Hugo Hens

Building Physics Heat, Air and Moisture

Fundamentals and Engineering Methods with Examples and Exercises

Third Edition

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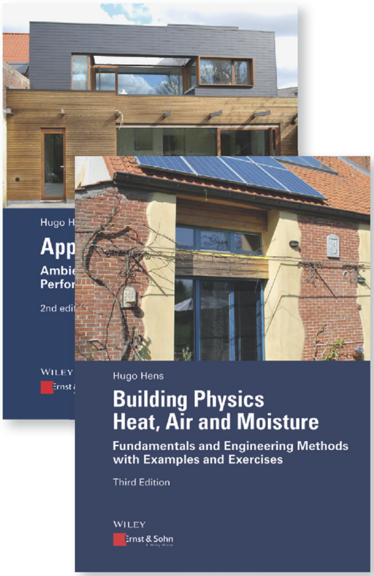
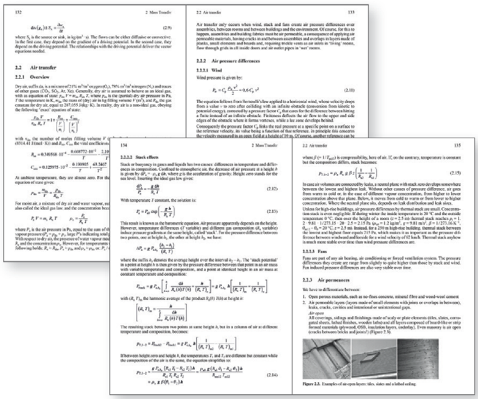
Building Physics and Applied Building Physics



As with all engineering sciences, Building Physics is oriented towards application, which is why, a first book treats the fundamentals and a second volume examines performance rationale and performance requirements as well as energy efficient building design and retrofitting.

- content well structured combining theory with typical building engineering practice
- solved examples and applications
- author with international appreciation (Scandinavia, Benelux, USA, Canada)



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Cover: Extremely low energy house in Belgium, newly built as an extension of an old farm.

Photo: Hugo Hens

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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 (KU Leuven), Belgium in 1952

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Preface

Until the first energy crisis of 1973, building physics was a dormant beauty within building engineering, with seemingly limited applicability in practice. While soil mechanics, structural mechanics, building materials, building construction and HVAC were perceived as essential, designers only demanded advice on room acoustics, moisture tolerance, summer comfort or lighting when really needed or in case problems arose. Energy was of no concern, while thermal comfort and indoor environmental quality were presumably guaranteed thanks to infiltration, window operation and the HVAC system. The energy crises of the 1970s, persisting moisture problems, complaints about sick buildings, thermal, visual and olfactory discomfort, and the move towards greater sustainability changed all this. Societal pressure to diminish energy consumption without degrading building usability activated the notion of performance-based design and construction. As a result, building physics and its potential to quantify performance moved to the front line of building innovation.

As for 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. Integrating the basics on heat and mass transfer is the main objective of this book, with mass limited to air, (water) vapour and moisture. It is the result of 38 years of teaching architectural, building and civil engineers, coupled with some 50 years of experience in research and consultancy. Where needed, information and literature from international sources has been used, which is why each chapter concludes with an extended reading list.

In an introductory chapter, building physics is presented as a discipline. The first chapter then concentrates on heat transport, with conduction, convection and radiation as main topics, followed by concepts and applications typical for building physics. The second chapter treats mass transport, with air, vapour and moisture as main components. Again, much attention is devoted to the concepts and applications related to buildings. The last chapter discusses combined heat, air and moisture transport. All three chapters are followed by exercises.

The book uses SI units. It should be suitable for those undertaking undergraduate and graduate studies in architectural and building engineering, although mechanical engineers, studying HVAC, and practising building engineers who want to refresh their knowledge, may also benefit. It is presumed that the reader has a sound knowledge of calculus and differential equations, along with a background in physics, thermodynamics, hydraulics, building materials and building construction.

Acknowledgements

A book reflects the work of many, not only the author, who writes by standing on the shoulders of those who have gone before. Therefore, I would like to thank the thousands of students I have encountered during 38 years of teaching. They gave me the opportunity to test the content. 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 Künzel of the Fraunhofer Institut für Bauphysik, Germany, showed the importance of experimental work and field testing to understand building performance, while Lars Erik Nevander of Lund University, Sweden, taught that solving problems in building physics does not always need complex modelling, mainly because reality in building construction is much more complex than any model could simulate.

Several researchers and PhD students have been involved during the four decades at the Laboratory of Building Physics. I am very grateful to Gerrit Vermeir (now Emeritus Professor), Staf Roels, Dirk Saelens and Hans Janssen, who became colleagues at the Department of Civil Engineering, Faculty of Engineering Sciences at KULeuven; Jan Carmeliet, now professor at ETH-Zürich; Piet Standaert, principal at Physibel Engineering; 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 Ghent University (UG); Rongjin Zheng, associate professor at Zhejiang University, China; Bert Blocken, full professor at the Technical University Eindhoven (TU/e); Griet Verbeeck, now professor at Hasselt University, and Wout Parys, now a principal at BauPhi Engineering and part-time professor at the Faculty of Engineering Technology of KULeuven, who all contributed by 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 the engineering-based performance approach each time. 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 has managed living together with a busy engineering professor, my three children who had to live with that busy father, and my grandchildren.

Hugo S.L.C. Hens
Leuven, July 2017

0 Introduction

0.1 Subject of the book

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

– **Building Physics: Heat, Air and Moisture, Fundamentals and Engineering Methods with Examples and Exercises**
– Applied Building Physics: Ambient Conditions, Building Performance and Material Properties
– Performance Based Building Design 1: From Below Grade Construction to Outside Walls with Transparent Insulation
– Performance Based Building Design 2: From Low-Slope Roofs to Finishes and Risk.

This volume discusses the physics behind the heat, air and moisture, also called hygrothermal response of materials, building assemblies and whole buildings. The second volume on applied building physics deals with the ambient conditions indoors and outdoors, the performance rationale, and the heat, air and moisture metrics at the levels of the whole building and the building assembly. In addition, extended tables with material properties are added. The third and fourth volumes on performance-based building design use these metrics and the requirements related to structural mechanics, acoustics, lighting, fire safety, economics and sustainability, to design and construct whole buildings and their composite parts.

Note that the term 'building physics' is hardly used in the English-speaking world, where 'building science' is more common. Yet building science differs as, on the one hand it does not encompass acoustics and lighting, while on the other hand it includes more practice-related topics ranging from HVAC issues to organizational concerns.

0.2 Building physics

0.2.1 Definition

As an applied science, building physics studies the hygrothermal, acoustic and visual performance of materials, building assemblies, spaces, whole buildings and, be it under the name urban physics, the built environment. The constraints faced are the user demands related to overall comfort, health and safety, together with architectural facts and figures, durability issues, economic restrictions and sustainability-related requirements.

The term 'applied' indicates the field is a tool directed towards problem solving. Topics tackled in the heat, air and moisture subfield are air-tightness, thermal insulation, transient thermal response, moisture tolerance, thermal bridging, salt transport, temperature and humidity-related stress and strain, net energy demand, gross energy demand, end energy use, primary energy consumption, ventilation, thermal comfort and indoor air quality. In the building acoustics subfield, the topics discussed include the air- and structure-borne noise transmission by outer walls, floors, partition walls, party walls, glazing and roofs, room acoustics and the

Building Physics: Heat, Air and Moisture: Fundamentals and Engineering Methods with Examples and Exercises. Third Edition. Hugo Hens.

abatement of installation and ambient noise. The lighting subfield includes daylighting, artificial lighting, and the impact that both have on human wellbeing and primary energy consumption. Urban physics finally looks to the thermal, acoustic, visual and wind comfort outdoors, wind and rain patterns in cities, the spread of air pollution in cities, the heat island effect, and all aspects related to energy management at the city level.

0.2.2 Constraints

0.2.2.1 Comfort

Comfort is typically defined as a condition of mind that expresses satisfaction with the surroundings. Attainment of comfortable conditions depends on what humans need to feel thermally, acoustically and visually at ease: not too cold, not too warm, not too noisy, no large contrasts in luminance, and so on.

Thermal comfort engages physiology and psychology. As exothermal creatures with a constant core temperature of about 37 °C (310 K), humans must be able to lose heat to the environment under any circumstance, whether by conduction, convection, radiation, perspiration, transpiration or breathing. Air temperature, its gradient, the radiant temperature, radiant asymmetry, contact temperatures, relative air velocity, air turbulence and relative humidity in the direct environment will fix the heat exchanged. For a given activity and clothing, humans will quote certain combinations of the named ambient parameters as comfortable, and others not, although adaptation influences satisfaction.

Acoustic comfort strongly relates to mental awareness. Physically, young adults can hear sounds with frequencies between 20 and 16 000 Hz. In terms of sound intensity, however, humans scale logarithmically with better hearing for higher frequencies. Acoustics therefore uses the logarithmic unit the decibel (dB), with 0 dB for audibility and 140 dB for the pain threshold. Undesired noises such as neighbours, traffic, industry and aircraft will disturb people, generate complaints and often create long-lasting disputes.

Visual comfort combines mental with physical aspects. Physically, the eye sees electromagnetic waves with wavelengths between 0.38 and 0.78 μm. The maximum sensitivity lies near 0.58 μm, the yellow-green range. But overall sensitivity adapts to the average luminance. When dark it increases 10 000 times compared with daytime, but the eyes perceive that change logarithmically. Great differences in brightness will disturb, while well-adapted lighting creates a feeling of cosiness.

0.2.2.2 Health and wellbeing

Wellbeing is determined not only by the absence of illness, but also an absence of neuro-vegetative complaints, psychological stress or physical unease. Dust, fibres, (S)VOCs, radon, CO, viruses and bacteria, moulds and mites, too much noise, thermal discomfort and great luminance contrasts are all disturbing to the users of buildings.

0.2.2.3 Architecture and materials

Building physics faces architectural and material restrictions. Façade and roof form, aesthetics pursued and the materials chosen will all shape the building, while their design engages a multitude of metrics and requirements. Conflicting structural and physical issues often complicate solutions. Necessary thermal cuts interfere with the strength and stiffness of the connections required. The creation of waterproof and vapour-permeable structures are not always compatible. The necessary acoustic absorption could interfere with vapour tightness, for example.

0.2.2.4 Economy

Not only must the building costs respect budget limits, but the total expenditure over the timespan a building is owned or used should be the lowest achievable. The initial investment, energy used, maintenance, future necessary upgrades and replacements play a decisive role. A building designed and constructed according to the metrics of building physics and all other advanced fields of study will generally incur lower costs than if done without consideration of fitness for purpose.

0.2.2.5 Sustainability

The environmental impact of human activity has increased substantially over recent decades with worrying consequences. Locally, building use produces solid, liquid and gaseous waste. Countrywide, construction and occupancy accounts for 35–40% of the end energy used. Fossil fuels still deliver the major part, meaning that the CO_2 produced by their burning overwhelms all other greenhouse gas releases.

The increasing impact of life-cycle inventory and analysis (LCIA) and the use of certification tools reflect the pursuit of sustainability. In LCIA, buildings are evaluated in terms of environmental impact from ‘cradle to cradle’, that is, from material production through construction and occupancy to demolition and re-use. For each stage, all material, energy and water inflows and polluting outflows are quantified, and the impact on human wellbeing and the environment is assessed. Certification programmes in turn focus on fitness for purpose that new buildings, retrofitted buildings and urban environments should offer.

0.3 Importance

The necessity of creating a comfortable indoor environment protected from the weather gave birth to the field now called ‘building physics’. As various ambient loads such as sun, rain, wind and noise, but also temperature, vapour and air pressure differentials, burden the building enclosure, an appropriate design should annihilate their impact when needed and use it when aiding comfort and wellbeing, while lowering source energy use as far as possible.

In earlier days, experience was the guide. Former generations disposed of a limited range of materials – wood, straw, loam, brick, natural stone, lead, copper, cast iron, blown glass – for which uses increased over the centuries. Standard solutions for roofs, roof edges and outer walls existed. From the size and orientation of the windows to the overall layout, everything was conceived to limit heating in the winter and overheating in summer. Because noise sources outside urban centres were scarce, acoustics was not a consideration, while a lifestyle adapted to the seasons saved energy.

That era ended with the industrial revolution. New materials flooded the market, such as steel, reinforced and pre-stressed concrete, nonferrous metals, synthetics, bitumen and insulation materials. More advanced technologies turned existing materials into innovative products: cast and float glass, rolled metal products and pressed bricks, for example. Advances in structural mechanics allowed designs of any form and span. Due to the widespread exploitation of fossil fuels such as coal, petroleum and natural gas, energy became cheap. Construction exploded and turned into a demand/supply market. The result was mass building of too often minimal quality.

The early twentieth century saw a 'modern school' of architects surfacing that experimented with alternative structural solutions, simple details and new materials. The buildings they designed were neither energy-efficient nor exemplary cases of good quality. Typical was the profuse use of steel, concrete and glass, all difficult materials from a hygrothermal point of view, and a reduction in overhangs and façade relief. The results were obvious failures that necessitated premature restoration, which a better knowledge of building physics could have prevented. Figure 0.1 shows a non-insulated Le Corbusier house built in 1926 that lacked moisture tolerance, so had to be rebuilt with insulation in the late 1980s. Previously, heating all rooms to a comfortable temperature required 20 000 litres of fuel a year. This

Fig. 0.1 House designed by Le Corbusier after restoration

reduced to 4000 litres a year after renovation, with the inhabitants heating the rooms only when being used.

To realise high-performance buildings fit for purpose, a good knowledge and correct application of all metrics related to building physics is essential. This replaces the time-consuming learning by trial and error of the past, for which building technologies and architectural fashions are evolving too rapidly.

0.4 History

Building physics surged at the crossroads of several disciplines: applied physics, comfort and health, building services, building design and construction.

0.4.1 Applied physics

0.4.1.1 Heat, air and moisture

Up until the early twentieth century, the subject of heat transmission was the main study area. Vapour diffusion gained interest in the late 1930s, when Teesdale of the US Forest Products Laboratory published a study on 'Condensation in Walls and Attics'. In 1952, a paper by J.S. Cammerer entitled 'Die Berechnung der Wasserdampfdiffusion in den Wänden' ['Calculation of water vapour diffusion in walls'] appeared in *Der Gesundheitsingenieur*. By the end of the 1950s the same journal published H. Glaser's upgraded calculation method for interstitial condensation by vapour diffusion in cold storage walls. Others, among them K. Seiffert, applied that method to the evaluation of building assemblies. His book *Wasserdampfdiffusion im Bauwesen* [*Water Vapour Diffusion in Buildings*] led to the use of vapour barriers becoming more or less inevitable. The main cause of interstitial condensation, air flow in and across assemblies, was largely overlooked. The impact was first noticed in Canada, a country with a timber-frame tradition. In 1961, A.G. Wilson of the National Research Council wrote:

> One of the most important aspects of air leakage in relation to the performance of Canadian buildings is the extent to which it is responsible for serious condensation problems. Unfortunately this is largely unrecognized in the design and construction of many buildings, and even when failures develop, the source of moisture is often incorrectly identified.

From the 1960s on, many researchers studied combined heat, air and moisture transport, among them O. Krischer, J.S. Cammerer and H. Künzel in Germany, A. De Vries, B.H. Vos and E. Tammes in the Netherlands, L.E. Nevander in Sweden and A. Tveit in Norway.

0.4.1.2 Acoustics

In the early twentieth century, physicists started showing an interest in noise control in buildings. In 1912, Berger submitted a PhD thesis at the Technische Hochschule München entitled *Über die Schalldurchlässigkeit* [*About Sound Transmission*]. In

1920, Sabine published his reverberation time formula. In the years thereafter, room acoustics became a favourite, with studies on speech intelligibility, optimal reverberation times, and reverberation times in anechoic rooms. A decade later, L. Cremer initiated a breakthrough in airborne sound transmission. In his paper *Theorie der Schalldämmung dünner Wände bei schrägem Einfall* [*Theory of sound insulation of thin walls at oblique incidence*], he recognized that coincidence between the sound waves in the air and the bending waves on a wall played a major role in degrading sound insulation. Later, his studies on structure-borne noise in floors advanced the idea of floating screeds as a solution. K. Gösele and M. Heckl fully established the link between building acoustics and construction through easy-to-use rules on how to build floors, walls and roofs with excellent air- and structure-borne sound attenuation. In the US, Beranek published his book *Noise and Vibration Control* in 1970, a remake of *Noise Reduction* of 1960, which became a standard reference for engineers who had to solve noise problems.

0.4.1.3 Lighting

Lighting came later. In 1931, a study was completed at the Universität Stuttgart, dealing with *Der Einfluss der Besonnung auf Lage und Breite von Wohnstraßen* [*The influence of solar irradiation on the location and width of residential streets*]. Later, physicists used radiation theory to calculate the illumination of surfaces and the luminance contrasts in the surroundings. By the end of the 1960s, the daylight factor was introduced as a quantity to evaluate the illumination indoors by natural light. More recently, since the energy crises of the 1970s, the relationship between artificial lighting and primary energy use has surged as a topic.

0.4.2 Thermal comfort and indoor air quality

By the nineteenth century, engineers were working on housing and urban hygiene. Max von Pettenkofer (1818–1901) (Figure 0.2) was the first to evaluate the impact of ventilation on the indoor CO_2 concentration. The 1500 ppm acceptability limit is attributed to him, as is the notion of a 'breathing material', the result of a link made later between finding more health complaints in stone buildings and fewer in brick dwellings, due to brick not completely blocking the passage of air. The true reason, of

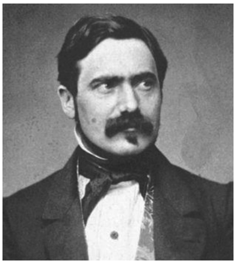

Fig. 0.2 Max von Pettenkofer

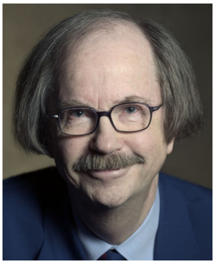

Fig. 0.3 P.O. Fanger

course, was the poorer thermal performance of stone constructions and the related increase in mould and humidity.

Thermal comfort moved to the forefront in the twentieth century. Research by Yaglou in the 1930s, sponsored by the American Society of Heating and Ventilation Engineers (ASHVE), a predecessor of ASHRAE, led to the notion of 'operative temperature'. Originally, his definition overlooked radiation, which changed after A. Missenard, a French engineer, critically reviewed the data and saw the impact of the radiant temperature. The late P.O. Fanger (Figure 0.3) firmly founded the relation between perceived thermal comfort and all parameters intervening in his book *Thermal Comfort*, published in 1970. Based on physiology, heat exchange between the clothed body and the ambient surroundings and the differences in comfort perception between individuals, he developed a steady-state thermal model for the active, clothed human. Since then, his Predicted Mean Vote (PMV) versus Predicted Percentage of Dissatisfied (PPD) curve forms the kernel of all comfort standards worldwide. After 1985, the adaptive model gained support, being a refinement of Fanger's work.

Concerns about indoor air quality led to the cataloguing of a multitude of pollutants with their impact in terms of health risks. Over the years, 'sick building syndrome' (SBS) accompanied the move to fully air-conditioned builds, which reinforced the need for an even better understanding. Nonetheless, 'better' did not always result from a sound interpretation of the facts. Too often, discontent with the job was overlooked. In this area also, P.O. Fanger had an impact with his work on perceived indoor air quality based on bad smells and air enthalpy.

0.4.3 Building services

In the nineteenth century, building services technicians were searching for methods to calculate the heating and cooling load. The knowledge that had developed in physics, which provided concepts such as the thermal transmittance of a flat assembly, helped a lot. Quite early, organizations such as ASHVE and the Verein Deutscher Ingenieure (VDI) had technical committees dealing with the topic. An active member of ASHVE was W.H. Carrier (1876–1950), recognized in the US as the father of air conditioning. He was the first to publish a usable psychometric chart.

For H. Rietschel, professor at the Technische Universität Berlin and author of a comprehensive book on *Heizung und Lüftungstechnik* [*Heating and Ventilation Techniques*], heat loss and heat gain through ventilation was of concern. Along with others, he noted that well-designed ventilation systems malfunctioned when the envelope lacked air-tightness. This sharpened the interest in air transport. Vapour in the air became a worry once air-conditioning (HVAC) gained popularity, while previously humidity had been of concern because of possible health effects. Sound attenuation troubled the HVAC community because of system noisiness, while lighting became a factor because HVAC engineers got contracts for lighting design. Since 1973, energy efficiency has dominated.

0.4.4 Building design and construction

The many complaints about noise and moisture, with which modernists had to wrestle, slowly changed the field of building physics into one that helped to avoid the construction failures of some 'state-of-the art' solutions. Concern about moisture tolerance began in the early 1930s when peeling and blistering of paints on insulated timber-frame facades became an issue. Insulation materials were new at that time. It motivated Teesdale to study interstitial condensation. Some years later, ventilated attics with insulation at ceiling level were tested by F. Rowley, Professor in Mechanical Engineering at the University of Minnesota. The results were instructions about vapour retarders and attic ventilation. In Germany, the Freiland Versuchsstelle Holzkirchen, founded in 1951, used building physics as a driver for upgraded construction quality. When, after 1973, energy efficiency became a hot topic and insulation a necessity, the knowledge gathered proved extremely useful for the construction of high-quality, well-insulated buildings and the development of glazing with better insulating properties, lower solar and better visual transmittance. In the 1990s, the need for better quality resulted in the performance rationale of IEA EBC Annex 32, 'Integral Building Envelope Performance Assessment'.

0.4.5 The situation at the University of Leuven (KULeuven) and elsewhere

At KULeuven, lecturing in building physics started in 1952, when the field became compulsory for architectural engineering and optional for civil engineering. Antoine de Grave, a civil engineer who was the head of the building department at the Ministry of Public Works, was nominated as professor. He taught the course until his passing away in 1975. He published two books: *Bouwfysica* [*Building Physics*] and *Oliestook in de woning* [*Oil heating in Houses*]. By 1975, building physics had also become compulsory for civil engineering. Shortly after, together with Gerrit Vermeir, then a researcher and after 1992 professor in building acoustics, we started a working group with the aim to push research and consultancy in building physics. In 1978 that group gave birth to the Laboratory of Building Physics, to become the Unit of Building Physics within the Department of Civil Engineering in 1990. Over the years, the topics tackled included the physical properties of building and insulating materials, the performance of well-insulated building assemblies, end energy use in buildings, indoor environmental quality, air- and structure-borne noise attenuation and room acoustics. In 1997, urban physics was added. A basic motivation behind the research and consultancy done was upgrading the quality of the built environment in cooperation with the building sector. Since my retirement in 2008, Staf Roels is teaching performance-based building design now, Dirk Saelens building services, energy use and indoor environmental quality, and Hans Janssen the basics. In 2011, first Arne Dijckmans and then Edwin Reynders succeeded Gerrit Vermeir in the field of building acoustics. In 2013, Bert Blocken, a former researcher at the Unit and now professor at the TU/e (Eindhoven), joined as part-time, specializing in urban physics.

Ghent University (UGent) waited until 1999 to nominate Arnold Janssens, then a postdoctoral researcher at the Unit, as full-time professor in building physics. He did a tremendous job there in organizing and heading research in that field. At the Free University Brussels (VUB) a part-time professorship was offered to F. Descamps, also a former researcher at the Unit and manager of an engineering office in building physics.

Before the Second World War in the Netherlands, Professor Zwikker gave lectures at the Technical University Delft (TU-Delft) analysing buildings from a physical point of view, but a course named 'Building Physics' only started in 1955 with Professor Kosten of the Applied Physics Faculty as chair-holder. In 1963 Professor Verhoeven took over. Shortly after, in Eindhoven, a technical university (TU/e) was founded in 1969 with Professor P. De Lange as first holder of the Chair of Building Physics at the Faculty of the Built Environment.

0.5 Units

The book uses the SI system (internationally mandatory since 1977), with base units of 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:

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

The ISO standards (International Standardization Organization) for symbols are applied. If a quantity is not included, the CIB-W40 recommendations (International Council for Building Research, Studies, and Documentation, Working Group 40 on Heat and Moisture Transfer in Buildings) and the Annex 24 list edited by the IEA EBC (International Energy Agency, Executive Committee on Energy in Buildings and Communities) are followed.

0.6 Symbols

Table 0.1 List of 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
g	Specific free enthalpy	J/kg
g	Acceleration due to 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, salt)	kg/s
H	Enthalpy	J
I	Radiation intensity	J/rad
K	Thermal moisture diffusion coefficient	kg/(m.s.K)

Table 0.1 (*Continued*)

Symbol	Meaning	SI units
K	Mass permeance	s/m
K	Force	N
L	Luminosity	W/m^2
M	Emittance	W/m^2
P	Power	W
P	Thermal conductance	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	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
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
ρ	Reflectivity	–
σ	Surface tension	N/m
⌋	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
Ψ	Porosity	potential
Ψ	Volumetric moisture ratio	–
Φ	Heat flow	m^3/m^{3}W

Table 0.2 List of currently used suffixes

Symbol	Meaning	Symbol	Meaning
Indices			
A	Air	m	Moisture, maximal
c	Capillary, convection	r	Radiant, radiation
e	External, outdoors	sat	Saturation
h	Hygroscopic	s	Surface, area, suction
i	Inside, indoors	rs	Resulting
cr	Critical	v	Water vapour
CO_2, SO_2	Chemical symbols for gases	w	Water, wind
		ϕ	Relative humidity

Table 0.3 List of notations used

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

Further reading

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