaert, principal at Physibel Engineering; Jan Lecompte; Filip Descamps, principal at Daidalos Engineering and part-time professor at the Free University Brussels (VUB); Arnold Janssens, professor at the University of Ghent (UG); Rongjin Zheng, associate professor at Zhejiang University, China; Bert Blocken, full professor at the Technical University Eindhoven (TU/e); Griet Verbeeck, associate professor at the University of Hasselt; and Wout Parys, all of whom contributed through their work. The experiences gained as a structural engineer and building site supervisor at the start of my career, as building assessor over the years, as researcher and operating agent of four Annexes of the IEA, Executive Committee on Energy in Buildings and Communities forced me to rethink my engineering-based performance approach time and again. The many ideas I exchanged and received in Canada and the USA from Kumar Kumaran, the late Paul Fazio, Bill Brown, William B. Rose, Joe Lstiburek and Anton Ten Wolde were also of great help.

Finally, I thank my family, my wife Lieve, who manages to live with a busy engineering professor, my three children who had to live with that busy father and my many grandchildren who do not know that their grandfather is still busy.

Leuven, January 2016

Hugo S.L.C. Hens

Contents

	Preface	xv
0	Introduction	1
0.1	Subject of the book	1
0.2	Building physics vs. applied building physics	1
0.3	Units and symbols.....	2
	Further reading.....	5
1	Outdoor and indoor ambient conditions	7
1.1	Overview.....	7
1.2	Outdoors	8
1.2.1	Air temperature	9
1.2.2	Solar radiation	12
1.2.2.1	Beam radiation	14
1.2.2.2	Diffuse radiation	16
1.2.2.3	Reflected radiation	17
1.2.2.4	Total radiation.....	17
1.2.3	Longwave radiation	18
1.2.4	Relative humidity and (partial water) vapour pressure.....	22
1.2.5	Wind	23
1.2.5.1	Wind speed	24
1.2.5.2	Wind pressure	24
1.2.6	Precipitation and wind-driven rain	26
1.2.6.1	Precipitation	27
1.2.6.2	Wind-driven rain	28
1.2.7	Microclimates around buildings.....	30
1.2.8	Standardized outdoor climate data	31
1.2.8.1	Design temperature	31
1.2.8.2	Reference years.....	31
1.2.8.3	Very hot summer, very cold winter day	31
1.2.8.4	Moisture reference years	31
1.2.8.5	Equivalent temperature for condensation and drying.....	34
1.2.8.6	Monthly mean vapour pressure outdoors	37
1.3	Indoors	37
1.3.1	Air temperatures.....	37
1.3.1.1	In general	37
1.3.1.2	Measured data	38
1.3.2	Relative humidity and vapour pressure	41
1.3.2.1	Vapour release indoors.....	41
1.3.2.2	Measured data	44
1.3.2.3	Indoor climate classes	47
1.3.3	Indoor/outdoor air pressure differentials	50
	Further reading	51

2	Performance metrics and arrays	54
2.1	Definitions.....	54
2.2	Functional demands	54
2.3	Performance requirements	54
2.4	A short history.....	55
2.5	Performance arrays	56
2.5.1	Overview.....	56
2.5.1.1	The built environment.....	56
2.5.1.2	Whole buildings and building assemblies.....	57
2.5.2	In detail	57
2.5.2.1	Functionality	57
2.5.2.2	Structural adequacy.....	57
2.5.2.3	Building physics related quality	60
2.5.2.4	Fire safety.....	60
2.5.2.5	Durability	61
2.5.2.6	Maintenance.....	61
	Further reading.....	62
3	Whole building level.....	63
3.1	Thermal comfort	63
3.1.1	General concepts.....	63
3.1.2	Physiological basis.....	63
3.1.2.1	Exothermic.....	63
3.1.2.2	Homoeothermic	65
3.1.2.3	Autonomic control system	65
3.1.3	Steady state thermal comfort, the physiology based approach.....	66
3.1.3.1	Clothing	66
3.1.3.2	Heat flow between body and ambient	66
3.1.3.3	Comfort equations.....	68
3.1.3.4	Comfort parameters and variables.....	69
3.1.3.5	Thermally equivalent environments and comfort temperatures	69
3.1.3.6	Comfort appreciation	71
3.1.4	Steady state thermal comfort, the adaptive model.....	72
3.1.5	Thermal comfort under non-uniform and under transient conditions.....	74
3.1.5.1	Refined body model.....	74
3.1.5.2	Local discomfort	76
3.1.5.3	Drifts and ramps.....	78
3.1.6	Standard-based comfort requirements.....	80
3.1.7	Comfort related enclosure performance	81
3.2	Health and indoor environmental quality	83
3.2.1	In general	83
3.2.2	Health.....	84
3.2.3	Definitions.....	85
3.2.4	Relation between pollution outdoor and indoors	85
3.2.5	Process-related contaminants	86
3.2.5.1	Dust, vapour, smoke, mist and gaseous clouds.....	86

3.2.5.2	Fibres	86
3.2.5.3	Ozone	87
3.2.6	Building, insulation and finishing material related contaminants	87
3.2.6.1	(Semi) volatile organic compounds ((S)VOCs)	87
3.2.6.2	Formaldehyde (HCHO)	88
3.2.6.3	Phthalates	89
3.2.6.4	Pentachlorinephenols	89
3.2.7	Soil-related radon as contaminant	89
3.2.8	Combustion related contaminants	91
3.2.8.1	Carbon monoxide	91
3.2.8.2	Nitrous dioxide (NO ₂)	91
3.2.9	Bio-germs	92
3.2.9.1	Viruses	92
3.2.9.2	Bacteria	92
3.2.9.3	Mould	92
3.2.9.4	Dust mites	95
3.2.9.5	Insects	95
3.2.9.6	Rodents	96
3.2.9.7	Pets	96
3.2.10	Human related contaminants	96
3.2.10.1	Carbon dioxide (CO ₂)	97
3.2.10.2	Water vapour	97
3.2.10.3	Bio-odours	97
3.2.10.4	Tobacco smoke	98
3.2.11	Perceived indoor air quality	99
3.2.11.1	Odour	99
3.2.11.2	Indoor air enthalpy	101
3.2.12	Sick building syndrome (SBS)	102
3.2.13	Contaminant control	103
3.2.13.1	Minimizing emission	103
3.2.13.2	Ventilation	103
3.2.13.3	Air cleaning and personal protective measures	109
3.3	Energy efficiency	110
3.3.1	In general	110
3.3.2	Some statistics	111
3.3.3	End energy use in buildings	112
3.3.3.1	Lighting and appliances	112
3.3.3.2	Domestic hot water	116
3.3.3.3	Space heating, cooling and air conditioning	116
3.3.4	Space heating	116
3.3.4.1	Terminology	116
3.3.4.2	Steady state heat balance at zone level	118
3.3.4.3	Whole building steady state heat balance	123
3.3.4.4	Heat gain utilization efficiency	123
3.3.4.5	Annual end use for heating	125

3.3.4.6	Protected volume as one zone	125
3.3.5	Residential buildings, parameters shaping the annual net heating demand	125
3.3.5.1	Overview.....	125
3.3.5.2	Outdoor climate	126
3.3.5.3	Building use	127
3.3.5.4	Building design and construction.....	135
3.3.6	Residential buildings, parameters fixing net cooling demand	144
3.3.7	Residential buildings, gross energy demand, end energy use	146
3.3.8	Residential buildings ranked in terms of energy efficiency.....	146
3.3.8.1	Insulated.....	146
3.3.8.2	Energy efficient.....	146
3.3.8.3	Low energy	147
3.3.8.4	Passive	147
3.3.8.5	Near zero energy	147
3.3.8.6	Net zero energy	147
3.3.8.7	Net plus energy	147
3.3.8.8	Energy autarkic	148
3.3.9	Non-residential buildings, net and gross demand, end and primary energy use	148
3.3.9.1	In general	148
3.3.9.2	School retrofits as an exemplary case.....	148
3.4	Durability	152
3.4.1	In general	152
3.4.2	Loads.....	153
3.4.3	Damage patterns.....	153
3.4.3.1	Decrease in thermal quality.....	153
3.4.3.2	Decrease in strength and stiffness	154
3.4.3.3	Stress, strain, deformation and cracking.....	154
3.4.3.4	Biological attack	158
3.4.3.5	Frost damage.....	160
3.4.3.6	Salt attack.....	163
3.4.3.7	Chemical attack.....	167
3.4.3.8	Corrosion	168
3.5	Economics.....	170
3.5.1	Total and net present value	170
3.5.2	Optimum insulation thickness.....	171
3.5.3	Whole building optimum	173
3.5.3.1	Methodology	173
3.5.3.2	Example	174
3.6	Sustainability	178
3.6.1	In general	178
3.6.2	Life cycle inventory and analysis.....	179
3.6.2.1	Definition	179
3.6.2.2	Some criteria	181
3.6.2.3	Whole energy use and minimal environmental load	181

3.6.2.4	Recycling	182
3.6.3	High performance buildings.....	182
	Further reading.....	186
4	Envelope and fabric: heat, air and moisture metrics	195
4.1	Introduction.....	195
4.2	Airtightness	195
4.2.1	Air flow patterns	195
4.2.2	Performance requirements	197
4.2.2.1	Air infiltration and exfiltration	197
4.2.2.2	Inside air washing, wind washing and air looping	197
4.3	Thermal transmittance.....	198
4.3.1	Definitions.....	198
4.3.1.1	Opaque envelope assemblies above grade	198
4.3.1.2	Whole envelope	199
4.3.2	Basis for requirements.....	199
4.3.2.1	Envelope parts.....	199
4.3.2.2	Whole envelope	200
4.3.3	Examples of requirements.....	200
4.3.3.1	Envelope parts.....	200
4.3.3.2	Whole envelopes.....	200
4.4	Transient thermal response	204
4.4.1	Properties of importance	204
4.4.2	Performance requirements	206
4.4.3	Consequences for the building fabric.....	206
4.5	Moisture tolerance.....	208
4.5.1	In general	208
4.5.2	Construction moisture	208
4.5.2.1	Definition	208
4.5.2.2	Performance requirements	208
4.5.2.3	Consequences for the building fabric.....	209
4.5.3	Rain.....	210
4.5.3.1	The problem.....	210
4.5.3.2	Performance requirements	212
4.5.3.3	Modelling.....	213
4.5.3.4	Consequences for the building envelope.....	215
4.5.4	Rising damp	217
4.5.4.1	Definition	217
4.5.4.2	Performance requirements	217
4.5.4.3	Modelling.....	218
4.5.4.4	Avoiding or curing rising damp	221
4.5.5	Pressure heads.....	222
4.5.5.1	Definition	222
4.5.5.2	Performance requirements	223
4.5.5.3	Modelling.....	223
4.5.5.4	Protecting the building fabric.....	223

4.5.6	Accidental leaks	224
4.5.7	Hygroscopic moisture	224
4.5.7.1	Definition	224
4.5.7.2	Performance requirements	226
4.5.7.3	Modelling.....	226
4.5.7.4	Consequences for the building fabric.....	226
4.5.8	Surface condensation	226
4.5.8.1	Definition	226
4.5.8.2	Performance requirements	226
4.5.8.3	Modelling.....	227
4.5.8.4	Consequences for the envelope.....	228
4.5.9	Interstitial condensation	228
4.5.9.1	Definition	228
4.5.9.2	Modelling.....	229
4.5.9.3	Performance requirements	232
4.5.9.4	Consequences for the building envelope.....	233
4.5.9.5	Remark.....	234
4.5.10	All moisture sources combined.....	234
4.5.10.1	Modelling.....	234
4.5.10.2	Performance requirements	234
4.5.10.3	Why models still have limitations	236
4.5.10.4	Three examples where full models were hardly of any help	240
4.6	Thermal bridges	244
4.6.1	Definition	244
4.6.2	Performance requirements	245
4.6.3	Consequences for the envelope.....	245
4.7	Contact coefficients.....	245
4.8	Hygrothermal stress and strain	246
4.9	Transparent parts: solar transmittance.....	247
4.9.1	Definition	247
4.9.2	Performance requirements	247
4.9.3	Consequences for the envelope.....	248
	Further reading.....	248
5	Timber-framed outer wall as an exemplary case	253
5.1	In general	253
5.2	Assembly	253
5.3	Heat, air, moisture performances	253
5.3.1	Airtightness.....	253
5.3.2	Thermal transmittance.....	255
5.3.3	Transient response	257
5.3.4	Moisture tolerance.....	257
5.3.4.1	Construction moisture.....	257
5.3.4.2	Rain control.....	257
5.3.4.3	Rising damp	258
5.3.4.4	Hygroscopic moisture and surface condensation	258

5.3.4.5	Interstitial condensation	258
5.3.4.6	More advanced modelling.....	264
5.3.4.7	Thermal bridging	265
6	Heat-air-moisture material properties	266
6.1	Introduction.....	266
6.2	Dry air and water.....	267
6.3	Materials, thermal properties.....	268
6.3.1	Definitions.....	268
6.3.2	Design values	268
6.3.2.1	Non-certified materials (ISO 10456).....	268
6.3.2.2	Design values (NBN B62-002 (2001))	272
6.3.3	Measured data	281
6.3.3.1	Building materials	281
6.3.3.2	Insulation materials	287
6.4	Materials, air-related properties.....	290
6.4.1	Design values.....	290
6.4.1.1	Measured values.....	291
6.5	Materials, moisture properties.....	304
6.5.1	Design values for the vapour resistance factor (ISO 10456).....	304
6.5.1.1	Building and finishing materials	304
6.5.1.2	Insulation materials	309
6.5.2	Measured values.....	309
6.5.2.1	Building materials	310
6.5.2.2	Insulation materials	323
6.5.2.3	Finishes	324
6.5.2.4	Miscellaneous	326
6.5.2.5	Vapour retarders.....	327
6.6	Surfaces, radiant properties	328
	Further reading.....	329
 Appendix A: Solar radiation for Uccle, Belgium, 50° 51' north, 4° 21' east		 331

0 Introduction

0.1 Subject of the book

This is the second volume in a series of four books:

- Building Physics: Heat, Air and Moisture
- **Applied Building Physics: Boundary Conditions, Building Performance and Material Properties**
- Performance Based Building Design: from below grade construction to cavity walls
- Performance Based Building Design: from timber-framed construction to partition walls.

Subjects discussed in this volume are: outdoor and indoor ambient conditions, performance concept, performance at the urban, building and building envelope level and the heat–air–moisture material properties. The book figures as a hinge between ‘Building Physics: Heat, Air and Moisture’ and the two volumes on ‘Performance Based Building Design’. Although it does not deal with acoustics and lighting in detail, they form an integral part of the performance arrays and are mentioned as and when necessary.

The outdoor and indoor ambient conditions and related design approaches are highlighted in Chapter 1. Chapter 2 advances the performance concept with its hierarchical structure, going from the urban environment across the building and building assemblies down to the layer and material level. In Chapter 3, the main heat, air and moisture linked performances at the building level are discussed, while Chapter 4 analyses related metrics of importance for a well-performing building envelope and fabric. Chapter 5 deals with timber-framed walls as an exemplary case, and Chapter 6 lists the main heat, air and moisture material property values needed to predict the response of building assemblies.

A performance approach helps designers, consulting engineers and contractors to better ensure building quality. Of course, physical integrity is not the only factor adding value to buildings. Functionality, spatial quality and aesthetics – aspects belonging to the architect’s responsibility – are of equal importance, though they should not cause us to neglect the importance of an overall outstanding building performance.

0.2 Building physics vs. applied building physics

Readers who would like to know more about the engineering field ‘building physics’, its importance and history, should consult the first volume, ‘Building Physics: Heat, Air and Moisture’. It might seem that adding the term ‘applied’ to this second volume is unnecessary – building physics is, by definition, applied. Rather, the word stresses the focus of this book: entirely directed towards its use in building design and construction.

0.3 Units and symbols

The book uses the SI system (internationally mandated since 1977). Its base units are 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:

Force:	newton (N);	$1 \text{ N} = 1 \text{ kg} \cdot \text{m} \cdot \text{s}^{-2}$
Pressure:	pascal (Pa);	$1 \text{ Pa} = 1 \text{ N/m}^2 = 1 \text{ kg} \cdot \text{m}^{-1} \cdot \text{s}^{-2}$
Energy:	joule (J);	$1 \text{ J} = 1 \text{ N} \cdot \text{m} = 1 \text{ kg} \cdot \text{m}^2 \cdot \text{s}^{-2}$
Power:	watt (W);	$1 \text{ W} = 1 \text{ J} \cdot \text{s}^{-1} = 1 \text{ kg} \cdot \text{m}^2 \cdot \text{s}^{-3}$

For symbols, the ISO-standards (International Standardization Organization) are followed. If a quantity is 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 0.1 List with symbols and quantities.

Symbol	Meaning	SI units
<i>a</i>	Acceleration	m/s^2
<i>a</i>	Thermal diffusivity	m^2/s
<i>b</i>	Thermal effusivity	$\text{W}/(\text{m}^2 \cdot \text{K} \cdot \text{s}^{0.5})$
<i>c</i>	Specific heat capacity	$\text{J}/(\text{kg} \cdot \text{K})$
<i>c</i>	Concentration	$\text{kg}/\text{m}^3, \text{g}/\text{m}^3$
<i>e</i>	Emissivity	—
<i>f</i>	Specific free energy	J/kg
	Temperature ratio	—
<i>g</i>	Specific free enthalpy	J/kg
<i>g</i>	Acceleration by gravity	m/s^2
<i>g</i>	Mass flux	$\text{kg}/(\text{m}^2 \cdot \text{s})$
<i>h</i>	Height	m
<i>h</i>	Specific enthalpy	J/kg
<i>h</i>	Surface film coefficient for heat transfer	$\text{W}/(\text{m}^2 \cdot \text{K})$
<i>k</i>	Mass related permeability (mass could be moisture, air, salt . . .)	s
<i>l</i>	Length	m
<i>l</i>	Specific enthalpy of evaporation or melting	J/kg

Table 0.1 (Continued)

Symbol	Meaning	SI units
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	$J/(kg \cdot K)$
t	Time	s
u	Specific latent energy	J/kg
v	Velocity	m/s
w	Moisture content	kg/m^3
x,y,z	Cartesian coordinates	m
A	Water sorption coefficient	$kg/(m^2 \cdot s^{0.5})$
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
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	$kg/(m \cdot s \cdot K)$
K	Mass permeance	s/m
K	Force	N
L	Luminosity	W/m^2
M	Emittance	W/m^2
P	Power	W
P	Thermal permeance	$W/(m^2 \cdot K)$
P	Total pressure	Pa
Q	Heat	J
R	Thermal resistance	$m^2 \cdot K/W$

Table 0.1 (Continued)

Symbol	Meaning	SI units
R	Gas constant	J/(kg · K)
S	Entropy	J/K
S	Saturation degree	—
T	Absolute temperature	K
T	Period (of a vibration or a wave)	s, days, . . .
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	—
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
Φ	Heat flow	W