
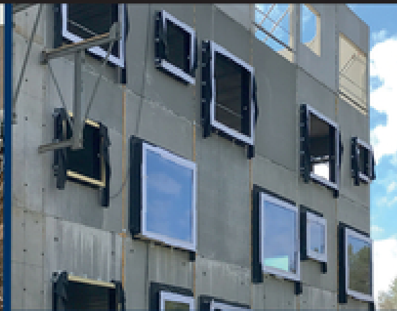

Hugo Hens

Performance-Based Building Design

From Below Grade to Floors, Walls, Roofs, Windows and Finishes

Second Edition

Ernst & Sohn
A Wiley Brand
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Hugo Hens

Second, revised edition

Ernst & Sohn
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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Hugo Hens

Building Physics – Heat, Air and Moisture

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- combines theory with typical building engineering practice
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- with solved problems and examples
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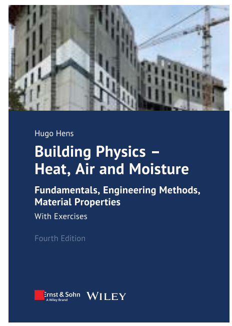

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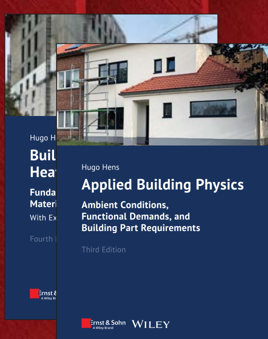

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Contents

Preface

Before the energy crises of the 1970s, designing buildings based on performance was hardly an issue. It was an art. However, together with the move towards more energy efficiency after 1973, the interest in handling a performance approach grew. The book "Applied Building Physics" forwarded an overall rationale at the whole building and building assembly level, for the last with emphasis on the heat, air, moisture requirements and metrics.

This third book in this series of three dealing with building physics and its application looks to the impact a performance requirement-linked approach has on building design and construction. It starts with a resumption of what is expected from buildings, followed by discussing a range of materials needed to guarantee a correct heat, air and moisture response. Then, the focus turns to preparing the building site, the excavations needed, the foundations, the below-grade parts and spaces, the structural systems commonly used, the floors, different types of outer walls, different types of roof assemblies, the glazing, windows, outer doors, glass façades, inside walls, balconies, all kind of shafts, chimneys, stairs, timber-frame construction, wall, floor and ceiling finishes. The whole book ends with looking to the risks deficiencies may cause.

Each time again, not only the heat, air and moisture-related metrics but also structural integrity, acoustics, durability, fire safety, maintenance, sustainability and buildability are discussed. To do so, besides years of teaching, research and curing damage cases due to failing performance, a bunch of national and international sources and literature has been consulted, which is why each chapter ends with an extended has read list.

The book uses SI units. It could be of help for undergraduate and graduate students in architectural and building engineering, although also practicing building engineers, who want to refresh their knowledge, may benefit. It is presumed that the reader has some background in structural engineering, building physics, building materials and building construction.

Acknowledgements

The book reflects the work of many, not only of the author. Therefore, we thank the thousands of students we had during 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. Although we started our career as a structural engineer, our predecessor Professor *Antoine de Grave* planted the seeds that fed the interest in building physics. The late *Bob Vos* of TNO, the Netherlands, and *Helmut Künzel* of the Fraunhofer Institut für Bauphysik (IBP), Germany, showed the importance of experimental work and field testing to understand building performance, while the late *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 KU Leuven, 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 and professor emeritus now, to *Staf Roels*, *Dirk Saelens*, *Hans Janssen* and *Bert Blocken*, who succeeded me as professors at the unit.

The experiences gained as a structural engineer and building site supervisor for a medium-size architectural office the first 4 years of my career, as building assessor during some 50 years, as researcher and as operating agent of four IEA, Executive Committee 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 USA with Kumar Kumaran of NRC, the late *Paul Fazio* of Concordia University in Montreal, *Bill Brown*, *William B. Rose* of the University of Illinois in Urbana-Champaign, *Joseph 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, October 2023 *Hugo S.L.C. Hens*

About the Author

Dr Ir. Hugo S.L.C. Hens is an emeritus professor at 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 the operating agent of Annexes 14, 24, 32 and 41 of the IEA EXCO on Energy in Buildings and Communities. He was holder of the prestigious Franqui Chair at the Free University Brussels (VUB) in 2006 and is a fellow of the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE).

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 looking to performance-based building design are:

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

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, see Table 0.1

Table 0.1 List with symbols and quantities.

Symbol	Meaning	Units
a	Acceleration	m/s^2
a	Thermal diffusivity	m^2/s
b	Thermal effusivity	$\text{W}/(\text{m}^2\ \text{K s}^{0.5})$
c	Specific heat capacity	$\text{J}/(\text{kg K})$
c	Concentration	kg/m^3, g/m^3
e	Emissivity	—

(Continued)

Table 0.1 List with symbols and quantities. (Continued)

Symbol	Meaning	Units
f	Specific free energy	J/kg
f_{hi}	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 may be moisture, air, salt …)	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 coordinates	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
G	Free enthalpy	J
G	Mass flow (mass = vapour, water, air and 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

Table 0.1 List with symbols and quantities. (Continued)

Symbol	Meaning	Units
M	Emittance	W/m^2
N	Vapour diffusion constant	s^{-1}
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}
δ	Vapour conductivity	s
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

Table 0.2 List with suffixes and notations.

Symbol	**Meaning**
Indices	
A	Air
c	Capillary, convection
e	Outside, outdoors
h	Hygroscopic
i	Inside, indoors
cr	Critical
CO_2, SO_2	Chemical symbol for gasses
m	Moisture, maximal
r	Radiant, radiation
sat	Saturation
s	Surface, area, suction
rs	Resulting
v	Water vapour
w	Water
ϕ	Relative humidity
Notation	
[], bold	Matrix, array, value of a complex number
Dash (for example: $\overline{a}$)	Vector