

**Hugo Hens**

# **Applied Building Physics**

**Boundary Conditions, Building  
Performance and Material Properties**



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Boundary Conditions,  
Building Performance and  
Material Properties



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Printed in the Federal Republic of Germany.

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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 Louvain, K. U. Leuven, Belgium in 1952*

# Preface

## Overview

Until the first energy crisis of 1973, building physics existed as a shadow field in building engineering, with seemingly limited applicability. While soil mechanics, structural mechanics, building materials, building construction and HVAC were seen as essential, designers only sought advice on room acoustics, moisture tolerance, summer comfort or lighting when really needed or when, after construction, problems arose. Energy was not even a concern, while indoor environmental quality was presumably guaranteed thanks to ever present infiltration, window ventilation and the heating system. The energy crises of the seventies, persisting moisture problems, complaints about sick buildings, thermal, visual and olfactory discomfort, and the move towards more sustainability changed that all. The societal pressure to diminish energy consumptions in buildings without degrading usability acted as a trigger that activated the whole notion of performance based design and construction. As a result, building physics and its potential to quantify performances was suddenly pushed to the forefront of building innovation.

As all engineering sciences, building physics is oriented towards application, which is why, after a first book on fundamentals, this second volume examines the performance rationale and performance requirements as a basis for sound building engineering. Choices have been made, among others to limit the text to a thorough discussion of the heat-air-moisture performances only. The subjects treated are: the climate outdoors and conditions indoors, the performance concept, performances at the building level, performances at the building enclosure level and heat-air-moisture material properties. The book incorporates thirty five years of teaching architectural, building and civil engineers, bolstered by forty years of experience, research and consultancy. Where needed information and literature from international sources has been used, which is indicated by an extensive list with references at the end of each chapter.

The book is written in SI-units. It should be usable for undergraduate and graduate students in architectural and building engineering, although mechanical engineers studying HVAC, and practising building engineers who want to refresh their knowledge, will also benefit from it. The level of presentation assumes that the reader has a sound knowledge of the basics treated in the first book on fundamentals, along with a background in building materials and building construction.

## Acknowledgments

A book of this magnitude reflects the work of many, not only that of the author. Therefore, I want first of all to thank my thousands of students. They gave us the opportunity to test the content and helped us in upgrading with the corrections they proposed and the experience they offered in pointing out which parts should be better explained.

The book could not have been written in this form without standing on the shoulders of those who preceded me. Although I started my career as a structural engineer, my predecessor, Professor Antoine de Grave planted the seeds that slowly nurtured my interest in building physics and its applications. The late Bob Vos of TNO, the Netherlands, and Helmut Künzel 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, showed that application does not always correspond to extended

modelling, mainly because reality in building construction is much more complex than any model may be.

During the four decades at the Laboratory of Building Physics, several researchers and PhD-students got involved. I am very grateful to Gerrit Vermeir, Staf Roels and Dirk Saelens who became colleagues at the university; to Jan Carmeliet, professor at the ETH-Zürich; to Piet Standaert, a principal at Physibel Engineering; to Jan Lecompte at Bekaert NV; Filip Descamps, a principal at Daidalos Engineering and part-time professor at the Free University Brussels (VUB); Arnold Janssens, professor at the University of Ghent (UG); Hans Janssen, associate professor at the Technical University Denmark (TUD); Rongjin Zheng, associate professor at Zhejiang University, China, and Bert Blocken, associate professor at the Technical University Eindhoven (TU/e), who all contributed by their work. The experiences gained by operating four Annexes of the IEA, Executive Committee on Energy Conservation in Buildings and Community Systems, also forced me to rethink the performance approach. The many ideas I exchanged in Canada and the USA with Kumar Kumaran, Paul Fazio, Bill Brown, William B. Rose, Joe Lstiburek and Anton Ten Wolde, were also of great help. A number of reviewers took time to examine the book. Although we do not know their names, we thank them here.

Finally, I want to acknowledge my family. My loving mother who died too early. My late father, who reached a respectable age. My wife, Lieve and my three children who managed living together with a busy engineering professor, and my many grandchildren.

Leuven, May 2010

*Hugo S. L. C. Hens*

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# 0 Introduction

## 0.1 Subject of the book

This is the second volume in a series of books on Building Physics and Applied Building Physics:

- Building Physics: Heat, Air and Moisture
- **Applied Building Physics: Boundary Conditions, Building Performance and Material Properties**
- Applied Building Physics and Performance Based Design 1
- Applied Building Physics and Performance Based Design 2

In this volume the subjects are: indoor and outdoor climate, the performance concept, performances at the building and building enclosure level and heat-air-moisture material properties. The book thereby functions as a hinge between 'Building Physics: Heat, Air and Moisture' and 'Applied Building Physics and Performance Based Design 1 and 2'. Although acoustics and lighting are not treated in detail, they form an integral part of the performance array and are mentioned where and when needed.

In Chapter 1 outdoor and indoor conditions are described and design and calculation values discussed. Chapter 2 specifies the performance concept and its hierarchical structure, from the urban environment over the building level down to the material's level. Aspects typical for performances are definability in an engineering way, their predictability at the design stage and controllability during decommissioning. In Chapter 3, the main heat, air, moisture related performances at the building level are discussed. Chapter 4 analyzes the hygrothermal performance requirements of importance for a good building enclosure design, while Chapter 5 treats the material properties needed for predicting the heat, air, moisture response of buildings and building enclosures.

A performance approach helps designers, consulting engineers and contractors to guarantee building quality. However physical requirements are not the only track that adds value. Although functionality, spatial quality and aesthetics, i.e. aspects belonging to the architect's responsibility, are of equal importance, they should not become an argument for neglecting the importance of a highly performing building and building services design.

## 0.2 Building Physics and Applied Building Physics

For the readers who like to know more about the engineering field of 'Building Physics', its importance and history, we refer to 'Building Physics: Heat, Air and Moisture'. Honestly, the term 'applied' may be perceived to be a pleonasm. Building Physics is by definition applied. But by inserting the word, the focus is unequivocally directed towards usage of the knowledge building physics generates, in building and building services design plus building construction.

### 0.3 Units and symbols

The book uses the SI-system (internationally mandated since 1977). The base units are the meter (m), the kilogram (kg), the second (s), the Kelvin (K), the ampere (A) and the candela. Derived units, which are important when studying building physics and applied building physics, are:

Unit of force: Newton (N);  $1 \text{ N} = 1 \text{ kg} \cdot \text{m} \cdot \text{s}^{-2}$   
 Unit of pressure: Pascal (Pa);  $1 \text{ Pa} = 1 \text{ N/m}^2 = 1 \text{ kg} \cdot \text{m}^{-1} \cdot \text{s}^{-2}$   
 Unit of energy: Joule (J);  $1 \text{ J} = 1 \text{ N} \cdot \text{m} = 1 \text{ kg} \cdot \text{m}^2 \cdot \text{s}^{-2}$   
 Unit of 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 the symbols, the ISO-standards (International Standardization Organization) are followed. If a quantity is not included in these standards, 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, ECBCS (International Energy Agency, Executive Committee on Energy Conservation in Buildings and Community Systems) are applied.

**Table 0.1.** List with symbols and quantities.

Symbol	Meaning	Units
<i>a</i>	Acceleration	m/s <sup>2</sup>
<i>a</i>	Thermal diffusivity	m <sup>2</sup> /s
<i>b</i>	Thermal effusivity	W/(m <sup>2</sup> · K · s <sup>0.5</sup> )
<i>c</i>	Specific heat capacity	J/(kg · K)
<i>c</i>	Concentration	kg/m <sup>3</sup> , g/m <sup>3</sup>
<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 <sup>2</sup>
<i>g</i>	Mass flow rate, mass flux	kg/(m <sup>2</sup> · s)
<i>h</i>	Height	m
<i>h</i>	Specific enthalpy	J/kg
<i>h</i>	Surface film coefficient for heat transfer	W/(m <sup>2</sup> · K)
<i>k</i>	Mass related permeability (mass may be moisture, air, salt.)	s
<i>l</i>	Length	m
<i>l</i>	Specific enthalpy of evaporation or melting	J/kg
<i>m</i>	Mass	kg
<i>n</i>	Ventilation rate	s <sup>-1</sup> , h <sup>-1</sup>
<i>p</i>	Partial pressure	Pa
<i>q</i>	Heat flow rate, heat flux	W/m <sup>2</sup>
<i>r</i>	Radius	m
<i>s</i>	Specific entropy	J/(kg · K)

Symbol	Meaning	Units
$t$	Time	s
$u$	Specific latent energy	J/kg
$v$	Velocity	m/s
$w$	Moisture content	kg/m <sup>3</sup>
$x, y, z$	Cartesian co-ordinates	m
$A$	Water sorption coefficient	kg/(m <sup>2</sup> · s <sup>0.5</sup> )
$A$	Area	m <sup>2</sup>
$B$	Water penetration coefficient	m/s <sup>0.5</sup>
$D$	Diffusion coefficient	m <sup>2</sup> /s
$D$	Moisture diffusivity	m <sup>2</sup> /s
$E$	Irradiation	W/m <sup>2</sup>
$F$	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 · s · K)
$K$	Mass permeance	s/m
$K$	Force	N
$L$	Luminosity	W/m <sup>2</sup>
$M$	Emittance	W/m <sup>2</sup>
$P$	Power	W
$P$	Thermal permeance	W/(m <sup>2</sup> · K)
$P$	Total pressure	Pa
$Q$	Heat	J
$R$	Thermal resistance	m <sup>2</sup> · 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 <sup>2</sup> · K)
$V$	Volume	m <sup>3</sup>
$W$	Air resistance	m/s
$X$	Moisture ratio	kg/kg
$Z$	Diffusion resistance	m/s
$\alpha$	Thermal expansion coefficient	K <sup>-1</sup>
$\alpha$	Absorptivity	–
$\beta$	Surface film coefficient for diffusion	s/m
$\beta$	Volumetric thermal expansion coefficient	K <sup>-1</sup>

Symbol	Meaning	Units
$\eta$	Dynamic viscosity	$\text{N} \cdot \text{s}/\text{m}^2$
$\theta$	Temperature	$^{\circ}\text{C}$
$\lambda$	Thermal conductivity	$\text{W}/(\text{m} \cdot \text{K})$
$\mu$	Vapour resistance factor	–
$\nu$	Kinematic viscosity	$\text{m}^2/\text{s}$
$\rho$	Density	$\text{kg}/\text{m}^3$
$\rho$	Reflectivity	–
$\sigma$	Surface tension	$\text{N}/\text{m}$
$\tau$	Transmissivity	–
$\phi$	Relative humidity	–
$\alpha, \phi, \Theta$	Angle	rad
$\xi$	Specific moisture capacity	$\text{kg}/\text{kg}$ per unit of moisture potential
$\Psi$	Porosity	–
$\Psi$	Volumetric moisture ratio	$\text{m}^3/\text{m}^3$
$\Phi$	Heat flow	W

**Table 0.2.** List with suffixes and notations.

Symbol	Meaning
<b>Indices</b>	
A	Air
c	Capillary, convection
e	Outside, outdoors
h	Hygroscopic
i	Inside, indoors
cr	Critical
$\text{CO}_2, \text{SO}_2$	Chemical symbol for gasses
m	Moisture, maximal
r	Radiant, radiation
sat	Saturation
s	Surface, area, suction
rs	Resulting
v	Water vapour
w	Water
$\phi$	Relative humidity
<b>Notation</b>	
[ ], bold	Matrix, array, value of a complex number
dash	Vector (ex.: $\vec{a}$ )



## 0.4 References

- [0.1] 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, Rijswijk.
- [0.2] ISO-BIN (1985). Standards series X02-101 – X023-113.
- [0.3] Kumaran, K. (1996). *Task 3: Material Properties*. Final Report IEA EXCO ECBCS Annex 24. ACCO, Louvain, pp. 135.