Heat transfer
in building envelopes
in steady state conditions

Building Physics – Bauphisik

Fisica dell'involucro edilizio

Study of the phenomena due to building envelope:

- temperature field, heat flow and study of the temperature distribution;
- transpiration problems of structures and mass transport (vapour) through the building envelope;
- optimization for the durability of the envelope

Thermal conduction

- **Foundamental law: Fourier's postulate**

$$dq = -\lambda \, dS \frac{\partial t}{\partial n}$$

Steady state conditions: **single layer**

$$q = S \frac{\lambda}{s} (t_{si} - t_{se})$$

multi-layer

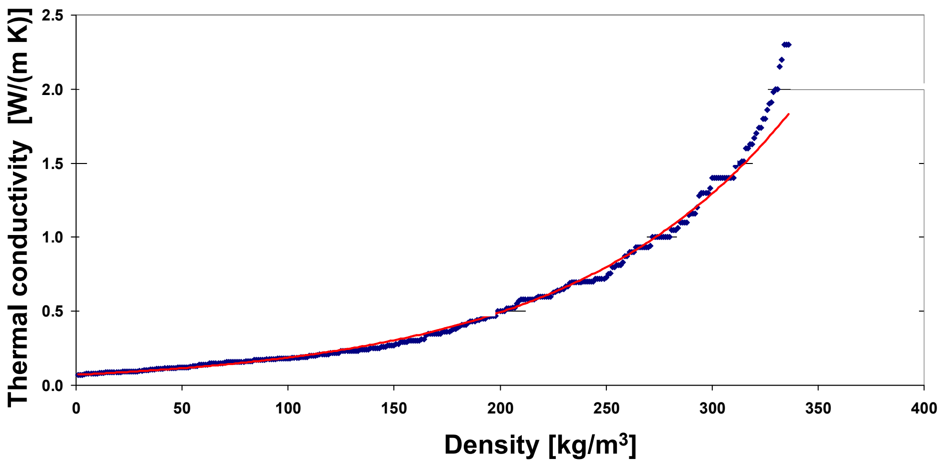
$$q = \frac{S \, (t_{si} - t_{se})}{\Sigma \, (s_i / \lambda_i)}$$

- **Thermal conductvity λ [W/(m K)]**

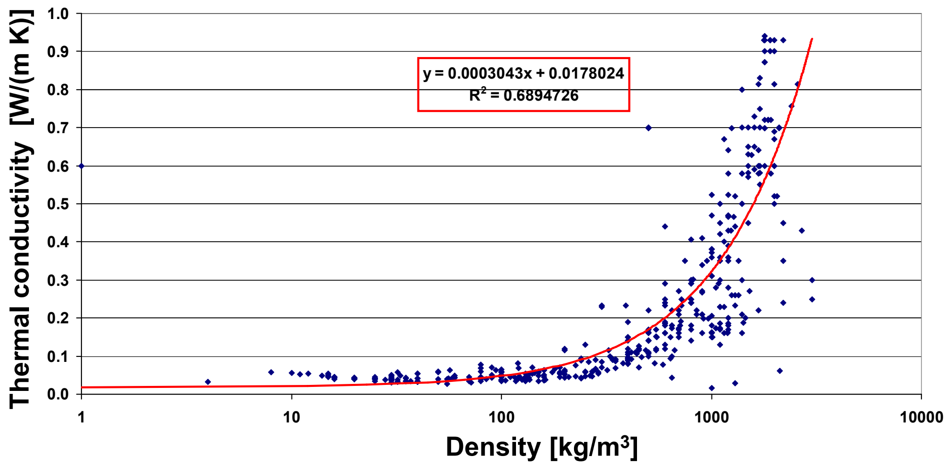
Example of materials

Material	Thermal conductivity [W/(m K)]
Light concrete	0.40
Reinforced concrete	2.00
Glass	1.00
Stone	2.50
Bricks	0.50
Hollow bricks	0.40
Internal plaster	0.50
External plaster	0.90
Gypsum board	0.12
Rock wool	0.045
Glass wool	0.05
Expanded polystyrene foam (EPS)	0.04
Extruded polystyrene foam (EPS)	0.03
Polyurethane	0.035
Glass foam	0.052
Cork boards	0.045
PVC	0.19

Concrete-based materials



Materials with λ < 1 W/(m K)



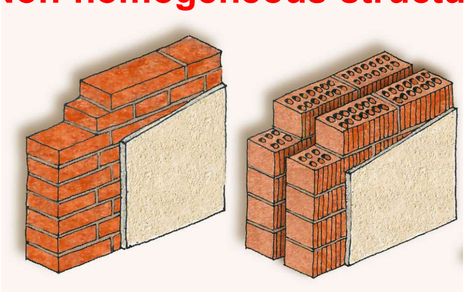
Recommendation:

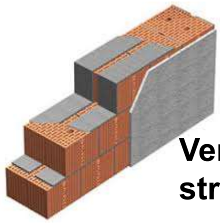
Usually it is recommended to increase the thermal conductivity by about 10% to consider the vapour content in operating conditions in reality (the declared values have been established in laboratory with low content of humidity).

Other parameters to be considered:

Beside the thermal conductivity, usually the density and the vapour permeability are also usual parameters for building materials which are required for the building energy calculations

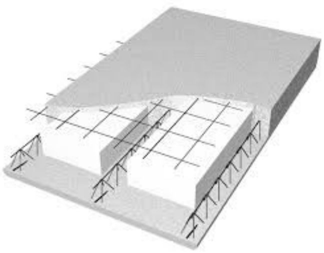
Non-homogeneous structures





Vertical structures

Horizontal structures



Heat transfer in non-homogeneous structures

For these types of building technologies the thermal resistance has to be evaluated.

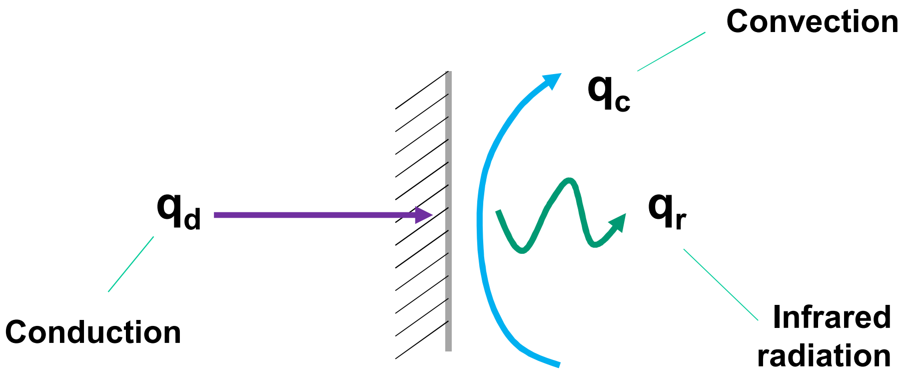
Specific national standards provide the values of unitary thermal resistance for walls and floors widely used in Italy, based on the results of laboratory tests and detailed calculations, carried out in recent years.

In these cases a fictitious conductivity can be used:

$$\lambda^* = s/R$$

Heat transfer on surfaces

Heat balance on a surface not considering the solar gains or other radiant loads (e.g. lighting)



Convection

A fluid flow at temperature t brushes against a solid surface at temperature t_s

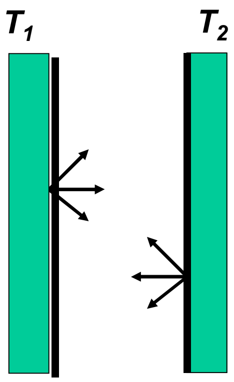
Heat flux:

$$q = h_c\, S\, (t_s - t) \qquad t_s > t$$

Coefficient of the convective heat transfer

h_c [W/(m² K)]; [kcal/(m² h °C)]

Infrared radiation



Plane, parallel, front facing surfaces at temperature, respectively, T_1 and T_2

$$q = \frac{\sigma_n S (T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

σ_n: Stephan-Boltzmann's constant

5.76×10^{-8} W/(m² K⁴)

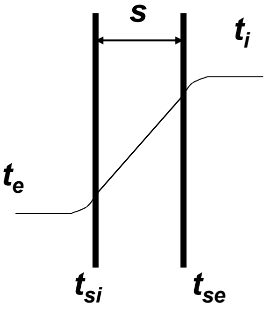
ε_1, ε_2 : emissivity of the two surfaces. For usual finishing materials of walls

$$\varepsilon_1 = \varepsilon_2 = 0.9 \longrightarrow 1 < \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1 < 1.1$$

$$q = \sigma_n S (T_1^4 - T_2^4) = 4\, \sigma_n\, S\, T_m^3 (T_1 - T_2) = h_r\, S\, (T_1 - T_2)$$

h_r radiant heat transfer coefficient = 5.5 W/(m² K)

Overall heat transfer on a surface



-Outdoor temperature and indoor temperature t_e and t_i

- Surface temperature t_{si} t_{se}

On the external surface the heat flux is:

- For convection with the external air
  $q = h_{ce}\ S\ (t_{se} - t_e)$
- For radiation:
  $q = h_{re}\ S\ (t_{se} - t_e)$
- overall:
  $q = (h_{re} + h_{ce})\ S\ (t_{se} - t_e)$

External overall heat transfer coefficient h_{se}

Similarly, on the inner surface of the layer the heat flux is:

$$q = (h_{ri} + h_{ci})\ S\ (t_{si} - t_i)$$

h_{si} Internal overall heat transfer coefficient

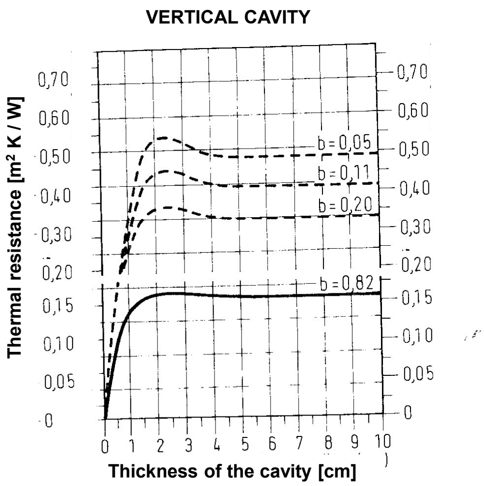
$$h_{si} = h_{ri} + h_{ci} = 1/R_{si}$$

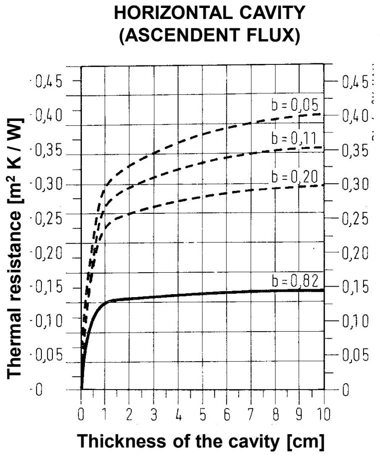
$$h_{se} = h_{re} + h_{ce} = 1/R_{se}$$

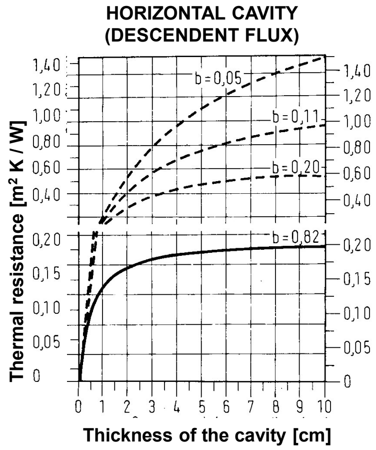
Surface thermal resistance

Position of the Surface	R_{si} [m2 K / W]	R_{se} [m2 K / W]
Vertical or inclination a of the surface to the horizontal such that 90° ≥ b ≥ 60° (heat flow direction ±30° from the horizontal plane)	0.13	0.04
Vertical or inclination a of the surface to the horizontal such that 60° ≥ b ≥ 0° (heat flow direction more than 30° from the horizontal plane)	0.10	0.04

Air cavities







U-value of a building element

$$q^* = \frac{\lambda}{s} (t_{si} - t_{se})$$

$$q^* = h_{si} \ (t_{si} - t_i)$$

$$q^* = h_{se} \ (t_{se} - t_e)$$

$$U = \frac{1}{\frac{1}{h_{si}} + \frac{\lambda}{s} + \frac{1}{h_{se}}}$$

Trasmittance
U-value
[W/(m² K)]

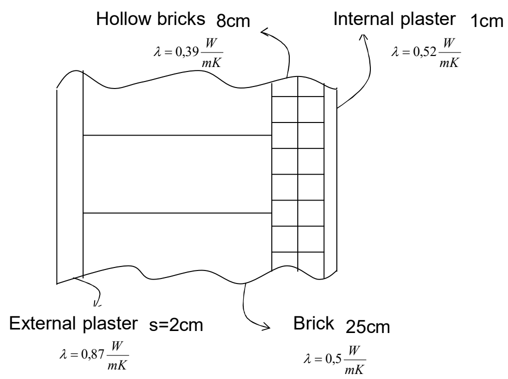
$$q = U \, S \, (t_i - t_e)$$

For a multi-layer wall:

$$U = \frac{1}{\frac{1}{h_{si}} + \Sigma \frac{\lambda}{s} + \Sigma\ R + \frac{1}{h_{se}}}$$

$$R_{tot} = \frac{1}{h_{si}} + \Sigma \frac{\lambda}{s} + \Sigma\ R + \frac{1}{h_{se}}$$

EXAMPLE OF THERMAL TRANSMITTANCE



$$R_e = \frac{1}{25} = 0{,}04 \frac{m^2K}{W}$$

$$R_1 = \frac{0{,}02}{0{,}87} = 0{,}023 \frac{m^2K}{W}$$

$$R_2 = \frac{0{,}25}{0{,}5} = 0{,}5 \frac{m^2K}{W}$$

$$R_3 = \frac{0{,}08}{0{,}34} = 0{,}235 \frac{m^2K}{W}$$

$$R_4 = \frac{0{,}01}{0{,}52} = 0{,}019 \frac{m^2K}{W}$$

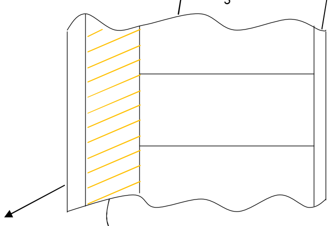
$$R_i = \frac{1}{8} = 0{,}125 \frac{m^2K}{W}$$

$$U = \frac{1}{R_e + R_1 + R_2 + R_3 + R_4 + R_i} = \frac{1}{R_{TOT}}$$

$$R_{TOT} = 0{,}942 \frac{m^2K}{W}$$

$$U = 1{,}062 \frac{W}{m^2K}$$

Same materials as the slide before: instead of the hollow brick there is an insulation layer



$$R_1 = 0{,}023 \frac{m^2K}{W}$$

$$R_2 = \frac{0{,}06}{0{,}04} = 1{,}5 \frac{m^2K}{W}$$

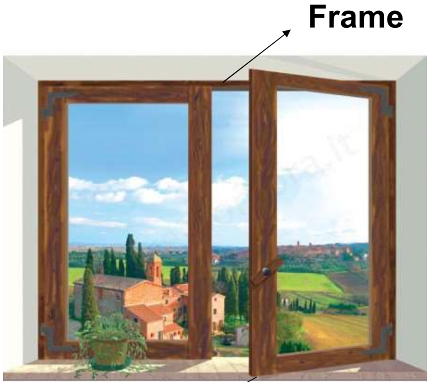
$$R_3 = 0{,}5 \frac{m^2K}{W} \qquad R_i = 0{,}125 \frac{m^2K}{W}$$

$$R_4 = 0{,}019 \frac{m^2K}{W} \qquad R_e = 0{,}04 \frac{m^2K}{W}$$

$$R_{TOT} = 2{,}207 \frac{m^2K}{W}$$

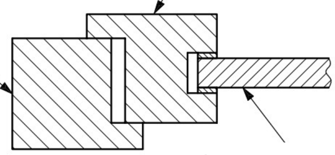
$$U = \frac{1}{R_{TOT}} = 0{,}453 \frac{W}{m^2K}$$

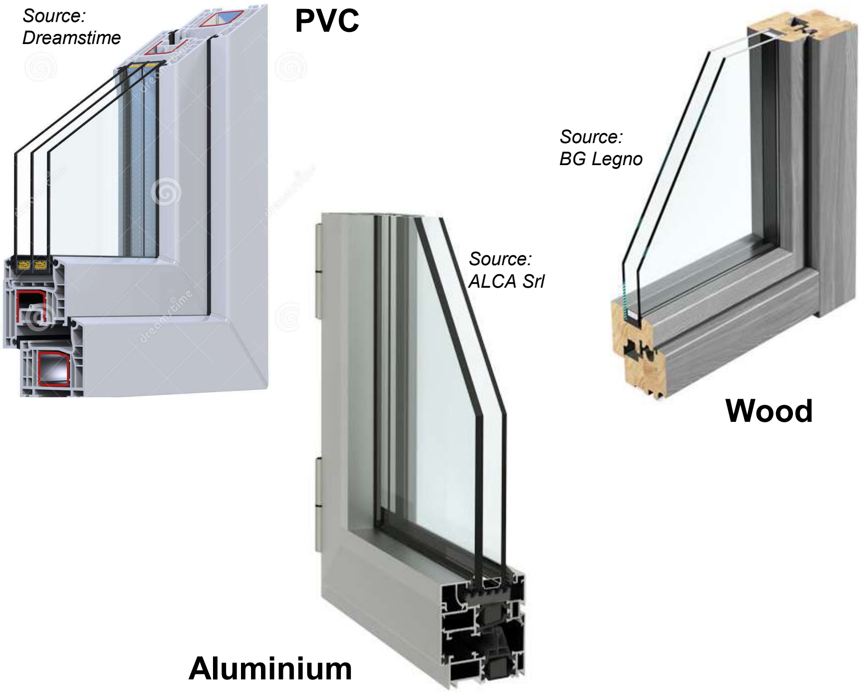
Windows



Source:
Trompe l'oeil

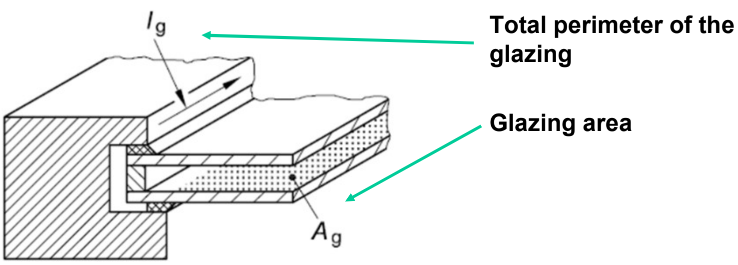
Source:
EN ISO 10077



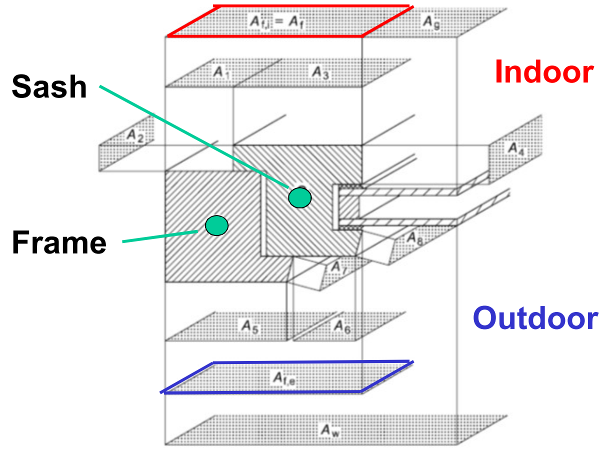


Definitions

The glazed area A_g of a window is the smaller of the visible areas seen form both sides any overlapping of gaskets is ignored.
The total visible perimeter of the glazing l_g is the sum of the visible perimeter of the glass panes in the window . If the perimeters are different on either side of the pane, then the larger of the two shall be used.



Internal projected frame area ($A_{f,i}$): area of the projection of the internal frame, including sashes, if present, on a plane parallel to the glazing panel.
External projected frame area ($A_{f,e}$): area of the projected of the external frame, including sashes if present on a plane parallel to the glazing panel.



$$A_f = \max.\ (A_{f,i}\ ;\ A_{f,e})$$

$$A_W = A_f + A_g$$

U-value of glazing

Single glass

s = 4 mm = 0,004 m

λ = 1 W/(m K)

$$R_v = \frac{s}{\lambda} = \frac{0{,}004\ \text{m}}{1\ \text{W/(m K)}} = 0{,}004\ \ \text{m}^2\ \text{K / W}$$

$$R_i = 1/h_i = 1/8 = 0{,}125\ \ \text{m}^2\ \text{K / W}$$

$$R_e = 1/h_e = 1/25 = 0{,}04\ \ \text{m}^2\ \text{K / W}$$

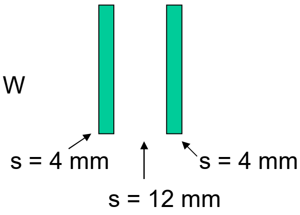
$$R_{tot} = R_e + R_i + R_v = 0{,}04 + 0{,}004 + 0{,}125 = 0{,}169\ \ \text{m}^2\ \text{K / W}$$

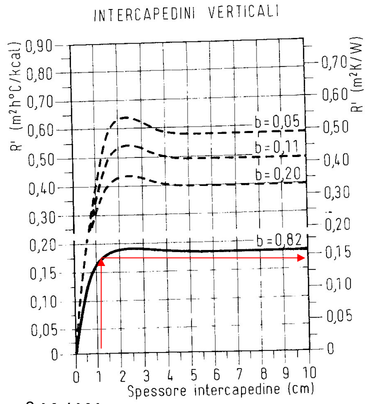
$$U_g = 1/R_{tot} = 1 / 0{,}169 = 5{,}92\ \ \text{W/(m}^2\ \text{K)}$$

Double glass

$$b = \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

$R_v = 0{,}004 \quad m^2\,K/W$





$\varepsilon_1 = \varepsilon_2 = 0{,}9 \longrightarrow 1/\varepsilon_1 = 1{,}11$

$$b = \frac{1}{2{,}22 - 1} = 0{,}82$$

From the chart $\quad R' = 0{,}15 \quad m^2\,K/W$

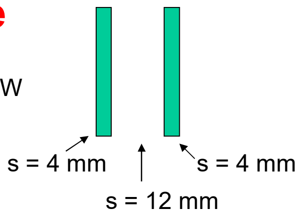
$R_{tot} = R_e + R_v + R' + R_v + R_i + =$
$= 0{,}04 + 0{,}004 + 0{,}15 + 0{,}004 + 0{,}125 = 0{,}323 \quad m^2\,K/W$

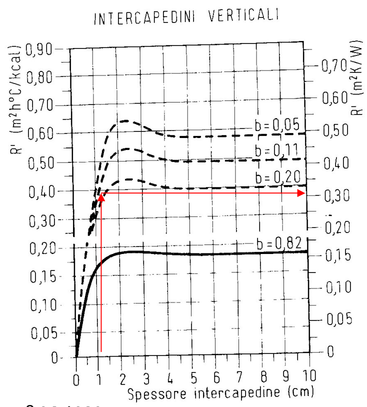
$U_g = 1/R_{tot} = 1/0{,}323 = 3{,}1 \quad W/(m^2\,K)$

Low emissivity double pane

$$b = \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

$R_v = 0{,}004 \quad m^2\,K/W$





$\varepsilon_1 = 0{,}9; \; \varepsilon_2 = 0{,}2 \longrightarrow 1/\varepsilon_1 = 1{,}11$

$1/\varepsilon_2 = 5$

$$b = \frac{1}{6{,}11 - 1} = 0{,}196$$

From the chart $\quad R' = 0{,}30 \quad m^2\,K/W$

$R_{tot} = R_e + R_v + R' + R_v + R_i + =$
$= 0{,}04 + 0{,}004 + 0{,}30 + 0{,}004 + 0{,}125 = 0{,}473 \quad m^2\,K/W$

$U_g = 1/R_{tot} = 1/0{,}473 = 2{,}11 \quad W/(m^2\,K)$

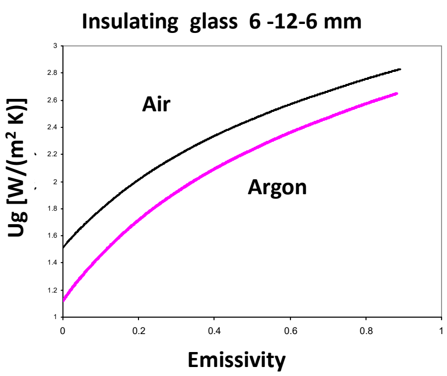
General results with different combinations of air spaces

Thermal resistance of unventilated air spaces for coupled and double vertical windows

Thickness of air space	Thermal resistance R_s $m^2 \cdot K/W$				
	One side coated with a normal emissivity of				Both sides uncoated
mm	0,1	0,2	0,4	0,8	
6	0,211	0,191	0,163	0,132	0,127
9	0,299	0,259	0,211	0,162	0,154
12	0,377	0,316	0,247	0,182	0,173
15	0,447	0,364	0,276	0,197	0,186
50	0,406	0,336	0,260	0,189	0,179

Influence of the gas inside the cavity

% di gas	Argon	Kripton
100%	1.9	1.7
90%	2.0	1.8
70%	2.0	1.9
50%	2.1	2.0



Thermal transmittance of double and triple glazing filled with different gases for vertical glazing

Glazing				Thermal transmittance for different types of gas space [a] U_g				
Type	Glass	Normal emissivity	Dimensions mm	Air	Argon	Krypton	SF_6 [b]	Xenon
Double glazing	Uncoated glass (normal glass)	0,89	4-6-4	3,3	3,0	2,8	3,0	2,6
			4-8-4	3,1	2,9	2,7	3,1	2,6
			4-12-4	2,8	2,7	2,6	3,1	2,6
			4-16-4	2,7	2,6	2,6	3,1	2,6
			4-20-4	2,7	2,6	2,6	3,1	2,6
	One pane coated glass	⩽ 0,2	4-6-4	2,7	2,3	1,9	2,3	1,6
			4-8-4	2,4	2,1	1,7	2,4	1,6
			4-12-4	2,0	1,8	1,6	2,4	1,6
			4-16-4	1,8	1,6	1,6	2,5	1,6
			4-20-4	1,8	1,7	1,6	2,5	1,7
	One pane coated glass	⩽ 0,15	4-6-4	2,6	2,3	1,8	2,2	1,5
			4-8-4	2,3	2,0	1,6	2,3	1,4
			4-12-4	1,9	1,6	1,5	2,3	1,5
			4-16-4	1,7	1,5	1,5	2,4	1,5
			4-20-4	1,7	1,5	1,5	2,4	1,5
	One pane coated glass	⩽ 0,1	4-6-4	2,6	2,2	1,7	2,1	1,4
			4-8-4	2,2	1,9	1,4	2,2	1,3
			4-12-4	1,8	1,5	1,3	2,3	1,3
			4-16-4	1,6	1,4	1,3	2,3	1,4
			4-20-4	1,6	1,4	1,4	2,3	1,4
	One pane coated glass	⩽ 0,05	4-6-4	2,5	2,1	1,5	2,0	1,2
			4-8-4	2,1	1,7	1,3	2,1	1,1
			4-12-4	1,7	1,3	1,1	2,1	1,2
			4-16-4	1,4	1,2	1,2	2,2	1,2
			4-20-4	1,5	1,2	1,2	2,2	1,2

U-values of frames

They differ from the material they are made.

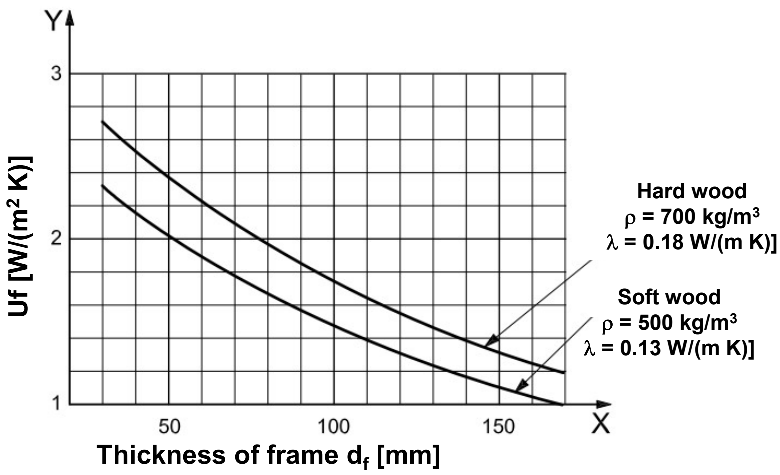
There are 2 possible calculations:

1. With the simplified method of EN ISO 10077-1
2. With a detailed method of EN ISO 10077-2

Who has to evaluate the U_f and U_g?
Always the producer: the window has to be CE marked and Uf and Ug have to be declared

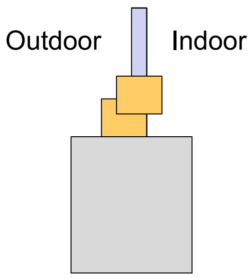
But, in existing buildings if no declaration is present the designer has to evaluate the Uw

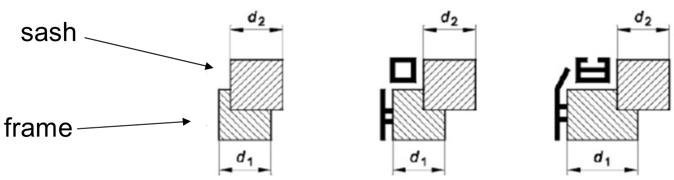
U-values of wooden frames



How to evaluate d_f in a wooden window frame:

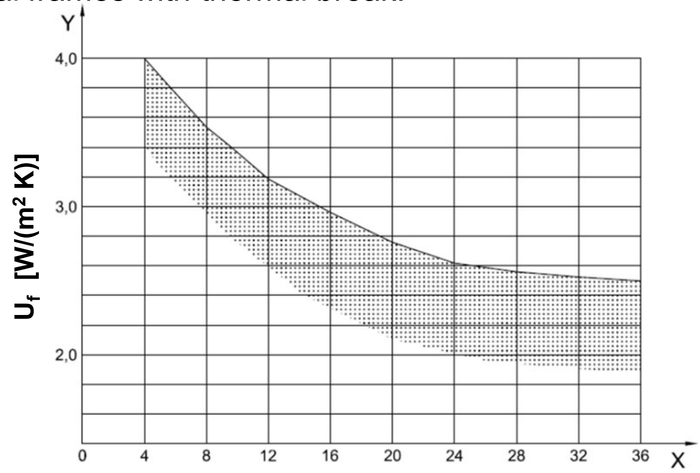
$d_f = 0.5 \cdot (d_1 + d_2)$





U-values of metal frames

For metal frames without thermal break use U_{f0} = 5.9 W/(m^2·K)
For metal frames with thermal break:



Minimum distance between the aluminium sections [mm]

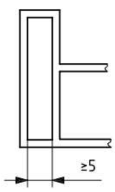
U-values of plastic frames

Thermal transmittances for plastic frames with metal reinforcements

Frame material	Frame type	U_f W/(m^2·K)
Polyurethane	with metal core thickness of PUR ⩾ 5 mm	2,8
PVC-hollow profiles [a]	two hollow chambers external internal	2,2
	three hollow chambers external internal	2,0

[a] With a distance between wall surfaces of each hollow chamber of at least 5 mm (refer to Figure D.1).

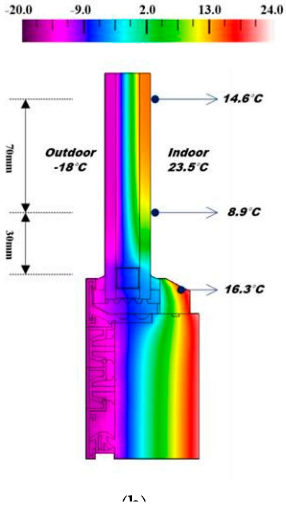
Dimensions in millimetres

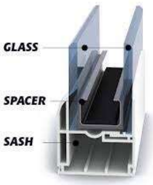


Combined effect of frame, window and spacer

U_g can be applied to the central area of the window (only glass, not including spacers or frame. Frame transmittance, U_f, is calculated without the glazing element.

The combined effect of the frame, window and spacer is considered in the thermal linear loss Ψ_g depending on the material of the spacer.





Junction effects

Values of linear thermal transmittance for common types of glazing spacer bars (e.g. aluminium or steel)

Frame type	Linear thermal transmittance for different types of glazing Ψ_g	
	Double or triple glazing uncoated glass air- or gas-filled	Double [a] or triple [b] glazing low-emissivity glass air- or gas-filled
Wood or PVC	0,06	0,08
Metal with a thermal break	0,08	0,11
Metal without a thermal break	0,02	0,05

[a] One pane coated for double glazed.
[b] Two panes coated for triple glazed.

Calculation of the thermal transmittance

$$U_w = \frac{\text{Overall heat flux}}{\text{Overall surface of the window}}$$

$$U_w = \frac{(U_g\,A_g + U_f\,A_f + l_g\,\Psi_g)}{(A_g + A_f)}$$