Thermal bridges and surface condensation

Thermal bridges

A thermal bridge is defined by the International Standard EN ISO 10211 [1] as a part of the building envelope where the otherwise uniform thermal resistance is significantly changed by at least one of the following conditions:

- full or partial penetration of the building envelope by materials with a different thermal conductivity;
- change in thickness of the fabric or difference between internal and external areas such as occur at wall/floor/ceiling junctions.

In Fig. 1(a) an intermediate floor slab interrupts the continuity of an external floor, whereas Fig. 1(b) shows a thermal bridge determined by a combination of both factors due to the presence of a concrete pillar in a corner junction.

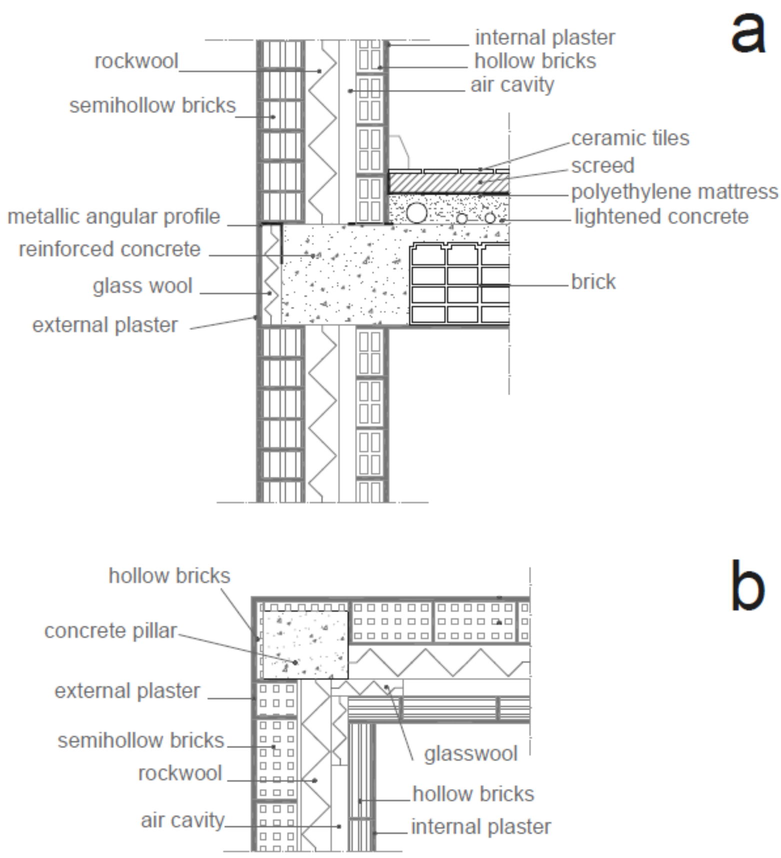

Figure 1. Details of thermal bridges due to (a) intermediate floor slab junction with external walls; (b) corner junction.

In other words, thermal bridges are parts of the building envelope where the thermal resistance deviates from its nominal value due to a discontinuity of the construction materials or of the geometry. Therefore, a thermal bridge leads to an additional heat flow from the indoor to the outdoor environment that must be included in the calculation of the energy needs of the building.

Thermal bridges are subdivided into linear and point thermal bridges depending on their geometry. If the cross-section of the building construction is uniform in one of the three directions, such as in Figure 2(a), the thermal bridge is linear and the additional heat flow due to the thermal bridge applies all along the length of constant direction. In this case, the additional heat flow due to the thermal bridge can be evaluated by solving a 2D heat conduction problem.

Otherwise, the thermal bridge is a point thermal bridge and a 3D heat conduction problem must be solved to determine the corresponding additional heat flow as shown in Figure 2(b).

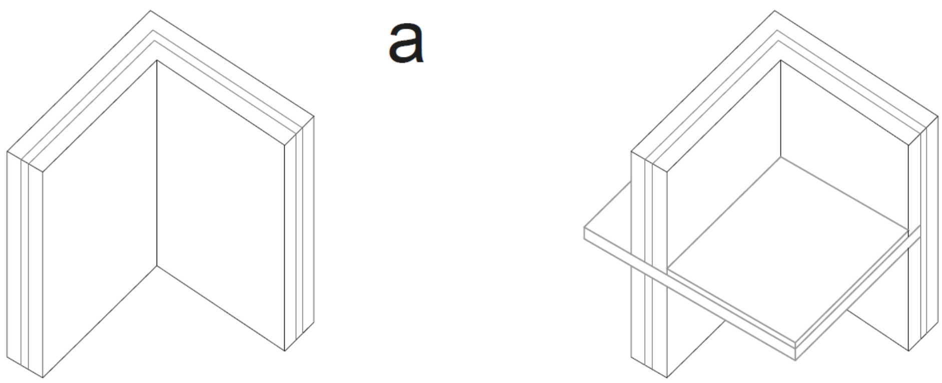

Figure 2. (a) Linear and (b) point thermal bridge.

Based on this classification, the heat transfer coefficient due to transmission through the envelope is modified by the presence of thermal bridges as follows:

$$H_T = \sum_i U_i A_i + \sum_k \psi_k l_k + \sum_j \chi_j \tag{1}$$

Where ψ_j and l_j are the linear thermal transmittance (W/(m K)) and the length (m) of the j-th linear thermal bridge and χ_k is the point thermal transmittance (W/ K) of the k-th three-dimensional thermal bridge. For sake of simplicity, the overall heat transfer coefficient reported in Eq. (1) omits the contributions due to the heat loss towards unheated spaces and the ground.

Lengths of linear thermal bridges are measured using internal dimensions, overall internal dimensions or external dimensions, according to the dimension system being used for the building [1]. Internal dimensions (*i*) are measured between the finished internal faces of each room in a building; overall internal dimensions (*oi*) are measured between the finished internal faces of the external elements of the building and external dimensions (*e*) are measured between the finished external faces of the external elements of the building [1]. Therefore, the difference between internal and overall internal dimensions is that the former exclude and the latter include the thickness of internal partitions. Figure 3 shows that the overall internal dimensions may coincide either with (a) internal or (b) external dimensions.

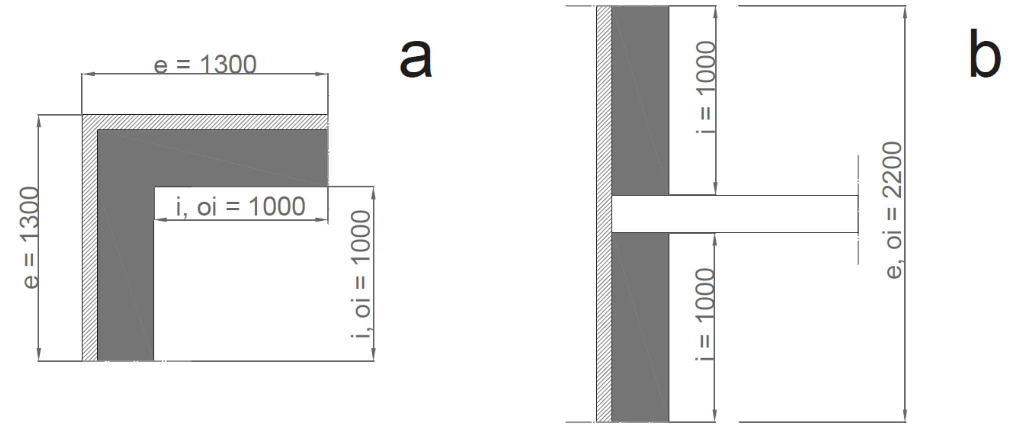

Figure 3. Internal, overall internal and external dimensions on two exemplary thermal bridges: (a) corner junction; (b) intermediate floor slab [2].

There are different methods to assess the thermal transmittance ψ. When selecting a particular method, its accuracy should reflect the accuracy required in calculating the overall heat transfer of the building envelope. Possible methods for determining ψ include: numerical calculations (typical accuracy ±5%); thermal bridge catalogues and manual calculation (typical accuracy ±20%) and default values such as those suggested by Standard EN ISO 14683 (typical accuracy 0% to 50%) [2].

The parameters used to calculate the default values of linear thermal transmittance represent worst-case situations. Thus, they should not lead to underestimate the additional heat flow of linear thermal bridges, once the correct case is chosen. Figure 4 shows one of the Tables with the default values of linear thermal transmittance proposed by the Standard. For each case, the Table provides the value of linear thermal transmittance corresponding to internal (ψ_i), overall internal (ψ_{oi}) and external dimensions (ψ_e).

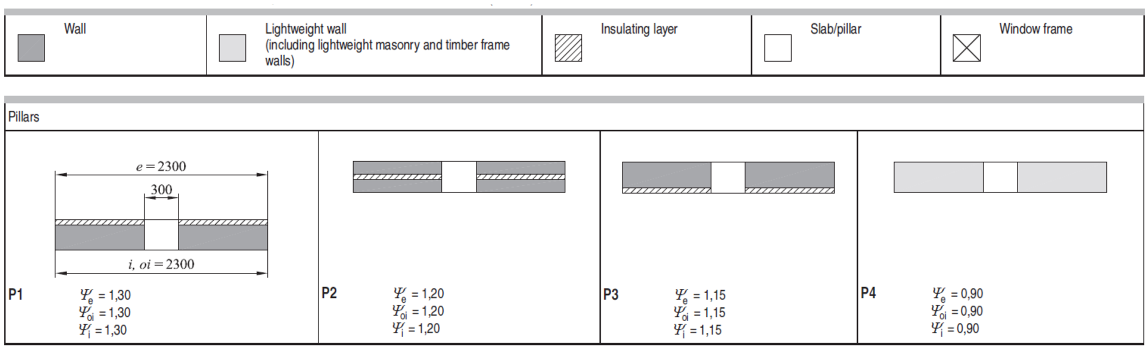

Figure 4. Default values of linear thermal transmittance for pillars suggested by EN ISO 14683.

In order to find the heat exchange between the internal and external environment through thermal bridges, numerical methods have to be used because of the complex geometry and due to the presence of materials with different thermal conductivity (EN ISO 14683 has been abandoned in Europe).

According to Fourier's law, the heat flux density exchanged by conduction through an infinitesimal area A of thermal conductivity k is given by:

$$q_e = -k\,\nabla T \tag{2}$$

where ∇T is the temperature gradient. The following equation holds true for the conservation of energy applied to an infinitesimal volume:

$$dQ_e + dQ_v = dU \tag{3}$$

Where dU is the variation of internal energy and dQ_v is the heat generated inside the control volume. Combining Equations (2) and (3) and applying the Divergence Theorem as explained in Bonacina et al. [3] leads to the general formulation of the heat conduction equation:

$$k\,\nabla^2 T + q_v = \rho\,c_p \frac{\partial T}{\partial t} \tag{4}$$

Since thermal bridges are evaluate in steady-state conditions and there usually no internal generation of energy, Equation (4) can be simplified to reach the following form for three-dimensional problems:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) = 0 \tag{5}$$

One of the three terms in Eq. (5) disappears in case of linear thermal bridges that can be solved using only two coordinates.

Detailed calculation methods rely on the solution of Equation (5) by means of numerical methods, such as finite difference or finite elements methods. Once the geometry and the thermal conductivity of all the construction materials of the considered thermal bridge are set, the boundary conditions must be set on each of the boundary surfaces. The boundary conditions can be either a fixed temperature (Dirichlet condition) or a fixed heat flow rate. Usually, the presence of heat exchange by convection on the internal and external surfaces imposes a third type of boundary condition (Neumann condition), that is a fixed temperature of the fluid (typically air) that is exchanging heat by convection with the boundary surface, given a certain convection heat transfer coefficient. The three types of boundary conditions are illustrated in Figure 5. Please note that what is conventionally named "convective heat exchange coefficient" on a surface in programs is indeed a joint effect of radiation and convection, hence it is an overall heat exchange coefficient.

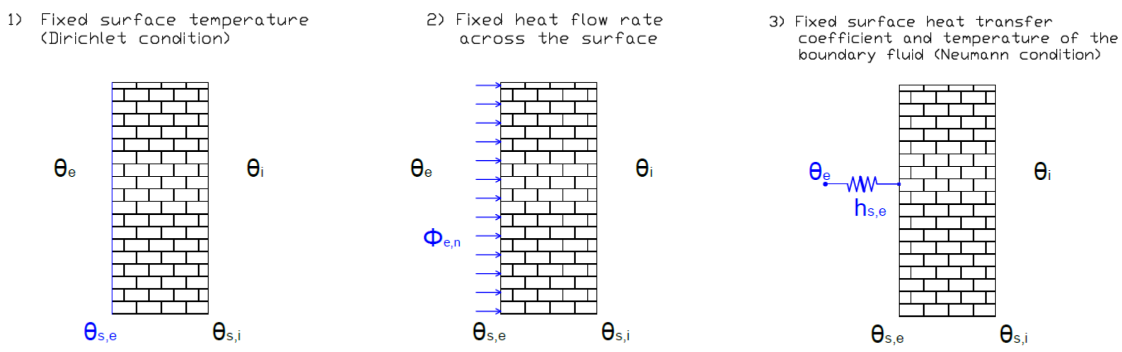

Figure 5. Boundary conditions of type: (1) Fixed surface temperature; (2) fixed heat flow rate and (3) Neumann condition.

Far from the discontinuity, the effect of the thermal bridge ceases leading to a 1-D problem; therefore, the heat flux is normal to the internal and external building surfaces. This means that choosing the cut-off planes far enough from the core of the thermal bridge allows to set the adiabatic conditions on surface resulting from the intersection of the building envelope and the cut-off plane. This is the reason why the International Standard EN ISO 10211 prescribes minimum distances of the cut-off planes from the thermal bridge [1]. The adiabatic condition is a boundary condition of the second type. Instead, the convective heat transfer coefficients and the undisturbed air temperatures must be set on the building surfaces facing the indoor and the outdoor environments. Figure 6 shows an example of boundary conditions for a linear thermal bridge.

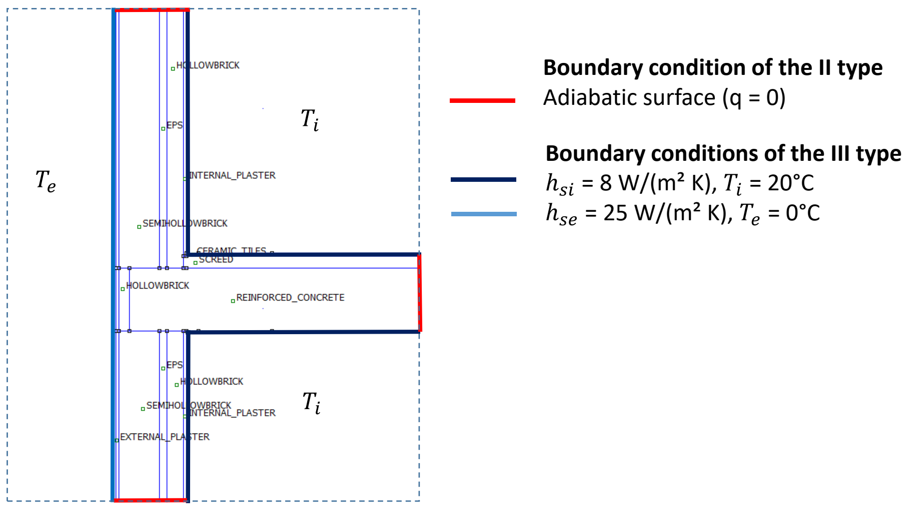

Figure 6. Example of boundary conditions for a linear thermal bridge [2].

The domain is discretized by a set of triangular elements called mesh. A solution of the heat conduction problem can be found by using solvers based on finite difference or finite elements methods. The solution consists in calculating the temperature in each point of the thermal bridge. The heat exchanged by conduction through the thermal bridge can be found by integrating the temperature gradient over any surface S that separates the two environments.

$$Q_{ie} = -\int k \frac{\partial T}{\partial n} dS \tag{6}$$

The thermal coupling coefficient (L_{2D} or L_{3D} depending on the geometry of the problem) is the heat flow rate per temperature difference between two environments which are thermally connected by the construction under consideration:

$$L_{2D} = \frac{Q_{ie}}{l\,(T_i - T_e)} \tag{7}$$

$$L_{3D} = \frac{Q_{ie}}{(T_i - T_e)} \tag{8}$$

where l in Equation (7) is the length of the thermal bridge. The unit of measurement of linear and point thermal transmittances and of the thermal coupling coefficients are resumed in Table 1.

Table 1. Symbols and units.

Variable	Symbol	SI unit
Linear thermal transmittance	ψ	W/(m K)
Point thermal transmittance	χ	W/K
2D thermal coupling coefficient	L_{2D}	W/(m K)
3D thermal coupling coefficient	L_{3D}	W/K

The linear/point thermal transmittance represents the additional heat flow rate due to the presence of the thermal bridge divided by length and by the temperature difference between the environments. In other words, the latter is defined as the difference between the heat flow rate crossing the considered building construction in steady-state conditions with and without considering the effect of the thermal bridge. According to this definition, the linear thermal transmittances can be determined as:

$$\psi = L_{2D} - \sum_i U_i l_i \tag{9}$$

where l_i is not the length of the thermal bridge, but the length over which the value U_i applies.

Similarly, the following holds true for point thermal bridges:

$$\chi = L_{3D} - \sum_i U_i A_i - \sum_j \psi_j l_j \tag{10}$$

where A_i is the area over which the value U_i applies, and l_j is the length over which the linear thermal transmittance ψ_j applies. The latter is calculated according to Equation (9) on the j-th flanking element of the three-dimensional model. The flanking elements are those part of the building construction that, if isolated, can be considered as a two-dimensional element.

When the thermal bridge separates more than two environments, one thermal coupling coefficient must be calculated for each of the mutual thermal connections between the environments as shown in Figure 7.

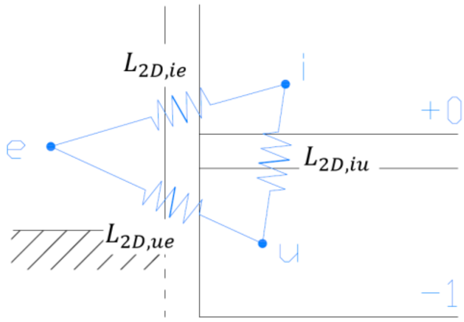

Figure 7. Mutual thermal connections of three environments.

Annex E of the Standard EN ISO 10211 provides a useful calculation example for a suspended floor where there is a third environment, i.e. an unheated space below the floor [1]. The calculation includes two options: with and without ventilation in the unheated space.

Surface condensation

The additional heat flow due to thermal bridges bring to local decreases of the internal surfaces temperatures that may bring to surface condensation, in case the latter reaches the dew point temperature. Surface condensation can cause damage to unprotected building materials that are sensitive to moisture. According to Standard ISO 13788 [4], surface condensation can be accepted temporarily and in small amounts, e.g. on windows and tiles in bathrooms, if the surface does not absorb the moisture and adequate measures are taken to prevent its contact with adjacent sensitive materials [4].

Furthermore, there is a risk of mould growth when monthly mean relative humidities on the considered surface are above a critical relative humidity, which should be taken as 80% unless specified differently by National Regulation.

Before considering the effect of thermal bridges, one must be aware of the different average internal surface temperature corresponding to structures with different thermal insulation levels. For instance, consider two external walls: the first is made up by 22 cm of semi-hollow bricks (U = 1.9 W/(m^{2}K)) while the second is made by 30 cm of porous bricks and 8 cm external coating with polystyrene panels (U = 0.23 W/(m^{2}K)).

Assuming 0°C as external temperature and 20°C as internal air temperature, the internal surface temperature becomes 15.2°C in the first case and 19.4°C in the second case. The dew-point temperature at 50% (65%) relative humidity and 20°C, which are the commonly used nominal conditions of the air in the indoor environment, is 9.3°C (13.2°C). Therefore, the average internal surface temperature in buildings with good thermal insulation is significantly higher than the dew-point temperature. Therefore, surface condensation problems in new buildings may only occur in correspondence of thermal bridges. On the other hand, it is much more likely to find surface condensation and mould growth in buildings with low thermal insulation.

Figure 9 shows the vapour mass balance in a building with air change G_a and internal generation of vapour G_v, both expressed in kg/hours. The mass conservation leads to:

$$G_a x_e + G_v = G_a x_i \tag{11}$$

where x_e and x_i are the specific humidity of the external and internal air, respectively. By rearranging Equation (11) and expressing the air change rate in terms of volumes per hour (n), the latter become:

$$x_i = x_e + \frac{G_v}{\rho_a n\, V} \tag{12}$$

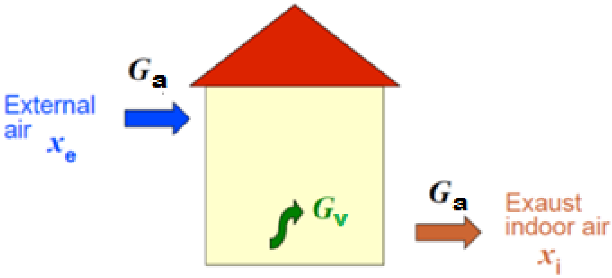

Figure 9. Vapour mass balance.

Thus, the amount of vapour in the indoor environment x_i depends on the external conditions (temperature and relative humidity of the air), on the internal generation of vapour and on the air change due to ventilation and infiltration.

In general, the vapour pressure in the indoor environment is higher than the outdoor water vapour pressure and the difference between the two is called moisture excess. Inside the building there are sources of water vapour, such as: people, personal hygiene (e.g. showers), cooking, clothes washing and drying etc.

The Standard ISO 13788 describes a methodology to assess the risk of surface condensation for each month of the year. Since the weather conditions -and consequently the boundary conditions for the determination of the internal surface temperature- change month by month, the Standard adopts a temperature factor at the internal surface $f_{R_{si}}$ defined as the difference between the temperature of the internal surface and the external air temperature, divided by the difference between the internal operative temperature and the external air temperature:

$$f_{R_{si}} = \frac{T_{si} - T_e}{T_i - T_e} \tag{13}$$

calculated with a surface resistance at the internal surface R_{si}. This factor may be derived for plane elements and where multidimensional heat flow occurs, i.e. in thermal bridges. In the first case, the definition of $f_{R_{si}}$ can be rewritten as:

$$f_{R_{si}} = \frac{\frac{q}{A}\,(R - R_{si})}{\frac{q}{A}\,R} = 1 - \frac{R_{si}}{R} = 1 - R_{si}U \tag{14}$$

In the case of thermal bridges, the temperature distribution must be calculated with a finite element software or a similar programme as described in the Standard EN ISO 10211. In this case, the temperature factor of the thermal bridge must be calculated using the lowest value of internal surface temperature according to Equation (13).

The temperature factor at the internal surface measures the relative decrease of internal surface temperature, for any temperature difference between internal and external environment. Thus, it only depends on the considered building envelope and on the internal surface resistance R_{si} used in the calculation. The value of R_{se} shall be taken as 0.04 m^2 K/W. For condensation or mould growth on opaque surfaces, an internal surface thermal resistance of 0,25 (m^2·K)/W shall be taken to represent the effect of corners, furniture, curtains or suspended ceilings, if there are no national standards.

Table 2. Default values of R_{si} for different internal surfaces.

Internal surface	$\boldsymbol{R_{si}}$ [(m^2 K)/W]
Opaque surface	0.25
Windows and doors – upwards direction	0.10
Windows and doors – horizontal direction	0.13
Windows and doors – downwards direction	0.17

In well-insulated building envelopes the internal surface temperature is closed to the operative temperature, thus $f_{R_{si}}$ approaches 1. On the contrary, a bad thermal insulation leads to a drop in the internal surface temperature, thus reducing the value of the temperature factor.

Once $f_{R_{si}}$ has been determined, the external weather conditions must be defined for each month of the year: average dry-bulb air temperature and relative humidity. For Italian municipalities, the Italian Standard UNI 10349 [5] provides mean monthly values of the air temperature and of the partial vapour pressure p_v. The corresponding values of relative humidity may be found from the definition of relative humidity:

$$RH(p_v, T) = \frac{p_v}{p_{v,sat}(T)} \tag{15}$$

where the denominator is the water vapour saturation pressure at temperature T. Annex E of the Standard EN ISO 13788 provides empirical correlations to find it:

$$p_{v,sat} = \begin{cases} 610.5\, e^{\frac{17.269\,T}{237.3+T}} & for\ T \geq 0°C \\ 610.5\, e^{\frac{21.875\,T}{265.5+T}} & for\ T < 0°C \end{cases} \tag{16}$$

The Standard suggests to use an average indoor air temperature T_i = 20°C if the considered month belongs to the heating season (i.e. when the heat supply system is on), T_i = 18°C if heat supply system is off and the average outdoor temperature is below 18°C, and equal to the external temperature itself (T_i = T_e) otherwise.

Three methods are proposed to calculate the average vapour pressure of the indoor air.

In the first method, a humidity class is attributed to the considered building based on its end-use as shown in Table 3. The Standard provides a correlation between the mean monthly outdoor temperature and the vapour pressure difference between indoor and outdoor air for each of the five humidity classes as shown in Figure 9. Therefore, this method can be resumed by:

$$p_{v,i} = p_{v,e} + \Delta p_v(\overline{T}_e, humidity\ class) \tag{17}$$

Table 3. Internal humidity classes.

Humidity class	Building
1	Unoccupied buildings, storage and dry goods
2	Offices, dwellings with normal occupancy and ventilation
3	Buildings with unknown occupancy
4	Sports halls, kitchens, canteens
5	Special buildings, e.g. laudry, brewery, swimming pool

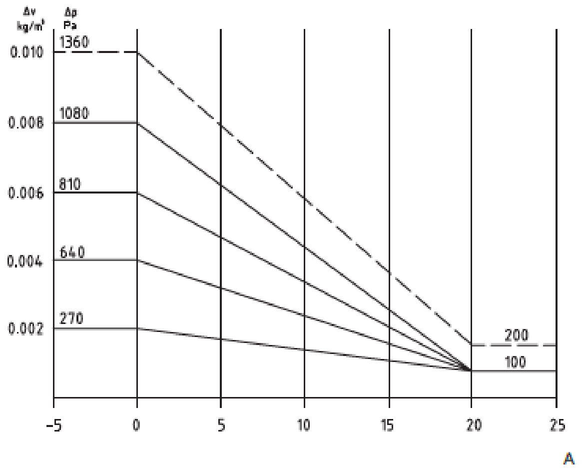

Figure 11. Vapour pressure difference vs monthly mean outdoor temperature for each internal humidity class.

Alternatively, the internal water vapour pressure can be calculated from the internal vapour generation G_v. To this end, it is useful to recover some concepts from psychrometrics. At low vapour concentrations and at environment temperatures, moist air behaves as an ideal mixture of two ideal gases: "dry air" and "water vapour". Therefore, the Dalton-Gibbs law applies:

$$p_{atm} = p_a + p_v \tag{18}$$

Specific humidity *x* is defined as the ratio between the mass of water vapor and the mass of the dry air contained in the same volume of moist air [6].

$$x = \left.\frac{m_v}{m_a}\right|_{V,T} = \left.\frac{\rho_v}{\rho_a}\right|_{T} \tag{19}$$

The ideal gas law shown in Equation (20) applies to both dry air and water vapour, where *R* is the specific gas constant for the considered gas component, that is equal to the ratio between the Boltzmann constant and its molar mass..

$$\frac{p}{\rho} = R\,T \tag{20}$$

Combining Equations (19) and (20) gives:

$$x = \frac{R_a}{R_v}\frac{p_v}{p_{atm} - p_v} = 0.622\ \frac{p_v}{p_{atm} - p_v} \tag{21}$$

The internal water vapour pressure can be found by using the vapour mass balance in Equation (12) together with Equation (21), obtaining:

$$p_{v,i} = p_{v,e} + \frac{p_{atm}}{0.622}\frac{G_v}{\rho_a n\,V} \tag{22}$$

The second method can be used when the mean monthly internal relative humidity RH_i is known, by using Equations (15) and (16). In case the value is not known, Annex A of the Standard provides a method to estimate it based on the climate and the mean monthly external temperature.

When the humidity of the air is controlled by e.g. air-conditioning, the internal relative humidity is constant and equal to the set-point of the controller. Therefore, the third method uses a constant value of RH_i to determine the internal water vapour pressure.

The maximum acceptable (or critical) relative humidity on the internal surface, $RH_{si,crit}$ is set to be 80%. Above this value, there is risk of mould growth. Therefore, the minimum acceptable saturation vapour pressure is:

$$p_{v,sat_{min}} = \frac{p_{v,i}}{RH_{si,crit}} = \frac{p_{v,i}}{0.80} \tag{23}$$

This minimum value of saturated vapour pressure (below which the relative humidity on the surface exceeds 80% and there is risk of mould growth) corresponds to minimum value of internal surface temperature. Again, Annex E of the Standard provides the empirical correlations to find the temperature corresponding to a certain saturated vapour pressure:

$$T = \begin{cases} \dfrac{237.3\ \ln\left(\frac{p_{sat}}{610.5}\right)}{17.269 - \ln\left(\frac{p_{sat}}{610.5}\right)} & for\ p_{sat} \geq 610.5\ Pa \\ \dfrac{265.5\ \ln\left(\frac{p_{sat}}{610.5}\right)}{21.875 - \ln\left(\frac{p_{sat}}{610.5}\right)} & for\ p_{sat} < 610.5\ Pa \end{cases} \tag{24}$$

The resulting minimum acceptable temperature on the internal surface, $T_{si,min}$ allows determine the minimum acceptable temperature factor (or design temperature factor) of the internal surface:

$$f_{R_{si,min}} = \frac{T_{si,min} - T_e}{T_i - T_e} \tag{25}$$

Twelve values of monthly design temperature factors $f_{R_{si,min}}$ must be calculated and then the following condition must be verified:

$$f_{R_{si}} > f_{R_{si,min}} \quad (26)$$

If the above condition is met in each month of the year, there is no risk of surface condensation.

The assessment of surface condensation on low thermal inertia elements such as, for example, windows and their frames, which show fast response to temperature changes, requires a different procedure [4]. Condensation on the inside surface of window frames can be an inconvenience if the water runs onto adjacent decorations, and can cause corrosion in metal frames or rot in wooden ones by penetrating joints, e.g. between the frame and glass.

There are two main differences in the procedure for low thermal inertia elements. First, the external temperature is not defined as the average monthly external temperature but as the average, taken over several years, of the lowest daily mean temperature.

The second difference resides in the definition of critical conditions on the internal surface. Because of their impermeable surface finish, indeed, mould growth is rarely a problem on window frames. The maximum acceptable relative humidity at the frame surface is therefore $RH_{si,crit}$ = 100%.

All the other steps of the procedure remain unchanged.

In the event of surface condensation, two possible measures can be taken. The first is straightforward: increasing the thermal insulation of the envelope will increase the internal surface temperature and its corresponding temperature factor. The second is to increase the air change rate by means of a mechanical ventilation system. If the problem only occurs in a particular room (e.g. a kitchen or a bathroom) and there is no mechanical ventilation system, room air extractors can solve the problem. Instead if mechanical ventilation is present a higher air change rate can be set. In both cases, higher air flow rates will lead to a higher energy demand for space heating. A possible solution is to control the air flow rate as a function of the moisture content, so that a higher air change rate occurs when the external temperature is lower and so the amount of water vapour transported inside the building.

References

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