Hugo Hens

Building Physics – Heat, Air and Moisture

Fundamentals, Engineering Methods, Material Properties

With Exercises

Fourth Edition

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Fundamentals, Engineering Methods, Material Properties and Exercises

Hugo Hens

Fourth, revised Edition

Ernst & Sohn
A Wiley Brand

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Cover: New Bioscience Centre of the KULeuven, Belgium, under construction

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at http://dnb.d-nb.de.

Print ISBN: 978-3-433-03422-4
ePDF ISBN: 978-3-433-61183-8
oBook ISBN: 978-3-433-61182-1
ePub ISBN: 978-3-433-61184-5

Coverdesign: Petra Franke/Ernst & Sohn GmbH using a design by Sophie Bleifuß, Berlin, Germany
Typesetting: Straive, Chennai, India

Printing:
Binding:

Printed on acid-free paper.

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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- **applicable independent of national or other standard requirement**

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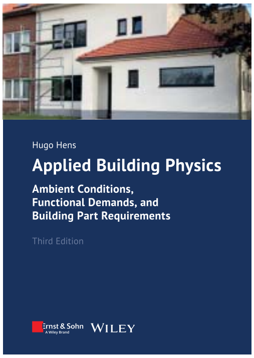

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3. revised edition · 9 / 2023 ·
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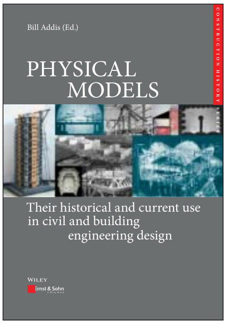
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Preface

Until the energy crisis of 1973, building physics was a dormant beauty within building engineering, with seemingly limited applicability in practice. While soil mechanics, structural mechanics, construction materials, building itself and heating, ventilation, air conditioning (HVAC) were perceived as essential, designers only demanded advice on room acoustics, moisture tolerance, summer overheating or lighting when really needed or when in newly occupied buildings problems arose. Energy was no concern, while thermal comfort and indoor environmental quality were presumably guaranteed thanks to air infiltration, window opening and the HVAC system. 1973 and the energy crisis of 1979, persisting moisture problems, complaints about sick buildings, thermal, visual and olfactory discomfort, the move to more sustainability and, since the 1980s, global warming with today the quest for carbon neutrality changed this all. Besides, the pressure to diminish energy use and carbon emitted without degrading building usability more than activated the importance of a performance-based building and building part design and construction. As a result, building physics and related potentiality to quantify performances moved to the frontline of building innovation.

Like all engineering sciences, building physics is oriented towards application. This demands a sound knowledge of the basics in each of its branches: heat and mass transfer, acoustics, lighting, energy and indoor environmental quality. Advancing the basics on heat and mass transfer is the main objective of this volume, be it for mass flow limited to air, water vapour and moisture. In the introduction, building physics as a discipline is sketched and its history is given. The first chapter then concentrates on heat transport, with conduction, convection and radiation as main topics, followed by common concepts linked to and applications in the field of building and building part or assembly design and construction. The second chapter treats mass transport, with air, water vapour and moisture as the main topics. Also here, attention goes to the concepts and applications related to whole buildings and building parts. The third chapter discusses combined heat, air and moisture transport. All chapters end with exercises. In the fourth chapter, standard lists with heat, air and moisture material properties and measured data are given.

This content is the result of 38 years of teaching 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 and 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 list of references and further reading. The book uses SI units. It could be of help for undergraduate and graduate students in architectural and building engineering, although also students in mechanical engineering studying HVAC and practising building engineers, who want to refresh their knowledge, may benefit. Presumed is the reader has a sound knowledge of calculus and differential equations along with a background in physics, thermodynamics, hydraulics, construction materials and building design and construction.

Compared to the third edition published in 2017, the book has been reorganised, corrected, revised and expanded where appropriate for this fourth edition.

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. Also, the book should not 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 demands 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, professor emeritus now, to Staf Roels, Dirk Saelens, Hans Janssen and Bert Blocken, who succeeded me as professors at the unit.

The experience gained the first 4 years of my career as a structural engineer and building site supervisor for a medium-sized architectural office, as building assessor during some 50 years, and 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 grand children.

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

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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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 building physics are:

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

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.

Table 1 List with symbols and quantities.

Symbol	Meaning	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	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 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	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
W	Work	J
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)
λ	Wavelength	m
μ	Vapour resistance factor	–
ν	Kinematic viscosity	m^2/s
ρ	Density	kg/m^3

(Continued)

Table 1 List with symbols and quantities. (Continued)

Symbol	Meaning	Units
ρ	Reflectivity	–
σ	Surface tension	N/m
ω	Thermal pulsation	J/(m^2.K)
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 2 List with currently used suffixes.

Symbol	Meaning	Symbol	Meaning
Indices			
A	Air	m	Moisture, maximal
c	Capillary, convection	r	Radiant, radiation
e	Outside, outdoors	sat	Saturation
h	Hygroscopic	s	Surface, area, suction
i	Inside, indoors	rs	Resulting
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 (ex..:$\bar{a}$)	Vector

0

Introduction

0.1 Subject of the Book

This is the first 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

Discussed are the physics governing the heat, air, moisture, also called the hygrothermal response of materials, building assemblies and whole buildings with added a chapter with tables and measured values concerning the heat, air, moisture properties of building, insulating and finishing materials. The second volume on Applied Building Physics in turn deals with the ambient conditions to be considered, the performance requirements at the whole building and the heat, air, moisture requirements and metrics at the building assembly's level. The third volume on 'Performance-Based Building Design: from Below Grade over Floors, Walls, Roofs, and Windows to Finishes' finally document the overall structural, building physics, fire safety, economics and sustainability-related performance metrics, which help realising high-quality buildings.

By the way, the notion 'Building Physics' is hardly used in the Anglo-Saxon world. 'Building science', the field is called there. A difference with Building Physics is that Building Science does not include acoustics and lighting and focuses more directly on practice-related issues.

0.2 Building Physics?

0.2.1 Definition

As an applied science, 'Building Physics' studies the hygrothermal, acoustical and visual performances at the material, building assembly, space, whole building

Building Physics – Heat, Air and Moisture: Fundamentals, Engineering Methods, Material Properties and Exercises, Fourth Edition. Hugo Hens.

and built environment level, the last then under the name ‘Urban Physics’. The constraints faced are user demands related to overall comfort, healthiness and safety, several architectural restrictions, durability issues, economical demands and sustainability-related challenges with, given the reality of a global warming, energy use and decarbonisation as key concerns.

The term ‘applied’ indicates that Building Physics is oriented to the application with the theory as tool, not as purpose. Topics tackled in the heat, air, moisture subfield are airtightness, thermal insulation, transient thermal response, moisture tolerance, thermal bridging, salt transport, temperature and humidity-induced stresses and strains, net energy demand, gross energy demand, end energy use, ventilation, thermal comfort and indoor air quality.

In the building acoustics subfield, the topics discussed include acoustical comfort, the air- and structure-borne noise transmission through outer walls, floors, partitions, party walls, glazing and roofs, room acoustics and the abatement of installation and ambient noise. In the lighting subfield, the topics handled concern, daylighting, artificial lighting and the impact both have on human wellbeing and end energy use.

Urban physics finally looks among others to the thermal, acoustical, visual and wind-induced comfort issues outdoors, the wind and rain patterns on buildings in cities, the spread of air pollution, the heat island effect and the energy management at the city level.

0.2.2 Constraints

0.2.2.1 Comfort

Comfort can be defined as the state of mind that expresses satisfaction with the conditions in the direct environment. Attaining a comfortable situation there depends on the human need to feel thermally, acoustically and visually at ease: neither too cold nor too warm, not too noisy, no unacceptable contrasts in luminance, etc.

Thermal comfort engages the human physiology and psychology. As exothermal creatures with a core temperature of $\approx 37\,^\circ\mathrm{C}$ (310 K), humans have to lose heat to the environment under all circumstances, be it by conduction, convection, radiation, perspiration, transpiration or breathing. The air temperature, its gradient, the radiant temperature, the radiant asymmetry, the contact temperatures, the air velocity relative to the body, the air turbulence and the relative humidity (RH) in the direct environment are the parameters that determine how much heat will be exchanged. For a given activity and clothing, certain combinations will be quoted as comfortable, others as uncomfortable, although adaptation plays.

Acoustical comfort is strongly connected to mental awareness. Physically, young adults hear frequencies between 20 and 16 000 Hz. But, as humans scale sound intensity logarithmically with a better hearing for higher frequencies, a logarithmic quantity has been introduced to judge sound and noise: the decibel (dB), with 0 dB as audibility limit and 140 dB as pain threshold. Undesired noises produced by neighbours, traffic, industry and aircraft may give complaints and are often the cause of protracted disputes.

Visual comfort finally combines mental and physical facts. Physically, the eyes see electromagnetic waves having wavelengths between 0.38 and 0.78 μm with a maximum sensitivity around 0.58 μm, the yellow-green light, while the overall sensitivity adapts to the mean luminance, up to 10 000 times higher when dark than during daytime, although the eyes perceive this logarithmically. Besides, too large differences in brightness disturb and a well-adapted lighting creates cosiness.

0.2.2.2 Health and Well-being

Not only the absence of illness, but also no neuro-vegetative complaints, no psychological stress and no physical unease determines what's perceived as healthiness and well-being. Dust, fibres, (S)VOCs, radon, CO, viruses and bacteria, moulds and mites, too much noise, thermal discomfort, to large luminance contrasts, all are menacing factors.

0.2.2.3 Architecture and Materials

Applying the tools and knowledges building physics offers always faces architectural and material-linked constraints. While façade and roof form, aesthetics and the materials chosen shape buildings, at the same time their design must satisfy a huge set of performance metrics. Conflicting structural and physical issues often complicate solutions. Necessary thermal cuts may interfere with the strength and stiffness demands connections have to ensure. Being waterproof and vapour permeable at the same time is not always compatible. Necessary acoustic absorption could oppose vapour tightness. Some materials may not turn and stay wet, etc.

0.2.2.4 Economy

Not only the construction costs must respect the budget available but also the total present value, an economic parameter that adds the initial investment to the costs of end energy consumed, maintenance, upgrades and replacements over the usage period transposed to today, should preferentially be the lowest achievable. A building designed and constructed according to the performance metrics advanced by building physics and other engineering fields will generally generate a lower total present value than if done without such fitness for purpose approach.

0.2.2.5 Sustainability

From a human welfare point of view, it should be a blessing if the new and renovated buildings, that a worldwide growing population needs, could offer a better comfort and good indoor environmental quality (IEQ). However, related ever-growing energy need, if fossil based, will have worrying consequences in terms of global warming. At the same time, building use gives other solid, liquid and gaseous waste, whereby NO_2, if heating with fossil fuels, is of growing concern.

The pursuit for more sustainability is reflected in a growing use of life cycle inventory and analysis tools (LCIA) plus certification instruments. In LCIA, buildings are evaluated on their environmental impact 'cradle to cradle', i.e., from material and component production over construction and occupancy to demolition with related reuse of materials and components. Per step, all material, energy and water inflows and all polluting outflows are quantified and the impact on human well-being and environment assessed. Certification instruments instead focus on the fitness for purpose results that new and renovated buildings or urban environments guarantee.

0.3 Importance?

The necessity to create a comfortable indoors that protects people from the fickle of the weather gave birth to the knowledge field called Building Physics. Basic thereby is that an appropriate design should annihilate when needed the impact of the various loads on the building enclosure, take sun, rain, wind, noise, temperature, vapour and air pressure differentials, but use these when aiding comfort and well-being, while demanding as little energy as doable.

In earlier days, experience was guiding. Former generations only had a limited range of materials available – wood, straw, loam, brick, natural stone, lead, copper, cast iron, and blown glass – for which how to use them evolved over centuries. Standard solutions for roofs, roof edges and outer walls took shape. From the size and orientation of the windows to the overall layout, everything was conceived to limit the heating needs in winter and overheating in summer. Because outside the urban centres, deafening noisy sources were scarce, at the countryside sound was hardly a problem, while a lifestyle adapted to the seasons saved energy. Came the industrial revolution. New materials such as steel, reinforced concrete, prestressed concrete, nonferrous metals, synthetics, bitumen and insulation inundated the market. Advanced technologies turned existing materials into innovative products, take cast and floated glass, rolled metals, pressed bricks, etc. Structural mechanics allowed any span. Energy, first coal, later petroleum, natural gas and electricity, was so cheap that efficient use was no issue. Building exploded and turned into a demand/supply market. The result was mass construction, often of dubious quality.

The early twentieth century saw a ‘modern school’ of architects emerging, who experimented with alternative structural solutions, simple details and new materials. The buildings they designed were neither energy efficient nor of good building physical quality. Typical was the profuse use of steel, concrete and glass, all difficult materials from a heat, air, moisture point of view. Overhangs and façade reliefs were banned. As a consequence, their buildings suffered from obvious failures requiring premature restoration, what a sound knowledge of building physics could have prevented. Figure 0.1 shows the house Guiette, designed by Le Corbusier, built in 1926, before and after renovation in 1987. Just built, the outer walls and low-sloped roof lacked any thermal insulation, which in winter gave surface condensation against the ceiling in the sleeping rooms under the roof, with water dripping down in the beds. The house got damaged during World War 2 and was sloppy restored after, whereby the originally white stuccoed outer walls got covered with grey slates, see figure. The renovation saw the roofs insulated and against the outer walls the application of a white stuccoed outside insulation. Before, heating the whole to a temperature of 18 °C demanded ≈16 000 l of fuel a year. After, if fully heated some 6500 m^3