Chapter 4
Thermal Behaviour of Historical Buildings, Materials and Components: Methodological Framework, Calculation, Results

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4.1 Introduction

The energy-saving target, in the refurbishment of historical buildings, should be considered a fundamental element for their reuse, as the running costs may represent a significant economic problem especially for the public administrations that in Italy are widely located in these representative buildings (Magrini and Franco 2016, Franco et al. 2015, Magrini et al. 2015).

The absence of regulatory minimum requirements for the energy performance of historical buildings doesn't mean that they must not be considered as a target and that some actions cannot be evaluated in terms of technical feasibility in respect of the architectural and historical constraints. This kind of buildings is used also as home or it hosts representative institutions, trade-banks, and other private enterprises. Their high maintenance costs, especially for heating or cooling systems, may determine a progressive moving of the activities to less expensive buildings: the ancient buildings risk to be subdued to a progressive degradation without an active role in the social context. The reduction of the energy consumption can be designed by means of wall insulation.

However, actions on the building envelope are difficult to realize and, in any case, they must be evaluated with care: thermal insulation, when applicable, may cause worse hygrometrical behaviour of the walls. Moreover, it may be useful a good thermal insulation designed jointly with the evaluation of the thermal inertia influence on the heat transfer behaviour (Magrini 2016, Magrini et al. 2013).

In the following, the calculation method of the energy performance of buildings is outlined, and some relevant parameters of the opaque envelope are highlighted. Some definitions and fundamental concepts, on which the calculations to be carried

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out are based, are briefly summarized. The application of the calculation methods is supported by examples. Some common historical building walls are considered, and the calculation of their thermal features is performed. The application of an insulating layer on the existing structures is evaluated. The choice of three insulating materials is proposed, taking into account both their thermal and hygrometrical behaviour.

4.2 The Calculation Method of the Energy Performance of Buildings

The Directive 2010/31/EU (Directive 2010) of the European Parliament and of the Council on the energy performance of buildings indicates requirements regarding the common general framework for a methodology for calculating the integrated energy performance of buildings. It shall be determined on the basis of the calculated or actual annual energy that is consumed for the heating and cooling energy needs and domestic hot water needs.

Among the aspects taken into consideration by the methodology, there are: thermal capacity; insulation; passive heating; thermal bridges; the design, positioning and orientation of the building, outdoor climate; passive solar systems and solar protection; indoor climatic conditions; internal loads. Also the positive influence of the local solar exposure conditions should be taken into account.

The measures to ensure that minimum energy performance requirements for buildings may not be applied to "buildings officially protected as part of a designated environment or because of their special architectural or historical merit, in so far as compliance with certain minimum energy performance requirements would unacceptably alter their character or appearance".

The methodology for calculating energy performance takes into account the existing European Standards. In the EN ISO 13790 Standard (Energy performance of buildings—Calculation of energy use for spaces—heating and cooling), two approaches for the design and evaluation of thermal and energy performance of buildings are indicated.

The calculation methods can be:

- quasi-steady-state methods to obtain the heat balance over each month or a whole season, taking into account dynamic effects by the simplified determination of an utilization factor
- dynamic methods that perform the heat balance over short time steps and take into account the heat storage properties of the building

The methodology provides calculation procedures to obtain the energy need for space heating and cooling by means of a monthly quasi-steady-state calculation method, a simple hourly dynamic calculation method; and detailed (e.g. hourly) dynamic simulation methods.

Referring to the first method, for example, the building energy need for space heating, $Q_{H,nd}$, in conditions of continuous heating, is calculated by:

$$Q_{H,nd} = Q_{H,ht} - \eta_{H,gn} Q_{H,gn} \tag{4.1}$$

where

$Q_{H,nd}$ is the building energy need for continuous heating, assumed to be greater than or equal to 0 [MJ].
$Q_{H,ht}$ is the total heat transfer for the heating mode [MJ].
$Q_{H,gn}$ gives the total heat gains for the heating mode [MJ].
$\eta_{H,gn}$ is the dimensionless utilization factor.
and the total heat transfer, $Q_{H,ht}$, is given by:

$$Q_{H,ht} = Q_{tr} + Q_{ve} \tag{4.2}$$

where Q_{tr} is the total heat transfer by transmission and Q_{ve} is the total heat transfer by ventilation.

Focusing the attention on Q_{tr}, it depends on the temperature difference between indoor and outdoor environment (t_i–t_e) on the heating or cooling time period τ and on H_{tr}, the overall heat transfer coefficient by transmission, determined by:

$$H_{tr} = H_D + H_g + H_U + H_A \tag{4.3}$$

where each term represents a heat transfer coefficient by transmission:

H_D: direct heat transfer coefficient by transmission to the external environment [W/K]
H_g: steady-state heat transfer coefficient by transmission to the ground [W/K]
H_U: transmission heat transfer coefficient by transmission through unconditioned spaces [W/K]
H_A: heat transfer coefficient by transmission to adjacent buildings [W/K]

For the first two approaches (quasi-steady-state and simple hourly dynamic methods), the basic physical data must be the same while, for the detailed simulation methods, the compliance with steady-state properties needs to be demonstrated.

Some of the most important features of the building envelope are considered by means of the transmission heat transfer coefficients H_D, H_g, H_U, or H_A. Indicating each of them generally as H_x, they can be calculated through the following expression (EN ISO 13789):

$$H_x = b_{tr,x}\left[\sum_i A_i \cdot U_i + \sum_k l_k \cdot \psi_k + \sum_j \chi_j\right] \tag{4.4}$$

where

A_i is area of the i-element of the building envelope [m^2].
U_i is thermal transmittance of the i-element of the building envelope [W/(m^2 K)].
l_k is length of the k-linear thermal bridge [m].
ψ_k is linear thermal transmittance of the k-thermal bridge [W/(m K)].
χ_j is point thermal transmittance of the j-point thermal bridge [W/(K)].
$b_{tr,x}$ is adjustment factor for the external temperature; it has to be applied when the envelope element borders on a space which has a different temperature than external environment

4.3 Main Parameters for the Thermal Characterization of Walls

For the assessment of the heat transfer coefficient H_x, the thermal transmittance of the building walls U and of the thermal bridges ψ must be defined. The EN ISO 6946 provides the method of calculation of the thermal transmittance of building components and building elements. It is determined by the calculation of the thermal resistance of each thermally homogeneous layer of the component that depends on its composition and thickness. Also surface heat transfer coefficients and air layer thermal resistances can be calculated according to the values defined by the EN ISO 6946 Standard.

4.3.1 Thermal Transmittance

The thermal parameters of the building envelope may be really hard to define in the case of historical buildings: the wall composition usually is not well known.

If it is possible to assume the thermal conductivity of the wall materials and their thickness, the thermal resistance of each layer can be calculated as:

$$R = d/\lambda \tag{4.5}$$

where

d is the thickness of the material layer in the component.
λ is the design thermal conductivity of the material (calculated or obtained from tabulated values).

The total thermal resistance, R_T, of a plane building component, characterized by thermally homogeneous layers perpendicular to the heat flow is calculated as the sum of the thermal resistances of the single layers as:

$$R_T = R_{si} + R_1 + R_2 + ...R_n + R_{se} \tag{4.6}$$

where

R_{si} and R_{se} are the internal and external surface resistances, respectively.
R_1, $R_{2,}$... R_n are the design thermal resistances of each layer.
Finally, the thermal transmittance U [W/(m^2 K)] is obtained as:

$$U = 1/R_T \tag{4.7}$$

A methodology to evaluate the heat transmittance of a building wall by means of in situ measurement is indicated in the international Standard 9869, based on the use of the heat flow meter (HFM) and thermometers.

The sensor measurements must be registered over a period of complete days. The minimum test duration is 72 h (3 days) if the temperature is stable around the HFM. Otherwise, it may last more than 7 days.

The U-value can be obtained by dividing the mean density of heat flow rate by the mean temperature difference.

Some difficulties may be encountered in the installation of the apparatus because the sensors must be mounted in an area representative of the whole element; they should not be under the direct influence of either a heating or a cooling device or under the draught of a fan. The outer surface of the element should be protected from rain, snow, and direct solar radiation.

4.3.1.1 Example: Thermal Transmittance Calculation

Given a wall structure with its layers' characteristics and thermal properties, it is possible to calculate the thermal transmittance U. In Table 4.1, the calculation details are reported, with reference to three common wall structures that can be found in historical buildings (brick and/or stone wall). Maintaining the same thickness, the U-value is significantly different in the four layouts, and therefore the knowledge of the wall composition is an important element for the thermal energy calculations.

The thermo-physical properties (ρ, material density in kg/m^3, λ, thermal conductivity in W/(m K)) of the materials are taken by the Italian national standard UNI 10351 "Building materials and products—Hygrothermal properties. Procedure for determining the design values", and it is assumed that the surface resistances are referred to horizontal flux through a vertical wall (Fig. 4.1).

4.3.2 Thermal Bridges

A thermal bridge is considered "part of the building envelope, where the otherwise uniform thermal resistance is significantly changed by full or partial penetration of

Table 4.1 Example of thermal transmittance evaluation for historical building common walls

(a) Brick wall layer	d [cm]	ρ [kg/m^3]	λ [W/(m K)]	R [m^{2}K/W]
Internal surface resistance				0.13
1. Internal plaster	3	1400	0.70	0.04
2. Composite layer: Brick	80	1800	0.72	1.11
3. External plaster	3	1800	0.90	0.03
External surface resistance				0.04
Total resistance R_T [m^2 K/W]				1.36
Thermal transmittance $U = R_T{}^{-1}$ [W/(m^2 K)]				0.74
(b1) Brick (60%) and stone wall layer	d [cm]	ρ [kg/m^3]	λ [W/(m K)]	R [m^2 K/W]
Internal surface resistance				0.13
1. Internal plaster	3	1400	0.70	0.04
2. Composite layer: Brick (60%) and stone	80	2080	1.40	0.57
3. External plaster	3	1800	0.90	0.03
External surface resistance				0.04
Total resistance R_T [m^2 K/W]				0.82
Thermal transmittance $U = R_T{}^{-1}$ [W/(m^2 K)]				1.22
((b2) Brick (20%) and stone wall layer	d [cm]	ρ [kg/m^3]	λ [W/(m K)]	R [m^2 K/W]
Internal surface resistance				0.13
1. Internal plaster	3	1400	0.70	0.04
2. Composite layer: Brick (20%) and stone	80	2360	2.06	0.39
3. External plaster	3	1800	0.90	0.03
External surface resistance				0.04
Total resistance R_T [m^2 K/W]				0.63
Thermal transmittance $U = R_T{}^{-1}$ [W/(m^2 K)]				1.58
(c) Stone wall layer	d [cm]	ρ [kg/m^3]	λ [W/(m K)]	R [m^2 K/W]
Internal surface resistance				0.13
1. Internal plaster	3	1400	0.70	0.04
2. Composite layer: stone	80	2500	2.40	0.33
3. External plaster	3	1800	0.90	0.03
External surface resistance				0.04
Total resistance R_T [m^2 K/W]				0.58
Thermal transmittance $U = R_T{}^{-1}$ [W/(m^2 K)]				1.73

the building envelope by materials with a different thermal conductivity, and/or a change in thickness of the fabric, and/or a difference between internal and external areas, such as occur at wall/floor/ceiling junctions" (EN ISO 10211).

In general, the hypothesis of mono-dimensional heat flow through this element is not correct since it causes two-dimensional or three-dimensional heat flows. In order to take into account the incidence of a thermal bridge in the transmission heat transfer coefficients calculation, the linear thermal transmittance ψ [W/(m K)] is

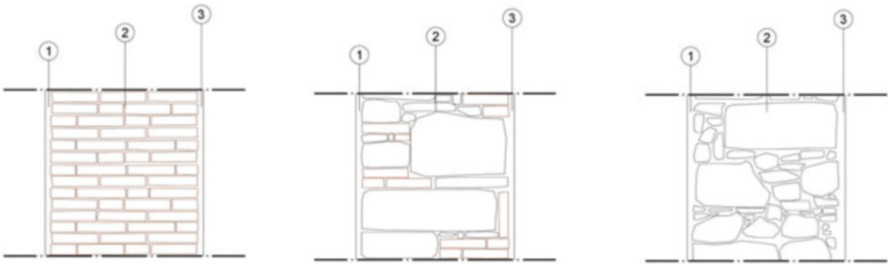

Fig. 4.1 Example of stone and/or brick wall

used. It can be defined as the heat flow rate in steady-state conditions, divided by the length of the junction and by the temperature difference between internal and external surfaces.

As shown in the Eq. (4.4), thermal bridges have a significant weight on the heat flow rate calculations and the internal surface temperature, and therefore their influence on the envelope energy performance assessment must be correctly evaluated.

In the past, a "thumb rule" usually applied to take into account the presence of thermal bridges was represented by 20% U-value increasing, even if their influence, in some cases, could be also around 30%. Actually, it is possible to determine its linear thermal transmittance through numerical methods, indicated in the EN ISO 10211 Standard.

The definition of a geometrical model of a thermal bridge for the numerical calculation of heat flows and surface temperatures is outlined, considering that:

- all physical properties are independent from temperature.
- there are no heat sources within the building element.

Reference values could be used for some standard structures referring to a catalogue of thermal bridges and values of ψ (EN ISO 14683) in relation to some different geometrical dimension, as follows:

ψ_e: linear thermal transmittance determined according to the external dimensions, measured between the finished external faces of the building external elements [W/(m K)]

ψ_{oi} linear thermal transmittance determined according to the overall internal dimensions, measured between the finished internal faces of the building external elements including the thickness of internal partitions [W/(m K)]

ψ_i: linear thermal transmittance determined according to the internal dimensions measured between the finished internal faces of each room in a building excluding the thickness of internal partitions [W/(m K)]

National regulations in some cases allow to assume the indications given by thermal bridges catalogues. Some information can be taken by the "Catalogue des ponts thermiques" (OFEN 2003) and in the "Abaco dei ponti termici" of Regione Lombardia (Regione Lombardia 2011).

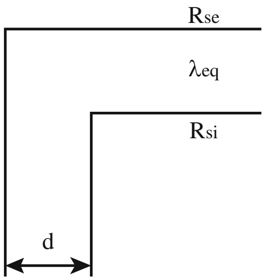

Fig. 4.2 Example of a thermal bridge (vertical corner without thermal insulation)

Table 4.2 Linear thermal transmittance ψ_i of a corner for three historical building common walls

Wall structure	d [m]	U [W/(m^2 K)]	λ_{eq} [W/(m K)]	ψ_i [W/(m K)]
Brick wall	0.86	0.74	0.72	0.29
Brick (60%) and stone wall	0.86	1.22	1.32[a]	0.48[b]
Brick (20%) and stone wall	0.86	1.58	1.85[a]	0.66[b]
Stone wall	0.86	1.73	2.10[a]	0.75[b]

[a]Value out of the range of applicability
[b]The probability that the estimate of ψ_i falls within the confidence interval may be lower than 95%

4.3.2.1 Example of Linear Thermal Transmittance Evaluation

From the last catalogue, an example of a common thermal bridge for a corner, that can be applied also in the case of historical buildings is shown in Fig. 4.2. Its linear thermal transmittance can be calculated as indicated in Table 4.2. The values reported in the catalogue are valid for typical wall thicknesses of existing buildings. They are not always suitable for the wall thicknesses of ancient buildings. Therefore in some cases, the probability that the estimated linear thermal transmittance falls within the confidence interval may be lower than 95%.

The linear thermal transmittance ψ_i [W/(m K)], determined according to the internal dimensions, can be calculated as:

$$\psi_i = 0.064 - 0.073\,U + 0.358\,\lambda_{eq} \tag{4.8}$$

where

$$U = \left[R_{si} + \left(d/\lambda_{eq}\right) + R_{se}\right]^{-1} \; \left[\mathrm{W}/\left(m^2 K\right)\right] \tag{4.9}$$

d = thickness of the whole wall [m]
λ_{eq} = conductivity of the whole plane wall structure as if it were constituted by a single layer [W/(m K)]
Range of applicability:
$U = 0.47 \div 2.09$ W/(m^2 K)
$\lambda_{eq} = 0.23 \div 0.81$ W/(m K)
Confidence interval IC: IC$_i$ (95%) = ± 0.02 W/(m K)

4.3.3 Dynamic Thermal Characteristics of the Envelope

The dynamic thermal characteristics of the envelope that can be considered in the energy performance evaluation are indicated in the EN ISO 13786 Standard. Among the parameters that can be used to outline the effects on the heat storage of the building envelope, there are:

- the periodic thermal transmittance Y_{ie} [W/(m^2 K)], defined as the amplitude of the heat flow rate through the component surface adjacent to a zone which is kept at constant temperature, divided by the amplitude of the temperature in the adjacent zone (which also could be the external environment).
- the decrement factor *f*, expressed by the ratio between the periodic thermal transmittance Y_{ie} [W/(m^2 K)] and the quasi-steady-state thermal transmittance *U* [W/(m^2 K)]. It represents the effect of the envelope on the inward heat flow rate,

$$f = \frac{|Y_{ie}|}{U} \tag{4.10}$$

- the time shift $\Delta\tau$, defined as the period of time between the maximum amplitude of a cause and the maximum amplitude of its effect, helps to evaluate the envelope influence on the thermal behaviour.

An example of the values obtained following the methodology reported in the EN ISO 13786 Standard are resumed in Table 4.3, showing the highest time shift Δt value for the stone wall that is characterized by the maximum value of surface mass m_s. In this case, the high thermal transmittance *U* means high heat flux through the wall, while its thermal inertia produce a relevant effect reducing the outdoor climate variations and maintaining the indoor thermal conditions scarcely influenced by the external ones. Regarding the periodic thermal transmittance, it should be maintained low in the regions with high solar radiation to make the best use of the wall inertia against the overheating during daytime.

As an example, in the existing building refurbishment (not mandatory for the historical ones), the Italian National legislation indicates upper limits of the *U*-value for vertical walls varying from 0.24 to 0.43 W/(m^2 K) depending on the climatic zone.

Table 4.3 Example of dynamic parameters evaluation for three historical building common walls

Wall structure	d [m]	U [W/(m^{2}K)]	m_s [kg/m^2]	Y_{ie} [W/(m^2 K)]	f	Δt [h]
Brick wall	0.86	0.74	1536	0.003	0.003	30
Brick (60%) and stone wall	0.86	1.22	1760	0.012	0.009	24
Brick (20%) and stone wall	0.86	1.58	1984	0.022	0.014	22
Stone wall	0.86	1.73	2096	0.027	0.016	21

Moreover, for locations where the average monthly value of the irradiance on the horizontal plane is greater than or equal to 290 W/m^2 at least one of the following conditions on all the opaque vertical walls must be verified:

– the surface mass, m_s, >230 kg/m^2
– the modulus of the periodic thermal transmittance $Y_{ie} < 0.10$ W/(m^2 K)

The typical historical building walls usually are characterized by high U-values and therefore the mean heat losses are high, in the heating period. On the contrary, their inertia is very high (high thermal mass and low dynamic thermal transmittance) and then the climatic variations affect less the internal climatic conditions, in the cooling period.

The evaluation of the dynamic thermal behaviour of the envelope can be performed by means of transient building simulation models, which consider the heat storage in the structure and the time dependence of boundary conditions.

The quasi-steady-state methods are considered approximatively affordable to represent the thermal behaviour of buildings during the heating season, but not in other periods of the year. In this case, a transient model is suitable to have more detailed results.

As the cooling energy needs have been increased during the last years, the European Directive 2010/31/EU indicates to adopt strategies to enhance the thermal performances also during summer period. Higher attention must be put on the thermal properties, which influence the internal overheating, such as heat thermal capacity, specific mass, periodic thermal transmittance, time shift, and decrement factor. In particular, the minimum requirements according to the climatic conditions have to be fixed at national level: it represents a priority for the countries of the Mediterranean area, where the dynamic envelope features to reduce the cooling energy needs have to be evaluated with attention because it represents an interesting resource.

4.3.4 Vapour Transmission Through Walls

Several aspects related to the presence of water may affect building structures, such as capillary rise of water in the walls, condensation inside building components due to infiltration of indoor air (hot and humid), problems with tightness to rainwater, salts migration inside materials, and hygrometric surface problems (growth of mould and moisture condensation). A further problem is linked to the moisture transfer through the building envelope because it can meet such a low temperature as to cause its condensation. The phenomenon takes place generally in building materials because they are normally permeable to water vapour.

The moisture transfer through a wall depends not only on the thermo-physical features of the wall layers, but also on the internal and external thermo-hygrometric conditions.

Usually, the historical building walls have such thermal properties that do not allow interstitial condensation. However, the hygrometric assessment of historical building components presents considerable practical interest when the reuse and the possible change of the building use is planned. Therefore, for example, it is useful to determine if the operating conditions may lead to a progressive deterioration of the structures. Moreover, if measures for energy performance improvement are considered, as the thermal insulation is often allowed only on the internal face of the wall, the risk of moisture problems can be increased.

The condensation phenomena may be relevant as they generally occur easily in the case of internal insulation applications. In this case, in the interface between the internal face of the existing wall layer (brick or stone layer) and the insulating material, liquid water can damage the insulating material thermal properties, such as its thermal conductivity, making useless its application.

Degradation of the building structures and unhealthy environments can be the consequences of these phenomena, such as:

- growth of fungal colonies on the inner surface of the building envelope
- presence of condensed water on the surface and inside of the walls
- decay of wooden structures
- plaster degradation
- reduction of the thermal insulation
- dimensional changes and damage of artefacts
- salts migration, efflorescence

The International Standard EN ISO 13788 indicates a method for the assessment of moisture problems in the walls, simplifying the complex physical behaviour and neglecting the interaction between moisture and heat transfer.

The methodology considers the moisture transfer through a wall as a function of inside and outside temperature and humidity conditions, and of dimensional and thermo-physical characteristics of its layers. In the Standard also surface phenomena, due to high values of internal relative humidity and low surface temperature of the walls are considered and an evaluation method is described.

To evaluate the risk of interstitial condensation, the graphical method, known as Glaser method, is proposed, referring to the monthly mean values of the climatic data. Material thermal properties and layer thicknesses must be estimated; the temperature and the internal moisture production must be calculated or assumed by the building use.

The water vapour pressure and the saturation pressure trends are compared through the wall layers. The saturation pressure P_s [Pa] can be calculated as a function of the temperature distribution within the layers by means of the following expressions:

$$t \geq 0°\mathrm{C}\, P_s = 610,5\ \mathrm{e}^{\frac{17,269 \cdot t}{237,3+t}} \tag{4.11}$$

$$t \geq 0°\text{C}\, P_s = 610,5\ e^{\frac{21,875 \cdot t}{265,5+t}} \quad (4.12)$$

The vapour pressure P_v [Pa] on the external and internal surface of the wall depends on temperature and humidity. It can be expressed as function of the saturation pressure $P_s = f(t)$ and the relative humidity φ [−]:

$$P_v = \varphi P_s \quad (4.13)$$

In absence of condensation, the trend of P_v can be represented by means of the Fick's Law. The vapour flow rate per unit area g'_v through a is related with the difference ΔP_v between the vapour pressures of the air on its surfaces. Assuming steady-state conditions, g'_v [kg/(m^2 s)] can be expressed as:

$$g'_v = \delta_o \Delta P_v / s_d \quad (4.14)$$

where

δ_o = reference vapour permeability of air = 200×10^{-12} kg/(m s Pa)
$s_d = d\ \delta_o/\delta$ [m]
d = layer thickness [m]
δ = vapour permeability [kg/(m s Pa)]

From a graphical comparison of the two trends, if the vapour pressure reaches the value of the saturation, there is condensation.

The standard indicates that the assessment is positive if both the following two criteria are met:

- the calculation (usually on a monthly basis) demonstrates that any condensation can be completely dry throughout the year.
- the condensation in a layer does not exceed the limit values of the materials involved.

4.3.4.1 Example: Interstitial Condensation Risk Evaluation

The calculation procedure indicated in the EN ISO 13788 Standard can be briefly summarized by means of a case study represented by a brick (20%) and stone wall. With a thickness of 40 cm, it can represent the wall below the windows in a historical building: the application of an insulating layer on the internal side may be considered a measure to reduce heat loss (Table 4.4).

The calculations are referred to the environmental conditions indicated in Table 4.5. The internal moisture production may be considered low, corresponding to offices, dwellings with normal occupancy and ventilation (as indicated in EN ISO 13788); therefore, the internal vapour pressure is defined as function of the external vapour pressure and temperature:

$$P_{vi} = P_{ve} + 100 + [(540 - 100)/20](20 - t_e) \quad (4.15)$$

Table 4.4 Thermal properties of an insulated brick (20%) and stone wall

Layer	d [cm]	ρ [kg/m^3]	λ [W/(m K)]
1. Plasterboard and surface finishing	1.5	900	0.21
2. Insulating layer	2–12	40	0.036
3. Internal plaster	3	1400	0.70
4. Composite layer: brick (20%) and stone	40	2360	2.06
5. External plaster	3	1800	0.90

Table 4.5 Internal and external climatic conditions

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
t_e [°C]	10.2	10.3	10.9	15.1	18.5	22.2	24.4	23.4	22	18	13.1	9.8
P_{ve} [Pa]	918	782	812	1109	1333	1804	2033	1806	1691	1276	1021	808
t_i [°C]	20	20	20	20	18.5	22.2	24.4	23.4	22	18	20	20
P_{vi} [Pa]	1234	1095	1112	1317	1466	1856	2036	1831	1747	1420	1273	1132

The calculations are executed for each month starting from the first month of the heating season and verifying that condensation doesn't occur. On the contrary, it would be necessary to proceed backwards with the search of the first month of condensation. Starting with the month of October, the surface temperatures t_{pi} and t_{pe} and each t_x [°C] at the x interface between layers are calculated by the following expressions:

$$t_{pi} = t_i - (t_i - t_e)R_{si}/R_T \tag{4.16}$$

$$t_{pe} = t_e + (t_i - t_e)R_{se}/R_T \tag{4.17}$$

$$t_x = t_{x-1} - (t_i - t_e)R_x/R_T \tag{4.18}$$

where each $R_x = d/\lambda$ value is indicated in Table 4.6, where the calculations are developed referring to the thermal properties of mineral wool ($\rho = 40$ kg/m^3).

Starting from the assumption that there is no condensation and therefore the vapour flow rate through the wall is constant, the two surface values can be connected by a straight-line segment in a plot P_v vs. s_d. Analytically, the vapour pressure of each interface is calculated according to Fick's law:

$$g'_v = \delta_o(P_{vi} - P_{ve})/s_{dtot} = \delta_o(P_{v,x-1} - P_{v,x})/s_{d,x} \tag{4.19}$$

In Table 4.7, the calculations for 1 month (January) are indicated, and in the plot of Fig. 4.3 the comparison between P_v and P_s is shown. The two lines do not cross; therefore, there is not the risk of interstitial condensation. However, in the interface

Table 4.6 Calculation details for the wall

Layer	d [cm]	λ [W/(mK)]	R [W/(m^2 K)]	δ (10^{-12}) [kg/(m s Pa)]	s_d [m]
0. Internal thermal resistance R_{si}			0.13		
1. Plasterboard and surface finishing	1.5	0.21	0.071	23	0.13
2. insulating layer	10	0.036	2.78	193	0.104
3. Internal plaster	3	0.70	0.043	18	0.33
4. Composite layer: brick (20%) and stone	40	2.06	0.194	11	7.27
5. External plaster	3	0.90	0.033	18	0.33
0. External thermal resistance R_{se}			0.04		
Total resistance R_T [m^2 K/W]			3.29		
Total equivalent thickness s_{dtot}					8.17
Thermal transmittance $U = R_T{}^{-1}$ [W/(m^2 K)]			0.30		

Table 4.7 Vapour and saturation pressure calculation

Interface	R [W/(m^2 K)]	s_d [m]	t [°C]	P_s [Pa]	P_v [Pa]
			20	2337	1234
0–1	0.13	0	19.6	2282	1234
1–2	0.071	0.13	19.4	2252	1229
2–3	2.78	0.104	18.6	2138	1228
3–4	0.043	0.33	11.0	1312	1212
4–5	0.194	7.27	16.5	1881	1525
5–0	0.033	0.33	10.4	1262	931
	0.04		10.3	1254	918

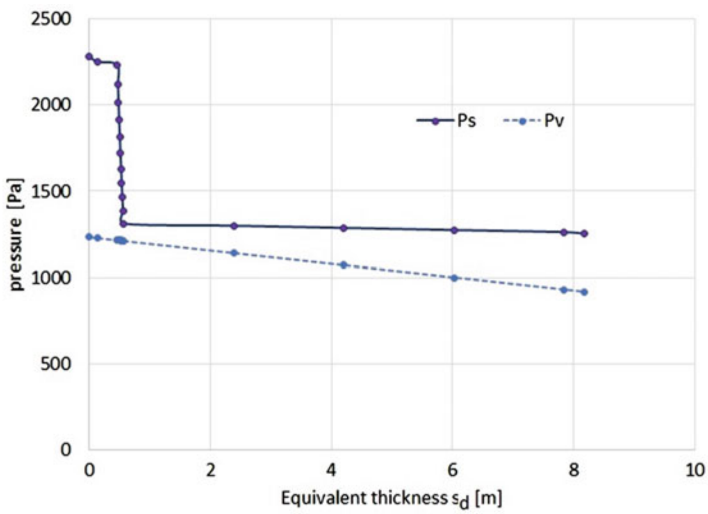

Fig. 4.3 Glaser method: comparison between the vapour pressure and the saturation pressure calculated with the climatic conditions of January

between the insulation layer and the existing wall, the difference between the vapour pressure and its upper limit, represented by the saturation pressure, is small. If higher moisture content would be taken into account for a different use of the building, the calculation will lead to condensation. In this case, the need of a vapour barrier on the internal face of the insulating layer should be considered.

4.4 Some Typologies of Walls and Their Characteristics

The thermal parameters of some typologies of historical building walls are presented, indicating thermal transmittance, thermal mass, periodic thermal transmittance, time shift, and decrement factor.

In Table 4.8, the wall typologies and their parameters are reported. For the calculations, surface thermal resistances indicated in EN ISO 6946 Standard are applied. The variables indicated have the following meaning:

d = thickness [cm]
ρ = density [kg/m^3]
λ = thermal conductivity [W/(m K)]
c = specific heat [kJ/(kg K)]
U = thermal transmittance [W/(m^2 K)]
m_s = specific mass [kg/m^2]
Y_{ie} = dynamic thermal transmittance [W/(m^2 K)]
$\Delta\tau$ = time shift [h]
f = decrement factor [−]

Note: the plaster thickness from 3 to 6 cm on the external side produce a U-value variation lower than 5%.

4.5 Thermo-Hygrometric Analysis in the Energy Refurbishment

The overall energy consumption of a building is influenced by factors such as the geometry, the orientation, the presence of opaque and transparent surfaces, their characteristics, the heating system, and the location in the urban area. Some of them cannot be changed under renovation, and therefore they represent constraints to the improvement of building energy performance. In addition to them, the limits due to the preservation of the characters of the building, its historical architectural and artistic value are elements that reduce the possibilities to obtain good energy performance. However, the effort to realize the maximum energy saving must be one of the targets of the restoration to allow a sustainable management of the building.

Table 4.8 Thermo-physical parameters of some historical building walls typologies

01 BM—brick masonry wall					
Layer	d	ρ	λ	c	
1. Internal plaster	3	1400	0.700	840	
2. Brick	25–100	1800	0.720	1000	
3. External plaster	3–6	1800	0.900	840	
Layers thicknesses	U	m_s	Y_{ie}	Δt	f
3 – 25 – 3	1.686	546	0.407	10.3	0.242
3 – 38 – 3	1.292	780	0.118	15	0.091
3 – 51 – 3	1.048	1014	0.034	19.8	0.033
3 – 64 – 3	0.881	1248	0.010	24.5	0.011
3 – 77 – 3	0.760	1482	0.003	29.2	0.004
3 – 90 – 3	0.737	1716	0.001	34	0.001
3 – 103 – 3	0.650	1950	0.00	38.7	0.00
02 BM—brick masonry wall					
Layer	d	ρ	λ	c	
1. Internal plaster	3	1400	0.700	840	
2. Brick	25–100	1800	0.720	1000	
Layers thicknesses	U	m_s	Y_{ie}	Δt	f
3 – 25	1.786	492	0.513	9.42	0.287
3 – 38	1.350	726	0.148	14.2	0.110
3 – 51	1.086	960	0.043	18.9	0.04
3 – 64	0.908	1194	0.012	23.6	0.014
3 – 77	0.780	1428	0.004	28.4	0.005
3 – 90	0.684	1662	0.001	33.1	0.002
3 – 103	0.609	1896	0.00	37.8	0.00
03 BSM—brick (60%) and stone masonry wall					
Layer	d	ρ	λ	c	
1. Internal plaster	3	1400	0.700	840	
2. Brick (60%) and stones	30–100	2080	1.390	1000	
3. External plaster	3–6	1800	0.900	840	
Layers thicknesses	U	m_s	Y_{ie}	Δt	f
3 – 30 – 3	2.165	720	0.46	10	0.212
3 – 40 – 3	1.873	928	0.22	12.9	0.117
3 – 50 – 3	1.651	1136	0.105	15.7	0.064
3 – 60 – 3	1.476	1344	0.05	18.5	0.034
3 – 70 – 3	1.334	1552	0.024	21.3	0.018
3 – 80 – 3	1.217	1760	0.012	24.2	0.009
3 – 90 – 3	1.119	1968	0.006	27	0.005
3 – 100 – 3	1.036	2176	0.003	29.8	0.003
04 BSM—brick (20%) and stone masonry wall					
Layer	d	ρ	λ	c	
1. Internal plaster	3	1400	0.700	840	
2. Brick (20%) and stones	30–100	2360	2.060	1000	

(continued)

Table 4.8 (continued)

04 BSM—brick (20%) and stone masonry wall					
3. External plaster	3–6	1800	0.900	840	
Layers thicknesses	*U*	m_s	Y_{ie}	Δt	*f*
3 – 30 – 3	2.552	804	0.561	9.3	0.22
3 – 40 – 3	2.271	1040	0.295	11.7	0.13
3 – 50 – 3	2.045	1276	0.155	14.2	0.076
3 – 60 – 3	1.861	1512	0.081	16.7	0.044
3 – 70 – 3	1.706	1748	0.043	19.1	0.025
3 – 80 – 3	1.576	1984	0.022	21.6	0.014
3 – 90 – 3	1.464	2220	0.012	24	0.008
3 – 100 – 3	1.367	2456	0.006	26.5	0.004
05 SBR—masonry wall in stone and brick rows					
Layer	*d*	ρ	λ	*c*	
1. Internal plaster	3	1400	0.700	840	
2. Brick and stones	30–100	2000	0.900	1000	
3. External plaster	3–6	1800	0.900	840	
Layers thicknesses	*U*	m_s	Y_{ie}	Δt	*f*
3 – 30 – 3	1.72	696	0.295	12	0.171
3 – 40 – 3	1.45	896	0.12	15	0.083
3 – 50 – 3	1.247	1096	0.049	18.5	0.039
3 – 60 – 3	1.095	1296	0.020	22	0.018
3 – 70 – 3	0.977	1496	0.008	25	0.008
3 – 80 – 3	0.88	1696	0.003	29	0.004
3 – 90 – 3	0.80	1896	0.001	32	0.002
3 – 100 – 3	0.74	2096	0.001	36	0.001
06 SIC—stone masonry wall with inner concrete					
Layer	*d*	ρ	λ	*c*	
1. Internal plaster	3	1400	0.700	840	
2. Brick	12	800	0.720	1000	
3. Concrete	5–20	1500	0.700	1000	
4. Brick	25	1800	0.720	1000	
5. External plaster	3–6	1800	0.900	840	
Layers thicknesses	*U*	m_s	Y_{ie}	Δt	*f*
3 – 12 – 5 – 25 – 3	1.20	467	0.255	11.5	0.212
3 – 12 – 10 – 25 – 3	1.12	542	0.163	13.2	0.147
3 – 12 – 15 – 25 – 3	1.026	617	0.104	14.8	0.102
3 – 12 – 20 – 25 – 3	0.956	692	0.067	16.5	0.070
07 SM—stone masonry wall					
Layer	*d*	ρ	λ	*c*	
1. Internal plaster	3	1400	0.700	840	
2. Stone blocks	40–100	2500	2.400	1000	
3. External plaster	3–6	1800	0.900	840	
Layers thicknesses	*U*	m_s	Y_{ie}	Δt	*f*

(continued)

Table 4.8 (continued)

07 SM—stone masonry wall					
3 – 40 – 3	2.42	1096	0.32	11.4	0.132
3 – 50 – 3	2.2	1346	0.173	13.7	0.079
3 – 60 – 3	2.01	1596	0.093	16	0.046
3 – 70 – 3	1.86	1846	0.051	18.4	0.027
3 – 80 – 3	1.73	2096	0.027	20.8	0.016
3 – 90 – 3	1.61	2346	0.015	23.1	0.009
3 – 100 – 3	1.51	2596	0.008	24.5	0.005
08 SM—stone masonry wall without finishing					
Layer	d	ρ	λ	c	
1. Internal plaster	3	1400	0.700	840	
2. Stone blocks	40–100	2500	2.400	1000	
Layers thicknesses	U	m_s	Y_{ie}	Δt	f
3 – .40 – 3	2.63	1042	0.456	10.55	0.173
3 – 50 – 3	2.37	1292	0.247	13	0.104
3 – 60 – 3	2.16	1542	0.133	15.2	0.062
3 – 70 – 3	1.98	1792	0.072	17.6	0.036
3 – 80 – 3	1.83	2042	0.039	20	0.021
3 – 90 – 3	1.70	2292	0.021	22.3	0.012
3 – 100 – 3	1.59	2542	0.011	0.65	0.007
09 FR—flat roof					
Layer	d	ρ	λ	c	
1. Internal plaster	3	1400	0.700	840	
2. Reinforced concrete slab and brick	16–24	900	0.24	1000	
Layers thicknesses	U	m_s	Y_{ie}	Δt	f
3 – 16	1.14	186	0.641	6.6	0.564
3 – 24	0.824	258	0.252	10.2	0.306
10 FR—flat roof					
Layer	d	ρ	λ	c	R
1. Internal floor layer	2	1700	1470	1000	
2. Lime mortar	3	2000	1.40	1000	
3. Wooden plank	3	710	0.180	1000	
4/5. Secondary wooden beams + air gap	25–40				0.180
6. Plasterboard + finishing layer	1.5	900	0.21	840	
Layers thicknesses	U	m_s	Y_{ie}	Δt	f
2 – 3 – 3 – 30 – 1.5	1.60	129	1.21	3.4	0.754
11 FR—flat roof					
Layer	d	ρ	λ	c	R
1. Internal floor layer	2	1700	1470	1000	
2. Lime mortar	3	2000	1.40	1000	
3. Wooden plank	3	710	0.180	1000	
4/5. Secondary wooden beams	25–40	–	–	–	
Layers thicknesses	U	m_s	Y_{ie}	Δt	f
2 –3 – 3	2.69	115	2.28	2.52	0.847

(continued)

Table 4.8 (continued)

12 FR—flat roof					
Layer	d	ρ	λ	c	R
1. Internal floor layer	2	1700	1470	1000	
2. Lime mortar	3	2000	1400	1000	
3. Concrete	15	2000	1160	1000	
4. Rock—stone	20–40	1700	1200	1000	
Layers thicknesses	U	m_s	Y_{ie}	Δt	f
2 – 3 – 15 – 20	2.0	734	0.37	11.2	0.186
13 FR—flat roof					
Layer	d	ρ	λ	c	R
1. Internal plaster	2	1400	0.700		
2. Slab (brick blocks + reinforced concrete beams)	16	900	–		0.330–0.370
	24				
3. Reinforced concrete	4	2400			
4. Mortar	2	2000	1.40		
5. Concrete substrate	2–12	2000	1.060		
6. Bituminous waterproofing membrane	1	1200	0.170		
7. Cement mortar substrate (under the pavement)	3	2000	1.4		
8. External floor	3	1500	0.700		
Layers thicknesses	U	m_s	Y_{ie}	Δt	f
2 – 22 – 10 – 1 – 3 – 3	1.34	785	0.12	14.8	0.09
2 – 30 – 10 – 1 – 3 – 3	1.27	945	0.069	17	0.054
14 FR—flat roof					
Layer	d	ρ	λ	c	R
1. Internal plaster	2	1400	0.700	–	
2. Slab (brick blocks + reinforced concrete beams)	16	900	–		0.330–0.370
	24				
3. Reinforced concrete	4	2400			
4. Cement mortar	2	2000	1.40		
5. Concrete substrate	2–12	2000	1060	–	
6. Bituminous waterproofing membrane	1	1200	0.170	–	
Layers thicknesses	U	m_s	Y_{ie}	Δt	f
2 – 22 – 10 – 1	1.467	680	0.186	13	0.127
2 – 30 – 10 – 1	1.38	840	0.107	15.2	0.077
15 R—roof					
Layer	d	ρ	λ	c	R
1. Wooden plank	3	550	0.150	1600	
2. Roof slate in "ardesia" stone	1.5	1500	0.3	1000	
Layers thicknesses	U	m_s	Y_{ie}	Δt	f
3 – 1.5	2.38	39	2.34	1	0.983

Note: the 3–40–3 cm wall corresponds to the wall under the windows of the case study described in another chapter

Therefore, even if sometime the substitution of the heating generator is the most evident action to reduce energy consumption, the possibilities offered by synergistic actions on elements of the building envelope and plant components should be examined. The aim should be the best agreement between the need of preservation and the opportunity of maintain also the ancient buildings live and with an active role in the urban context.

The first step for an integrated analysis on the energy consumption reduction can be represented by the evaluation of the impact of the external walls insulation, when possible. Reducing the U-value of the building envelope can lead to calculate a reduction of the heat losses and consequently often the need of an energy generation system of smaller size besides the lower energy consumption.

In this way, also the indoor comfort can be improved: the wall surface temperature of an insulated wall can be higher, the heat exchange by radiation between the human body and the different surfaces is reduced, and it becomes more similar to the heat exchange by convection with air, with a feeling of thermal field homogeneity.

The possibilities for the thermal insulation in historical buildings exclude in the majority of the cases external insulation and air layer insulation (appropriate for cavity walls). The most common solution remains the internal insulation: it is effective mostly if the insulating layer thickness is higher than 4–6 cm, especially in the continental climatic conditions. However, this thickness could reduce the internal surface of the living spaces, and it has to be correctly designed and planned.

Regarding the dynamic thermal performance of the walls, the position of the insulation greatly influences the thermal inertia of the structure. The heat storage is determined by the properties of materials, which are involved in the heating transmission of the envelope.

In addition, the moisture transfer is influenced by the insulating material: higher thermal insulation allows maintaining higher surface temperature of the wall internal side and reduces the risk of surface moisture problems. Nevertheless, the situation should be carefully assessed in terms of risk of interstitial condensation, when the insulating layer is applied on the internal side of the wall.

4.5.1 Effects of the Insulation on Historical Building Walls

The reduction of the thermal transmittance U offers the chance to reduce heat loss through the building envelope. Even if the insulation of historical building walls often is not easy to plan, verifying this possibility is useful for a more complete analysis of the measures to adopt for the reduction of the energy consumption and of the management costs of a building.

Table 4.9 Hygrothermal properties of insulation materials

Type	λ [W/(m K)]	δ [kg/(m s Pa)]	ρ [kg/m^3]
Plasterboard with finishing (PL)	0.21	23×10^{-12}	600
Mineral wall (MW)	0.036	193×10^{-12}	40
Wooden fibreboard (WF)	0.040	97×10^{-12}	110
Polystyrene (PY)	0.033	1.3×10^{-12}	35

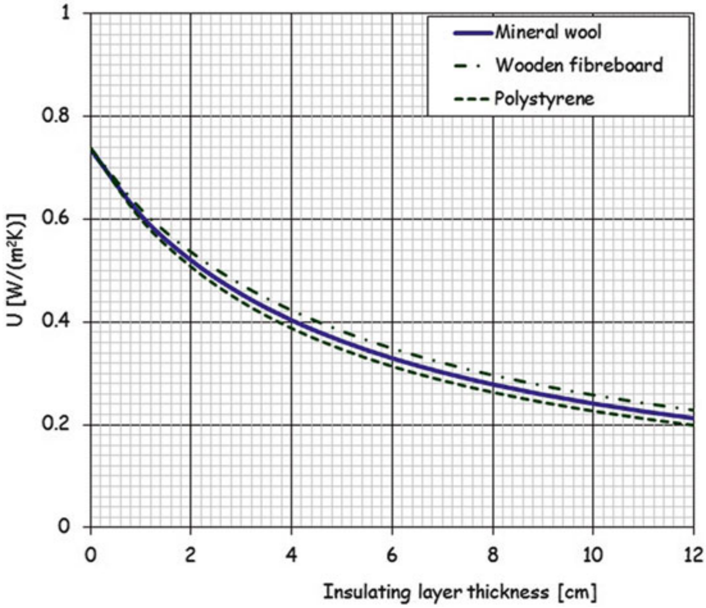

Fig. 4.4 Brick wall. U-value by varying the insulation thickness

The effects of the thermal insulation of some of the structures of the database (Table 4.8) are calculated, considering the application of an insulating layer on the internal side of a wall. Reference to a wall thickness of 86 cm is considered as the base case.

For each structure, three different kinds of insulated materials widely used in building refurbishment are considered (Table 4.9). Their properties are gathered from the technical files of commercial products. The insulating layer is covered by means of a plasterboard panel and a surface finishing layer.

The following graphs (Figs. 4.4, 4.5, 4.6 and 4.7) allow to check the insulation thickness needed to improve the thermal transmittance U. As the periodic thermal transmittance Y_{ie} has usually very low values and the thermal mass is high, their variations are not calculated as already satisfactory.

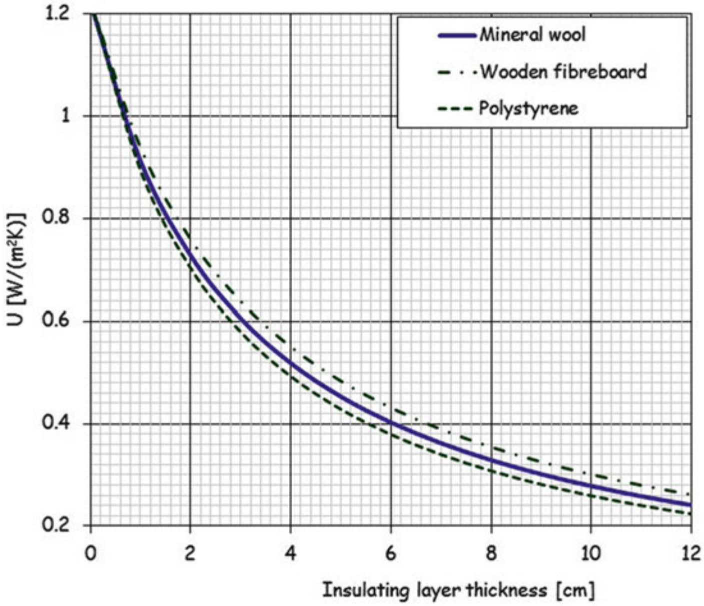

Fig. 4.5 Brick 60% and stone wall. *U*-value by varying the insulation thickness

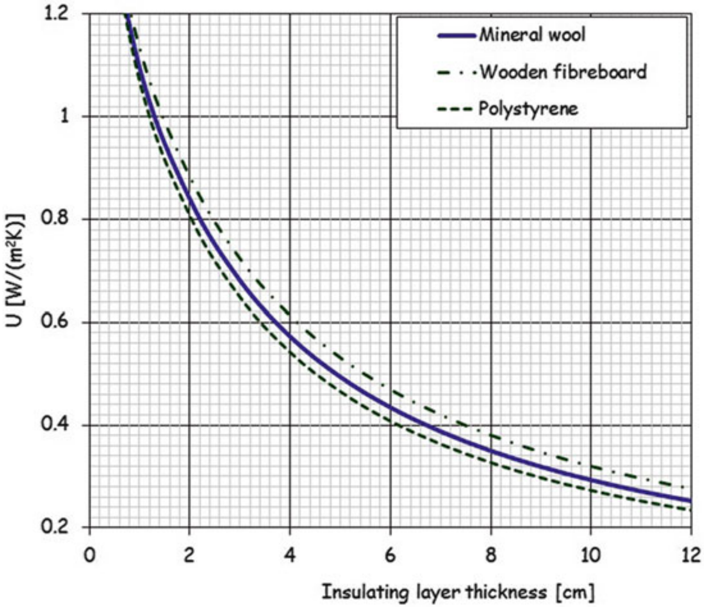

Fig. 4.6 Brick 20% and stone wall. *U*-value by varying the insulation thickness

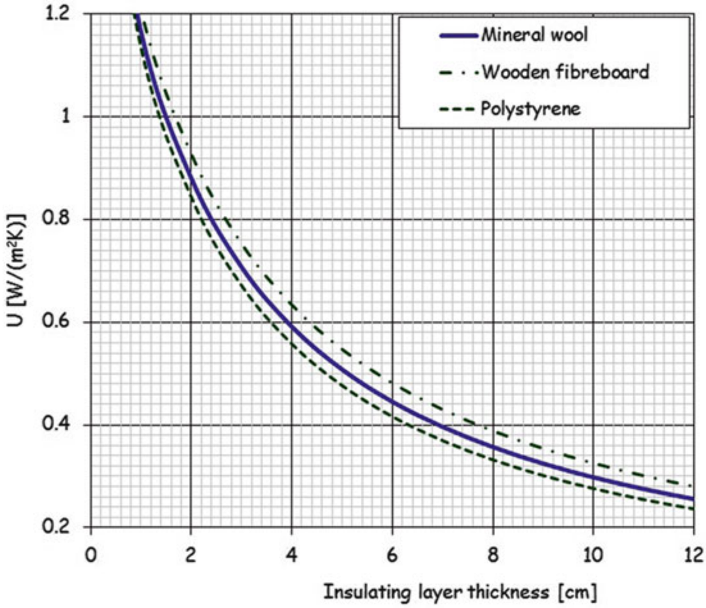

Fig. 4.7 Stone wall. *U*-value by varying the insulation thickness

It is important to verify that an insulation improvement of the wall satisfy also the hygrometric assessment. Sometimes, for continental climatic conditions, mostly in the case of internal insulation, a good opportunity in terms of energy saving may increase the risk of interstitial condensation.

Applying the procedure for the interstitial condensation evaluation, with a low internal moisture production (corresponding to offices, dwellings with normal occupancy and ventilation, as indicated in EN ISO 13788), an indication on the maximum insulating layer thicknesses, suitable for a positive assessment, is shown in Table 4.10.

The climatic data of six different regions in Europe are resumed in Table 4.11 (t_e in °C, P_{ve} in Pa).

The hygrometric assessment shows that in the considered climatic conditions the existing walls are not subdued to the risk of vapour condensation. The thermal insulation applied on the internal side of the wall, however, can produce condensation also for a small thickness of mineral wool panel or wooden fibreboard. Polystyrene represents often a better choice, but its hygrometrical performances must be evaluated accurately.

Table 4.10 Results of the hygrometrical assessment

		Genoa	Milan	Paris	Madrid	Brussels
01 BM	Existing	O	O	O	O	O
	MW	O	X(11)	X(8)	O	X(9)
	WF	O	O	X(9)	O	X(10)
	PY	O	O	O	O	O
03 BSM	Existing	O	O	O	O	O
	MW	O	X(5)	X(3)	X(6)	X(4)
	WF	O	X(5)	X(4)	X(7)	X(4)
	PY	O	O	O	O	O
04 BSM	Existing	O	O	O	O	O
	MW	O	X(4)	X(2)	X(4)	X(2)
	WF	O	X(4)	X(2)	X(4)	X(2)
	PY	O	O	X(4)	O	O
07 SM	Existing	O	O	O	O	O
	MW	O	X(2)	X(1)	X(3)	X(2)
	WF	O	X(2)	X(2)	X(3)	X(2)
	PY	O	X(3)	X(2)	X(6)	X(2)

O—no risk of interstitial condensation
X—the wall satisfies the two criteria (acceptable maximum condensate quantity and complete evaporation)
(*n*) maximum thickness of the insulating layer for a positive assessment (if not indicated, the assessment is positive up to 12 cm)

Table 4.11 Climatic conditions considered in the calculations

Climate		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Genoa	t_e	10.2	10.3	10.9	15.1	18.5	22.2	24.4	23.4	22	18	13.1	9.8
	P_{ve}	833.0	932.7	1042.1	1167.5	1523.9	1915.8	2354.7	2263.8	1962.0	1500.3	1153.5	953.3
Milan	t_e	4	7.1	10.6	13.4	19.4	22.8	24.5	24.3	19.8	14.1	7.5	3.5
	P_{ve}	556.8	479.4	698.1	885.2	1285.3	1857.4	1820.5	1817.2	1609.6	1300.7	803.6	523.3
Paris	t_e	3.9	4.2	7.0	10.0	14.3	16.8	19.4	19.7	15.7	11.3	6.4	4.5
	P_{ve}	735.4	558.7	754.7	891.2	1081.4	1486.4	1469.5	1555.8	1387.2	1090.8	859.3	754.3
Madrid	t_e	5.6	6.9	10.0	11.7	16.9	20.6	25.5	24.7	20.1	14.2	9.4	5.9
	P_{ve}	656.5	690.5	744.7	762.5	1151.7	1257.8	1293.8	1407.5	1339.6	1133.4	884.9	773.6
Brussels	t_e	3.1	3.2	6.4	8.9	12.9	15.6	18.4	17.4	14.5	10.9	6.6	4.9
	P_{ve}	644.6	663.8	804.8	868.6	1141.3	1320.4	1640.9	1492.9	1333.7	1047.6	817.6	754.7

Nomenclature

A	wall surface [m^2]
A_i	area of the i-element of the building envelope [m^2]
$b_{tr,x}$	adjustment factor for the external temperature
c	heat capacity [J/(kg K)]
d	thickness [cm]
f	decrement factor [−]
H_A	heat transfer coefficient by transmission to adjacent buildings [W/K]
H_D	direct heat transfer coefficient by transmission to the external environment [W/K]
H_g	steady-state heat transfer coefficient by transmission to the ground [W/K]
H_{tr}	heat transfer coefficient by transmission
H_U	transmission heat transfer coefficient by transmission through unconditioned spaces [W/K]
l_k	length of the k-linear thermal bridge [m]
m_s	surface mass [kg/m^2]
P_s	saturation vapour pressure [Pa]
P_v	vapour pressure [Pa]
$Q_{H,gn}$	total heat gains for the heating mode [MJ]
$Q_{H,ht.}$	total heat transfer for the heating mode [MJ]
$Q_{H,nd}$	building energy need for continuous heating [MJ]
Q_{tr}	total heat transfer by transmission [MJ]
Q_{ve}	total heat transfer by ventilation [MJ]
R	thermal resistance [m^2 K/W]
s_d	equivalent thickness [m]
t	temperature [°C]
t_i	internal temperature [°C]
t_e	external temperature [°C]
U	thermal transmittance [W/(m^2 K)]
U_i	thermal transmittance of the i-element of the building envelope [W/(m^2 K)]
Y_{ie}	dynamic thermal transmittance [W/(m^{2}K)]
$\Delta\tau$	time shift [h]
δ	vapour permeability [kg/(m s Pa)]
δ_o	reference vapour permeability of air $= 200 \times 10^{-12}$ kg/(m s Pa)
$\eta_{H,gn}$	gain utilization factor [−]
λ	thermal conductivity [W/(m K)]
ρ	density [kg/m^3]
φ	relative humidity [−]
χ_j	point thermal transmittance of the j-point thermal bridge [W/(K)]
ψ_k	linear thermal transmittance of the k-thermal bridge [W/(m K)]

Appendix

CEN: Energy performance of buildings—Calculation of energy use for space heating and cooling, EN ISO 13790:2008, European Committee for Standardization.

CEN: Hygrothermal performance of building components and building elements—Internal surface temperature to avoid critical surface humidity and interstitial condensation—Calculation methods, EN ISO 13788:2013, European Committee for Standardization.

CEN: Building materials and products—Hygrothermal properties, Tabulated design values and procedures for determining declared and design thermal values, EN ISO 10456: 2008, European Committee for Standardization.

CEN: Building components and building elements—Thermal resistance and thermal transmittance, EN ISO 6946: 2008, European Committee for Standardization.

CEN: Thermal bridges in building construction—Heat flows and surface temperatures—Detailed calculations. EN ISO 10211: 2008, European Committee for Standardization.

CEN: Thermal performance of building components—Dynamic thermal characteristics—Calculation methods, EN ISO 13786:2008, European Committee for Standardization.

ISO 9869–1:2014 Thermal insulation—Building elements—In situ measurement of thermal resistance and thermal transmittance—Part 1: Heat flow meter method.

UNI 10351—building materials and products—Hygrothermal properties. Procedure for determining the design values (in Italian)

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