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Boundary Conditions, Building Performance and Material Properties
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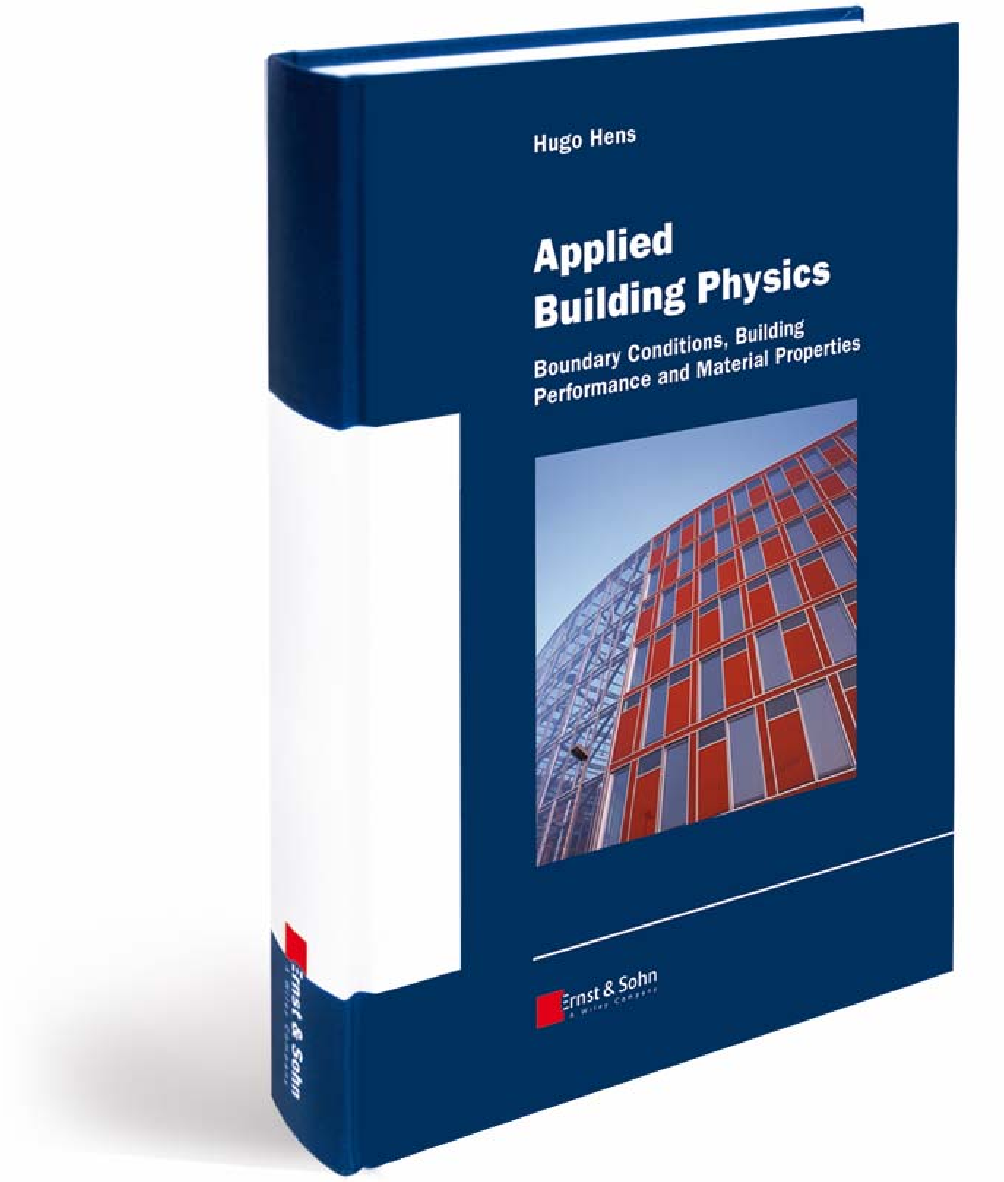

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4 Heat-air-moisture performances at the envelope level

4.1 Introduction

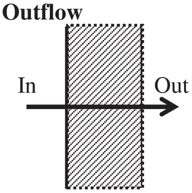
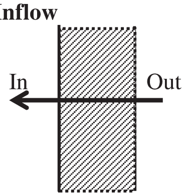
Chapter 3 looked at some main performances at the building level. This Chapter 4 steps one level down, looking to the building envelope with the heat-air-moisture performances as exemplary case. For the opaque parts, these are: (1) air-tightness, (2) thermal transmittance, (3) thermal transient response, (4) moisture tolerance and (5) hygrothermal load. In that quintet, air-tightness figures as the throughline for those that follow. If it is lacking, thermal transmittance decouples from insulation quality, transient response degrades and moisture tolerance becomes more risky. For the transparent parts, mastering solar gains replaces thermal transient response. For the floors belonging to the envelope, the contact coefficient of the floor finish should not be overlooked.

4.2 Air-tightness

4.2.1 Flow patterns

Not only the other hygrothermal performances but also the acoustical performances and performances at the building level such as thermal comfort, primary energy consumption and fire safety are impacted by lack of air-tightness.

When judging air-tightness as an envelope performance seven flow patterns may interact:

Pattern	Cause	Consequences
Outflow 	Envelope part not airtight Difference in temperature between the inside and the outside Envelope parts at leeside Overpressure inside	Thermal transmittance no longer reflecting insulation quality High interstitial condensation risk, larger deposits Faster drying to the outside Uncontrolled adventitious ventilation indoors
Inflow 	Envelope part not air-tight Difference in temperature between the inside and the outside Envelope parts at the windside Under pressure inside	Thermal transmittance no longer reflecting insulation quality Worse transient thermal response Increased mould and surface condensation risk Faster drying, mainly to the inside Drop in sound insulation for airborne noise outside Uncontrolled adventitious ventilation indoors

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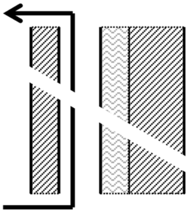
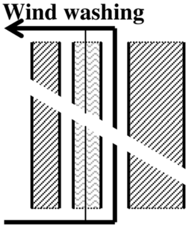
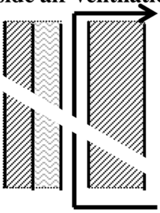
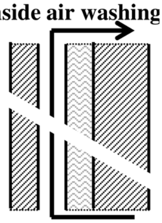
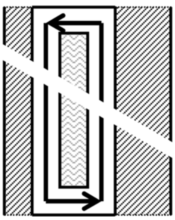
Pattern	Cause	Consequences
Cavity ventilation 	Cavity at the outer side of thermal insulation with air inlets and outlets in the cladding or an air permeable cladding Wind pressure differences along the outside surface Temperature difference between the cavity and outdoors Inlet and outlet at different heights	Small increase in thermal transmittance Typically considered as beneficial for moisture tolerance, though condensation by undercooking at the cavity side of the cladding more likely Drop in sound insulation for airborne noise
Wind washing 	Cavity at the inner side of the thermal insulation disclosed for outside air, cavity filled with air-permeable insulation material Wind pressure differences along the outside surface, temperature difference between the cavity and outside	Large increase in thermal transmittance Worse transient thermal response Increased risk on mould and surface condensation inside Drop in sound insulation for airborne noise
Inside air ventilation 	Cavity at the inner side of thermal insulation disclosed for inside air Temperature and height differences along the inside surface Air pressure differences along the inside surface	Small increase in thermal transmittance Drop in sound insulation for airborne noise
Inside air washing 	Cavity at the outer side of thermal insulation disclosed for inside air Temperature and height differences along the inside surface Air pressure differences along the inside surface	Large increase in thermal transmittance High interstitial condensation risk, larger deposits Drop in sound insulation for airborne noise
Air looping 	Air cavity at both sides of the thermal insulation, leaks at different heights in the insulation layer or, air permeable insulation. Temperature difference across the insulation	Large increase in thermal transmittance Somewhat higher interstitial condensation risk

Limiting air in and outflow to the utmost demands inclusion of an air barrier in the envelope. If mounted inside, such a barrier also minimizes inside air washing. At the outside, it acts as wind-barrier, controlling wind washing while allowing outside air ventilation in a cavity between it and the cladding. For tempering both indoor air and wind washing to a maximum, one should combine an air barrier inside with a wind barrier outside of the thermal insulation. In case the insulation layer itself is perfectly airtight, wind washing, inside air washing and air looping are excluded. Eliminating the cavity between an airtight insulation layer and the outside cladding excludes outside air ventilation, inside air washing and air looping. With no cavity at the backside of an airtight insulation layer, wind washing, inside air ventilation and air looping are avoided.

4.2.2 Performance requirements

4.2.2.1 Air in and outflow

The answer to the question of how air-tight an envelope should be is: perfectly. In practice, however, this is fiction. Even if imposed and even if the design should guarantee perfection, limits in building ability will induce imperfections that relegate the 'perfect' requirement to the realm of fairy tales. Therefore, another approach is advisable. Air leakage short-circuits the diffusion resistance between the inside and interfaces in the assembly where condensation is probable. Whether this will result in unacceptable moisture deposits there depends on the overall composition of the envelope part and the climate in and outdoors with vapour and air pressure excess inside as main players. The air-tightness requirements should therefore be coupled to the indoor climate class and the air pressure differentials expected. That gives the following upper limit for indoor climate class 1, 2 and 3 buildings: (1) no concentrated leakages in terms of cracks, perforations, open joints, etc., (2) area averaged air permeance coefficient $\leq 10^{-5}$ kg/(m$^2 \cdot$ s $\cdot$ Pa^b)

4.2.2.2 Inside air washing, wind washing and air looping

Assume we call equivalent thermal transmittance the area- and time-averaged heat flow rate across the assembly, whatever may be the cause, divided by the difference in inside and outside reference temperature. That quantity could also be written as the thermal transmittance, multiplied with a so-called Nusselt number, Inside air washing, wind washing and air looping now should not increase the equivalent thermal transmittance compared to the thermal transmittance with a percentage beyond x. If for example x is set 10%, than Nusselt may not pass 1.1.

Example: partially filled cavity wall, wind washing

Consider a cavity wall with 9 cm thick brick veneer, 3 cm wide cavity, partial fill with 10 cm PUR, inside leaf in 14 cm thick light-weight fired clay blocks ($R = 0.88\ \text{m}^2 \cdot \text{K/W}$) and airtight pargetting inside (Figure 4.1). The wall is 2.7 m high. Top and bottom of the veneer wall contain two weep holes per meter run. Bad workmanship however causes the cavity fill to stop above the lower and below the upper weap holes while the fill is mounted so carelessly that the layer stands somewhere between the inner leaf and the veneer wall.

How does wind washing affect the thermal transmittance?

Figure 4.1

Wind washing redistributes the outside air flow between the cavity behind the veneer wall (suffix 1) and the air layer behind the insulation (suffix 2), proportional to the third power of their widths:

$$G_a = G_{a,1} + G_{a,2} \qquad G_{a1} = G_a \frac{d_1^3}{d_1^3 + d_2^3} \qquad G_{a2} = G_a \frac{d_2^3}{d_1^3 + d_2^3}$$

As the heat flow across the insulation will be small compared to the one across the veneer, temperature in the outer cavity will hardly differ from the equilibrium value without ventilation, giving as fair approximation for the temperature in the air layer behind the insulation:

$$\theta_2 = \theta_{2,\infty} + \left(\theta_e - \theta_{2,\infty}\right) \exp\left(-\frac{R_1 + R_2}{c_a\ G_{a,2}\ R_1\ R_2}\ z\right)$$

where R_1 is the thermal resistance across the thermal insulation between the air layer behind the insulation and outside, R_2 is the thermal resistance across the inside leaf between the inside and that air layer behind and $\theta_{2,\infty}$ the temperature one should have in that air layer without wind washing. The effective thermal transmittance, the Nusselt number and thermal insulation efficiency then are:

$$U_{eq} = U \underbrace{\left\{1 - c_a\ G_{a,2} \frac{U\ R_1^2}{H} \left[\exp\left(-\frac{1}{U\ R_1\ R_2\ c_a\ G_{a,2}}\ H\right) - 1\right]\right\}}_{\text{Nu}}$$

$$\eta_{is} = 100 \frac{d_{ins,eq}}{d_{ins}} = 100 \frac{U}{U_{eq}} \left(\frac{1 - U_{eq}\ R_0}{1 - U\ R_0}\right)$$

where U is the thermal transmittance, equal to $1/(R_1 + R_2)$, H the height between the upper and lower weap holes in m and R_0 the thermal resistance of the assembly if the insulation was a layer with thickness zero.

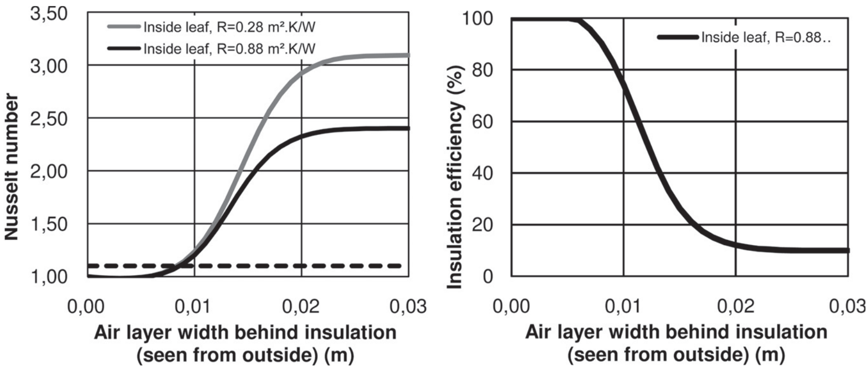


Figure 4.2. Partially filled cavity wall, wind washing at a mean free field wind speed of 4 m/s at 10 m height, Nusselt number and insulation efficiency as function of the air layer width behind the insulation. Nu passes 1.1 for a width beyond 8 mm.

Figure 4.2 shows how the insulation efficiency and the Nusselt number depend on the air layer width behind the insulation. Nusselt 1.1 already requires careful workmanship. In fact the insulation efficiency drops quickly once the air layer exceeds an average width of 8 mm.

4.3 Thermal transmittance (U)

4.3.1 Definitions

4.3.1.1 Envelope parts

When air flow is excluded whole thermal transmittance of an envelope part calculates as:

$$U = U_\beta + \frac{\sum_j \left(\psi_j\, L_j\right) + \sum_k \chi_k}{A} \quad (\mathrm{W/(m^2 \cdot K)}) \tag{4.1}$$

where U_0 is the clear wall thermal transmittance, ψ_j linear thermal transmittances (W/(m · K)) and L_j the length of all linear thermal bridges and χ local thermal transmittance (W/K) of the local thermal bridges within the part with area A. That formula does not apply for floors on grade, floors above basements, floors above crawl spaces and transparent parts.

4.3.1.2 Envelope

The building envelope contains a whole of building parts, linear and local thermal bridges, a lowest floor and transparent parts, all coupled in parallel. The average envelope thermal transmittance then looks like:

$$U_m = \frac{U_{fl}\, A_{fl} + \sum_{\text{opaque}} U\, A + \sum_j \left(\psi_j L_j\right) + \sum_k \chi_k + \sum_w U_w\, A_w}{A_T} \quad (\mathrm{W/(m^2 \cdot K)}) \tag{4.2}$$

where U_{fl} is the mean thermal transmittance and A_{fl} the area of the lowest floor, U the thermal transmittance and A the area of all other opaque building elements and A_w the area and U_w the thermal transmittance of all transparent parts.

4.3.2 Basis for performance requirements

4.3.2.1 Envelope parts

Values should be low enough to keep mould risk in outside edges and corners below 5%. In cool climates that demands thermal transmittances U_0 below 0.46 W/(m^2 · K). At the same time, the optimum in terms of life cycle costs should be aimed for, giving a range from 0.2 to 0.6 W/(m^2 · K). Of course one could also pose minimal total energy consumption or minimal total pollution as a target, a track leading to thermal transmittances below 0.15 W/(m^2 · K).

4.3.2.2 Envelope

The only way to get optimum values from a life cycle cost perspective is by applying a whole building approach, as explained in Chapter 3.

4.3.3 Examples of performance requirements

Already before the EU Energy Performance Directive of 2003 went into force, many European countries imposed legal requirements to the thermal transmittances of opaque and transparent building parts (U_{max}). Some also limited the envelope's thermal transmittance in relation to the compactness of the building. Even today, due to the long service life of a good thermal insulation, energy performance requirements remain complemented by insulation requirements.

4.3.3.1 Envelope parts

Table 4.1 gives maximum thermal transmittances for normally heated buildings as required in a few countries and regions.

4.3.3.2 Envelope

Imposing maximum thermal transmittances per building element has disadvantages. It does not dissuade the use of large glazed surfaces. Even with the well insulating glass systems of today, large surfaces do not offer much benefit in cool climates as insolation in winter is low. Also compactness is not observed. An alternative therefore is imposing upper limits to the end energy demand per unit of protected volume, as done by the EPR. A not so harsh approach consists of limiting that part of the net heating demand that is most easily controlled during design: the transmission losses. These are proportional to the product of the envelope area (A_T) and its thermal transmittance (U_m):

$$Q_{T,ann} \div U_m \; A_T \quad \text{(MJ/a)} \tag{4.3}$$

Requiring the product $U_m A_T$ to be proportional to the protected volume can be expressed by:

$$U_m = \alpha \, V / A_T = \alpha \, C$$

with C compactness in m. So, in a [C, U_m]-coordinate system a straight line through the origin with slope α is found. The smaller that slope, the more severe are the limits to the transmission losses (Figure 4.3a). Keeping that line straight under all circumstances however is not possible.

Table 4.1. Maximum thermal transmittances.

Element	**U_{max} (W/(m^2 · K))**	
	New construction	**Retrofit**
Belgium (Flanders)		
Walls	0.4	0.4
Roofs	0.3	0.3
Floors above grade	0.4[1] (R_{min} = 1 m^2 · K/W)	1.2
Floors above basements and crawlspaces	0.4[1] (R_{min} = 1 m^2 · K/W)	0.9
Floors above outdoor spaces	0.6	0.6
Walls contacting the ground	R_{min} = 1 m^2 · K/W	0.9
Separation walls and floors between dwellings	1.0	1.0
Glass	1.6	1.6
Windows	2.5	2.5
Germany (normally heated buildings)		
Walls		0.24
Roofs		0.24
Low sloped roofs		0.20
Floors above grade		0.30
Floors above basements and crawlspaces		0.30
Floors above outdoor spaces		0.30
Walls contacting the ground		0.30
Glass		1.10
Windows		1.30
UK		
Walls	0.30/0.35	
Roofs	0.16	
Floors	0.25	
Windows	2.00	
Sweden	**Oil or gas heating**	**Electrical heating**
Walls	0.18	0.10
Roofs	0.13	0.08
Floors	0.15	0.10
Windows	1.30	1.10
Outer doors	1.30	1.10

At high compactness, the insulation requirements may become so weak that mould growth, surface condensation and comfort complaints become likely. At very low compactness, the insulation requirement may be of such severity that the investments explode, worse, buildability becomes questionable. Actually, the necessary usage of glazed surfaces turns that straight line through the origin anyhow into a fiction. In fact, one has:

$$U_{\mathrm{m}} = U_{\mathrm{m,op}} + \left(A_{\mathrm{T,w}}/A_{\mathrm{T}}\right)\left(U_{\mathrm{w}} - U_{\mathrm{m,op}}\right) \approx U_{\mathrm{m,op}} + \left[A_{\mathrm{T,w}}/V\left(U_{\mathrm{w}} - U_{\mathrm{m,op}}\right)\right] C$$

i.e. a straight line of the form $a + b\,C$ with $U_{\mathrm{m,op}}$ the average thermal transmittance of the opaque building elements, U_{w} the average thermal transmittance and $A_{\mathrm{T,w}}$ total window area. As the protected volume V may be written as $A_{\mathrm{fl}}\, h$ with h the floor height, the slope b seems

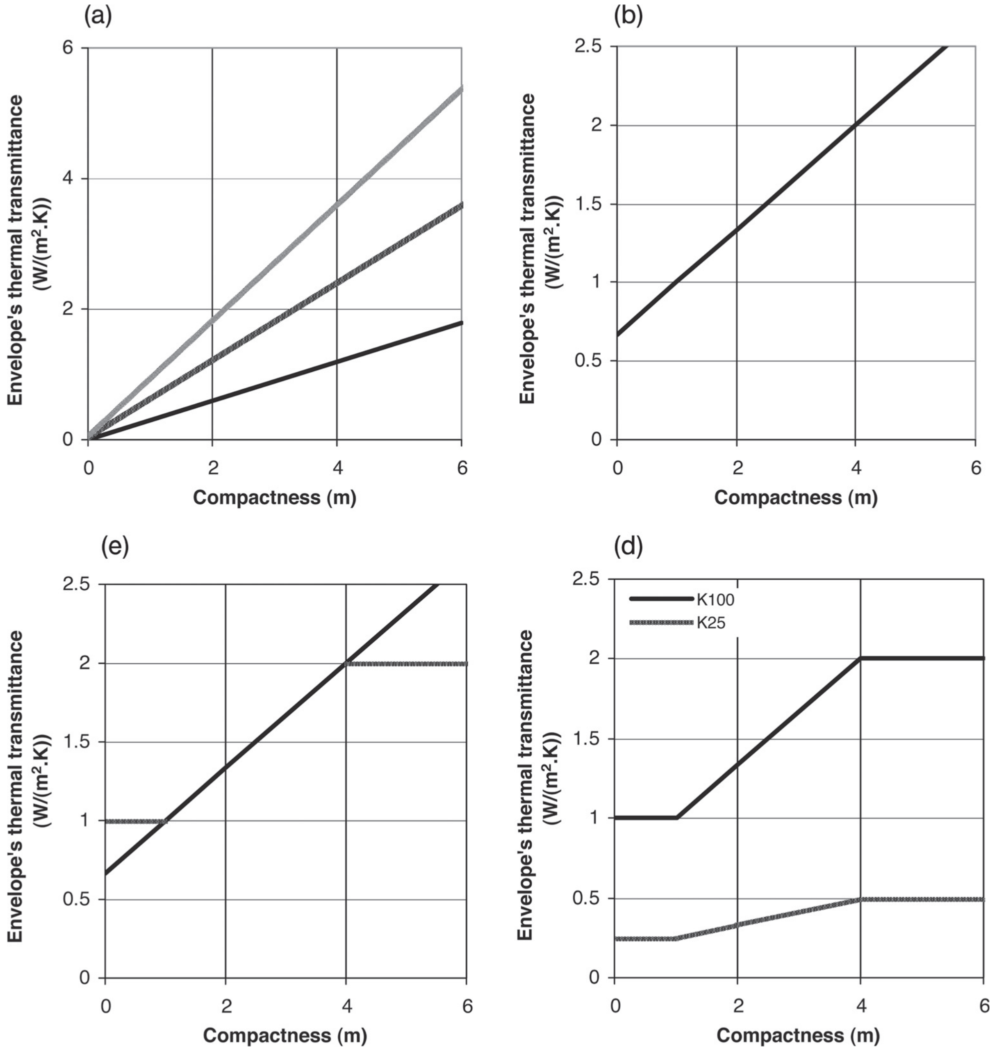


Figure 4.3. Compactness (C) versus envelope thermal transmittance (U_{m}) relation.

proportional to the ratio between glass and floor area and inversely proportional to the floor height h (Figure 4.3b). Fixing a and b delivers the basis for formulating an envelope thermal transmittance performance requirement. An example is found in the Belgian legislation which defines a reference line with a equal to 2/3 and b equal to 1/3. By that, the straight line intersects the compactness axis in the point (–2, 0). Weakening the thermal transmittance requirement at low and upgrading them at high compactness is done by keeping a value 1 W/(m^2 · K) for a compactness below 1 m and 2 W/(m^2 · K) for a compactness above 4 m (Figure 4.3c). The broken line found that way is called 'level of thermal insulation K100'. Each building with the (C, U_m)-pair on that line obtains that level. Any other level is now defined by a broken line proportional to the K100 reference. As an equation:

$$\begin{array}{ll} C \le 1\ \text{m} & K = 100\, U_m \\ 1 < C < 4\ \text{m} & K = \dfrac{100\, U_m}{2/3 + C/3} \qquad (\text{W}/(\text{m}^2 \cdot \text{K})) \\ C \ge 4\ \text{m} & K = 50\, U_m \end{array} \tag{4.4}$$

See Figure 4.3d. Imposing a performance requirement on the envelope thermal transmittance is easy that way. Low energy for example demands more or less K25. The only thing still needed are rules to calculate compactness, envelope and building part surfaces and, thermal transmittance of all separate building parts.

Some countries define compactness the other way around: not V/A_T in m, but A_T/V in m^{-1}. The straight line than becomes a hyperbola. As an example Figure 4.4 gives the actual German envelope thermal transmittance requirements. The same corrections are applied as explained above: constant values, now below compactness 0.2 m^{-1} and above compactness 1.05 m^{-1}, hyperbolic in between:

$$\begin{array}{ll} C' \le 0.2\ \text{m}^{-1} & U_m = 1.05 \\ 0.2 < C' \le 1.05\ \text{m}^{-1} & U_m = 0.3 + \dfrac{0.15}{C'} \qquad (\text{W}/(\text{m}^2 \cdot \text{K})) \\ C' > 1.05\ \text{m}^{-1} & U_m = 0.44 \end{array} \tag{4.5}$$

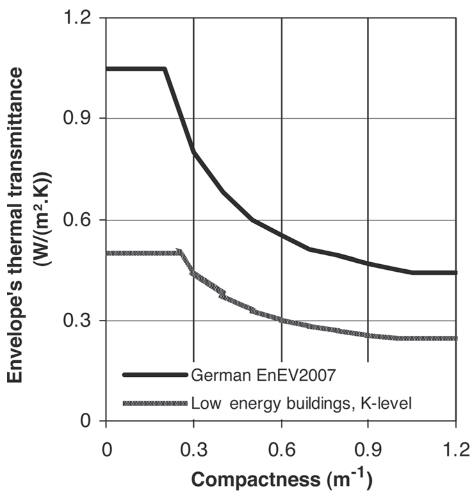


Figure 4.4. German envelope thermal transmittance requirements.

4.4 Transient thermal response

4.4.1 Properties of importance

4.4.1.1 Opaque envelope parts

In regions with a cool climate, transient thermal response of the enclosure is one of the parameters determining summer thermal comfort. In regions with a warmer climate, energy consumption for cooling is a main beneficiary. Characteristics determining the transient thermal response of an opaque one-dimensional building element are:

Harmonic load (period: 1 day)	Others
Temperature damping D_θ	Time constant τ
Dynamic thermal resistance D_q	
Admittance Ad	

An important advantage of the harmonic properties is that they are analytically calculable. Quantifying a time constant instead demands simplified models or a numerical approach.

Example of a simplified model:
the building element seen as a resistance-capacitance-resistance circuit

First the thermal capacity per layer ($C = \rho\ c\ d$ in J/K) is calculated and considered as a vector in the layer's centre. All layers together give a vector field whose resultant ($\Sigma\ C_j$) is situated in what is called the point of action. Assume x is the ordinate of that point along an x-axis with origin in the contact interface with environment 1. Thermal resistance between environment 1 and x is called R_{1x}, thermal resistance between environment 2 at the other side and x R_{2x}. The heat balance for the circuit R_{1x} / $\Sigma\ C_j$ / R_{2x} then becomes (Figure 4.5):

$$\frac{\theta_1 - \theta_x}{R_{1x}} + \frac{\theta_2 - \theta_x}{R_{2x}} = \left(\sum C_j\right)\frac{\theta_x}{dt}$$

where θ_x is the temperature in the point of action, θ_1 the uniform temperature in environment 1 and θ_2 the uniform temperature in environment 2. A step increase or decrease of temperature θ_1 or θ_2 at time zero gives as a solution:

$$\theta_x = \theta_{x,\infty} + \left(\theta_{x,0} - \theta_{x,\infty}\right)\exp\left(-\frac{t}{\overline{R}\sum C_j}\right)$$

where $\overline{R}$ is the harmonic mean of R_{x1} and R_{x2}:

$$\overline{R} = \frac{R_{1x}\ R_{2x}}{R_{1x} + R_{2x}}$$

The time constant is: $\tau = \overline{R}\sum C_j$

That formula shows the time constant increases with both total capacity and the harmonic mean of both thermal resistances. In that mean the smallest thermal resistance has the largest impact.

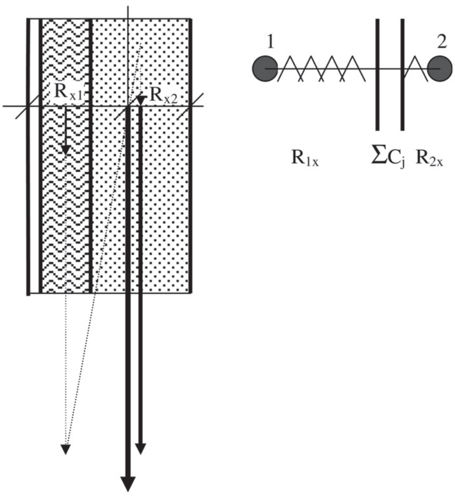


Figure 4.5. The <thermal resistance R_1/capacitance $\Sigma\ C$/thermal resistance R_2 > analogue.

4.4.1.2 Transparent envelope parts

Transparent parts act as a hatch for short wave solar radiation and a source of indirect solar gains by convection and long wave radiation of absorbed short wave irradiation. Both fix the solar transmittance g of the part.

4.4.2 Performance requirements

4.4.2.1 Opaque envelope parts

Imposing limit values for the harmonic properties is less evident. The maximum thermal transmittance (U_{max}) fixes the lowest value the dynamic thermal resistance amplitude will touch, as following relation holds: $[D_q] > 1/U_{max}$. The lower U_{max}, the larger the minimal dynamic thermal resistance will be.

The maximum thermal transmittance also borders the lowest possible admittance amplitude, while the highest amplitude possible never passes the thermal surface film coefficient: $U_{max} \le [\text{Ad}] \le h_i$. That way, low U_{max}-values and high h_i-values open a large window of admittance values. A high admittance makes heat storage easier, which is why a performance requirement could be: $[\text{Ad}] \ge h_i/2$

Temperature damping amplitude may finally have values between 1 and infinity. The relevance of very high values, however, is relative. If for example the sol-air temperature outside swings between 10 and 80 °C on a daily basis, than the amplitude of the complex inside temperature will equal $35/[D_\theta]$, which translated into numbers gives:

$[D_\theta]$	$\hat{\alpha}_i$ °C
1	35.0
2	17.5
4	8.8
8	4.4
16	2.3
32	1.1
74	0.6

A difference between night and day of 2.3 °C will hardly be decisive for thermal comfort. For that reason it suffices to impose a lower limit, for example: $[D_\theta] \ge 15$.

4.4.2.2 Transparent envelope parts

In cool climates solar transmittance should accommodate two conflicting requirements: in view of energy efficiency as close as possible to 1 during the heating season, in view of thermal comfort and energy efficiency if cooling is needed, as low as possible during the warm half-year, however without hindering daylighting. The best solution therefore follows from a combined end energy consumption/summer comfort analysis, using building energy software tools. A possible reference for summer comfort is the number of weighted temperature excesses

(WTE). If all other parameters are invariant, glass surface area and solar shading should be fixed in a way that number does not exceed 100. The WTE-hours are given by summing up the excess factors (EF) the hours the building is used:

$$\begin{aligned} &|\mathrm{PMV}| \le 0.5 \quad \mathrm{EF} = 0 \\ &|\mathrm{PMV}| > 0.5 \quad \mathrm{EF} = 0.47 + 0.22|\mathrm{PMV}| + 1.3|PMV|^2 + 0.97|\mathrm{PMV}|^3 - 0.39|\mathrm{PMV}|^4 \end{aligned} \tag{4.6}$$

where PMV is the predicted mean vote at an hourly basis (see Chapter 3, thermal comfort). Following array with $f_{gl} = A_{gl}/A_{fac}$ the glass to façade surface ratio allows a quick rating of the advisable solar transmittance (g) during the warm half-year:

Inside partitions	$g f_{gl}$	
	Low ACH	**High ACH**
Light	0.12	0.17
Heavy	0.14	0.25

4.4.3 Consequences for the building fabric

4.4.3.1 Opaque envelope parts

How are high admittances structurally achieved? The following simple model demonstrates the answer. Take an assembly composed of two layers, one light and insulating, thermal resistance R, and the other heavy and hardly insulating, capacitance C. The thermal surface film coefficients at both sides are h_1 respectively h_2. The heat balance becomes:

$$\frac{\theta_1 - \theta_x}{R + 1/h_1} + \frac{\theta_2 - \theta_x}{1/h_2} = C\,\frac{\theta_x}{dt} \tag{4.7}$$

where θ_x is the central temperature in the capacitance, θ_1 the temperature in the environment at the insulation side and θ_2 the temperature in the environment at the heavy layer side. Assume environment 1 is the outside ($h_1 = h_e$, θ_1). The outside temperature fluctuates harmonically, period T. In such a case also the inside temperature (θ_2) will vary harmonically with a same period T and an amplitude α_2 dampened and shifted in time compared to the temperature outdoors:

$$\theta_2 = \alpha_2 \exp\left(\frac{i\,2\,\pi\,t}{T}\right) \tag{4.8}$$

Temperature damping is defined now for a complex heat flow rate zero at the inside surface (surface 2). That presumes a heat flow rate of zero between the capacitance and indoors or: $\alpha_x = \alpha_2$. That way the heat balance (4.7) is reduced to (after elimination of the time function exp (i 2 π t/T)):

$$\frac{\alpha_1 - \alpha_2}{R + 1/h_1} = \frac{i\,2\,\pi\,C}{T}\,\alpha_2$$

Complex temperature damping then is ($R_1 = R + 1/h_1$): $D_\theta^{1,2} = \alpha_1 / \alpha_2 = 1 + i\,2\,\pi\,R_1\,C/T$ with as amplitude:

$$\hat{D}_\theta^{1,2} = \sqrt{1 + \left(\frac{2\,\pi\,R_1\,C}{T}\right)^2}\,. \tag{4.9}$$

That value increases quasi linearly with the part's time constant (R_1 C).

Now, the situation is reversed, with 2 being the outside and 1 the inside, or θ_2 the cause and θ_1 the consequence. The complex heat flow rate α_1' now becomes zero, changing the heat balance into ($h_2 = h_e$):

$$h_2\,(\alpha_2 - \alpha_1) = \frac{i\,2\,\pi\,C}{T}\,\alpha_2$$

and giving as complex temperature damping $D_\theta^{2,1} = \alpha_2 / \alpha_1 = 1 + i\,2\,\pi\,C/(T\,h_2)$, and an amplitude of:

$$\hat{D}_\theta^{2,1} = \sqrt{1 + \left(\frac{2\,\pi\,C}{T\,h_2}\right)^2} \tag{4.10}$$

Due to a surface thermal resistance value $1/h_2$ which is far below the sum of the thermal resistance $1/h_1 + R$ ($h_1 = h_2 = h_e$!), the temperature damping amplitude $D_\theta^{1,2}$ is much larger now than $D_\theta^{2,1}$. If 1 in the square root is neglected, then the ratio between the two ($\hat{D}_\theta^{1,2} / \hat{D}_\theta^{2,1}$) equals $1 + R\,h_e$. For an insulation with thermal resistance 1.5 $m^2 \cdot K/W$ that ratio equals 38.5 ($h_e = 25$ $W/(m^2 \cdot K)$). Achieving a high temperature damping thus demands an opaque assembly composed of a heavy and an insulating layer with the insulating layer outside and the heavy layer inside. A damping amplitude 15 requires a time constant R_1 C of 205 800 s or 2.38 days. Higher thermal resistances R_1 allow reducing the thickness of the capacitive layer for the same damping result. A lower thermal resistance instead demands a thicker capacitive layer for the same damping result. As an illustration:

R_1 **$m^2 \cdot K/W$**	**C** **$J/(m^2 \cdot K)$**	**Assembly (the parts in italic not buildable in practice)** **($\hat{D}_\theta = 15$)**
1	205 800	4 cm thermal insulation at the outside 9 cm concrete or 19 cm thick hollow fired clay bricks inside
2	102 900	8 cm thermal insulation at the outside *5.5 cm concrete* or 9 cm thick hollow fired clay bricks inside
4	51 450	16 cm thermal insulation at the outside *2.75 cm concrete or 4.5 cm thick hollow fired clay bricks at the inside*
8	25 725	32 cm thermal insulation at the outside *1.375 cm concrete or 2.25 cm thick hollow fired clay bricks at the inside*

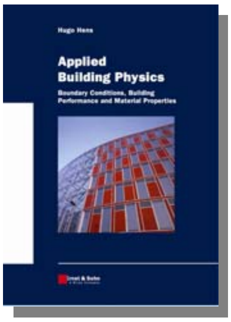
A same discourse for the admittance shows highest values are attained with a capacitive layer inside, not screened by even a thin insulating layer or a low thermal surface film resistance inside ($1/h_i$).

4.4.3.2 Transparent envelope parts

Solar screening is the way to go, either by using sun absorbing or reflecting glazing systems, movable outside screens or fixed shading elements.

Hugo S. L. C. Hens

Applied Building Physics
Boundary Conditions, Building Performance and Material Properties



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