Hugo Hens

Applied Building Physics

- content well structured combining theory with typical building engineering practice
- equally suitable as a textbook and for practitioners
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As with all engineering sciences, Building Physics is oriented towards application, hence, after a first book on fundamentals this volume on Applied Building Physics discusses the heat, air, moisture performance metrics that affect building design, construction and performance.

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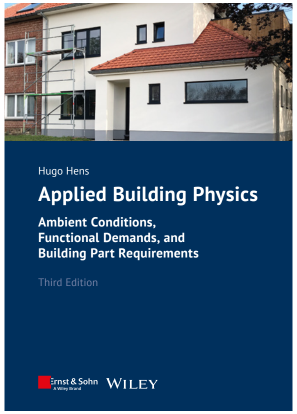

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ABOUT THE BOOK

While a first book on building physics refreshes the physics behind the heat, air, moisture behaviour of buildings, and building components, this second book on applied building physics focuses on the question of what a well-balanced building performance consists of. First, the environmental loads on buildings are explained – i.e. all those parameters that describe the external and internal environmental conditions, with an emphasis on practical implementation. Then follows a comprehensive presentation of those performance requirements that are important at the whole-building level, mainly considering thermal, acoustic, visual and olfactory comfort, indoor air quality, energy consumption, durability, economy and sustainability. This is followed by an in-depth discussion of the requirements regarding thermal, air and moisture behaviour as well as the measured variables at the level of the building construction and components.

The analyses and calculations described in this book result in sustainable buildings made of functional and durable building constructions, with comfortable and healthy indoor climate.
Compared to the second edition, the whole text, included the figures, for the third edition has been reorganised, corrected, revised and expanded where appropriate. Chapter 3 saw the discussion on comfort not only limited to the thermal but extended to the acoustic, visual and olfactory comfort. Also, the indoor air quality part is expanded as is the part on sustainability. Chapter 4 got under interstitial condensation an example from practice added. The last chapter on material properties has been moved to the book on building physics and is replaced by an appendix for quick reference, only containing standard values, for which standard lists are missing.

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Contents

Preface

While the first volume on Building Physics looked to the fundamentals governing the heat, air, moisture response of building parts and whole buildings, this second volume on Applied Building Physics shows how building physics may help in upgrading building and building part design and construction by applying the discipline related performance rationales, requirements and metrics to guarantee a sound building quality. How, starts with the ambient conditions out- and indoors acting as the environmental loads buildings and building parts or assemblies face. Then a move is made to the performance fields of importance at the whole building level, after which, directly linked to the book on Building Physics, the heat, air, moisture requirements and metrics actually expected when designing and realizing building parts assemblies pass the review.

This content to a large extent reflects the 38 years of teaching Building Physics and Applied 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, 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 further reading list. The book uses SI units. It could be of help for undergraduate and graduate students in architectural and building engineering, although also practising building engineers, who want to refresh their knowledge, may benefit. Presumed anyhow is that the reader has a sound knowledge of the fundamentals treated in the first book, along with a background in construction materials and building design and construction.

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. The book should also not have 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 ask complex modelling, mainly because reality in building construction is much more complex than any model can simulate.

During the four decades at the Unit of Building Physics and Sustainable Construction within the Department of Civil Engineering of the 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, now professor emeritus, to Staf Roels, Dirk Saelens, Hans Janssen and Bert Blocken, who succeeded me as professors at the unit.

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

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

Introduction

Subject of the Book

This is the second 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

The term 'applied' could be perceived as a pleonasm since 'Building Physics' is by definition referring to a body of knowledge, whose application is essential for the correct performance of new construction and renovation. Whatever, the subjects discussed in this second book offer a link between 'Building Physics: Heat, Air and Moisture' and the volume on 'Performance-Based Building Design'.

Highlighted in Chapter 1 are the climate, the indoor environment and several related design approaches. Chapter 2 advances the performance concept with its hierarchical structure, from the urban environment down to whole buildings, building assemblies, the layers assemblies consist of and the materials used. In Chapter 3, several fields of importance that fix building physics-related performance requirements at the whole building level are discussed. Chapter 4 analyses the heat, air, moisture performance metrics, to which building envelopes must comply to ensure a correct behaviour. Chapter 5 advances timber frame walls as example of a construction choice with possibly a problematic heat, air, moisture response, while for the sake of completeness, the Appendix repeats lists with material property values, already discussed in 'Building Physics: Heat, Air and Moisture, Fundamentals, Engineering Methods, Material Properties and Exercises'.

Well known is that a performance-based approach should guarantee building quality. Of course, physical integrity is not the only value of importance in the built environment. Also, functionality, spatial quality and aesthetics, all belonging to the architect's responsibility, are, but these should never figure as arguments to neglect a correct overall structural and physical performance.

Applied Building Physics: Ambient Conditions, Functional Demands, and Building Part Requirements, Third Edition. Hugo Hens.

Expectancy	Applies to	e
High	Naturally ventilated office buildings in regions where air conditioning is the norm, regions where heat waves are limited in duration	0.9–1.0
Moderate	Naturally ventilated office buildings in regions where air-conditioning is less common, regions with warm summers	0.7–0.9
Low	Naturally ventilated office building in regions where air conditioning is the exception, regions where it is hot the whole year	0.5–0.7

3.2.2.6 Thermal Comfort Under Non-uniform, Non-steady-state Conditions

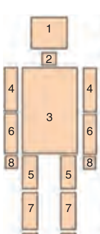
3.2.2.6.1 In General

Steady state presumes a same skin temperature all-over the body, an ambient at same air temperature all around, a same radiant temperature all around, a same RH all around and a same relative air velocity all over the body. All this is sheathing reality. A dressed skin has no uniform temperature and does not sense the same conditions all around. Instead, the body is partly clothed and the blood pumped around gives different skin temperatures from spot to spot. The air temperature may change from head to ankles. Each body part may see another radiant temperature. RH could change along the clothed body and the relative air velocity felt varies with which body parts are moving how.

3.2.2.6.2 Refined Body Model

Studying thermal comfort under spatial non-uniform, non-steady-state conditions start with splitting the body into 15 parts (1, 2, 3, 2 × 4, 2 × 5, 2 × 6, 2 × 7, 2 × 8, 2 × 9, see Figure 3.4), each part consisting of a bone core surrounded by muscles, fat and the skin. The large part 3 houses the respiratory tract, the heart and the internal organs. Each part has an own thermal conductivity, an own mass and an own clo-value. The connector is the blood flow and the heat it conducts. The figure also lists the mass per part for an individual weighing 71 kg. Of course, these weights differ between people, which partly explains why they react differently.

The local skin and core temperature noted by the control system allows the relay to choose the thermoregulatory response: sweating, shivering, vasodilatation or -constriction pumping more or less blood around. A core temperature of 36.8 °C and an average skin temperature of 33.7 °C fix the basal situation. Maximum vasodilatation occurs at 37.2 °C core temperature with the blood flow touching seven



	Mass (kg)								
Body part →	1	2	3	4	5	6	7	8	9
Brain	1.398								
Abdomen			11.14						
Lung			2.919						
Bone	1.777	0.233	4.169	0.473	1.482	0.266	0.655	0.164	0.412
Muscles	0.452	0.581	11.98	1.580	2.539	0.883	1.120	0.141	0.215
Fat	0.282	0.071	9.014	0.240	1.134	0.134	0.508	0.149	0.347
Skin	0.187	0.031	1.231	0.181	0.341	0.101	0.153	0.093	0.127

Figure 3.4 The body parts.

times the basal one maximum constriction at 10.7 °C average skin temperature with the blood flow touching 1/8 of the basal one. Between these limits, the cardiac output distributes the blood over the 15 parts proportionally to their skin surface, while a core temperature above 36.8 °C guides vasodilatation and an average skin temperature below 33.7 °C vasoconstriction. Calculation of course requires a fine grid per part with the local thermal sensation (S_{local}) function of the skin and overall core temperature plus their derivatives to time:

$$S_{\text{local}} = F\left(\theta_{\text{skin}}, \frac{\mathrm{d}\theta_{\text{skin}}}{\mathrm{d}t}, \theta_{\text{core}}, \frac{\mathrm{d}\theta_{\text{core}}}{\mathrm{d}t}\right) \tag{3.25}$$

Although the model masters non-uniform, non-steady-state thermal conditions, in practice, the consequences are linked to drifts and ramps in temperature or bundled into what's called local discomfort.

3.2.2.6.3 Drifts and Ramps

Temperature transients indoors mainly include temperature drifts and ramps. Both refer to non-cyclic, monotonous drops and rises of the operative temperature. Drifts are uncontrolled, ramps HVAC-controlled. Cyclic variations on the other hand refer to situations where the operative temperature changes repeatedly. Acceptability depends on controlled or not, rise or drop rate (°C/h) and size of the cyclic peak-to-peak difference. No negative impacts on thermal comfort are seen when drifts, ramps and cycles result from human action as opening or closing windows. Abrupt and important changes beyond human control instead trouble. For the operative temperature to remain comfortable, drifts and ramps with periods of 15′ to 4 hours may not exceed following values:

Time period	**15′**	**30′**	**1 hr**	**2 hr**	**4 hr**
Operative temperature, drifts/ramps allowed (°C)	±1.1°	±1.7°	±2.2°	±2.8°	±3.3°

For cyclic variations with periods shorter than 15 minutes, the peak-to-peak differences must remain below 1.1 °C. If superimposed on longer cyclic variations, that 1.1 °C should be combined with the drift and ramp restrictions.

3.2.2.7 Local Discomfort

3.2.2.7.1 Draught

Draught complaints and related chilling of the neck, the lower back and the ankles are common in air-heated and air-cooled buildings. Cause is the higher convective surface film coefficient (h_{co}) there, which increases with the square root of the product between the local air velocity (v in m/s) and its ratio to the standard deviation, called the turbulence intensity (Tu, %):

$$h_{\text{c}} = h_{\text{co}} + 0.27\sqrt{v\text{Tu}}\ (\text{W}/(\text{m}^2\ \text{K})) \tag{3.26}$$

Also the flow direction has impact, with air blowing from behind worse than air blowing in front and a flow top down worse than a flow down up, although the draught rate (DR) used as evaluation tool does not make a distinction:

$$\mathrm{DR} = (34 - \theta_a)(\bar{v} - 0.05)^{0.62}\ (0.37\bar{v}\mathrm{Tu} + 3.14)$$
$$\bar{v} < 0.05\ \mathrm{m/s} \rightarrow \bar{v} = 0.05\ \mathrm{m/s}, \quad \mathrm{DR} > 100 \rightarrow \mathrm{DR} = 100 \tag{3.27}$$

3.2.2.7.2 Vertical Differences in Air Temperature

Figure 3.5 shows the percentage of dissatisfied (PD) when seated as function of the difference in air temperature between head and ankles.

3.2.2.7.3 Radiant Asymmetry

The body always faces two horizontal and two vertical half-spaces with own radiant temperature. This gives comfort problems when the difference between the two passes given values.

Figure 3.6a shows PD for vertical radiant asymmetry with 5% dissatisfied expected for the upper half 14 °C colder than the lower. When the upper half instead is warmer, a 4.5 °C difference suffices for 5% dissatisfied. This fixes what's allowed as mean temperature of a heated ceiling, see Table 3.4. Of course, the temperature of the whole ceiling still depends on the view factor with the head, a reality resembling a dot seeing the ceiling from some distance ($F_{h,c}$). At design conditions, accepted is that the temperature (θ_{eb}) assumed for a heated ceiling passing this PD = 5% limit is:

$$\theta_{\mathrm{ceil,max}} \leq 1.67\theta_{\mathrm{ceil}} - 0.67\theta_{\mathrm{o,comfort}} \tag{3.28}$$

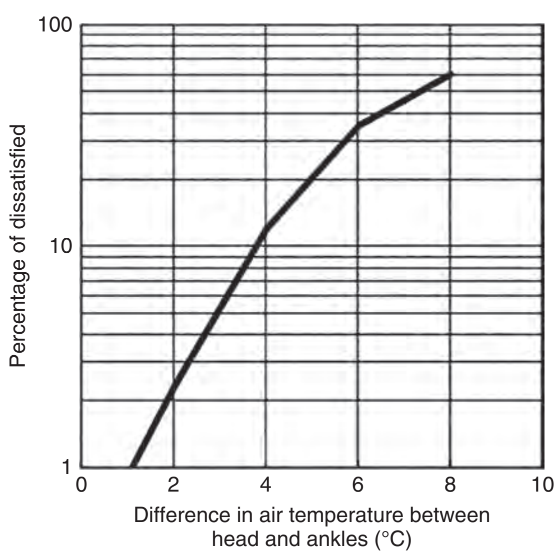


Figure 3.5 Seated persons, temperature difference between head and ankles, % dissatisfied (PD).

Table 3.4 Permitted mean temperature of a radiant ceiling.

$F_{h,c}$	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20	0.22	0.24	0.26	0.28
θ_{ceil} (°C)	50	43	38	35.2	33	31.3	30	28.6	27.5	26.8	26.0	25.8

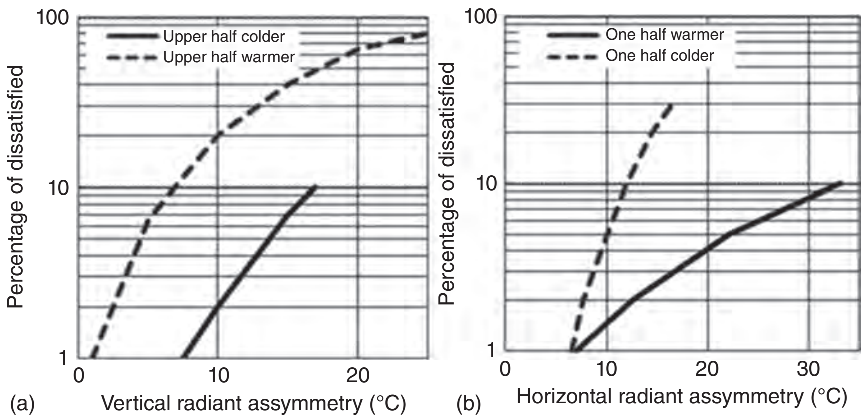


Figure 3.6 (a) Vertical radiant asymmetry, percentage of dissatisfied (PD); (b) horizontal radiant asymmetry, percentage of dissatisfied (PD).

Figure 3.6b shows PD for horizontal radiant asymmetry. If caused by a cold surface, the 5% PD stands for a 10 °C difference. A single glass wall could give this, which is why the figure is also tabled as the single glass effect. Warmer half-space surfaces instead rarely generate complaints.

3.2.2.7.4 Feet Comfort

Feet comfort is also an issue. Transmission gains from or transmission losses to the floor are not included in the steady state comfort balance as related heat exchange is mostly too limited. People nonetheless perceive feet comfort as critical. Parameters are the floor temperature (θ_{fl}) and its contact coefficient (b_{fl}). Their importance depends on how long barefoot the soles contact the floor and whether shoes are worn or not. As an array:

Contact duration	Very short	Short	Long
Barefoot	$\theta_{fl} = F(b_{fl})$	$\theta_{fl} = F(b_{fl})$	$\theta_{fl} = F(b_{fl})$
Wearing shoes	θ_{fl}	θ_{fl}, (b_{fl})	θ_{fl}

When barefoot, what's comfortable as floor temperature depends on the contact coefficient of the floor cover, see Table 3.5. Figure 3.7 in turn gives PD for long-lasting floor contact with shoes on. PD 10% stands for a floor temperature between 19 and 28 °C, with 28 °C the limit for floor heating and 19 °C the limit for floor cooling. In circulation zones, the short floor contact makes 17–30 °C allowable.

3.2.2.8 Standard-based Comfort Requirements

For the comfort requirements as given in ASHRAE standard 55-2017 and ISO EN standard 7730-2005, see Tables 3.6 and 3.7. While for conditioned spaces ASHRAE only imposes PPDs, ISO-EN allows a choice between high (I), good (II), acceptable (III) and low (IV) thermal comfort conditions.

Both also consider adaptation in naturally ventilated spaces, see Figure 3.8.

Table 3.5 Floor temperature and contact duration, floor covers listed from low to high contact coefficient.

Floor cover↓ Contact→	Floor temperature (°C)		
	Very short	Short	Long
Carpet	21	24.5	21–28
Cork	24	26	23–28
Parquet (Nordic pine)	25	25	22.5–28
Parquet (oak)	26	26	24.5–28
Vinyl tiles	30	28.5	27.5–29
Vinyl on felt	28	27	27.5–28
Linoleum on planks	28	26	24–28
Linoleum on concrete	28	27	26–28.5
Concrete	30	28.5	27.5–29
Marmora, tiles	30	29	28–29.5

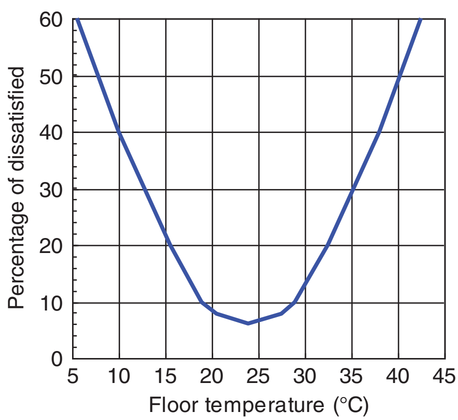


Figure 3.7 Wearing shoes, long floor contact, percentage of dissatisfied (PD).

The formulas used to get the straight lines shown are:

ANSI/ASHRAE 55-2017		
80% acceptability	Lower limit: $\theta_o = 14.4 + 0.3\bar{\theta}_{e,month}$	Upper limit: $\theta_o = 21.2 + 0.3\bar{\theta}_{e,month}$
90% acceptability	Lower limit: $\theta_o = 15.5 + 0.3\bar{\theta}_{e,month}$	Upper limit: $\theta_o = 20.3 + 0.3\bar{\theta}_{e,month}$
ISO EN 7730-2005		
Outdoors:	$\bar{\theta}_{e,ref} = (\theta_{e,-1} + 0.7\theta_{e,-2} + 0.6\theta_{e,-3} + 0.5\theta_{e,-4} + 0.4\theta_{e,-5} + 0.3\theta_{e,-6} + 0.2\theta_{e,-7})/3.8$	
Comfort	$\theta_o = 18.7 + 0.33\bar{\theta}_e$	
Category I	Lower limit: $\theta_o = 15.7 + 0.33\bar{\theta}_{e,ref}$	Upper limit: $\theta_o = 20.7 + 0.33\bar{\theta}_{e,ref}$
Category II	Lower limit: $\theta_o = 14.7 + 0.33\bar{\theta}_{e,ref}$	Upper limit: $\theta_o = 21.7 + 0.33\bar{\theta}_{e,ref}$
Category III	Lower limit: $\theta_o = 13.7 + 0.33\bar{\theta}_{e,ref}$	Upper limit: $\theta_o = 22.7 + 0.33\bar{\theta}_{e,ref}$

Table 3.6 ASHRAE 55-2017.

Comfort		**PPD≤ (%)**
Overall		10
Local	Draught	20
	Vertical air temperature difference, radiant asymmetry	5
	Feet	10

Table 3.7 ISO EN 7730-2005.

Overall						
	Overall comfort		**Operative temp. (°C)**		**Maximum air speed (m/s)**	
Category, (expectations)	**PPD (%)**	**PMV**	**Summer**	**Winter**	**Summer, 0.6 clo, cooling**	**Winter, 1 clo, heating**
I (high)	≤6	−0.2 to 0.2	23.5–22.5	21.0–23.0	0.18	0.157
II (good)	6–10	−0.5 to 0.5	23.0–26.0	20.0–24.0	0.22	0.18
III (acceptable)	10–15	−0.7 to 0.7	22.0–27.0	19.0–25.0	0.25	0.21
IV (low)	15–25	−1 to 1	21.0–28.0	17.0–26.0	0.28	0.24
Local						
			Radiant asymmetry (°C)			
Category, (expectations)	**Vertical temp. gradient (°C)**	**Floor temperature (°C)**	**Warm ceiling**	**Cold ceiling**	**Warm wall**	**Cold wall**
I (high)	≤2	19–29	≤5	≤14	≤23	≤10
II (good)	2–3	19–29	≤5	≤14	≤23	≤10
III (acceptable)	3–4	17–31	5–7	14–18	23–35	10–13

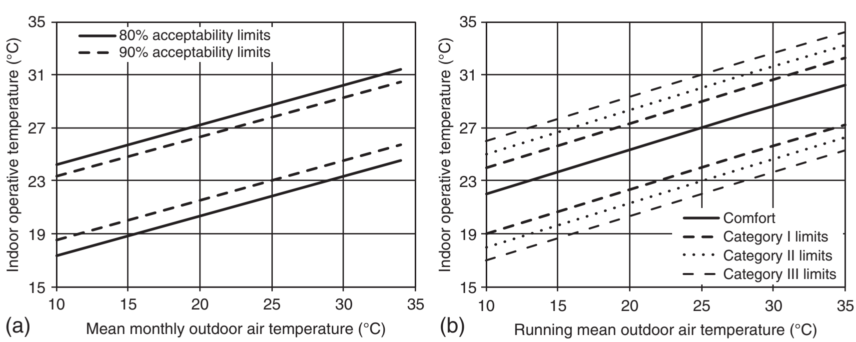


Figure 3.8 Adaptation; (a) ASHRAE 55-2017; (b) ISO EN 7730-2005.

3.2.2.9 Consequences for the Enclosure Performance

The operative temperature with as weighting factors 0.5 for the air and radiant temperature allows calculating the mean U_m-value room enclosures should need in heating climates to ensure acceptable thermal comfort. For this, all surfaces are considered grey. The radiant temperature in the space's centre then nears:

$$\theta_{\mathrm{r}} = \frac{\sum(A_j\theta_{\mathrm{s},j})}{\sum A_j} \tag{3.29}$$

with A_j the area and $\theta_{s,j}$ the temperature of each surface j. The steady state relation between surface temperature and U-value now is:

$$\theta_{\mathrm{s},j} = \theta_{\mathrm{o}} - (U_j/h_i)(\theta_{\mathrm{o}} - \theta_k) \tag{3.30}$$

where for partitions θ_k is the operative temperature in the adjacent space and for envelope parts the sol-air temperature outdoors. Per envelope part, the equation so becomes:

$$\theta_{\mathrm{s},l} = (1 - U_l/h_i)\theta_{\mathrm{o}} + (U_l/h_i)\theta_{\mathrm{e}}^*$$

For a partition with adjacent space k, reshuffling gives:

$$\theta_{\mathrm{s},m} = (1 - a_k U_k/h_i)\theta_{\mathrm{o}} + (a_k U_k/h_i)\theta_{\mathrm{o},k} \text{ with } a_k = (\theta_{\mathrm{o}} - \theta_{\mathrm{o},k})/\left(\theta_{\mathrm{o}} - \theta_{\mathrm{e}}^*\right)$$

The parameter a_k turns 0 when both spaces are heated at same operative temperature and nears 1 when the partitions are well insulated and the adjacent spaces unheated and intensely ventilated. Entering the equations for the envelope part and the partitions in Eq. (3.30) results in:

$$\theta_{\mathrm{r}} = \theta_{\mathrm{o}} - (U_m/h_i)\left(\theta_{\mathrm{o}} - \theta_{\mathrm{e}}^*\right) \quad \text{with} \quad U_m = \frac{\sum(A_l U_l) + \sum(a_k A_k U_k)}{\sum A_l + \sum A_k} \tag{3.31}$$

In it, $\sum A_l$ refers to all envelope parts, $\sum A_k$ to all partitions. Transposition in $0.5(\theta_{\mathrm{a}} + \theta_{\mathrm{r}})$ finally gives:

$$\theta_{\mathrm{o}} = \frac{h_i\theta_{\mathrm{a}} + U_m\theta_{\mathrm{e}}^*}{h_i + U_m} \tag{3.32}$$

Or, the lower the mean thermal transmittances U_m of a room enclosure, meaning the better insulated the envelope parts and the larger the share partitions have, the smaller the difference between operative and air temperature, as a rewrite shows:

$$\theta_{\mathrm{a}} = (1 + U_m/h_i)\theta_{\mathrm{o}} - (U_m/h_i)\theta_{\mathrm{e}}^*$$

Better insulation so allows lowering the air temperature without troubling thermal comfort, or, comfort-related envelope metrics may start by imposing a maximum gap between air and radiant temperature, resulting in an upper limit for the mean U-value of the envelope parts enclosing the space. This does not at all require the extreme thermal resistances passive building adepts claim. As Figure 3.9 shows, the central operative temperature is stabilising once the air-to-air mean thermal resistance of the envelope, included the window, passes 3 ($\mathrm{m^2\,K}$)/W. An additional advantage of a lower air temperature is less end energy needed to heat the ventilation air.

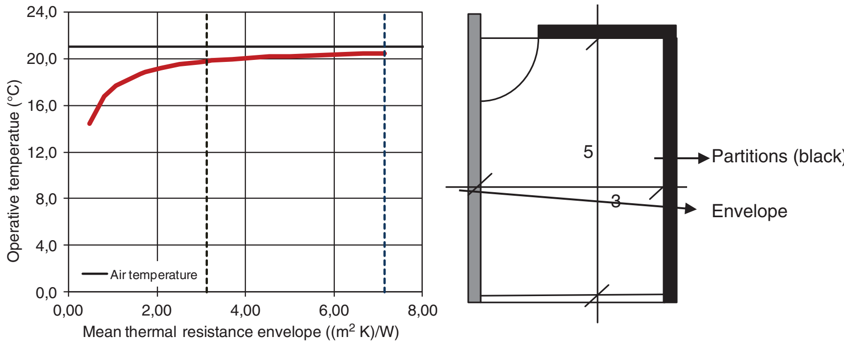


Figure 3.9 Office in the upper corner of a building, $V = 40.5\ \mathrm{m}^3$, $A = 15\ \mathrm{m}^2$, envelope $8.1\ \mathrm{m}^2$, window $\theta_\mathrm{l} = 21\,°\mathrm{C}$, $\theta_\mathrm{o} = F(R_\mathrm{m})$; partitions and floor separate the office from equally arm spaces.

3.2.3 Acoustical Comfort

3.2.3.1 Anatomy of the Ears

Hearing is linked to how the ears function (Figure 3.10). Three parts they contain. First come the external ears with the auricle and the auditory duct, having at its end the tympanic membrane. Beyond that membrane figures as second part the middle ear, consisting of a volume filled with air that is linked to the nasal cavity and so to the ambient via the Eustachian tube. The middle ear further contains the ossicles with the hammer, the anvil and the stirrup bone, while the oval and round fenestra is closing it at the back. As third part follows the inner ear, which includes the cochlea filled with ear liquid. It further counts 2.5 convolutions and is split in two by the cochlean septum, in which a little hole couples both. The septum contains the basilar membrane, upon which four rows of hair cells are sitting with each hair of the inner row and small groups of the other three rows coupled to the auditory nerves, with

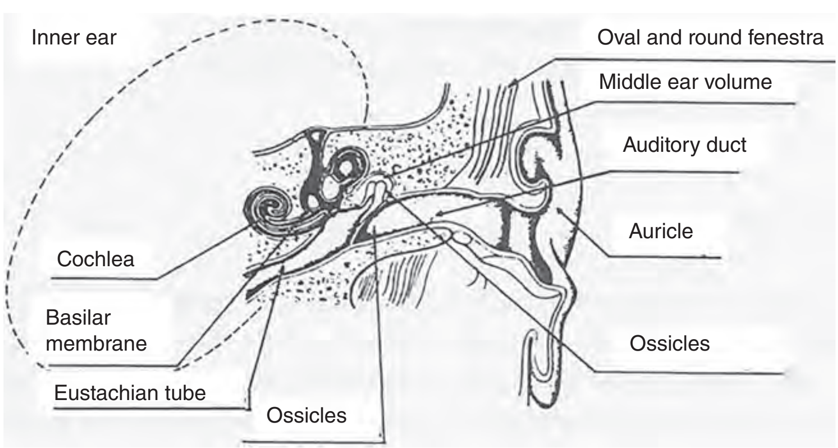


Figure 3.10 The human ear (Encyclopedia Britannica).

those from the left and the right ear crossing each other behind the external ear. Both anyhow are linked to the left and the right cerebral cortex with the link to the right figuring as priority direction for the left ear and the link to the left figuring as priority direction for the right ear.

3.2.3.2 Physiological Facts

Sound waves reaching the ear pass the auditory duct to touch the tympanic membrane that then starts vibrating with an extremely small amplitude, $\approx 10^{-9}$ m. The ossicles transport these vibrations to the oval fenestrum, which converts them into stationary waves crossing the ear liquid. These touch the basilar membrane and excitate so the hair cells, what induces an alternating electric current synchronic to the sound waves entering the ear, which is guided by the auditory nerves to the cerebral cortex. Depending on the frequency of the sound, the stationary waves exciting the basilar membrane may move in resonance with the amplitudes of the moving hair cells. At low frequencies, it is the most dampened hairs at the back that start resonating, while at 4000 Hz the least dampened at the front do. This is why the ears are most sensitive at 4000 Hz and much less at low frequencies, but also why deafness starts at 4000 Hz.

3.2.3.3 Effects of Unacceptable Noise

3.2.3.3.1 In General

Main problem with what's acceptable as noise is the large difference between individuals. This complicates how to evaluate nuisance, risk, consequences, etc. Therefore, only averages or requirements based on a percentage of individuals disturbed can be fixed. The different ear sensitivity between individuals, be it by illness, even makes establishing a starting value to compare situations difficult. Statements regarding the consequences of noise must therefore be read as 'there will be individuals with no or with stronger complaints than noted'.

3.2.3.3.2 From a Psychological Point of View

Too loud noises impede communication, disturb concentration, worsen labour performance, give sleep problems and could induce psychic disorders. Most people are remarkably immune to noises they like or produce themselves. Psychologic nuisance so typically concerns noises produced by others, that, if not disturbing, stand for 'acoustically comfortable'.

Impeded communication is a consequence of masking effects. Speech audibility gets troubled when an important part of the ambient noise belongs to the 500, 1000 and 2000 Hz band. Depending on what's called the 'Preferred Speech Interference Level (PSIL)', an audibility distance has been fixed, see Figure 3.11 and Table 3.8.

Looking to concentration and labour performance, that too much noise could have a disturbing effect is well known, though, remarkably, may also be a support. When the case, research learned that employees having sound-based duties show worse performance. For those intellectually active, negative impacts surface if quite high background sound pressure levels disturb speech intelligibility, positive impacts instead do when sounds, take music, mask unwished noises.

Due to its importance for health, substantial medical research on the impact of noise on sleep has been done. Three factors intervene. First comes sleep intensity,

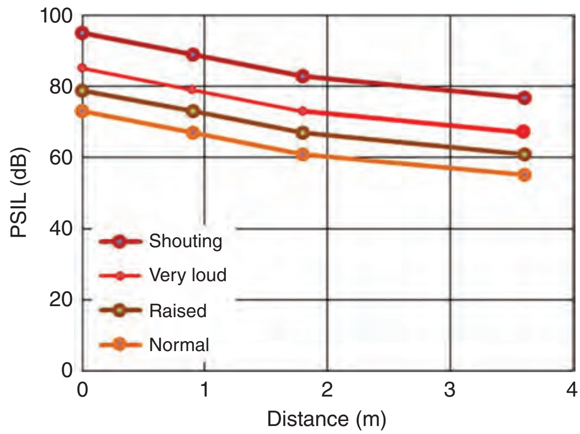


Figure 3.11 Preferred Speech Interference Level (PSIL) as a function of distance.

Table 3.8 Speech audibility.

	Distance speaker to listener (m)			
	Normal speaking		Very loud speaking	
PSIL (dB)	**Clearly audible**	**Not audible**	**Clearly audible**	**Not audible**
73 (= 80 dB(A))	0.16	0.5	0.8	2.5
63 (= 70 dB(A))	0.5	1.5	2.5	8.0
53 (= 60 dB(A))	1.5	5	8.0	25

light, normal or deep, with light as most noise sensitive. Second is the difference between individuals. The sound level at which 10% wake up lays some 40 dB(A) lower than at which 90% wake up. Some people can sleep in trains and aeroplanes, where the equivalent sound pressure level may touch 70 dB(A), while even quieter noises wake up others. Third is what the noise means for the sleeper. Baby's sucking noises, ≈20 dB(A), wake up mothers. Many only do when the alarm clock rings, etc. The three combined learned that a 1′ long meaningless 30–40 dB(A) noise does not wake up some 95% of the population.

The psychic disturbances mentioned are nuisance, irritability and fear. Some people do not feel comfortable because they know an annoying sound, no matter how soft, will not stop, take a fan, the evaporator outside of an air/water heat pump or the neighbour's radio. Irritating is the intermittent, repetitive sound of a dripping faucet. Really strong noises may even invoke fear.

To conclude, forwarding clear comfort limits expressed in dB(A) is not possible, although for undisturbed sleep, 30–35 dB(A) is the recommended limit.

3.2.3.3.3 From a Physiological Point of View

Damage by excessive noises may harm the ears but also invoke global neurovegetative complaints. For the ears, of importance is the duration and equivalent sound pressure level of the noise heard, see Table 3.9.

Table 3.9 Hearing problems caused by too loud, too long-lasting noises.

Duration	Equivalent sound pressure level (L_{eq} in dB(A))	Complaints after the noise ended
Short	Very high (≈130 dB(A))	Feeling a strong pain
Limited	High (≥90 dB(A))	Temporary deafness (from some seconds to days)
Long	Moderate (≥65 dB(A))	Ear tiredness
Very long	High (≥80 dB(A))	Increasingly impaired hearing with time

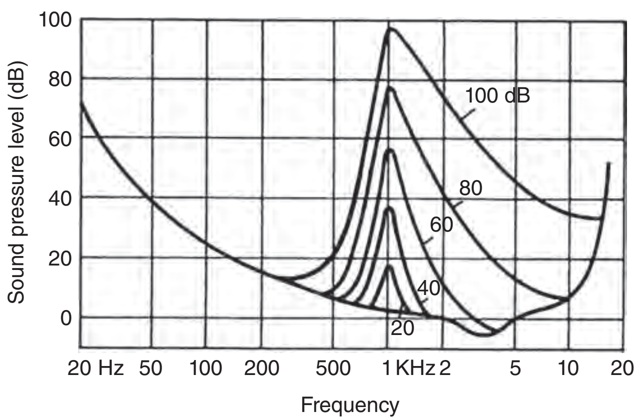


Figure 3.12 Masking curves for a 1000 Hz disturbing noise with increasing loudness.

Masking by disturbing noise may turn wished sound inaudible. This plays when both belong to the same octave band, while the impact increases the louder the disturber is, see the masking curves in Figure 3.12 for a 1000 Hz noise. Masking could even cause a loss of spatial orientation. In fact, intense disturbing noises may turn it difficult to situate other noise sources, which can be dangerous at work.

What concerns possible global neurovegetative complaints, the impact of short unexpected sounds differs from long-lasting noises. The first can accelerate the heartbeat, accelerate breathing and impact the metabolism while the second can induce dizziness, headache, less appetite, loss of consciousness or worse, anaemia.

Globally, lasting equivalent sound pressure levels under 65 dB(A) are physiologically seen as acceptable.

3.2.3.3.4 From a Pathological Point of View

An important consequence of long-lasting noise strain is a slowly evolving, irreversible perception of deafness. Contrary to conduction deafness by earwax in the auditory duct, a damaged or stiffened tympanic membrane or ossicle permanently degrades the ear sensitivity in all tierce bands, starting with a drop at 4000 Hz and expanding with time to turn problematic once attacking the frequencies for speech. Defined as hearing loss is the mean drop in the 500, 1000 and 2000 Hz octave band. If less than 25 dB, deafness remains doable but the more it goes above 25 dB, the larger the handicap becomes. The percentage of people experiencing perception deafness

Table 3.10 Perception deafness risk, up as *F* (age), down due to continuous loudness.

L_{eq} (dB(A)) ↓	Risk (%)									
Age	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**
Exposure (years)	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**25**	**40**	**45**
80	*0.7*	*1.0*	*1.3*	*2.0*	*3.1*	*4.9*	*7.7*	*13.5*	*24.0*	*40.0*
	0	0	0	0	0	0	0	0	0	0
85	*0.7*	*2.0*	*3.9*	*6.0*	*8.1*	*11.0*	*14.2*	*21.5*	*32.0*	*46.5*
	0	1.0	2.6	4.0	5.0	6.1	6.5	8.0	8.0	6.5
90	*0.7*	*4.0*	*7.9*	*12.0*	*15.0*	*18.3*	*23.3*	*31.0*	*42.0*	*54.5*
	0	3.0	6.6	10.0	11.9	13.4	15.6	17.5	18.0	14.5
95	*0.7*	*6.7*	*13.6*	*20.2*	*24.5*	*29.0*	*34.4*	*41.8*	*52.0*	*64.0*
	0	5.7	12.3	18.2	21.4	24.1	26.7	28.3	28.0	24.0
100	*0.7*	*10.0*	*22.0*	*32.0*	*39.0*	*43.0*	*48.5*	*55.0*	*64.0*	*75.0*
	0	9.0	20.7	30.0	35.9	38.1	40.1	41.5	40.0	35.0
105	*0.7*	*14.2*	*33.0*	*46.0*	*53.0*	*59.0*	*65.5*	*71.0*	*78.0*	*84.5*
	0	13.2	31.7	44.0	49.9	54.1	57.8	57.5	57.0	44.5
110	*0.7*	*20.0*	*47.5*	*63.0*	*71.5*	*78.0*	*81.5*	*85.0*	*88.0*	*91.5*
	0	19.0	46.2	61.0	68.4	73.1	73.8	71.5	64.0	51.5
115	*0.7*	*27.0*	*62.5*	*81.0*	*87.0*	*91.0*	*92.0*	*93.0*	*94.0*	*95.0*
	0	26.0	61.2	79.0	83.9	86.1	84.3	89.5	70.0	55.0

The italics give the age, the other the number of exposure years.

if being subjected to a continuous loudness level above 80 dB(A) during eight hours a day and five days a week, is listed in Table 3.10.

Up to 80 dB(A), the main risk factor is age. Above, the link to the dB(A) increases quickly. The conclusion is that, to avoid perception deafness due to continuous noise, the time-averaged noise level should remain below 80 dB(A).

3.2.3.4 Comfort Values

The psychological dB(A) limits listed in Table 3.11 are what actually fix the requirements as wished. The four urban zones from the table are:

Zone 1	Residential buildings in the countryside and suburbs more than 500 m away from important traffic routes
Zone 2	Residential buildings in city quarters or the countryside less than 500 m away from important traffic routes
Zone 3	Residential buildings in habiting and shopping quarters, close to light industry or in city quarters more than 5 and less than 10 km away from an airport
Zone 4	Residential buildings in city centres, in quarters along important traffic routes or highways or in city quarters less than 5 km from an airport or near heavy industry

Table 3.11 Equivalent sound pressure level indoors in dB(A), seen as comfortable.

Buildings, spaces			**Limit values (dB(A))**				
Concert room, recording studio		L_{eq}	25	$L_{10} = L_{eq}$ – value that should be kept 10% of the time			
		L_{10}	30				
Theatre		L_{eq}	30				
		L_{10}	35				
Conference room		L_{eq}	35				
		L_{10}	40				
Meeting room, movie theatre		L_{eq}	40				
		L_{10}	45				
Restaurant		L_{eq}	45				
		L_{10}	50				
Landscape office, shop, store		L_{eq}	35				
Workshop		L_{eq}	45–75				
Residential buildings ideally		L_{eq}	Daytime, 6–22 hr, 35 Nighttime, 22–6 hr, 25				
Depending on the urban zone			**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**	
Dwellings	Daytime rooms	L_{eq}	30	35	40	45	
		L_{10}	40	45	50	55	
	Sleeping rooms	L_{eq}	30	30	35	40	
		L_{10}	35	40	45	50	
Office buildings	Normal offices	L_{eq}	40	45	50	55	
		L_{10}	50	55	55	55	
	Staff offices	L_{eq}	35	40	45	50	
		L_{10}	45	50	55	55	
	Management	L_{eq}	30	35	40	45	
		L_{10}	40	45	50	55	
Schools	Classrooms	L_{eq}	30	35	40	45	
		L_{10}	40	45	50	55	
	Music rooms	L_{eq}	30	30	35	40	
		L_{10}	35	40	45	50	
	Gym	L_{eq}	35	40	45	50	
		L_{10}	45	50	55	55	

Of course, if the expectations look more demanding, the limit values could become stricter. Sound nuisance is a common complaint forwarded by residents of terraced houses and apartments, meaning that constructing and renovating in a way acoustical comfort remains guaranteed is compelling, demanding in new construction tie-free cavity party walls and heavy floors with floating screed.

For buildings in noisy environments, also the type of outer doors, windows and glazing should guarantee an excellent sound insulation.

3.2.4 Visual Comfort

3.2.4.1 Anatomy of the Eyes

Human eyes are sitting in bony cavities. Six extraocular three-layer muscles enclosing several anatomical structures control their movement: an outer layer containing the cornea and sclera, which shape the eye and support the deeper structures, a. middle layer including the choroid and the iris and an inner layer, called the retina, getting its oxygen from the blood along the choroid and retinal vessels, see Figure 3.13.

The spaces between the cornea and the lens are filled with aqueous humour, a clear water-like fluid, while the large space behind the lens is filled with vitreous humour, which is water containing proteins. The ligaments consist of hundreds of fine transparent fibres, which suspend the lens and transmit the muscular forces that focus it.

3.2.4.2 Physiological Facts

Healthy eyes see electromagnetic radiation with wavelengths between 400 and 800 nm (nanometres, 10^{-9} m), called the visible light and ranging from violet over blue to orange and red. Their sensitivity peaks at 550 nm, the yellow-green. The relative sensitivity looks as shown in Figure 3.14.

At low illumination levels, the peak shifts from 550 to 510 nm, while in the twilight, all colours turn greyish. If a light source emits the whole interval of wavelengths, the eyes see it as white, although also a mix of two or more coloured light sources can emanate the impression of white. This is also the case with a blue and orange or a red and green light emitting source. If falling on a white surface, white remains white, but if falling on a coloured surface, the colour seen turns troubled.

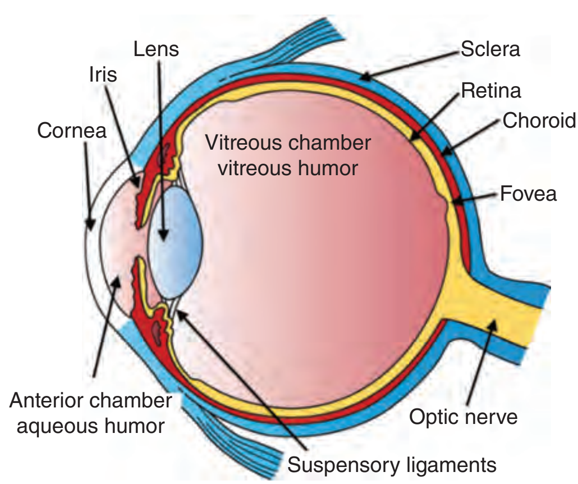


Figure 3.13 The human eye. Source: ThoughtCo.

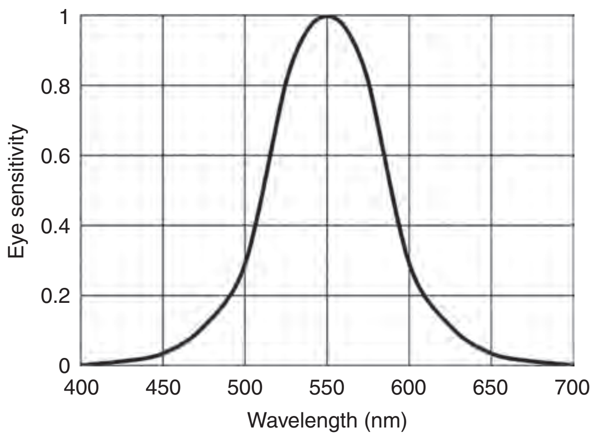


Figure 3.14 Eye sensitivity.

3.2.4.3 Comfort Values

Visual comfort concerns the reaction at any time of an individual to the quantity and quality of the light in space. It basically relates to being able to control the light colour and level. Too few or too much light causes discomfort, while too quick changes in lighting level or in contrast may be exhausting, as the eyes then have to adapt continuously. Factors intervening in how people see are age, the colour of their eyes with light-coloured ones tending to be more sensitive, the kind of light and the time of exposure.

Several aspects define if someone will feel visually comfortable: the aesthetic quality of a space, the quality of the light, the lighting ambience, the luminosity, the absence of glare, and even a view to the outside. Working in a window-less office, even if adequately illuminated, or in an office with windows to the outside in fact is appreciated differently. Many studies show the positive impact of the latter on mood and job satisfaction.

Assessing an environment visually requires analysing all artificial and natural light sources present, their distribution in space and their perception (colour, intensity). The way light influences body and mind is still not completely understood, but that there is an impact on health, sleep, mood and alertness is widely accepted. For a long time, research was focusing on how to provide enough artificial light to perform given tasks. Today, energy efficiency and questions about the impact of artificial light on health turned the interest to the benefits of daylight and how to build for maximization. Daylight is nearly always perceived as more comfortable than artificial light. In residential buildings, enough daylight has become an important requirement. The quantity used to express it is the daylight factor, calculated assuming a uniform cloudy sky with illuminance 5000 lx. The factor reaches its highest value against transparent envelope parts facing the outside and drops quickly when moving deeper inside, see Figure 3.15.

In offices, job satisfaction and well-being depend among others on having daylight and a view to the outside, telling which hour, which season and which weather it is.

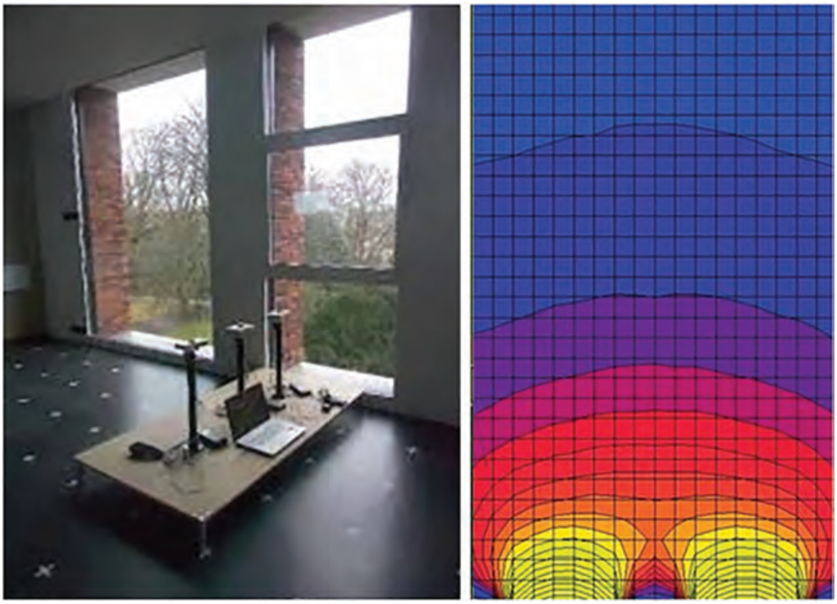


Figure 3.15 The daylight factor.

Table 3.12 Illuminances needed or experienced.

	Illuminance (lx)
Room, activity	
Children's sleeping room	300
Bathroom	100
Toilet	100
Horizontal surface, reading and writing	500
Office, vertical surfaces	300
Outdoors	
Cloudy	5 000
Sunny	100 000
At night, full moon	0.25

In practice, the visual comfort requirements look to the illuminances guaranteeing good seeing, see Table 3.12. Also given in it is the illuminance experienced outdoors.

Further on, the differences in glare in candela/m^2 the eyes perceive play an important role. Reason is the luminance of surfaces reflecting light. The criterium is that the ratio between darkest and clearest surface seen, meaning the surfaces with the lowest and highest illuminance, should not pass 1/10.

3.2.5 Olfactory Comfort

3.2.5.1 Anatomy of the Nose

The nose with its nostrils is the principal organ of the olfactory system. The nasal bones and cartilages plus the nasal septum separating the nostrils and splitting the nasal cavity in two, fix its shape. Mucosa are lined along the nasal cavity and the paranasal sinuses. The walls of the nasal cavity also contain shell-like bones, called the nasal conchae. The nostrils in turn are littered with nasal hair. Also see Figure 3.16.

3.2.5.2 Physiological Facts

Although the main function of the nose is breathing, the one of interest here is smelling. Responsible for that are specialised olfactory cells, called receptor neurons, contained in the olfactory mucosa of the upper nasal cavity. There, nasal glands, called the Bowman's, are olfactory active and that, together with the nasal conchae, which direct the air to this odour sensing region. To smell, the molecules inhaled must dissolve in the mucus the nostrils contain, where they excite the neurons. The olfactory nerve fibres do not project these neurons directly on the cerebral cortex but on the olfactory medialis and lateralis area. Other neurons switch to the olfactory bulb, whereafter they reach the hippocampal, the uncus and the hypothalamus. To be short, the actions generated are not immediately directed to the cerebral cortex, which means it takes a while to smell an odour and get the emotion and reaction.

3.2.5.3 Comfort Values

Olfactory comfort is mainly defined by focusing on what's negative. Excessively strong or distinct odours that disrupt the physical and psychological comfort, irritate the eyes, nose and throat and give nausea and headaches, should be avoided by all means. Even more, people judge the air quality by smelling. As evaluating objectively malodour is difficult, the late P.O. Fanger introduced at the end of the 1980s a perception-based methodology, called the olf/decipol rationale, with 1 olf linked to the bio-odours a lightly active male adult, who takes a shower five

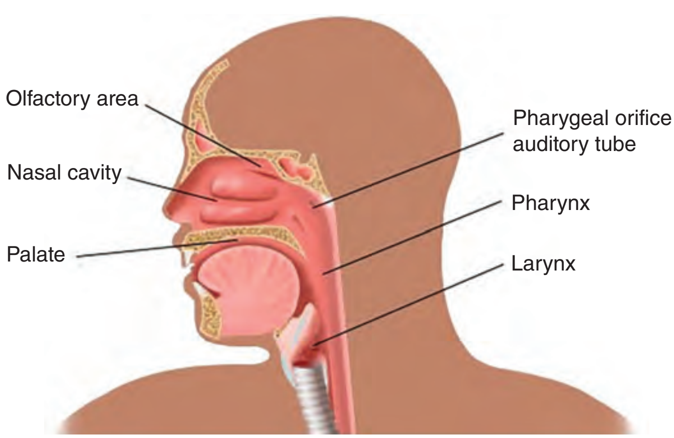


Figure 3.16 The human nose. Source: Encyclopedia Britannica.

5

The Envelope Parts Heat Air Moisture (HAM) Performances applied to Timber-Frame

5.1 In General

This fifth chapter illustrates how the envelope-linked heat-air-moisture performance metrics could help when designing timber-frame outer walls. Timber frame, the reference in North America and Scandinavia, gained some popularity in north-western Europe, mainly due to the thick insulation layers, it allows without blowing up the wall thickness beyond reasonable. Some drawbacks compared to massive walls insulated outside and to filled brick cavity walls anyhow remain: a much poorer thermal storage capacity, overheating in summer more likely, moisture tolerance more critical, worse fire safety, sound insulation more of a problem, design mistakes and poor workmanship generating higher damage risk, etc.

5.2 Assembly

In- to out, a timber-frame outer wall might be composed as follows (see Figure 5.1):

Layer	***d* (m)**	**λ (W/(m K))**	**μ (−)**	**$K_a = a\Delta P_a^{\,b-1}$ (kg/(m² s Pa))**	
				a	***b*−1**
Gypsum board No leaks	0.012	0.2	7	$3.1 \cdot 10^{-5}$	−0.19
Idem, 1 *leak* ϕ 20 *mm/m*²				$3.8 \cdot 10^{-4}$	−0.39
Glass wool insulation	?	0.04	1.2	$2.3 \cdot 10^{-3}$	−0.11
Plywood sheathing	0.022	0.14	20-30	$5.4 \cdot 10^{-4}$	−0.46
Building paper	⟵		?		⟶
Cavity	0.04		0		
Timber siding[a)]	0.012	0.14	0	$4.1 \cdot 10^{-4}$	−0.32

a) Timber siding, $\mu = 0$? The timber has a diffusion resistance factor far beyond 1, but the many leaks between planks make the sheathing so air permeable that its diffusion resistance can be neglected.

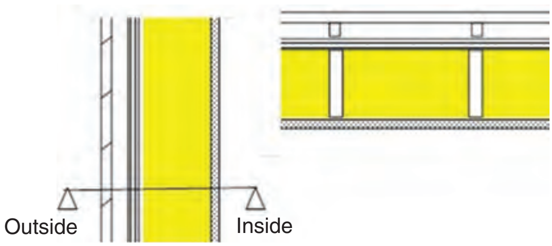


Figure 5.1 Timber-frame outer wall.

Figure 5.2 Timber frame, some view on how construction proceeds.

Figure 5.2 shows how a timber-frame construction proceeds. Often, factory prefabricated wall and roof elements are used that are transported to the building side, where mounting and joining together follow. Doing so offers a better guarantee all performance metrics ensuring a problem-free service life are accounted for.

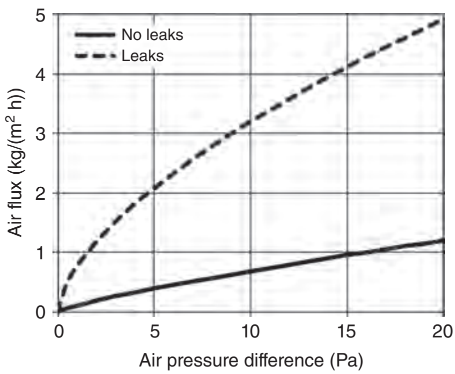
5.3 Performance Evaluation

5.3.1 In General

Further discussion only considers the heat, air, moisture related performance metrics. Of course, in practice, the whole matrix with metrics, see Chapter 2, should guide the design and execution.

5.3.2 Airtightness

Considered is a wall having a 10 cm thick insulation layer. If the inner gypsum board finish should be mounted leak-free, the wall's air permeance will near $3\ 10^{-5}\Delta P_a{}^{-0.2}$ kg/(m^2 Pa s), so, hardly different from the value an intact gypsum board guarantees. However, one leak ϕ 20 mm per m^2 of gypsum already increases the air permeance to $2.1\ 10^{-4}\Delta P_a{}^{-0.38}$ kg/(m^2 Pa s), 7 times the value without, but, thanks to the other layers, still 1.8 times lower than for a really leaky mounted



ΔP_a	Air flux	
	No leaks	Leak ϕ20/m^2
Pa	m^3/(m^2 s)	m^3/(m^2 s)
0	0.00	0.00
2	0.16	0.98
4	0.28	1.51
8	0.48	2.32
12	0.66	2.98
20	1.00	4.09

Figure 5.3 Air flux across the wall (leaks assumed smeared out).

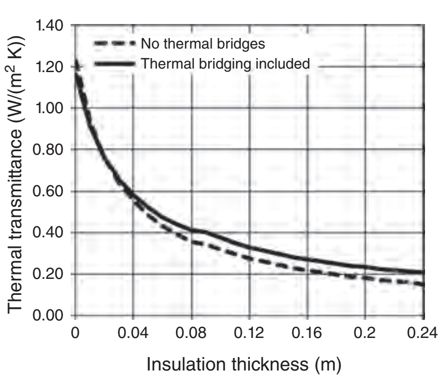
gypsum board. Figure 5.3 with table added shows the related air fluxes in kg/(m^2 h) as function of the air pressure difference over the finished wall. At 5 Pa difference, the leaky wall sees ≈2 m^3 air passing through per hour and m^2, while leak-free, only 0.35 m^3 does. Clearly, an airtight inner lining is of major importance to guarantee airtightness, at least if the wall is lacking an air barrier build-in.

5.3.3 Thermal Transmittance

In case the wall is airtight, the clear wall thermal transmittance equals:

$$U_o = \frac{1}{0.043 + 0.012/0.14 + 0.17 + 0.022/0.14 + X/0.04 + 0.06 + 0.125}$$
$$= \frac{0.04}{0.026 + X}$$

with X the insulation thickness. See Figure 5.4 and the table added. A timber-frame wall clearly allows low U_o-values without excessive enlargement of the wall thickness (20 cm insulation in a 26 cm thick wall).



X (cm)	U_0 W/(m^2 K)	Whole U W/(m^2 K)
0	1.23	1.16
4	0.55	0.58
8	0.36	0.41
12	0.27	0.33
16	0.22	0.27
20	0.18	0.23
24	0.15	0.20
28	0.13	0.18
32	0.12	0.17

Figure 5.4 Clear and whole wall thermal transmittance.

But no thermal bridging is fiction. Studs, bottom, top and connecting plates, all increase the heat flow. For insulation thicknesses beyond 8 cm, the related linear thermal transmittances are:

Stud	$\psi \approx 0.017\ \text{W}/(\text{m}^2\ \text{K})$
Bottom plate	$\psi \approx 0.010\ \text{W}/(\text{m}^2\ \text{K})$
Top and connecting plates	$\psi \approx 0.023\ \text{W}/(\text{m}^2\ \text{K})$

In a 2.6 m high wall with the stud's centre to centre 40 cm apart, each field contains a 2.48 m high stud and a 0.4 m long bottom, top and connecting plate. The last column in the table in Figure 5.4 lists related whole-wall thermal transmittances. The thicker the insulation, the more influential thermal bridging becomes, which is why in well-insulated walls the studs, bottom, top and connecting plates get engineered I-shapes, see Figure 5.5.

Also, perfect airtightness is an illusion. A 2.6 m high wall has, if leaky, an air permeance of $2.1\ 10^{-4}\Delta P_a{}^{-0.38}$ kg/(m^2 Pa s) and if tight, of $3\ 10^{-5}\Delta P_a{}^{-0.2}$ kg/(m^2 Pa s). In case the leaks are uniformly distributed over each m^2 of wall, then, with all doors closed and windless weather outdoors, thermal stack remains the only driving force giving as air pressure difference along the wall's height (z):

$$\Delta P_a = \frac{1}{2}[0.043(z - H/2)(\theta_\text{i} - \theta_\text{e})]$$

For 17 °C inside/outside temperature difference, the differences 0.65 and 1.95 m height equal −0.48 and 0.48 Pa, resulting in down 0.42 m^3/h inflow and up 0.42 m^3/h outflow. Could ideal workmanship have kept the gypsum board leak-free, these flows should not have passed −0.05 and +0.05 m^3/h. Table 5.1 lists the apparent thermal transmittance that in both cases should be measured at both heights by a heat flux meter glued against the inner face.

The formula used is:

$$U_\text{app,si} = \frac{c_a g_a}{1 - \exp(c_a g_a R_T)}$$

With leaks, the apparent thermal transmittance measured turns seemingly worse at 0.65 m and better at 1.95 m height, while the difference with the U_o-value increases

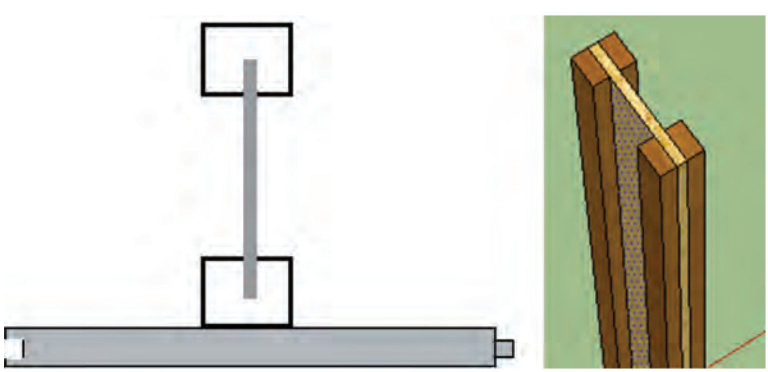


Figure 5.5 I-shaped engineered stud.

Table 5.1 Apparent thermal transmittance measured on the inside face, air in- and outflow.

Insulation thickness (cm)	U_o (W/(m^2 K))	Ideal workmanship, gypsum board tight		Gypsum board leaky	
		$U_{0.65}$ (W/(m^2 K))	$U_{1.95}$ (W/(m^2 K))	$U_{0.65}$ (W/(m^2 K))	$U_{1.95}$ (W/(m^2 K))
0	1.23	1.24	1.22	1.30	1.16
4	0.55	0.56	0.54	0.62	0.49
8	0.36	0.36	0.35	0.43	0.29
12	0.27	0.28	0.27	0.35	0.21
16	0.22	0.22	0.21	0.29	0.15
20	0.18	0.19	0.17	0.25	0.12

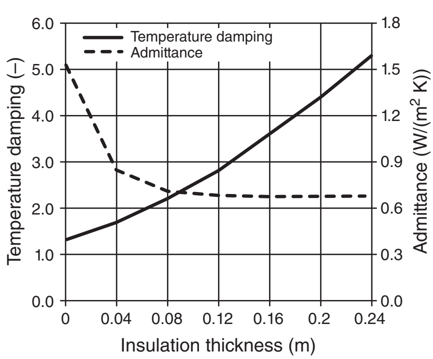
together with leakage! Or, air in- and outflow deprives U_o from being the prime indicator of energy use due to heat transmitted.

5.3.4 Transient Response

Timber frame walls are too lightweight to offer much heat storage. As a result, temperature damping and the admittance are both low. How they change with the insulation thickness applied shows Figure 5.6 and the table added.

Albeit when airtight, temperature damping increases more than linearly with the insulation thickness applied, even a 24 cm thick layer does not bring the equal to 15 metric within reach. Starting from non-insulated, the admittance first decreases with the insulation thickness to stabilize at a very low value once passing 12 cm. In case the wall is leaky, temperature damping still decreases where infiltration reigns and increases where exfiltration reigns.

A fair conclusion is that even in temperate climates, timber-frame dwellings need additional measures to avoid summer overheating, such as a restricted glass surface shaded by overhangs or by movable exterior screens at the sunny sides and, night ventilation. Advisable therefore is to combine a timber-frame envelope with massive



d_{insul}	Damping		Admittance	
	Value	Shift	Value	Shift
(cm)	-	(h)	W/(m^2 K)	(h)
0	1.3	3:18	1.54	1:42
4	1.7	5:00	0.84	2:48
8	2.2	6:00	0.71	3:36
12	2.8	6:42	0.68	4:00
16	3.6	7:18	0.67	4:18
20	4.4	7:48	0.68	4:36
24	5.3	8:18	0.68	4:42

Figure 5.6 Timber frame wall: temperature damping and thermal admittance.

Figure 5.7 Timber-frame dwelling with veneer wall as outside finish, the condenser outdoors indicates active cooling has been installed, happily in combination with PV, which in summer produces electricity used to activate the compressor.

floors and heavy-weight partitions. Anyhow, even in moderate climates, active cooling became widespread in whole timber-frame dwellings, see Figure 5.7.

5.3.5 Moisture Tolerance

5.3.5.1 Construction Moisture

Construction moisture should not be a problem on condition the timber is delivered air-dry. The sheathing and inside lining anyhow may have such moderate vapour resistances that drying, if needed, can proceed unhindered.

5.3.5.2 Rain

When raining, the cladding's front- and back plus the front of the building paper covering the plywood- or OSB-sheathing, called the 'house wrap', must be able to function as drainage planes. To protect the sheathing, the strips the wrap is composed of have to be draped the way shown in Figure 5.8.

Droplets blown away from the cladding's back to the house wrap will so run down along the overlapping strips to the bottom of the cavity between cladding and house

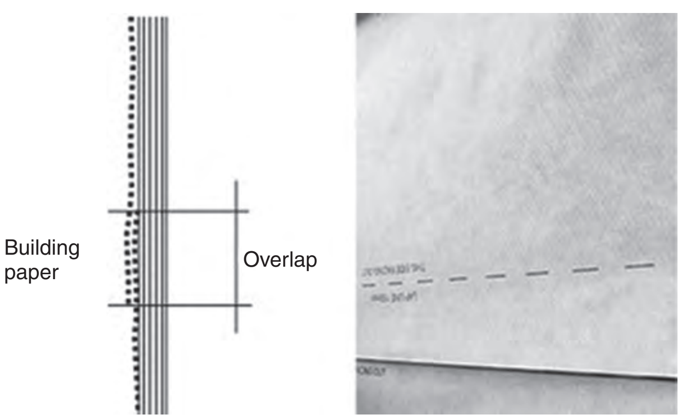


Figure 5.8 Building paper.

Figure 5.9 Timber-frame wall finished with brick veneer.

wrap, where a tray must direct it to the outside. The house wrap of course additionally increases the wall's air and wind-tightness.

When finished with a brick veneer, see Figure 5.9, a specific problem is jumping up. In sunny weather, the rainwater that the veneer buffers will evaporate, and the vapour so formed will diffuse to the inside where it, if the house wrap and the sheathing lack diffusion resistance, will increase the RH in that sheathing, in the insulation and, if the insulation's back lacks a vapour retarder, in the inside finish. With a vapour retarder, the vapour diffusing to the inside may condense against that retarder's face contacting the insulation, sometimes even in the insulation there.

That this is a problem was seen in a damage case, where the inhabitants of a newly constructed timber-frame passive house having outer walls finished at the outside with a brick veneer turned sick in summer due to a too high formol concentration in the air indoors. The cause was the high summer RH, see Figure 5.10, and linked to high hygroscopic moisture content in the OSB-boards covering the timber-frame outer walls at their inside with as interior finish a gypsum board against it, a solution applied to get an airtightness as requested by the passive house standard. The reason why both went that high was summer diffusion of rainwater absorbed by the veneer to the inside. As a consequence, the OSB released much more formaldehyde than when air-dry. As the problem reappeared each summer, the dwelling ended up declared inhabitable.

5.3.5.3 Rising Damp

Rising damp is easily avoided by inserting a watertight membrane below the bottom plates bearing the joists of the on-grade floor. If a termite attack is likely, a steel barrier should replace that membrane.

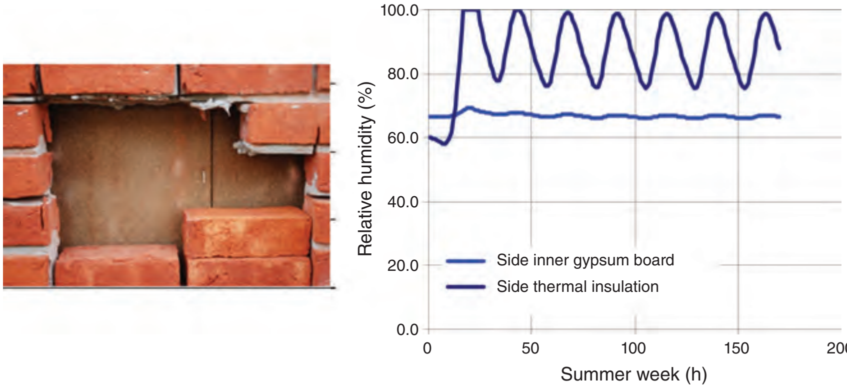


Figure 5.10 Timber-frame wall with brick veneer as outer finish, diffusion from the wet veneer to the indoors, consequences for the RH in the OSB boards closing the wall at the inside, with a gypsum board finish against.

5.3.5.4 Hygroscopic Moisture and Surface Condensation

Too much hygroscopic moisture causing mould growth but also surface condensation somewhere on the envelope's inside face will hardly be a problem in case solar-driven vapour flow to the inside is moderated, the wall is correctly and properly insulated, the temperature indoors remains above 12 °C and outside air ventilation meets the needs.

Of course, in temperate climates, more insulation will enlarge the annual sorption swings by an outer timber cladding. This could peel off the paint used as outer finish.

5.3.5.5 Interstitial Condensation

With an airtight timber-frame wall, only diffusion matters. If the outer sheathing is neither hygroscopic nor capillary, then each time the vapour pressure on its back is touching saturation, condensation against will give droplets. In reality, plywood and OSB, two timber-based materials often used as sheathing, are highly hygroscopic and slightly capillary, which will mostly turn 'interstitial condensation' into a change in sorption moisture with droplet formation against their back only when the moisture content there touches capillary.

Although too simplistic, in a first step, hygroscopic sorption and capillary action are overlooked. The thermal boundary conditions outdoors are best represented by the equivalent temperature for condensation and drying. Given in Chapter 1 were the values for Uccle, Belgium. Short wave absorptivity of the outside surface is set at 0.8, while the wall is looking north, so hardly sees the sun. The plywood sheathing has a μ-value of 10 when humid. The vapour-permeable house wrap represents a μd-value of 1 cm, while in the air filling the vented cavity in front reigns more or less the same vapour pressure as outdoors. In north-western Europe, the coldest month is January. For Uccle, all this gives following boundary conditions in case of a residential building (ICC = indoor climate class):