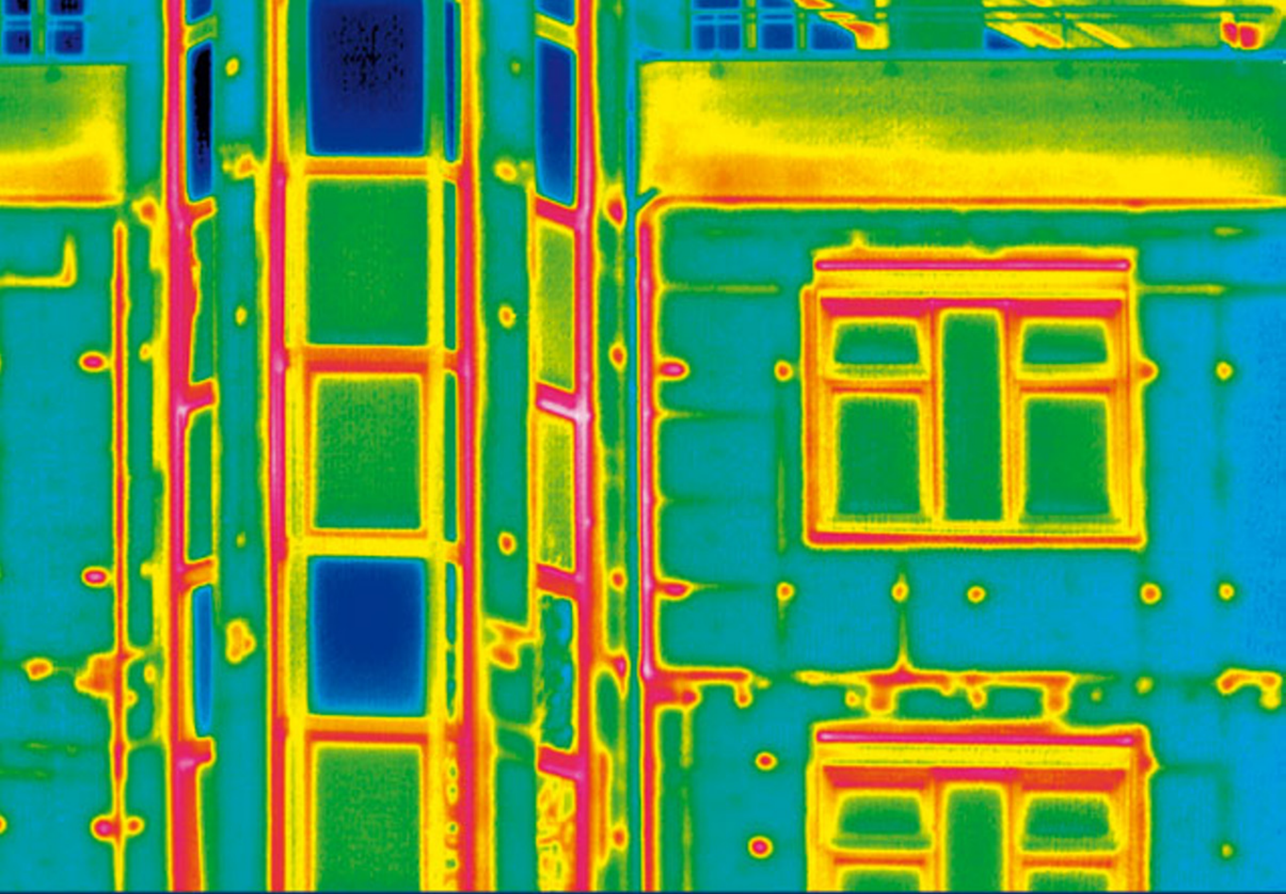

Hugo Hens

Building Physics Heat, Air and Moisture

Fundamentals and Engineering Methods with Examples and Exercises

2nd Edition

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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

This second edition represents a complete revision of the first edition, published in 2007. Where appropriate, the text was corrected, reworked, and extended. The exercises have been reviewed and solutions for all 33 problems added.

Preface

Overview

Until the first energy crisis of 1973, building physics was a rather dormant 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 demanded advice on room acoustics, moisture tolerance, summer comfort or lighting when really needed or problems arose. Energy was not even a concern, while thermal comfort and indoor environmental quality were presumably guaranteed thanks to infiltration, window operation and the HVAC system. The crises of the 1970s, persisting moisture problems, complaints about sick buildings, thermal, visual and olfactory discomfort, and the move towards more sustainability changed all that. The societal pressure to diminish energy consumptions in buildings without degrading usability opened the door for the notion of performance based design and construction. As a result, building physics and its potentiality to quantify performances suddenly moved into the frontline of building innovation.

As with all engineering sciences, building physics is oriented towards application. This demands a sound knowledge of the basics in each of the branches encompassed: 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 thirty years of teaching architectural, building and civil engineers, and forty-four years of experience, research and consultancy. Input and literature from over the world has been used, documented after each chapter by an extended literature list.

An introductory chapter presents building physics as a discipline. The first part concentrates on heat transport, with conduction, convection and radiation as main topics, followed by concepts and applications which are typical for building physics. The second part treats mass transport, with air, water vapour and moisture as the most important components. Again, much attention is devoted to the concepts and applications which relate to buildings. The last part discusses combines heat, air, moisture transport, who act as a trio. The three parts are followed by exemplary exercises.

The book is written in SI-units. It should be usable for undergraduate and graduate studies in architectural and building engineering, although also mechanical engineers studying HVAC, and practising building engineers who want to refresh their knowledge, may benefit. The level of presentation presumes 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 of this magnitude reflects the work of many persons in addition to the author. Therefore, we would like to thank the thousands of students we had during the thirty years of teaching building physics. They provided the opportunity to test the content. It is a book which would not been written the way it is, without standing on the shoulders of those in the field who preceded. 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 me the importance of experimental work and field testing for understanding-

ing building performance, while Lars Erik Nevander of Lund University, Sweden, taught that complex modelling does not always help in solving problems in building physics, mainly because reality in building construction is much more complex than any model may be.

During four decades at the Laboratory of Building Physics, many researchers and Ph. D.-students got involved in the project. I am very grateful to Gerrit Vermeir, Staf Roels Dirk Saelens and Hans Janssen who became colleagues at the university; to Jan Carmeliet, now professor at the ETH-Zürich; Piet Standaert, a 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, associate professor at the University of Ghent (UG); Rongjin Zheng, associate professor at Zhejiang University, China, and Bert Blocken, professor at the Technical University Eindhoven (TU/e), who all contributed by their work. The experiences gained by working 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, and Executive Committee on Energy Conservation in Buildings and Community Systems forced me to rethink the engineering based performance approach time and time again. The idea exchange we got in Canada and the USA from Kumar Kumaran, Paul Fazio, Bill Brown, William B. Rose, Joe Lstiburek and Anton Ten Wolde was also of great help. A number of reviewers took time to examine the first edition of this book. We would like to thank them, too.

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

Leuven, March 2012 *Hugo S. L. C. Hens*

Contents

0 Introduction

0.1 Subject of the book

This is the first of 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 1
- Performance Based Building Design 2

The notion of 'Building Physics' is somewhat unusual in the English speaking world. 'Building Science' is the more commonly used. However, the two differ somewhat. Building science is broader in its approach as it encompasses all subjects related to buildings that claim to be 'scientific'. This is especially clear when looking at journals that publish on 'Building Science'. The range of subjects treated is remarkably wide, ranging from control issues in HVAC to city planning and organizational issues.

In 'Building Physics: Heat, Air and Moisture', the subject is the physics behind heat, air and moisture transfer in materials, building assemblies and whole buildings. The second book, 'Applied Building Physics', deals with the inside and outside climate as boundary condition, followed by the performance rationale for the heat, air, moisture related performances at building part level. Extended tables with material properties are also included. Performance Based Building Design 1 and 2 then apply the performance rationale as an instrument in the design and execution of buildings. As such, they integrate the fields of building construction, building materials, building physics and structural mechanics.

0.2 Building Physics

0.2.1 Definition

Building Physics is an applied science that studies the hygrothermal, acoustical and light-related properties, and the performance of materials, building assemblies (roofs, façades, windows, partition walls, etc.), spaces, whole buildings, and the built environment. At the whole building level, the three sub-fields generate subjects such as indoor environmental quality and energy efficiency, while at the built environment level building physics is renamed 'Urban Physics'. Basic considerations are user requirements related to thermal, acoustic and visual comfort, health prerequisites and the more-or-less compelling demands and limitations imposed by architectural, material, economics and sustainability-related decisions.

The term 'applied' indicates that Building Physics is directed towards problem solving: the theory as a tool, not as a purpose. As stated, the discipline contains in essence three sub-fields. The first, hygrothermal, deals with heat, air, and moisture transport in materials, assemblies, and whole buildings and, the heat, air and moisture interaction between buildings and the outdoor environment. The specific topics are: thermal insulation and thermal inertia; moisture

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Second edition. Hugo Hens.

and temperature induced movements, strains and stresses; moisture tolerance (rain, building moisture, rising damp, sorption/desorption, surface condensation, interstitial condensation); salt transport; air-tightness and wind resistance; net energy demand and end energy consumption; ventilation; indoor environmental quality; wind comfort, etc. The second sub-sector, building acoustics, studies noise problems in and between buildings, and between buildings and their environment. The main topics are airborne and impact noise transmission by walls, floors, outer walls, party walls, glazing and roofs, room acoustics and the abatement of installation and environmental noises. Finally, the third sub-sector, lighting, addresses issues with respect to day-lighting, as well as artificial lighting and the impact of both on human wellbeing and primary energy consumption.

0.2.2 Criteria

Building Physics deals with a variety of criteria: on the one hand, requirements related to human comfort, health, and well-being, on the other hand restrictions because of architecture, material use, economics, and sustainability demands.

0.2.2.1 Comfort

Comfort is defined as a state of mind that expresses satisfaction with the environment. Attaining such a condition depends on a number of environmental and human factors. By thermal, acoustic and visual comfort we understand the qualities human beings unconsciously request from their environment in order to feel thermally, acoustically and visually at ease when performing a given activity (not too cold, not too warm, not too noisy, no large contrasts in luminance, etc.).

Thermal comfort connects to the global human physiology and psychology. As an exothermal creature maintaining a constant core temperature of about 37 °C (310 K), humans must be able, under any circumstance, to release heat to the environment, be it by conduction, convection, radiation, perspiration, transpiration, and breathing. Air temperature, air temperature gradients, radiant temperature, radiant asymmetry, contact temperatures, relative air velocity, air turbulence, and relative humidity in the direct environment determine the heat exchange by the six mechanisms mentioned. For a certain activity and clothing, humans experience some combinations of these environmental parameters as being comfortable, others as not, though the possibility to adapt the environment to one's own wishes influences satisfaction.

Acoustic comfort strongly connects to our mental awareness. Physically, young adults perceive sound frequencies between 20 and 16,000 Hz. We experience sound intensity logarithmically, with better hearing for higher than for lower frequencies. Consequently, acoustics works with logarithmical scales and units: the decibel (dB), 0 dB standing for the audibility threshold, 140 dB corresponding to the pain threshold. We are easily disturbed by undesired noises, like those made by the neighbours, traffic, industry, and aircraft.

Visual comfort combines mental with physical facts. Physically, the eye is sensitive to electromagnetic waves with wavelengths between 0.38 and 0.78 μm. The maximum sensitivity lies near a wavelength of ≈ 0.58 μm, the yellow-green light. Besides, eye sensitivity adapts to the average luminance. For example, in the dark, sensitivity increases 10,000 times compared to daytime. Like the ear, the eye reacts logarithmically. Too large differences in brightness are disturbing. Psychologically, lighting helps to create atmosphere.

0.2.2.2 Health

Health does not only mean the absence of illness but also of neuro-vegetative complaints, psychological stress, and physical unease. Human wellbeing may be compromised by dust, fibres, (S)VOC's, radon, CO, viruses and bacteria in the air, moulds and mites on surfaces, too much noise in the immediate environment, local thermal discomfort, etc.

0.2.2.3 Architecture and materials

Building physics has to operate within an architectural framework. Floor, façade and roof form, aesthetics and the choice of materials are all elements which shape the building, and whose design is based on among others the performance requirements building physics imposes. Conflicting structural and physical requirements complicate solutions. Necessary thermal cuts, for example, could interfere with strength and the need for stiffness-based interconnections. Waterproof and vapour permeable are not always compatible. Acoustical absorption opposes vapour tightness. Certain materials cannot remain wet for a long time, etc.

0.2.2.4 Economy

Not only must the investment in the building remain within budget limits, total present value based life cycle costs should also be as low as possible. In that respect, energy consumption, maintenance, necessary upgrades, and building life expectancy play a role. A building which has been designed and constructed according to requirements that reflect a correct understanding of building physics, could generate a much lower life cycle cost than buildings built without much consideration about fitness for purpose.

0.2.2.5 Sustainability

Societal concern about local, countrywide, and global environmental impact has increased substantially over the past decades. Locally, building use produces solid, liquid, and gaseous waste. Nationally, building construction and occupancy accounts for 35–40% of the primary energy consumed annually. A major part of that is fossil fuel related, which means also the CO_2-release by buildings closely matches that percentage. In terms of volume, CO_2 is the most important of the gases emitted that are responsible for global warming.

That striving for more sustainability is reflected in the increasing importance of life cycle analysis and of certification tools such as LEED, BREEAM and others. In life cycle analysis, buildings are evaluated in terms of environmental impact from 'cradle to grave', i.e. from material production through the construction and occupancy stage until demolition and reuse. Per stage, all material, energy and water inflows as well as all polluting solid, liquid, and gaseous outflows are quantified and their impact on human wellbeing and the environment assessed. Certification programmes in turn focus on the overall fitness for purpose of buildings and urban environments.

0.3 Importance of Building Physics

The need to build a comfortable indoor environment that protects humans against the vagaries of the outside climate, defines the role of building physics. Consequently, the separation between the inside and the outside, i.e. the building envelope or enclosure (floors, outer walls, roofs) is submitted to various climatologic loads and climate differences (sun, rain, wind and outside noise; differences in temperatures, in partial water vapour pressure and in air pressure). An appropriate envelope design along with correct detailing must consider these loads, attenuate them where possible or use them if possible in order to guarantee the desired comfort and wellbeing with a minimum of technical means and the least possible energy consumption.

In earlier days, experience was the guide. Former generations of builders relied on a limited range of materials (wood, straw, loam, natural stone, lead, copper and cast iron, blown glass), the knowledge of how to use those materials increasing over the centuries. They applied standard details for roofs, roof edges, and outer walls. From the size and orientation of the windows to the overall layout, buildings were constructed as to limit heating in winter and overheating in summer. Because noise sources were scarce, sound annoyance outside urban centres was unknown, and our ancestors saved on energy (wood) by a lifestyle adapted to the seasons.

A new era began with the industrial revolution of the 19th century. New materials inundated the marketplace: steel, reinforced and pre-stressed concrete, nonferrous metals, synthetics, bitumen, insulation materials, etc. More advanced technologies created innovative possibilities for existing materials: cast and float glass, rolled metal products, pressed bricks, etc. Better knowledge of structural mechanics allowed the construction of any form and span. Energy became cheap, first coal, then petroleum and finally natural gas. Construction exploded and turned into a supply-demand market. The consequence was mass building with a minimum of quality and, in the early 20th century, a ‘modern school’ of architects, who experimented with alternative structural solutions and new materials. These experiments had nothing to do with former knowledge. Architects designed buildings without any concern for either energy consumption or comfort, nor any understanding of the physical quality of the new outer wall and roof assemblies they proposed. Typical was the profuse application of steel, concrete, and glass, which are all difficult materials from a hygrothermal point of view. The results were and are, severe damage as well as premature restoration, which could have been avoided by a better knowledge of building physics. Figure 0.1 is an example of that: a house designed

Figure 0.1. House Guiette, designed by Le Corbusier, after restoration.

by Le Corbusier, built in 1926 and rebuilt at the end of the 1980s, included an upgrade of the overall thermal insulation. Before, end energy consumption for heating could have reached 20,000 litres of fuel a year if all rooms were kept at a comfortable temperature. Fortunately inhabitants adapted by heating rooms only used in the daytime.

Building physics is essential if we want to achieve high quality buildings that are fit our purposes. The field should replace time-consuming learning by experience, which cannot keep pace with the rapid evolution in technology and the changes in architectural fashion.

0.4 History of Building Physics

Building physics originated at the crossroads of three application-oriented disciplines: applied physics, building services and building construction.

0.4.1 Heat, air and moisture

In the first half of the 20th century, attention focused on thermal conductivity. In the nineteen thirties, measuring the diffusion resistance gained importance after Teesdale of the US Forest Products Laboratory published a study in 1937 on ‘Condensation in Walls and Attics’. In 1952, an article by J. S. Cammerer on ‘Die Berechnung der Wasserdampfdiffusion in der Wänden’ (Calculation of Water Vapour Diffusion in Walls) appeared in ‘Der Gesundheitsingenieur’. At the end of the 1950s, H. Glaser described a new calculation method for interstitial condensation by vapour diffusion in cold storage walls in the same journal. Others, among them K. Seiffert, applied that method to building assemblies, albeit he used highly unrealistic climatic boundary conditions. His book ‘Wasserdampfdiffusion im Bauwesen’ (Water vapour diffusions in buildings) led to what today is called the vapour barrier phobia, even more that the text overlooked the most important cause of interstitial condensation: air displacement in and across building assemblies. From the sixties on, more researchers studied combined heat and moisture transport, among them O. Krischer, J. S. Cammerer and H. Künzel in Germany, A. De Vries and B. H. Vos in the Netherlands, L. E. Nevander in Sweden and A. Tveit in Norway.

That air transport figured as main cause of interstitial condensation, was stated first in Canada, a timber-framed construction country. In a publication in 1961, A. G. Wilson of NRC 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’.

0.4.2 Building acoustics

In the early 20th century, physicists started showing interest in applying noise control to building construction. In 1912, Berger submitted a Ph. D. thesis at the Technische Hochschule München entitled ‘Über die Schalldurchlässigkeit’ (Concerning sound transmission). Sabine published his well-known reverberation time in indoor spaces formula in 1920. In the years after, room acoustics became a favourite subject with studies about speech intelligibility, optimal reverberation times, reverberation time in anechoic rooms, etc. One decade later, L. Cremer was responsible for a break-through in 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 the coincidence effect between sound waves in the air and bending waves on a wall played a major role. Later he studied impact noise in detail with floating floors as a solution. Other German engineers, such as K. Gösele and M. Heckl, established the link between building acoustics and building practice. In the USA, Beranek published his book 'Noise and Vibration Control' in 1970, a remake of 'Noise reduction' of 1960. It became the standard work for engineers, who had to solve noise problems.

0.4.3 Lighting

The application of lighting to buildings and civil engineering constructions 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 the radiation theory to calculate illumination on surfaces and luminance contrasts in the environment. In the late 1960s, the daylight factor was introduced as a quantity to evaluate natural illumination indoors. More recently, after the energy crises of the 1970s, the relation between artificial lighting and primary energy consumption surged in importance as a topic.

0.4.4 Thermal comfort and indoor air quality

In the 19th century, engineers were especially concerned with housing and urban hygiene. A predecessor was Max von Pettenkofer (1818–1901, Figure 0.2) who was the first to perform research on the relation between ventilation, CO_2-concentration and indoor air quality. The 1500 ppm threshold, which still figures as limit between acceptable and unacceptable, is attributed to him. He is also attributed with the notion of 'breathing materials', the result of an erroneous explanation of the link he assumed between the air permeability of bricks and stone and the many health complaints in stony dwellings.

In the twentieth century, thermal comfort and indoor air quality became important topics. In the service of comfort, research by Yaglou, sponsored by ASHVE (American Society of

Figure 0.2. Max von Pettenkofer.

Heating and Ventilation Engineers), a predecessor of ASHRAE (American Society of Heating, Refrigeration and Air Conditioning Engineers) lead to the notion of ‘operative temperature’. Originally, his definition overlooked radiation. This changed after A. Missenard, a French engineer, critically reviewed the research and saw that radiant temperature had a true impact. The late P. O. Fanger took a large step forward with the publication in 1970 of his book ‘Thermal Comfort’. Based on physiology, on the heat exchange between the clothed body and the environment and the random differences in terms of comfort perception between individuals, he developed a steady state thermal model of the active, clothed human. Since then, his ‘Predicted Mean Vote (PMV) versus Predicted Percentage of Dissatisfied (PPD)’ curve has become the basis of all comfort standards worldwide. After 1985, the adaptive model gained support worldwide as an addition to Fanger’s work.

In terms of indoor air quality, a growing multitude of pollutants were catalogued and evaluated in terms of health risks. Over the years, the increase in fully air-conditioned buildings simultaneously increased the number of sick building complaints. This reinforced the call for an even better knowledge of the indoor environment, although the claim ‘better’ did not always result from a sound interpretation of data. One overlooked for example too often discontent with the job as a reason to simulate symptoms. Also here, P. O. Fanger had a true impact with his work on perceived indoor air quality, based on bad smell and air enthalpy.

0.4.5 Building physics and building services

In the 19th century, building service technicians were searching for methods to calculate the heating and cooling load. They took advantage of the knowledge developed in physics, which provided concepts such as the ‘thermal transmittance of a flat assembly’. Already quite early, organizations such as ASHVE and VDI had technical committees, which dealt with the topics of heat loss and heat gain. An active member of ASHVE was W. H. Carrier (1876–1950), recognized in the USA as the ‘father’ of air conditioning. He published the first usable psychometric chart. In Germany, H. Rietschel, professor at the Technische Universtät Berlin and the author of a comprehensive book on ‘Heizungs und Lüftungstechnik’ (Heating and Ventilation Techniques), also pioneered in that field. Heat loss and heat gain through ventilation was one of his concerns. He and others learned by experience that well-designed ventilation systems did not function properly when the building envelope lacked air-tightness. This sharpened the interest in air transport.

Moisture became a concern around the period air-conditioning (HVAC) gained popularity. The subject had already been a focus of interest, mainly because moisture appeared to be very damaging to the insulation quality of some materials and could cause health problems. Sound attenuation entered the HVAC-field due to the noisiness of the early installations. Lighting was focussed on as more HVAC engineers received contracts for lighting design. From 1973 on, energy efficiency emerged as a challenge. That HVAC and building physics are twins is still observed in the USA where ‘building science’ often is classified with mechanical engineering.

0.4.6 Building physics and construction

The link with construction grew due as designers of the new building tradition wrestled with complaints about noise and moisture. Building physics then became an application oriented field that could help avoid the failures which new solutions designed and built according to the existing ‘state-of-the art’ rules could provide.

It all started in the early 1930s with peeling and blistering of paints on insulated timber framed walls (insulation materials were rather new at that time). This motivated the already mentioned Teesdale to his study on condensation. Some years later, ventilated attics with insulation on the ceiling became the subject of experimental work by F. Rowley, Professor in Mechanical Engineering at the University of Minnesota, USA. His results contained the first instructions on vapour retarders and attic ventilation. In Germany, the Freiland Versuchsstelle Holzkirchen that was created in 1951 did pioneering work by using building physics as a tool to upgrade building quality. In 1973, when energy efficiency became a hot topic and insulation a necessity, the knowledge developed at Holzkirchen, proved extremely useful for the development of high quality, well-insulated buildings, and the manufacturing of glazing systems with better insulating properties, lower solar transmittance, and better visual transmittance. In the nineties of last century, the need for a better quality resulted in a generalized performance approach, as elaborated by the IEA-ECBCS Annex 32 on ‘Integral Building Envelope Performance Assessment’ and promoted thanks to the certification tools introduced worldwide.

Also from a building acoustics point of view, the theory got translated in easy to use methods rationales for constructing floors, walls, and roofs with high sound transmission loss for airborne and contact noise. Examples are tie-less cavity party walls, composite light-weight walls, floating screeds and double glass with panes of different thickness, the air space filled with a heavy gas and one of the panes assembled as a glass/synthetic foil/glass composite.

0.4.7 What about the Low Countries?

At the University of Leuven (KU Leuven), Belgium, lecturing in building physics started in 1952. This made that university the pioneer in the Benelux. At the TU-Delft, already before World War II Professor Zwikker gave lectures on the physics of buildings, but a course named ‘Building Physics’ only started in 1955 with Professor Kosten of the applied physics faculty. In 1963, Professor Verhoeven succeeded him. At the TU/e in Eindhoven Professor P. De Lange occupied the chair on Building Physics in 1969. Ghent University waited until 1999 to nominate an assistant professor in building physics.

During the early years at the University of Leuven, building physics was compulsory for architectural engineers and optional for civil engineers. Half-way through the 1970s the course also became compulsory for civil engineers. Since 1990, after building engineering started, building physics is one of the basic disciplines for those entering that programme. From that date on, a strong link was also established with the courses on building services and performance based building design.

The first building physics professor was A. de Grave, a civil engineer and head of the building department at the Ministry of Public Works. He taught from 1952 until 1975, the year that he passed away. In 1957 he published his book ‘Bouwfysica’ (Building Physics), followed by ‘Oliestook in de woning’ (Oil heating at home). He was a practitioner, not a researcher. Former students still remember his enthusiastic way of teaching. In 1975, the author of this book took over. In 1977, we founded the laboratory of building physics. From the start, research and consultancy focussed on the physical properties of building and insulation materials, on upgrading the performances of well-insulated assemblies, on net energy demand, end energy consumption, and primary energy consumption in buildings, on indoor environmental quality, on airborne and contact noise attenuation and on room acoustics. Later-on, urban physics were added with wind, rain, and pollution as main topics.

0.5 Units and symbols

- The book uses the SI-system (internationally mandatory since 1977). Base units: the meter (m); the kilogram (kg); the second (s); the Kelvin (K); the ampere (A); the candela. Derived units, which are important when studying 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
a	Acceleration	m/s^2
a	Thermal diffusivity	$\text{m}^2\text{/s}$
b	Thermal effusivity	$\text{W/(m}^2 \cdot \text{K} \cdot \text{s}^{0.5})$
c	Specific heat capacity	$\text{J/(kg} \cdot \text{K)}$
c	Concentration	kg/m^3, g/m^3
e	Emissivity	–
f	Specific free energy	J/kg
	Temperature ratio	–
g	Specific free enthalpy	J/kg
g	Acceleration by gravity	m/s^2
g	Mass flow rate, mass flux	$\text{kg/(m}^2 \cdot \text{s)}$
h	Height	m
h	Specific enthalpy	J/kg
h	Surface film coefficient for heat transfer	$\text{W/(m}^2 \cdot \text{K)}$
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 flow rate, heat flux	W/m^2
r	Radius	m
s	Specific entropy	$\text{J/(kg} \cdot \text{K)}$

Table 0.1. (continued)

Symbol	Meaning	Units
t	Time	s
u	Specific latent energy	J/kg
v	Velocity	m/s
w	Moisture content	$\mathrm{kg/m^3}$
x, y, z	Cartesian co-ordinates	m
A	Water sorption coefficient	$\mathrm{kg/(m^2 \cdot s^{0.5})}$
A	Area	$\mathrm{m^2}$
B	Water penetration coefficient	$\mathrm{m/s^{0.5}}$
D	Diffusion coefficient	$\mathrm{m^2/s}$
D	Moisture diffusivity	$\mathrm{m^2/s}$
E	Irradiation	$\mathrm{W/m^2}$
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	$\mathrm{kg/(m \cdot s \cdot K)}$
K	Mass permeance	s/m
K	Force	N
L	Luminosity	$\mathrm{W/m^2}$
M	Emittance	$\mathrm{W/m^2}$
P	Power	W
P	Thermal permeance	$\mathrm{W/(m^2 \cdot K)}$
P	Total pressure	Pa
Q	Heat	J
R	Thermal resistance	$\mathrm{m^2 \cdot K/W}$
R	Gas constant	$\mathrm{J/(kg \cdot K)}$
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	$\mathrm{W/(m^2 \cdot K)}$
V	Volume	$\mathrm{m^3}$
W	Air resistance	m/s
X	Moisture ratio	kg/kg
Z	Diffusion resistance	m/s

Table 0.1. (continued)

Symbol	Meaning	Units
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	$N \cdot s/m^2$
θ	Temperature	°C
λ	Thermal conductivity	$W/(m \cdot K)$
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 currently used suffixes.

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 gases
m	Moisture, maximal
r	Radiant, radiation
sat	Saturation
s	Surface, area, suction

Table 0.2. (continued)

Symbol	Meaning
rs	Resulting
v	Water vapour
w	Water
ϕ	Relative humidity
Notation	
[ ], bold	Matrix, array, value of a complex number
Dash	Vector (ex.: $\overline{a}$)

0.6 Literature

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1 Heat Transfer

1.1 Overview

Thermodynamics gives a first definition of heat. The discipline divides the world into systems and environments. A system can be anything: a material volume, a building assembly, a building, a part of the heating system, etc. We can even look at a city as a system. 'Heat' indicates how energy is transferred between a system and its environment. Whereas 'work' is purposeful and organized, heat is diffuse and unorganized. Particle physics offers a second definition, by which heat denotes the statistically distributed kinetic energy of atoms and free electrons. In both cases, heat is the least noble, or most diffuse form of energy, to which each nobler form degrades according to the second law of thermodynamics.

Temperature as 'potential' determines the quality of heat. Higher temperatures mean higher quality, which refers to a higher mechanical energy of atoms and free electrons and the possibility to convert more heat into power via a cyclic process. It in turn is synonymous with higher exergy. Lower temperatures give heat a lower quality, which means less mechanical energy on the atomic scale and less exergy. Higher temperatures demand warming a system, i.e. adding heat. Lower temperatures require cooling a system, i.e. removing heat. Like any other potential, temperature is a scalar.

Heat and temperature cannot be measured directly. Yet, temperature is sensed and indirectly measurable because a great deal of material properties depends on it:

- Thermal expansion: for a mercury thermometer, we use the volumetric expansion of mercury as a measure for temperature
- Change of electrical resistance: for a Pt100 resistance thermometer, the electrical resistance of a platinum wire functions as a measure for temperature
- Change of contact potentials: this is the basis for the measurement of temperature with a thermocouple

The SI-system uses two temperature scales:

- *Empiric*
  Degree Celsius (indicated as °C, symbol θ).
  0 °C is the triple point of water, 100 °C the boiling point of water at 1 Atmosphere
- *Thermodynamic*
  Degree Kelvin (indicated as K, symbol: T).
  0 K is the absolute zero, 273,15 K the triple point of water

The relation between both is $T = \theta + 273.15$. Temperatures are given in °C or K, temperature differences in K. The USA uses degree Fahrenheit (°F) as temperature scale. The relation with °C is: °F = 32 + 9/5 °C.

Heat exists in sensitive form, which means temperature-related, or in latent form, which means as transformation heat. Sensitive heat is transferred by:

Conduction. The energy exchanged when vibrating atoms collide and free electrons move collectively. Heat moves by conduction between solids at different temperatures in contact

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with each other and between points at different temperatures within the same solid. The mode also intervenes when heat is exchanged in gases and liquids and in the contacts between gases and liquids at one side and solids at the other. Conduction always occurs from points at higher to points at lower temperature (2nd law of thermodynamics). The mode needs a medium and induces no observable macroscopic movement.

Convection. The displacement of molecule groups at a different temperature. Convection is by nature a consequence of macroscopic movement (transfer of enthalpy) and occurs in a pronounced way close to the contact between liquids and gases at one side and solids at the other. We distinguish forced, natural, and mixed convection depending on whether or not an external force, a difference in fluid density, or both cause the movement. In forced convection, work exerted by an exterior source may compel heat to flow from low to high temperatures. Convection needs a medium. Actually, in liquids and gases, convection always includes conduction. Also in convection mode, heat transfer between molecules occurs by conduction.

Radiation. Heat transfer, caused by the emission and absorption of electromagnetic waves. At temperatures above 0 K, each surface emits electromagnetic energy. Between surfaces at different temperatures, that emission results in heat exchanges. Heat transfer through radiation does not need a medium. On the contrary, it is least hindered in vacuum and follows physical laws, which diverge strongly from conduction and convection.

Latent heat moves along with a carrier, independent of temperature. Each time that carrier undergoes a change of state, related latent heat converts into sensitive heat or vice versa. For example, when water evaporates, it absorbs sensitive heat in a quantity equal to its latent heat of evaporation. The water vapour then diffuses to a cooler spot (= transfer) where it may condense with reemission of the latent heat of evaporation as sensible heat. These conversions influence the temperature course as well as the flow of sensitive heat in solids and building assemblies.

Why are heat and temperature so important in building physics? Heat flow means end energy consumption. Thermal comfort requires keeping the operative temperature in buildings at the right level. That requires heating and cooling. Both require the combustion of fossil fuels, converting work into heat, or transforming thermal electricity, hydraulic electricity or electricity generated by wind turbines and PV-cells into heat. In every developed country, heating and cooling of buildings has a substantial share in the primary energy consumption. Fossil fuels will eventually become scarce, and their combustion is responsible for environmental problems such global warming. Thermal electricity in turn is energy-intensive to generate. For all these reasons, the design and construction of buildings with low net heating and cooling demand has become a necessity. That presumes restricted heat flows traversing the envelope.

Temperatures influence comfort and durability. Sufficiently high surface temperatures contribute to a feeling of thermal well-being. However, summer indoor temperatures, which are too high, affect building usability. Further, the higher the temperature differences between layers in a building assembly, the larger the differential movements, the larger the thermal stresses and the higher crack risk. Temperatures below freezing in turn may damage moist porous materials, while high temperatures accelerate the chemical breakdown of synthetic materials. Differences in temperatures also induce moisture and dissolved salt displacement in porous materials, etc. Whether or not we can control these temperature effects, depends on how building assemblies are designed and constructed.

This section deals with heat transfer by conduction, convection, and radiation. It ends with typical building physics related applications on the building assembly and whole building level. But first, some definitions: