Chapter 7
Step 6: Understanding the Indoor Climate

Abstract In this chapter the building's physical properties, which affect the indoor climate are described. The building is the first barrier between the outside and the inside. The different pathways from source, to effect, are presented. The impact of heat, air and moisture transport through, and thermal and hygric buffering, by the building envelope and within an enclosed space are described. Understanding the different properties that describe heat, air and moisture movement and their related transport mechanisms, helps understanding how the indoor climate is formed. Furthermore when the indoor climate is understood in more detail, a more balanced decision can be made as to why and how to change or improve the indoor climate in a passive way by small (or large) alterations to the building.

Keywords Building physics • First barrier principle • Heat • Moisture • Air • Indoor climate

7.1 Introduction

In Chaps. 4, 5, and 6 the climate needs for the collection, buildings and users are described. Based on the application of this information to a specific case study, the climate specifications can be defined. But before these specifications are quantified and a first concept of a mitigation strategy is developed insight into how the indoor climate forms is essential. The unique combination of any form of active climate control and the way the building produces a specific indoor climate should be understood in detail.

The transport of heat, air and moisture as defined by the outdoor climate, building envelope and climate systems will be different for all the zones in a building. These specific building physical properties will define the climate near collections, the historic interior and the people visiting or working in the building. If the indoor climate generates unacceptable risks to the collection, the building and its finishes, modifying the building and/or the climate system can mitigate those risks, as can moving the collection or changing the use of certain rooms.

Most buildings that house collections were not designed with today's functionalities and demands in mind. This means that these old buildings will have been adapted step by step to meet the museum's requirements in terms of safety and security, light, pollution and indoor climate control. Generally buildings are

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restored and refurbished approximately twice every century. So, many historic buildings, including the ones with historic interiors, have changed quite drastically from their original appearance. In the past decades these adaptions to meet the new requirements are much more drastic and intrusive than of those in earlier years. Central heating and the transport of climatised air through the building required large systems to be introduced into the building. Modifying a building's fabric and/or the hygrothermal balance can result in the introduction of new risks. Understanding the building's physical properties, and the way these affect the indoor climate, is essential to be able to develop scenarios to understand and mitigate climate risks within the limitations and possibilities of the building.

7.2 First Barrier Principle

To gain insight into how the climate in a building/zone and close to the object is formed, it is obvious to look from the outside in. Questions can be asked to become better informed, such as: how and to what extent will outside air penetrate into the building? Will the hygrothermal conditions of the air change after entry? Is the temperature inside different than outside? Is moisture released or absorbed (moisture buffering) by the building, the interior, the collection and/or people? Is the air actively humidified, dehumidified, heated or cooled? To understand the way the indoor climate is formed one needs to understand the behavior of the building, the furnishing, equipment and use of the building. A relatively simple method to understand how the indoor climate in a building, zone, room, or near the object, is formed, is to properly study the pathway from outdoor heat and moisture sources, to the exposed objects and/or finishes and to distinguish all the barriers between source and object. The way in which the indoor climate is finally created is a complex interplay of various internal and external factors.

Starting outdoors, the most important heat source is the sun and the air temperature, important moisture sources are the absolute humidity of the air, determined for example by rain. Outdoor air will enter the building by controlled (ventilation) or by uncontrolled processes (infiltration). The air enters the building with a temperature and specific humidity that might be changed; changing the temperature by cooling or heating and/or by adding or removing moisture. Heat sources will add energy, while heat sinks will subtract energy from the air resulting in a higher or lower temperature. Moisture sources will add moisture, while moisture sinks will subtract the moisture content of the air. The capacity of these sources and sinks determines whether the temperature or the specific humidity inside is higher or lower than outside.

Two major outdoor sources can be distinguished: the sun as the source of thermal energy, heat, and rain as the source of water and water vapor, moisture, see Fig. 7.1. From these sources several lines are drawn: red lines for heat flow and green for moisture flow. These are the pathways that indicate how heat and moisture are being transferred from the outdoor to the indoor and vice versa. In the yellow boxes the absolute humidity and temperature are combined to give the relative humidity. Note that although the relative humidity plays a very important role in the indoor climate risks it is the temperature and absolute humidity that can be controlled.

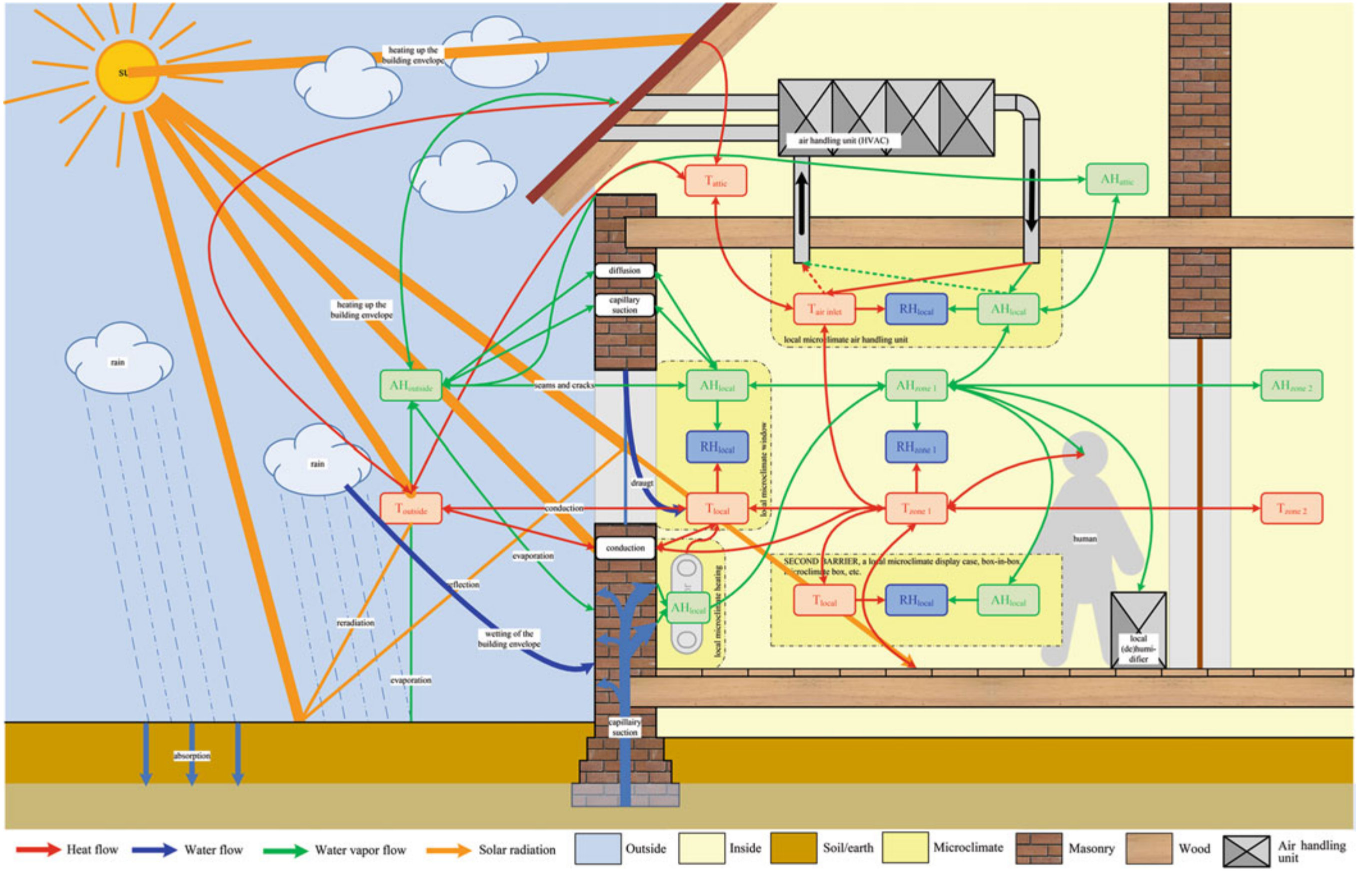


Fig. 7.1 Pathways from outdoor sources (sun and rain) to the received indoor climate

The most important outdoor heat source is the sun. The sun contributes in two different ways to the heating of a room. First (indirectly) when solar radiation heats up the earth, i.e. soil, buildings, pavement, etc. When a surface is hit by solar radiation this surface will heat up and start reradiate heat into the environment and produce a certain outdoor temperature ($T_{outdoor}$). When a façade or roof absorbs solar radiation, the material will become warmer and heat is transported through the building envelope to the inside. It is important to recognize that some of the absorbed thermal energy can also be stored within the mass of the building envelope. When solar radiation enters the building through the glazing system the indoor temperature (T_{zone}) will increase in a similar way by re-radiation of absorbed thermal energy. Internal heat sources like radiators or cold sources like cooling units will of course also influence the indoor room temperature. Finally the temperature in the zone is interrelated with the temperature of the adjacent zones, partly by conduction but mainly by convection processes.

The most important outdoor moisture source that influences the outdoor absolute humidity ($AH_{outdoor}$) is rain. Rainwater will be absorbed by the earth and the building facade. Evaporation from the earth or façade will lead to an increase of the absolute humidity of the outdoor air and thus the partial vapor pressure. Rainwater absorbed by the ground can also be transported into the building by capillary suction through the foundation of the building, as illustrated by the blue arrows in Figs. 7.1 and 7.32. Rainwater absorbed by the façade can be transported through the wall as water and water vapor by capillary suction and diffusion, respectively. Moisture can also be stored by the building envelope. Moisture sources, like people and plants, and moisture sinks, like thermal bridges, also influence the indoor absolute humidity. Finally the absolute humidity of the zone will also depend on the absolute humidity of the adjacent zones by convection mainly. Especially when damp cellars are involved. The absolute humidity may also differ inside from the outside due to a time delay effect caused by the flow rate of incoming air (i.e. air exchange rate) and moisture ad- or desorption (i.e. buffering) by the building mass, the interior finishes and/or the collection.

The relative humidity is a result of the temperature and absolute humidity. Pressure differences, resulting from temperature differences, will efficiently mix the absolute humidity. The absolute humidity can therefore be assumed to be more or less uniform within a zone. Gradients will be formed near air inlets of an HVAC-system and stand-alone (de)humidifiers. The local relative humidity is thus a result of the local temperature and the absolute humidity in the zone.

Finally, the relative humidity in the vicinity of the object can be determined by a second barrier, such as a bag, box or showcase that might enclose the object. The leakage rate, buffering capacity and thermal resistance determine the way the specific humidity and temperature of the zone influences the climate around the object, as described for the climate in the zone. The local relative humidity is further determined by the presence of buffering materials (hygroscopic packing materials and/or other objects).

For both temperature and moisture, seams and cracks will allow air to ex- or infiltrate (uncontrolled air flow) through the building envelope. The opening of windows and doors will allow for ventilation (controlled air flow), just like HVAC-systems. In this way heat energy and moisture is transported relatively quickly, since conduction and diffusion are slow processes and related to the thermal and hygric mass of the building. The characteristics of the building envelope determines to what extent the outdoor climate determines the indoor climate. Important properties of the building envelope that need to be considered are:

- Resistance to heat and cold;
- Resistance to water and water vapor;
- Buffering of heat (and cold) and water (and water vapor);
- Air permeability of the building envelope (in- and exfiltration).

These properties all together act as a first barrier that separates the outdoor climate from the indoor climate, and can be adjusted to help maintain a suitable indoor climate. Obviously, full climate control by HVAC and/or a (central) heating system greatly affects the indoor climate but the final climate class that can be maintained depends on the building physics.

7.3 Heat

The most important outdoor heat sources or sinks are air temperature and solar radiation. When the outside temperature differs from the inside temperature, a gradient over the building envelope is formed. If the outdoor temperature is lower than the indoor temperature the indoor air will lose heat to the outside (Fig. 7.2a) and vice versa (Fig. 7.2b).

The amount of heat gain or loss through the building envelope depends on the thermal resistance of the building materials used in the construction. Thick walls have a higher thermal resistance than thin walls made of the same material. However, improving the thermal resistance of buildings in cold climates is not efficient by only adding more of the same material, i.e. increasing thickness. Much more effective is

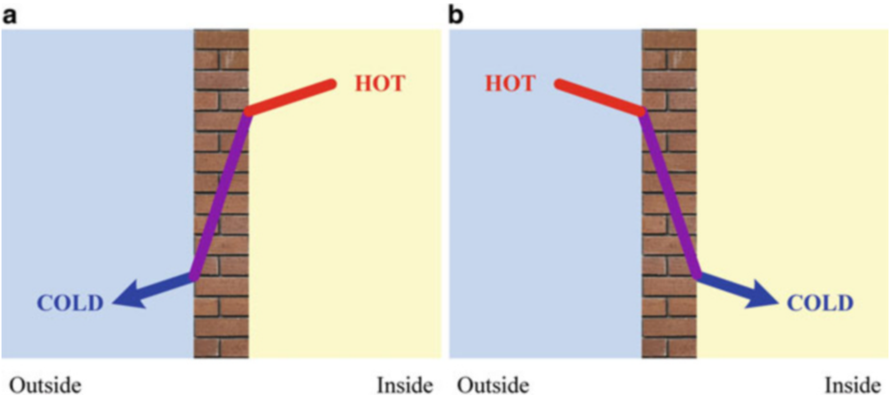


Fig. 7.2 A schematic representation of heat transfer through a wall (**a**) from the warm inside to the cool outside (typical winter situation in cold climates) and (**b**) from the warm outside to the relatively cool inside (typical situation in a tropical climate)

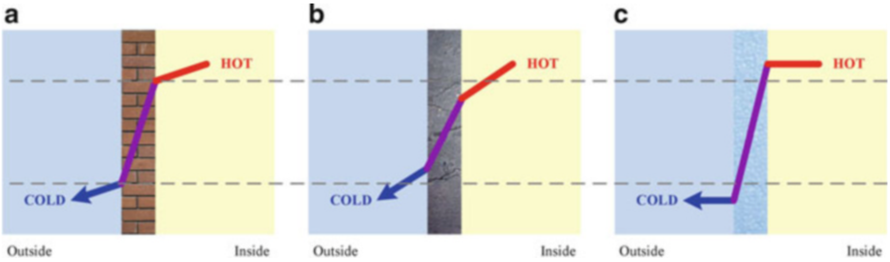


Fig. 7.3 A schematic representation of temperature gradients in different types of materials with similar thickness (**a**) brick, (**b**) concrete, both with a low thermal resistance and thus a small drop in temperature, and a large difference between the indoor and surface temperature (**c**) polystyrene, with a high thermal resistance and thus a large drop in temperature, and a small difference between the indoor and surface temperature

adding a material with a lower thermal conductivity which will decrease the thermal conductivity of the whole wall. The rationale is that when a non-insulating material (i.e. brick) is compared with an insulating material (i.e. mineral wool) with similar thickness, mineral wool will transfer less energy than brick per square meter for a given temperature difference. The result is that indoor surface temperatures of an uninsulated wall will be lower than the indoor air temperature, while the indoor surface temperature of an insulated wall will be close to the indoor temperature. This effect is illustrated in Fig. 7.3 for brick, concrete and polystyrene of similar thickness.

Brick is a relatively good thermal conductor. The outside surface temperature (Fig. 7.3a) will be slightly higher than the outside air temperature. The inside surface temperature will be slightly lower than the indoor air temperature. This will result in a relatively large temperature gradient over the brick wall. Concrete is a more effective thermal conductor (less effective insulator) than brick. Therefore the temperature gradient over the concrete wall will be much smaller (Fig. 7.3b). As a result the indoor surface temperature will be even lower and the outdoor surface temperature will be higher when compared to the surface temperatures of a brick wall. Insulation materials, like mineral wool, polystyrene or polyisocyanurate have very low thermal conductive properties (Fig. 7.3c). The temperature gradient within the material will therefore be very large. The inside surface temperature will be almost equal to the indoor air temperature and the outside surface temperature will be almost equal to the outdoor air temperature. Obviously, when the outdoor temperature is much higher than the inside temperature, the opposite gradients are formed in these materials.

At low outdoor temperatures, the building envelope can be significantly heated by solar gain. This means that indoor surface temperatures can be significantly higher than expected based on only outdoor air temperatures. Figure 7.4 shows the temperature gradients for an uninsulated (Fig. 7.4a) and an insulated (Fig. 7.4b) wall. The solid lines show the temperature gradients with solar gain and the dashed line without solar gain with low outdoor temperatures (winter) and high outdoor temperatures (summer). Both outdoor and indoor temperature are kept constant in this example to clearly see the influence of the solar gain. As can be seen, the indoor surface temperature increases significantly due to solar gain. In reality high solar gain will of course increase the indoor temperature, but the extent will depend on heat losses by transmission and ventilation.

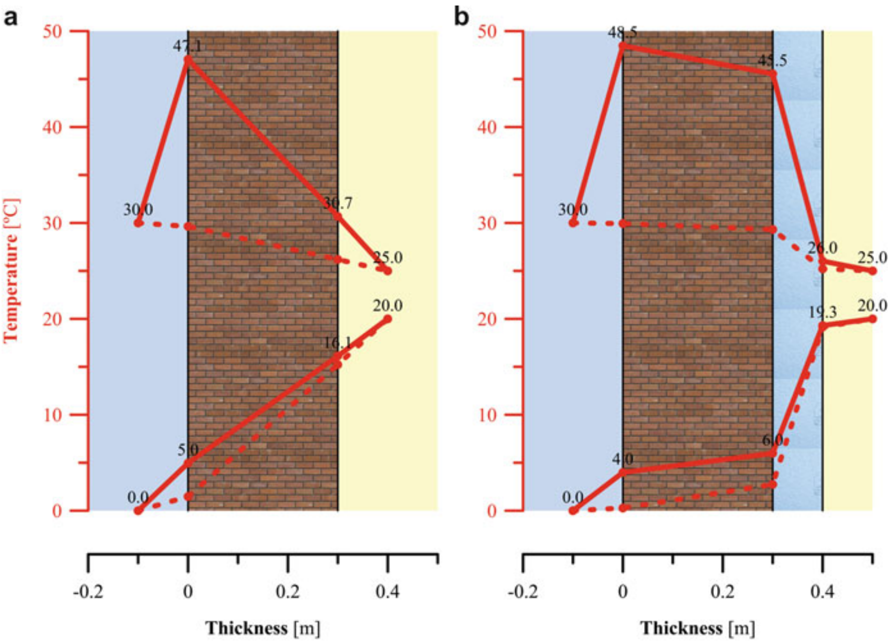


Fig. 7.4 Calculated surface temperatures with (*solid line*) and without (*dashed line*) solar radiation for a non-insulated (**a**) and insulated (**b**) brick wall

The total rate of heat gain or loss for a building depends on:

- The temperature difference between in- and outside;
- The material's thermal conductivity properties (i.e. thermal insulation);
- The thickness of the various layers of the building envelope;
- Leakiness of the building (the so-called air exchange rate: AER)

Depending on the outdoor climate, i.e. geographical location and the time of the year, the indoor air will gain or lose heat. In temperate climates especially, humans protect themselves from low and high temperatures by blocking the outdoor climate using materials with good insulation properties (low conductivity, see Table 7.1 in the next paragraph). In hot or very cold climates it is much more difficult to maintain a suitable and comfortable indoor temperature using only passive means, i.e. building physics. The use of additional systems for heating or cooling are generally required to meet human comfort requirements. For people, comfortable temperatures range from a lower limit of 17 or 18 °C (63–64 °F) to an upper limit of 25 °C (77 °F) (see Chap. 6) depending on the outdoor temperature. Objects and building fabrics also have optimal temperatures at which they are best preserved (see Chaps. 4 and 5).

7.3.1 *Understanding Heat Transfer*

Heat or energy can be transported by three different processes: conduction, radiation and convection as shown in Fig. 7.5.

Table 7.1 Conductivity coefficient of different building materials

Material		Conductivity [W/mK]	
Insulation	Traditional (e.g. mineral wool)	0.04	Low
	Capillary active (e.g. calcium silicate)	0.06–0.065	↓
Wood		0.14–0.17	
Gypsum board		0.23–0.46	
Plaster		0.52–0.93	
Brick		0.60–0.70	
Concrete		2.00	High
Metals		52–372	Very high

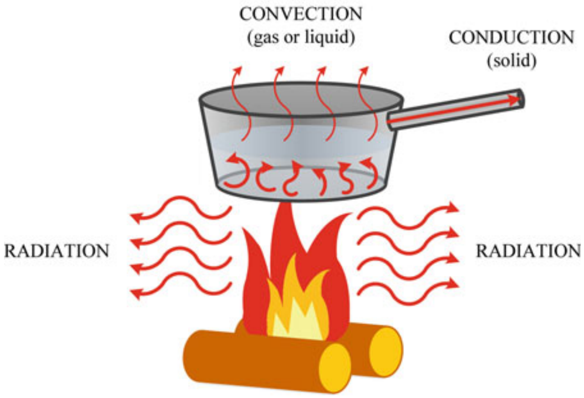


Fig. 7.5 Visualization of conduction, radiation and convection

Conduction is the energy transfer within a material due to a temperature difference (symbol: ΔT or Δθ, unit: °C or K). Considering the indoor climate, the most likely conduction takes place between the inner and outer surface of an external wall. A large temperature difference will result in a large heat transfer and vice versa. Obviously, some materials, like metals, conduct heat much easier than other materials, such as wood. Materials with a high thermal conductivity are widely used in cooling applications for combustion engines or electronic devices and materials with a low thermal conductivity are used as thermal insulation. The larger the thermal conductivity of a material (symbol: λ, unit: W/mK), the larger the heat transfer and the larger cooling or heating ability. In Table 7.1 the conductivity of some common materials is presented.

Thermal radiation is an electromagnetic wave generated by the thermal motion of charged particles in a material. Every material with a temperature above absolute zero (0 K, −273 °C, −459 °F) emits radiation. This means that a cold and a warm mass facing each other, will constantly exchange radiant heat. The warm body will cool down and the cold body will heat up. A person with an average body temperature of 37 °C (99 °F) in the vicinity of a cold surface, such as a window with a much lower temperature, e.g.7 °C (45 °F), will exchange heat and will experience the cold surface. The amount of heat transfer depends on the surface temperature and the emissivity coefficient (symbol: ε, unit: dimensionless ratio) of the material. It is important to understand that energy is mainly exchanged in the infrared part of the electromagnetic spectrum and that the emissivity coefficient depends on the wavelength. An example to explain this phenomenon is the low emissivity coefficient of about 0.2 of the color white in the visible part of the spectrum (low emission, low absorption, high reflection). But in the infrared part of the spectrum the emissivity coefficient is about 0.9 (high emission, high absorption, low reflection). So the color white acts as ‘black’ in the infrared part. This indicates that the human eye is not able to properly estimate the emission coefficients of surfaces.

The amount of energy that can be exchanged between a surface and it’s surroundings is directly related to the emissivity coefficient of that specific material. Materials, such as wood, stone and marble with a high emissivity ($\varepsilon = 0.9$–1) emit energy much more readily than materials with a low emissivity ($\varepsilon < 0.2$) such as polished silver and gold. In general one number is given for the emissivity coefficient over a series of wavelengths at a specific temperature (Table 7.2).

Thermal cameras visualize an infrared image based on the amount of energy that is radiated by surfaces. Generating a false color image, with colors indicating different surface temperatures. Since this temperature calculation is based on the Stefan–Boltzmann law using the emissivity coefficient, it is important to use the correct coefficient.

Convection is the collective movement of molecules within liquids and gases, including diffusion processes. Within buildings convective air movement is air moving near surfaces allowing energy transfer between surfaces and air. The amount of energy that is transferred depends on the temperature difference (symbol: ΔT or $\Delta\theta$, unit: °C or K) and the air velocity near the surface (symbol: v_a, unit: m/s). If there is no temperature difference or the air velocity is zero, then no energy will be exchanged. Cooling or heating of a surface will occur when the temperature differences and the air velocity are higher. This is the reason why strong winds are generally experienced as being colder than the actual air temperature (so-called wind chill). Heating systems strongly depend on the principles of convective air movement. Warm air generated by hot radiators rises and when cooler air is being supplied e.g.by an HVAC system, effective air circulation is created.

7.3.2 Heat Sources

As illustrated in Fig. 7.1 the indoor climate is influenced by external and internal heat sources. Generally the sun is the most significant and influential external heat source. Its energy will be transported by glazing systems. Unlike walls and roofs, the transmission of energy by glazing systems is rather unhindered because of its transparency. Transmitted solar energy will heat up internal surfaces. In turn these surfaces will heat up and start to reradiate this energy back into the room, making those surfaces internal heat sources.

Table 7.2 Emissivity coefficient of different building materials (FLIR Systems Inc. 2011)

Material	Emissivity coefficient [−]	Wavelength [μm]	Temperature [°C (°F)]
Aluminium (foil)	0.09	3	27 (81)
Aluminium (foil)	0.04	10	27 (81)
Aluminium (roughened)	0.18	10	27 (81)
Aluminium (weathered, heavily)	0.83–0.94	SW	17 (63)
Basalt	0.72		
Brass (oxidized)	0.03–0.07	LW	70 (158)
Brass (oxidized)	0.04–0.09	SW	70 (158)
Brass (sheet, rolled)	0.06	T	20 (68)
Brick (firebrick)	0.75–0.93	SW	17 (63)
	0.68		
Brick (masonry)	0.94	SW	35 (95)
Brick (masonry, plastered)	0.94	T	20 (68)
Concrete	0.93–0.94	T	20 (68)
Concrete (rough)	0.97	SW	17 (63)
Copper (commercial, burnished)	0.07	T	20 (68)
Copper (oxidized, heavily)	0.78	T	20 (68)
Copper (polished, mechanical)	0.015	T	22 (72)
Glass	0.92–0.94		
Gold (polished)	0.018	T	130 (266)
Granite (polished)	0.85	LLW	20 (68)
Granite (rough)	0,88	LLW	21 (70)
Gypsum board	0.80–0.95	T	
Human skin	0.98	T	32 (90)
Insulation (general)	0.90[a]		
Iron and steel (oxidized)	0.74	T	100 (212)
Iron and steel (polished)	0.07	T	100 (212)
Iron, cast (oxidized)	0.63	T	38 (100)
Iron, cast (polished)	0.21	T	38 (100)
Lead (oxidized, gray)	0.28	T	20–22 (68–72)
Paint (oil)	0.87	SW	17 (63)
Paper (black)	0.90	T	
Paper (white)	0.70–0.90	T	20 (68)
Plaster (plaster board)	0.91	SW	20 (68)
Silver (polished)	0.03	T	100 (212)
Tin (burnished)	0.04–0.06	T	20–60 (68–140)
Varnish (flat)	0.93	SW	20 (68)
Wood	0.88–0.93	T	
Wood (pine)	0.67–0,75	SW	70 (158)
Wood (planned Oak)	0.99	T	20 (68)

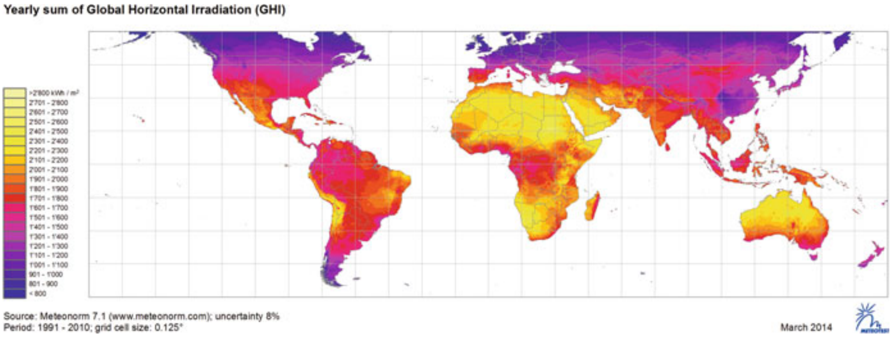
(continued)

Table 7.2 (continued)

Material	Emissivity coefficient [−]	Wavelength [μm]	Temperature [°C (°F)]
Wood (pine)	0.81–0,89	LW	70 (158)
	0.95		
Zinc (polished)	0.04–0.05	T	200–300 (392–572)

T total spectrum 2–20 μm, *SW* shortwave 2–5 μm, *LW* long wave 8–14 μm, *LLW* long long wave 6.5–20 μm

[a] This number is taken from De Wit (2009), p 10


Yearly sum of Global Horizontal Irradiation (GHI)

Source: Meteonorm 7.1 (www.meteonorm.com); uncertainty 8%
Period: 1991 - 2010; grid cell size: 0.125°
March 2014

Fig. 7.6 Yearly sum of the global horizontal irradiation (Source: © METEOTEST; taken from www.meteonorm.com)

Internal sources, especially in cold countries include radiators, which can be as hot as 70–90 °C (158–194 °F), and generate heat ranging from 1,700 to 2,700 W/m^2. Human beings are also heat sources, generating 80–300 W per person depending on their activity. Especially when larger groups are present for prolonged periods of time this source can become relevant. Electrical equipment such as lighting and computers will also generate heat. Lighting will typically generate heat ranging from 2.5 to 20 W/m^2. Office equipment like computers, printers etc. will generate about 100 W per computer or printer (or 10 W/m^2). More detailed information can be found in ISSO 33 (1996).

The sun emits a lot of energy, but only 1,350 W/m^2 (Hermans 2008) will reach our planet's surface, and can be absorbed and transformed into heat. This effect is called solar gain and the amount depends on the orientation and geographical location. In Fig. 7.6 the yearly sum of Global Horizontal Irradiance (symbol: GHI, unit: W/m^2) is shown for the world. The Global Horizontal Irradiance is the total amount of shortwave radiation (visible, near-ultraviolet and near-infrared radiation) received from above by a horizontal surface.

As the earth rotates, solar gain varies from day to day. Due to geographical location, the seasonal and hourly position of the sun changes. For two geographical locations Indonesia and The Netherlands the shading in January and July of a building is given for three different times: 8:00, 12:00 and 16:00 (Fig. 7.7).

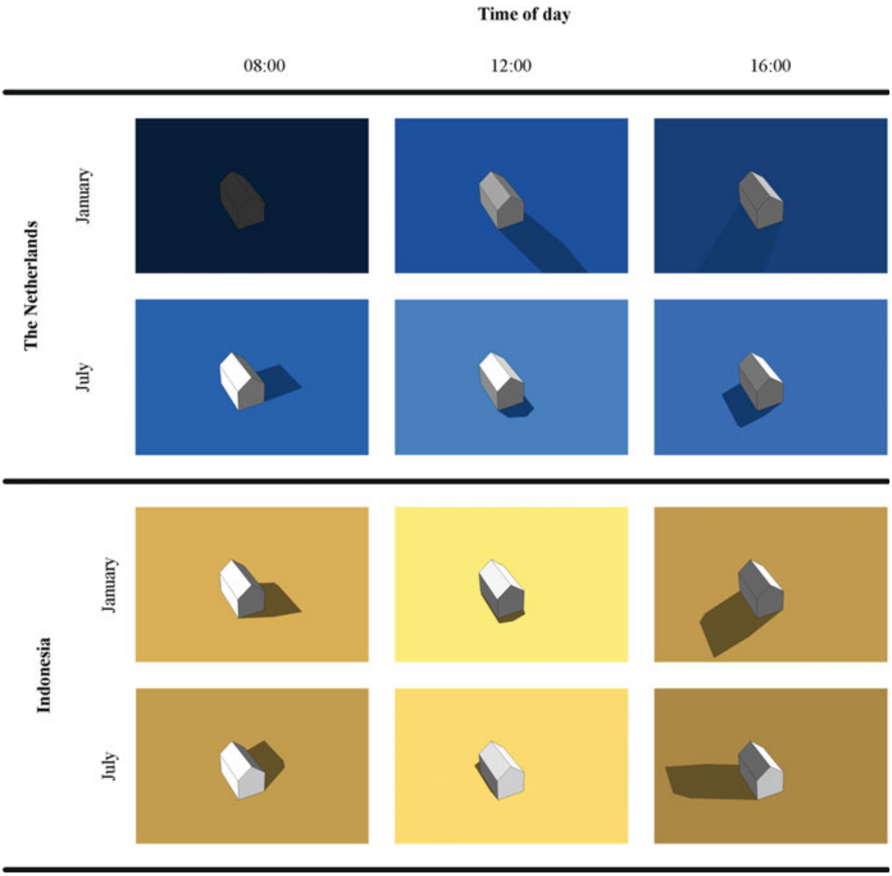


Fig. 7.7 Shading of a simple building at two locations (Indonesia and the Netherlands) for two seasons (January and July) at three times (8:00, 12:00 and 16:00)

From Fig. 7.7 it can be seen that in Indonesia the shadows in the morning have a slightly different direction. In the afternoon the shade is almost gone, i.e. the sun in both January and July is directly above the building. This means that high solar gains affect the roof most and the east and west walls next. For the Netherlands it can be seen that in January daylight is available for a short period of time. The sun rises at 8:00 and sets at 16:00. The shadow at 12:00 is very long. This means that the angle between the earth and the sun is small and therefore the total solar gain will be small. But the amount is still enough to be used to passively heat buildings (Department of Industries 2014; Cairns Regional Council 2011). In July daylight is available for a longer period. Both the roof and south, east and west walls are heated. These sun path patterns are generally well known to local people and this knowledge can be used to better estimate the effect of solar radiation.

When the sun heats up a window, the amount of heat transferred by the window depends not only on the conductive properties of the glass but also on the

Table 7.3 Overall heat transfer coefficients of different glazing systems and window frames (Taken from: NPR 2068:2002)

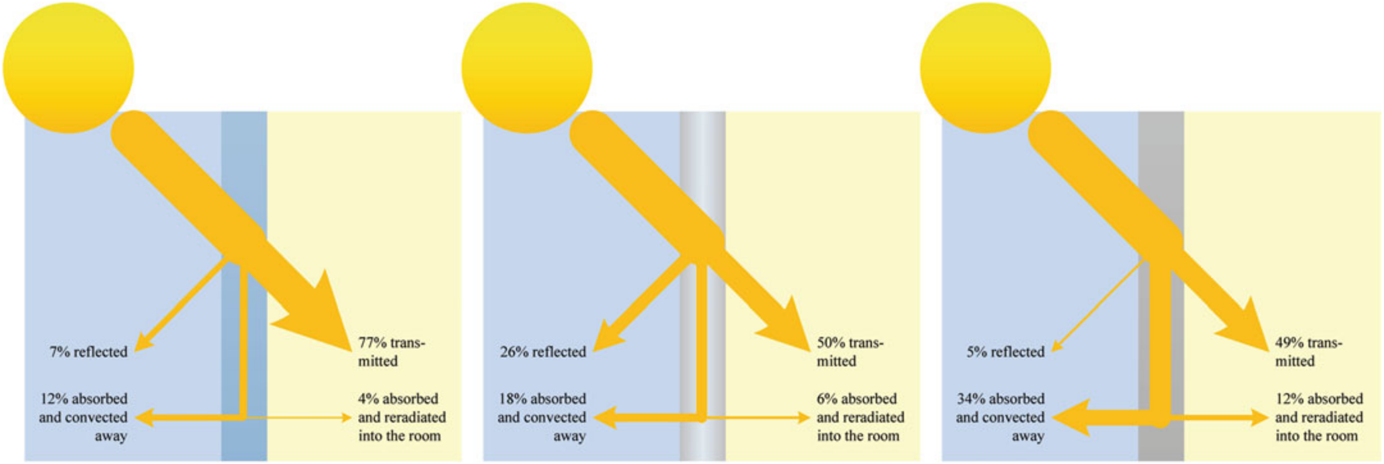
Glazing system	Overall heat transfer coefficient (U-value) [W/m^2/K]			
		Window frame		
	Glass	Wood or plastic	Metal, with thermal break	Metal, without thermal break
Single	5.8	5.2	5.4	6.2
Double	2.8	2.9	3.3	4.1
HR++	1.2	1.8	2.2	3.0
	1.0	1.6	2.1	2.9

conductive properties of the window frame. In Table 7.3 the overall heat transfer coefficient, the so-called U-value, is given for different glazing systems and window frames. The higher this U-value the worse the thermal performance of the material or building component. A low U-value usually indicates high levels of insulation. From this table it can be seen that the window frame plays a significant role in the overall performance when used in combination with energy efficient glazing, also called HR++ glazing or low e-glass.

The key purpose of windows is to allow sunlight to enter the building and to create a welcoming and comfortable atmosphere. When sunlight hits a window some radiation is reflected (symbol: ρ, unit: dimensionless ratio), some absorbed (symbol: α, unit: dimensionless ratio), but most will be transmitted (symbol: τ, unit: dimensionless ratio). For normal glass panes with a width of 4 mm, approximately 81 % of the solar radiation is transmitted to the inside. This is called the Solar Heat Gain Coefficient (SHGC or G-value), which can be defined as the quotient of the transmitted radiation, plus a portion of the absorbed solar radiation and total solar radiation. Reducing solar gain of interior spaces, is most efficiently done by increasing the reflection and reducing the transmittance and absorption characteristics of the transparent parts (Fig. 7.8). This can also be achieved by applying special filters to the (historic) glass (see Chap. 9).

In order to lower energy consumption for buildings in the northern Hemisphere during winter, the solar energy entering through windows can be used. In winter, solar gain will help to heat up the building decreasing energy demand for heating. In summer however solar gain needs to be limited to prevent overheating and thus increasing the energy demand for cooling. When choosing a new glazing system or adjusting the existing glazing system it is essential to have some kind of adjustable system to vary the SHGC depending of the season. In Table 7.4 the SHGC are provided for various glazing systems and internal and external shading systems.

In museum Oud-Amelisweerd, Bunnik, The Netherlands (Figs. 7.9 and 2.2) a high-tech dynamic solution was implemented. Entrance of daylight was required to enjoy the historic wall finishes and the other works of art, but an excess of solar gain needed to be avoided to minimize fluctuations in temperature and relative humidity. Especially since the modest HVAC-system (see also Sect. 2.6, Fig. 2.3) that was implemented has a limited capacity. The louvres on the south façade were reconstructed and mechanized (Fig. 7.9b). A high-tech system controls the



Clear glass

reflectance	7%
absorptance	16%
direct transmittance	77%
SHGC or G-value	0.81

Reflecting glass

reflectance	26%
absorptance	24%
direct transmittance	50%
SHGC or G-value	0.56

Heat absorbing glass

reflectance	5%
absorptance	46
direct transmittance	49%
SHGC or G-value	0.61

Fig. 7.8 A schematic representation of reflection, absorption and transmission properties of single clear, reflecting and heat absorbing glass panes

Table 7.4 Solar heat gain coefficients of various glazing systems and internal and external shading systems

System	SHGC [−]
Clear glass (Fig. 7.8)	0.81
Reflecting glass (Fig. 7.8)	0.56
Heat absorbing glass (Fig. 7.8)	0.61
Clear double glazing (ISSO 33)	0.70
Clear single or double glazing with internal sun screen (ISSO 33)	0.45
Clear single or double glazing with external sun screen (ISSO 33)	0.15
Clear single glass with filter	0.39–0.64[a]
Clear double glass with filter	0.29–0.56[a]

[a] Depending on type of filter. Data taken from datasheets from various types of filters from various types of manufactures

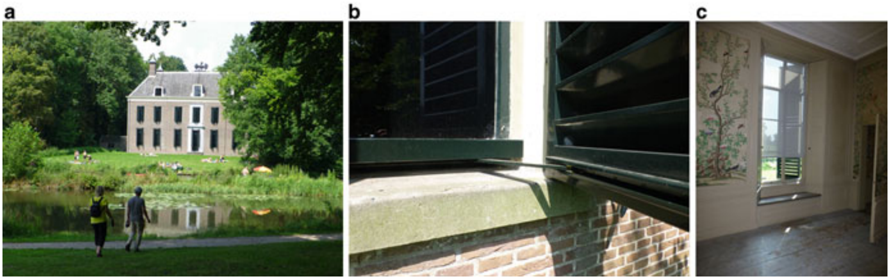


Fig. 7.9 Sunlight control of Museum Oud-Amelisweerd in Bunnik, The Netherlands: (**a**) the exterior of the museum, (**b**) the reconstructed and mechanized louvers as external shading system and (**c**) the electrified sun screens as internal shading systems

opening-closing based on in- and outdoor solar radiation measurements. The louvres are combined with internal mechanized sun screens (Fig. 7.9c). Both systems work together in order to keep solar gain to a minimum, whilst keeping visibility to a maximum. Filters placed on the existing glazing blocks all UV-radiation.

As shown in Fig. 7.8 the absorption of solar radiation by the clear glass window, is about 16 %. For non-transparent building parts, such as walls, the absorption of solar radiation is much higher (75–95 %, Table 7.2). Figure 7.4 shows that the effect of solar gain on the surface temperature can be quite large for an outdoor surface like a façade or roof. This can lead to internal stresses in the building fabric. In Pilette and Tayler (1988) the effect of partial shading on three types of window panes was investigated. The study showed that thermal stresses in the glass panes doubled when compared to fully shaded windows.

Figure 7.10 shows the heating of a historic interior by direct sunlight. As can be seen, sunlight penetrates deep into the room and hits the side of the fireplace. The thermogram on the right shows surface temperatures of 36 °C (97 °F), while the surrounding interior finishes are 20 °C (68 °F).

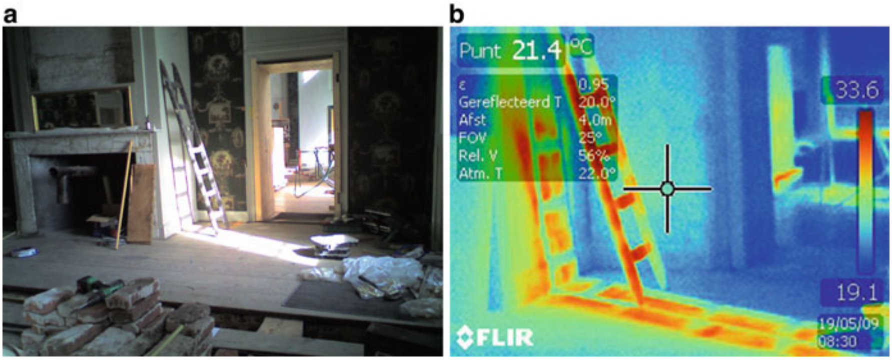


Fig. 7.10 Sunlight entering a historic interior increasing surface temperatures. A picture of a room with paper hangings during restoration (**a**). The surface temperatures are clearly influenced by the incoming solar energy, as can be seen on the thermal image (**b**)

The increased temperatures will cause a local drop in relative humidity. Obviously, these kind of relative humidity gradients can lead to mechanical damage as described in Chap. 4. Surfaces with temperatures increased above the ambient indoor temperature will radiate heat back into the room, acting as small radiators and further increasing the indoor temperature. Obviously, when culturally important surfaces such as paintings, are hit by direct sunlight local temperature and relative humidity gradients can reach levels that cause significant risks to the object.

This heating process is similar to the greenhouse effect, where absorbed heat is prevented from leaving. A greenhouse is built of materials that allow transmittance of sunlight, usually glass, sometimes plastic. Interior surfaces absorb the short infrared wavelengths radiation and reradiate the heat at longer infrared wavelengths. Glass can only transmit short wavelength radiation and not the long reradiated wavelengths. As a result the indoor temperature increases further leading to significant heating of the interior. The greenhouse effect has become a well-known phenomenon in the context of global warming.

Traditionally buildings in cold climates were actively and locally heated by means of a fireplace or coal stove. In the 1950s these were replaced by central heating systems with a central heating source coupled to heating panels in every room. The purpose of those heating panels is to compensate for energy losses from the building and to create a more uniform comfortable environment. Since these panels are kept as small as possible, relatively high surface temperatures need to be generated to transfer enough heat. Generating convective airflows and radiating heat in all directions, results in locally higher temperatures and lower relative humidities. As illustrated in Fig. 7.11 radiators close to cultural objects can locally influence the climate around these objects and parts of building. Please note that in this example the temperature was maintained at a relatively low level to reduce the risk of drying of the oil painting on canvas.

Fig. 7.11 A painting hanging over a radiator, with a low temperature set point (**a**). In the thermal image (**b**) a subtle heating of the underside of the canvas painting can be clearly seen

7.3.3 Thermal Bridges

A thermal bridge is a shortcut in the building envelope. A part of the building which allows for high heat transfer when compared to the surrounding building materials e.g. a metal cramp in a masonry wall. Thermal bridges result in locally high heat transfer and thus locally low temperatures and need to be avoided. This phenomena is very common in the northern hemisphere when insulation is added to the outer wall. Insulation can be added on the outside or on the inside of the building. Sometimes the wall cavity can be filled with insulation material. For insulation added to the outside of the outer wall and filled in wall cavities, these shortcuts are typically the existing windows and door reveals. For insulation added to the inside of the outer wall there are other potential penetration points that might be formed, such as joints between external and internal walls, and external walls and wooden or concrete floors with wooden beams, as a striking example with a risk of interstitial condensation and decay. In tropical regions the risks of building decay from thermal bridges is somewhat smaller

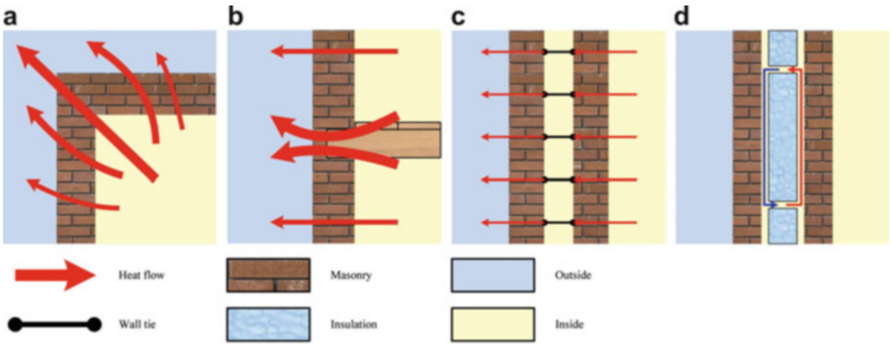


Fig. 7.12 Four types of thermal bridges can be identified: (**a**) geometrical, (**b**) structural, (**c**) systematic and (**d**) convective

but increased heat transfer and increased indoor surface temperature are still present. Thermal bridges can be categorized into four groups (Olsen and Radisch 2002):

- Geometrical thermal bridges;
- Structural thermal bridges;
- Systematic thermal bridges;
- Convective thermal bridges.

Geometrical thermal bridges (Fig. 7.12a) are cold bridges formed by geometrical aspects i.e. dimensional changes, which increases the heat emission or absorbing surface area. Examples are inner or outer corners (3D thermal bridges) or room edges (2D thermal bridges) of external partitions. Structural thermal bridges (Fig. 7.12b) are formed by deliberate penetrations of the building envelope. Examples are wooden beams and concrete slabs passing through the building fabric. Systematic thermal bridges (Fig. 7.12c) are thermal bridges that are repeated in a specific pattern. Examples are wooden beams of floors or wall ties in cavity walls. Convective thermal bridges (Fig. 7.12d) are formed by air flow, due to e.g. air leakages and penetration of pipes through structural elements. Obviously, in practice one can also find combinations of these.

It is not easy to study thermal bridges in practice, but computer modeling generally provides an efficient alternative. The input of dimensions, material properties and temperature gradients generates a two or three dimensional visualization of the gradients formed inside the structure. An example of this type of modeling is shown in Fig. 7.13.

It is obvious that by adding insulation to the inside, the floor will become colder. Outdoor temperatures will determine the risk of rot due to high relative humidities at the beam end (Morelli et al. 2010; Tersteeg 2009), as can be seen in Fig. 7.14.

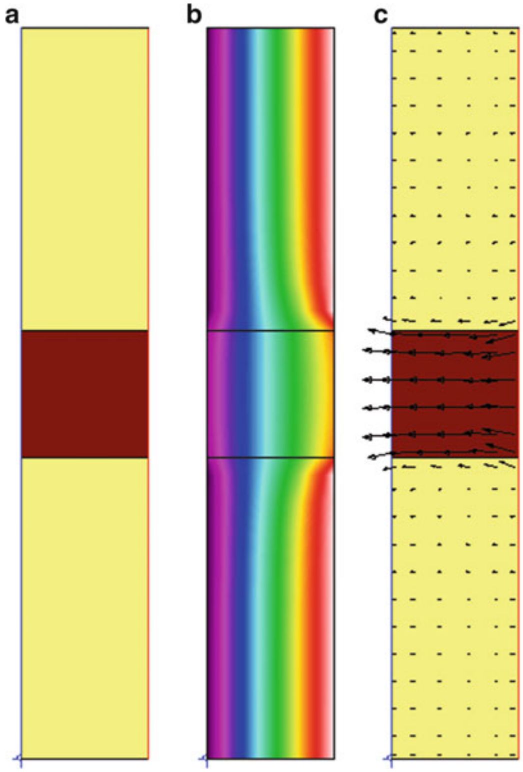


Fig. 7.13 A typical example to illustrate the effect of thermal bridges: (**a**) a 30 cm wall built up that consists of a high thermal insulator (mineral wool, *yellow*) around a low thermal insulator (brick, *brown*), (**b**) isotherms of the structure as a result of an outdoor temperature of 0 °C and an indoor temperature of 20 °C, (**c**) heat flux through the wall as a result of an outdoor temperature of 0 °C and an indoor temperature of 20 °C. Image (**b**) shows the outdoor surface temperature near the thermal bridge is higher than the surrounding surface temperature and the indoor surface temperature is lower than the surrounding indoor temperature. In image (**c**) the heat flux through the thermal bridges is higher that the surrounding wall

Many modelling studies have been performed to determine the optimal thickness of the insulation layer and the likelihood of thermal bridges (Song and Kim 1997; Schellen et al. 2008). For the restoration of the Rijksmuseum in Amsterdam a two dimensional hygrothermal model study was done by the Dresden University of Technology to analyze the hygrothermal effects of two internal insulation options for the external walls using cellular glass or calcium silicate (Häupl et al. 2005; Häupl 2007). It was concluded that a thickness of 35 mm calcium silicate is optimal. A thicker layer of 50 mm or the use of foam glass would increase the build-up of moisture inside the wall.

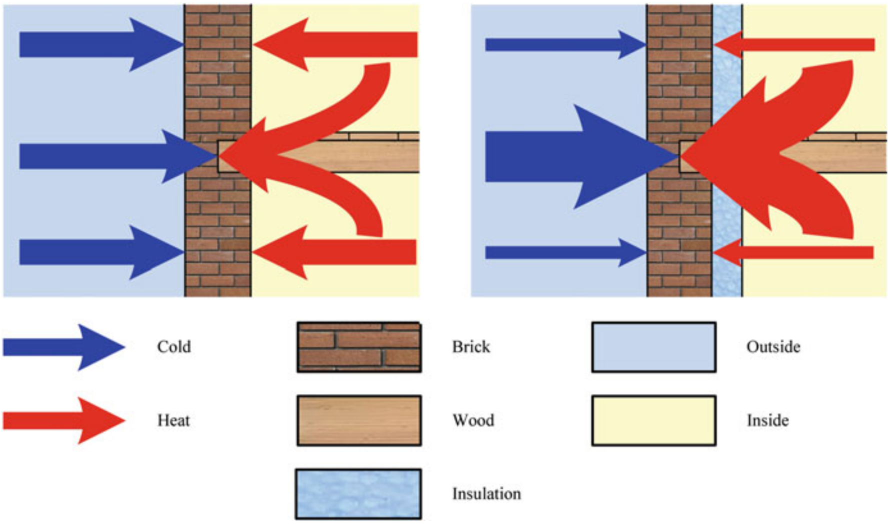


Fig. 7.14 Example of a wooden beam and wooden floor imposed in a masonry wall with and without insulation. Due to the inside insulation the heat flux through the wall deceases, while the heat flux through the beam end increases, making the area colder creating a thermal bridge

7.3.4 Thermal Mass

Massive buildings generally have large thermal mass or thermal inertia. This means that they are capable of storing thermal energy. The thermal mass depends on the specific density (symbol: ρ, unit: kg/m^3) and the specific heat capacity (symbol: c, unit: kJ/kg) of the building materials used. The higher the density or heat capacity, the higher the thermal mass. Thermal mass can be very beneficial to control the indoor climate because low winter temperatures are stored and will subsequently make the indoor climate colder during summer and vice versa. This effect can be nicely experienced when visiting a relatively cold church or bunker during a warm summer day. But even materials with high thermal mass become useless as a thermal buffer when the rate at which heat is absorbed or desorbed is too fast, or too slow. For materials this property depends not only on the density and heat capacity but also on the thermal conductivity (symbol: λ, unit: W/mK). The rate at which heat will adsorb or desorb is given by the thermal diffusivity (symbol: D_T, unit: m^2/s). The effective depth is a measure for the thickness of the wall that is actually effective to buffer the temperature. This effective depth depends on the thermal diffusivity and the length of a certain periodical fluctuation. The thermal buffer capacity is the product of the thermal mass and the effective depth. A very thin material will simply not have sufficient storage capacity and will therefore have a low thermal buffer capacity. A material which has a large thermal storage capacity but is a bad thermal conductor, i.e. low thermal diffusivity, will heat up and cool down too slowly for this property to be useful and vice versa. Their mutual

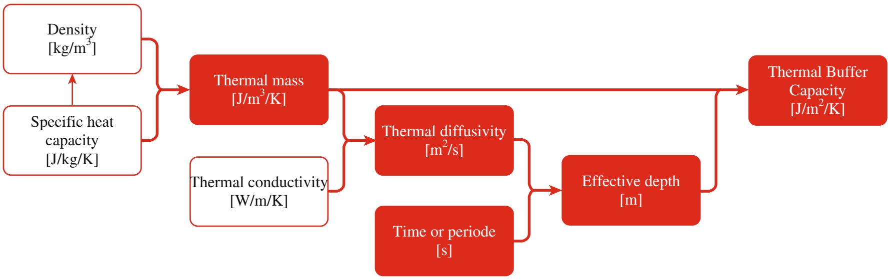


Fig. 7.15 The relationship between thermal properties (*solid boxes*) of building materials, the thermal buffer capacity and the derived physical quantities

Table 7.5 Effective depth calculated for different periods and building materials

Material	Period t [h]	Density ρ [kg/m^3]	Storage capacity c [J/kg/K]	Conductivity λ [W/K/m]	Effective depth d* [cm]	Thermal buffer capacity [kJ/m^2/K]
Concrete	24	2500	840	2	16.2	339.9
Concrete	2160	2500	840	2	153.5	3,224.2
Brick	24	1900	840	0.7	11.0	175.3
Lime plaster	24	1600	840	0.95	13.9	187.4
Wood	24	800	1880	0.17	5.6	83.9
Mineral wool	24	100	840	0.04	11.4	9.6

relationships are presented in Fig. 7.15. In general, the higher the thermal conductivity the higher the effective depth and the better the overall thermal buffering performance.

In Table 7.5 the effective depth is given for different building materials when submitted to a for a 24 h cycle. For concrete also a 3 month (2160 h) cycle is provided. The 3 month cycle shows that slow fluctuations will penetrate deeper into the building fabric. The effective depth for concrete for the diurnal and 3 month cycle are respectively 6.2 cm and to 153.5 cm. This means that the complete buffering of a 3 months cycle would require a thickness of 1.5 m of concrete. This may be found in bunkers but generally not in traditional buildings. On the other hand for the other materials the buffering of daily cycles only a thickness varying from 5.6 to 16.2 cm is needed, which can be found in most buildings. As can be seen from Table 7.5 concrete, brick and lime plaster are good thermal buffers (high thermal buffer capacity). It should be noted that when the practical available depth is smaller than the theoretical effective depth, the thermal buffer capacity will be the product of the thermal mass and the available depth.

The effect of a high thermal mass on the indoor climate is that in regions with considerable temperature difference between seasons, massive buildings tend to be cooler in summer and warmer in winter. This effect can be experienced in massive buildings such as churches, bunkers and castles in the northern hemisphere. As a practical consequence seasonal fluctuations are buffered to a lesser extent than diurnal fluctuations. Even though the wall thickness is generally too small for full seasonal buffering, most massive buildings in the Northern hemisphere still have sufficient thermal mass to reduce seasonal indoor (surface)temperature fluctuations and reduce the need for heating and cooling.

In regions with a more or less constant outdoor temperature throughout the year, such as the tropical regions thermal mass will result in a very stable, but high indoor temperature close to the outside temperature. These temperatures generally are too high for thermal comfort during both day and night. Therefore traditional buildings in those regions tend to be light weight, i.e. low mass and highly ventilated, to allow cool air to enter at night (Cairns Regional Council 2011).

In Fig. 7.16 the effect of the thickness of a brick wall, on the indoor surface temperature is plotted. The graph shows the indoor surface temperature for a 0.22 m (orange line) and a 0.44 m (red line) thick masonry wall. The indoor surface temperature is more or less constant at 24 °C (75 °F), while the outdoor temperature (brown line) and the solar radiation (yellow line) show large fluctuations. It can be seen that surface temperature fluctuations of the 0.44 m thick wall are smaller and shifted 3 h compared to those of the 0.22 m thick wall. This is the effect of a higher thermal storage capacity. Furthermore, the average indoor surface temperature of the 0.44 m thick wall is about 0.8 °C (1.4 °F) lower, compared to the 0.22 m thick wall. In Fig. 7.16 only diurnal temperature fluctuations are considered but for long-term fluctuations, such as seasonal fluctuations, the effect will be very similar.

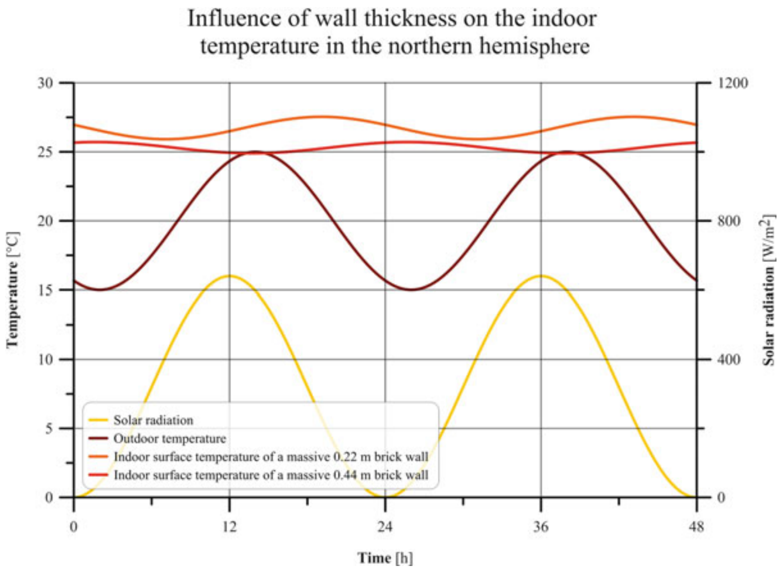


Fig. 7.16 Calculated indoor surface temperatures for a thick wall, i.e. large thermal mass and a thin wall, i.e. low thermal mass (Based on data from Tammes and Vos 1984)

For thermal mass to be effective, the storage capacity should be considerable and accessible. Considerable means that the material needs to have a fairly high density and a fairly high thermal capacity so it can absorb thermal energy. When thermal mass is in contact with the indoor climate it is accessible and useable. Sometimes alterations like thermal insulation will block access to the thermal mass, thus reducing the potential of the thermal mass considerably.

The diurnal effect of thermal mass is illustrated in Fig. 7.17. During winter, when the outdoor air is colder than indoors, thermal mass can be heated by solar radiation (Fig. 7.17a) and the building gains thermal energy, which is re-radiated into the room during the night (Fig. 7.17b).

In summer (Fig. 7.18) it is more effective to prevent warming up of thermal mass, e.g.by using sun blinds such as shutters and sunshades on the outside during the day. Heated outside air will exchange heat with the thermal mass (Fig. 7.18a). During the night this heat can be released by ventilation to the relatively cold night air and removed from the room (Fig. 7.18b). This is why in Mediterranean countries

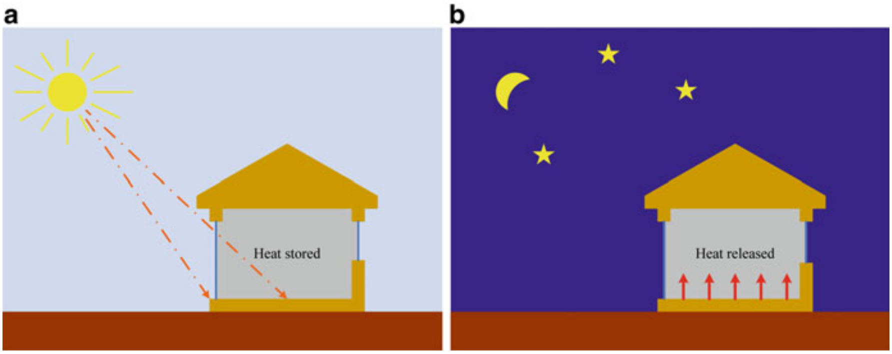


Fig. 7.17 A schematic representation of the concept of thermal mass in winter during day (**a**) and night (**b**) (Taken from: Department of Industries 2014)

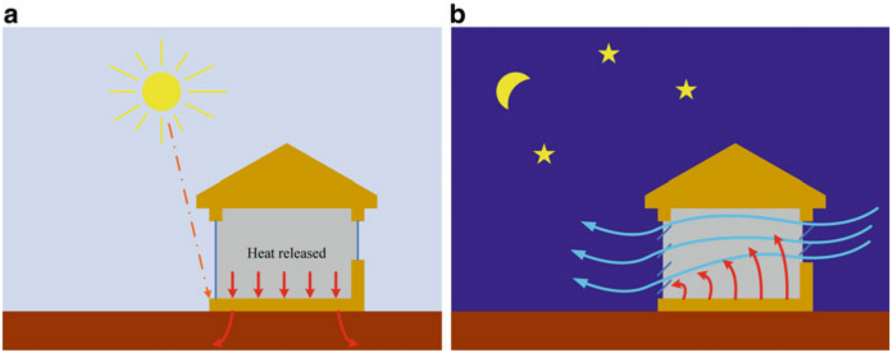


Fig. 7.18 A schematic representation of the concept of thermal mass in the summer during day (**a**) and night (**b**) (Taken from: Department of Industries 2014)

Fig. 7.19 Two buildings in Olinda, Brazil with different types of sun barriers: (**a**) a dwelling with closed windows (shutters) and doors during daytime and (**b**) a church window where the glazing system has additional shutters placed to the inside of the building and thus decreasing the sunlit area

Table 7.6 Thermal properties of the two selected vertical envelope constructions (Ferrari 2007)

Type	U-value [W/m^2 K]	R$_c$-value [m^{2}K/W]	Heat capacity [kJ/m^{2}K]	Thickness (excl. plaster) [cm]
Heavy	0.66	1.35	1,482.2	95
Light	0.66	1.35	47.3	6

shutters and windows are closed during the day and opened for maximum ventilation during the night. In tropical regions thermal mass plays only a small role in the daily cycles, since the temperature fluctuations are generally too small.

For thermal mass to be effective, temperature differences larger than 6 °C (11 °F) between day and night are generally required (Department of Industries 2014). If the temperature fluctuations are smaller, the temperature in the building will be about the same indoors as outdoors. For temperature differences larger than 10 °C (18 °F) high mass constructions are desirable (Department of Industries 2014). In tropical climates with small diurnal fluctuations, high mass constructions can cause thermal discomfort. The amount of energy stored during the day and released at night, keeps the indoor temperatures at high levels. Careful design of thermal mass, shading devices and insulation layers can overcome these problems, see Fig. 7.19a, b.

Ferrari (2007) presents the effectiveness of thermal mass on the reduction of energy demand. Two vertical envelope constructions were modelled: heavy and light (Table 7.6), with the same overall heat transfer coefficient.

For both constructions, the energy demand was calculated by simulation. The DOE-2 program was used to predict the hourly energy use and energy cost of the building using hourly weather information and a description of the building and its HVAC equipment and utility rate structure. Several variables were simulated: building typology (1 story, 2 stories, 4 stories and 16 stories), different climate scenario's (Rome, Milan and Palermo, Italy), different azimuths (south, west, north, east). In all the different scenarios, the overall conclusion was similar to the base case: the heavy construction was more energy efficient in both summer and winter (Fig. 7.20).

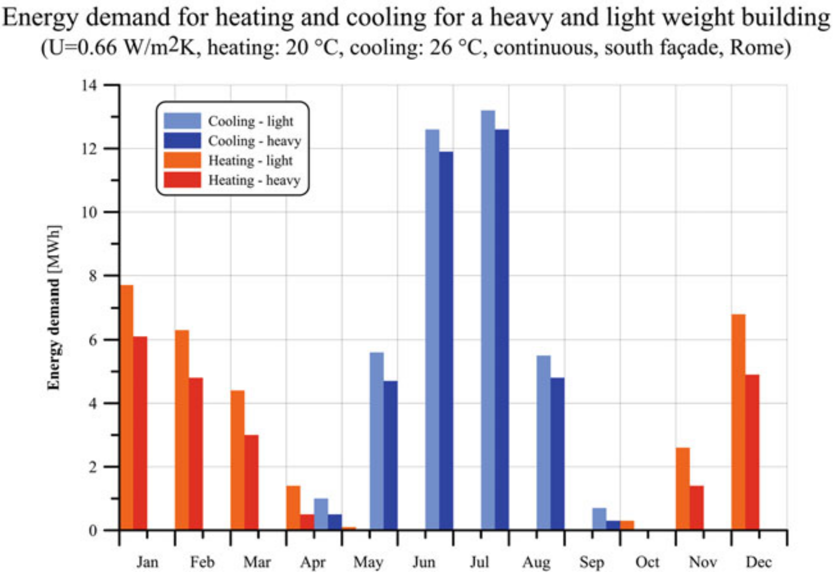


Fig. 7.20 Comparison of the energy demand for a light and heavy building envelope (Taken from: Ferrari 2007)

Special: Roofs in the Tropics

In tropical regions there are two strategies to maintain indoor temperatures at comfortable levels. The first is to reduce the infiltration of warm outside air by making the building airtight and adding a cooling system. This is an energy consuming way to control the indoor temperature. One of the positive side effects of cooling the indoor air, is dehumidification. A less energy consuming way to maintain acceptable indoor temperatures, is to use building materials and structures to control natural ventilation. First of all the influence of the sun needs to be limited. This means that windows on the east and west side need to be shaded or avoided and that heat transfer through the roof needs to be limited by insulation, preferably on the outside. The effect of insulating a concrete roof on the indoor temperature was investigated by Halwatura and Jayasinghe (2008). The research showed that an uninsulated concrete slab of 125 mm thickness (Fig. 7.21) can generate indoor surface temperatures higher than 40 °C (104 °F), which will be uncomfortable to people. Insulating the concrete slab on the outside reduces surface temperatures by approximately 10 °C (18 °F).

(continued)

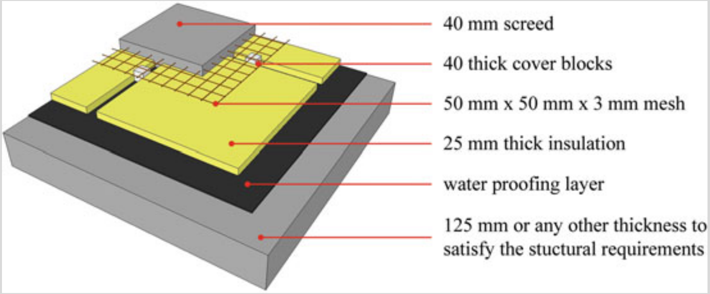


Fig. 7.21 Cross section of the concrete roof investigated by Halwatura and Jayasinghe (Drawing adapted from Halwatura and Jayasinghe (2008))

If altering the building and/or implementation of an HVAC-system are not possible, then ventilation remains the only option. This can also help to remove excess heat and reduce relative humidities to a certain extent.

Special: Dew Point and Condensation

In the Northern hemisphere, when outside temperatures are very low, condensation on the inside of windows panes can often be observed in rooms with a high moisture load, such as kitchens, bathrooms and sometimes even historic houses and museums.

When the surface temperature is low enough, water vapor in the boundary layer will condense to become liquid water: the relative humidity near the surface is 100 %. The temperature at which condensation occurs is the *dew point temperature* (T_d). For every combination of temperature and relative humidity there is a corresponding dew point temperature. The dew point temperature at 20 °C (68 °F) and a relative humidity of 50 % is approximately 9.3 °C (49 °F). So when the surface temperature drops below 9.3 °C, condensation will occur (Special: the psychrometric chart). In hot and humid climates the dew point temperature is much higher. At 75 % relative humidity and 30 °C (87 °F) the dew point temperature is 26 °C (78 °F). There are several dew point calculators available on the internet that can be used by providing the relative humidity and temperature.

In Fig. 7.22 a wooden window is shown with two panes of single glass. The window on the left contains single glazing without any coating and has no condensation. The window on the right is also single glazing but with a low emissive coating on the inside. The coating increases the thermal resistance of the boundary layer. Therefore less heat from the inside is lost through the window to the outside. The outisde temperature reduces the surface temperature of the glazing below the dew point temperature and surface condensation occurs. The outdoor and indoor climate conditions are the same for both windows.

(continued)

Fig. 7.22 Two window panes in a wooden window frame. The *left* window is a single clear pane. The *right* window pane is made of single clear glass coated with a low emissive metal oxide coating on the inside (Photo: H. Schuit 2013)

Notice that due to this process the air is dehumidified. In the presence of moisture sources, such as humidifiers, this process will continue. However, in the absence of a moisture source, condensation might stop due to a decrease of absolute humidity, with a subsequent decrease of the indoor relative humidity and thus a decrease of the dew point temperature. Having lowered the absolute humidity in the air, condensation is less likely to reoccur, if the temperature remains the same.

7.4 Air

Air or air flow is a way to transfer thermal energy or water vapor from one place to another. Air flow can be quite fast and can hold a significant amount of thermal energy or water vapor. Air flow can also be quite complex. Measurements have shown that the air flow in a corridor of an office building was occurring in two opposite directions at same time. Also the mixing of air can sometimes be complex. Air flow patterns can be visualized by smoke or simulation but can give only a rough indication of relatively large air flows. Knowledge of the driving forces will help understand the most common air flow patterns. This will also help in comprehending the way the indoor climate is formed and influenced (Fig. 7.23). The exchange of air between different zones, i.e. outside versus inside, or room versus staircase, is called the air exchange rate (AER). The AER expresses the total amount of infiltration,

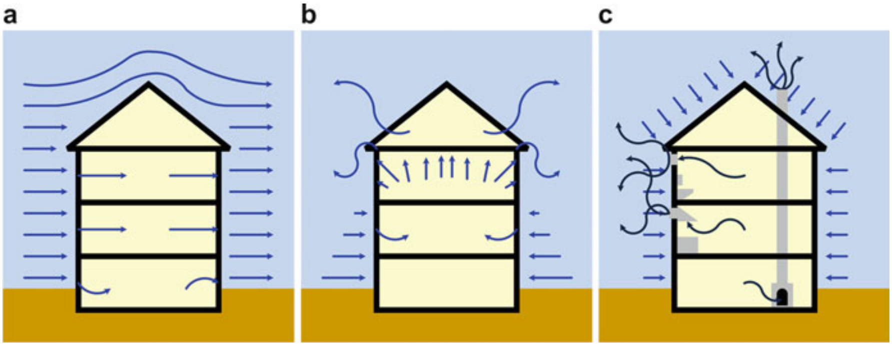


Fig. 7.23 Causes of air flow through a building (**a**) wind, (**b**) stack effect, (**c**) ventilation systems

exfiltration and ventilation of a given zone. The AER is defined as the amount of times a given volume is exchanged per unit time (day or hour).

7.4.1 Infiltration

Infiltration is the uncontrolled exchange of air between zones. It is caused by wind, negative pressurization of the building, and by air buoyancy forces, known more commonly as the stack effect. The pressure differences between the windward side and leeward side of a building will cause an air flow through the building. On the windward, i.e. the high pressure side air will enter the building through cracks and seams (Fig. 7.23a) and will leave on the leeward, i.e. the low pressure side of the building.

When a building is heated, the density of the air is reduced and it will rise. This will create a high-pressure area near the roof of the building, causing air to escape through seams and cracks at the upper levels. At ground level, a low-pressure area is formed, which will create air flows into the building (Fig. 7.23b). Obviously, exfiltration is the opposite of infiltration and describes the uncontrolled exchange of indoor air to the outside.

7.4.2 Ventilation

Ventilation is the controlled exchange of air between indoors and outdoors, or between different zones indoors. Ventilation can be divided into natural ventilation, which describes the passive process of opening doors and windows, and mechanical ventilation by means of active systems using one or more fans. The main purpose of ventilation is to supply a sufficient amount of fresh air to the people within a building, and to remove pollutants and excess moisture and smells from the building (Rode 2005).

Buildings with chimneys and appliances for air ventilation will generate an air flow due to a low indoor pressure. Open chimneys and fireplaces are very effective in transporting air via stack pressure. This air is replaced by outdoor air that enters into the building through seams, cracks and other openings (Fig. 7.23c).

7.4.3 Air Flow

Air flow with a certain temperature holds a specific amount of thermal energy. This amount depends on the temperature difference (symbol: ΔT or Δθ, unit: °C, °F or K), the density (symbol: ρ, unit: kg/m^3) and thermal heat capacity (symbol: c, unit: kJ/kg) of the air. The density of air at 20 °C (68 °F) is about 1.2 kg/m^3 with a heat capacity of 1,000 kJ/kg. For practical reasons these are usually assumed to be constant. The loss or gain of energy due to ventilation or infiltration has to be compensated when a more or less constant indoor climate is required. The higher the airflow rate, the more energy is lost or gained. This will determine the necessary capacity of heating, cooling, humidification and dehumidification. Therefore it is very helpful to know the amount of air that is exchanged with the outside, i.e. the air exchange rate (AER).

Assessing the AER for a closed zone seems relatively straightforward, but in practice adjoining rooms will exchange air, due to wind effects the building will allow some air to be exchanged with the outside and air is actively exchanged by an HVAC system making the real situation often quite complicated. The multitude of air exchanges are visualized in Fig. 7.24. Note that infiltration and exfiltration can

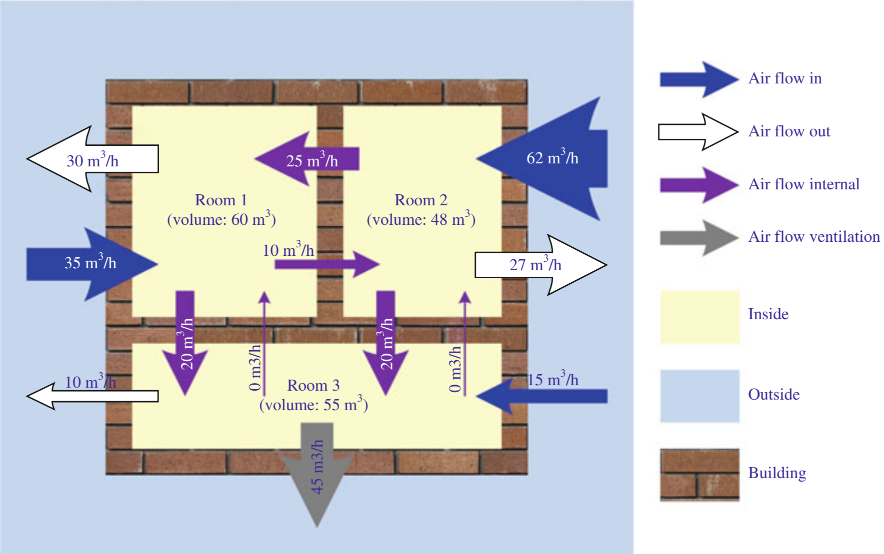


Fig. 7.24 A schematic representation of air exchanges for a fictional building. The *arrows* indicate the direction of air flow and the numbers the amount of air moved

take place simultaneously between the in- and outside but also between internal zones. Internal air flows can change rapidly due to outside conditions like wind and stack pressure.

To assess the air flow within a zone there are two basic rules:

1. The amount of air entering the building must be equal to the amount of air leaving the building, and
2. The air entering a zone must be equal to the amount of air leaving a zone.

The air flow in m^3/h can be determined by measuring the air velocity (m/s) over a certain surface (m^2). Practically this involves measuring air velocities at all openings in a zone and determining the size of these openings and multiplying them. The total flow rate is than calculated as the sum of all individual flow rates for each opening.

When in equilibrium the amount of air entering must be equal to the amount of air leaving, see Fig. 7.24. Thus: air flow in, equals air flow out. It can be seen that the amount of air entering for room 1, equals 35 + 0 + 25 = 60 mm^3 of air per hour. Similarly, the amount of air leaving equals 30 + 20 + 10 = 60 mm^3 of air per hour. Since the volume of the room is 60 m3 the AER is 1 per hour. Please note that the air flow from room 3 to room 1 (and from room 3 to room 2) is zero. This indicates that room 3 is depressurized and as we can see in Fig. 7.24 this is done by a mechanical ventilation system (grey arrow). What applies to room 1 must also apply to room 2 and 3 and to the building as a whole.

Most buildings are not air tight, especially historic buildings can be very leaky due to seams and cracks in the building envelope. To design an HVAC-system, the amount of air that needs to be climatised depends directly on the air tightness of a building. So the AER of the building must be known. Otherwise the subtle balance between air in (ventilation plus infiltration) and air out (exfiltration) can easily be disturbed by wind effects and the climatic specifications might never be met. But to achieve satisfactory air tightness, large alterations of the (historic) building envelope might be necessary, with subsequent loss of historic, architectural and cultural values.

Changing the air exchange of a building (zone) will have an impact on the moisture balance and the amount of fresh air brought in from outside. In Northern regions the building accumulates moisture from driving rain and ground water, this moisture will evaporate on the out- and inside of the building. When these buildings are insulated and made more airtight, not only the heat loss by conduction (transmission) and convection (ventilation) is reduced, but also the infiltration of outside air and therefore the ability of the building to remove moisture. Changing the historic moisture balance might reduce risks in the short term, but if done improperly it can also increase the risk of mold significantly.

7.5 Moisture

As illustrated in Fig. 7.1 the indoor climate is influenced by external and internal moisture sources. Generally rainwater is the most significant and influential external moisture source. Failure of the drainage system will cause wetting of walls, and subsequent evaporation to the inside might lead to e.g. mold and/or salt damage. Lack of maintenance is often the cause for failure of drainage systems, but other causes could be:

1. Debris, leaves and moss in parapet and central gutters;
2. Damaged lead or asphalt gutters;
3. Missing or loose mortar joints between ridge tiles;
4. Displaced or damaged slates;
5. Gaps in lead flashings at abutments, chimney stacks and parapets;
6. Cracks or missing mortar joints on top surfaces of coping stones and parapets;
7. Open joints in brickwork;
8. Structural movement e.g. opening of mortar joints;
9. Damaged and under-sized rainwater gutters and downpipes;
10. Hairline cracks in render;
11. Missing render;
12. Plant growth and debris in gutters and gulley's;
13. Higher external ground level.

In order to prevent water from entering the building, regular maintenance is essential. Best practice is to make annual inspections and plan future maintenance in advance. Obviously, the risk of water entering the building depends on the amount of rainfall and the capacity of the drainage system. The amount of precipitation depends on the geographical location and orientation. In Fig. 7.25 the average annual amount of precipitation is given in inches and centimeters for any location in the world. Regions with high precipitation, e.g. due to rainy seasons, should take measures to avoid excess of water entering the building and to ensure water drains away from the building fabric.

Some rainwater is absorbed by the ground. Foundations below the groundwater level will absorb and transport this water by capillary suction. As soon as the

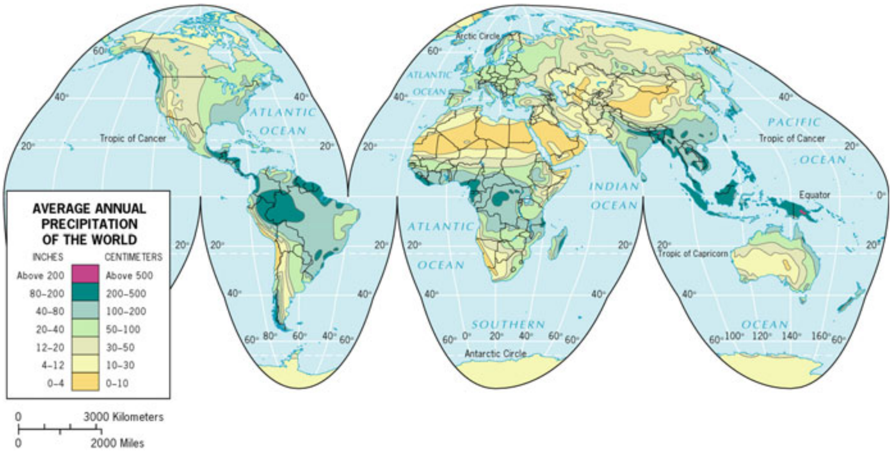


Fig. 7.25 Average annual precipitation of the world (Source: http://planetolog.com)

environmental conditions are suitable for drying, in general a low relative humidity, liquid water in the building material will evaporate at the surface to become water vapor. As long as the water source is infinite, like groundwater, there will be an equilibrium (see Fig. 7.32). Whether or not this will lead to building decay depends on the materials used and the exterior and interior finishes as described in Chap. 5.

Equipment can be used to change the indoor relative humidity. In humid climates dehumidification might be necessary. Dehumidification will extract water vapor from the indoor climate by condensation on a cold surface, see Chap. 9. Increasing ventilation with dry outside air, i.e. outside air with a lower absolute humidity than the indoor air (Fig. 7.26) or increasing the indoor temperature are options to reduce the relative humidity. The latter might be energy consuming and increases the risk of chemical degradation and lower thermal comfort at high temperatures.

In dry climates humidification might be needed. Humidification will add water vapor to the indoor climate by evaporating water. In Chap. 9 options to increase the relative humidity are discussed. Some indoor activities will also generate moisture. Visitors will exhale wetted air and when in great numbers might even change the absolute humidity. During a wedding at Our Lord in the Attic the absolute humidity increased from 8 to 10 g/kg due to the attendance of 100 people (Maekawa et al. 2007). The capacity of some typical moisture sources, found in homes are provided in Table 7.7.

In some cases the outdoor climate can be used as a moisture source or sink. This depends on two factors: First the actual indoor relative humidity is not the desired indoor relative humidity and secondly, the outdoor absolute humidity needs to be

Fig. 7.26 Sometimes ventilation is an easy, cheap and sustainable way to cool and dry the indoor air in tropical regions

Table 7.7 The typical moisture capacity of some indoor sources

Source	Typical moisture capacity	
Cooking	2.0 l	At a time
Dishwasher	0.5 l	Per use
Showering	0.5 l	Per use
Plants	1.0 l	Per day (average)
Dryer	3.5 l	At a time (after centrifugation)
People	0.25–0.50 l	Per person per hour

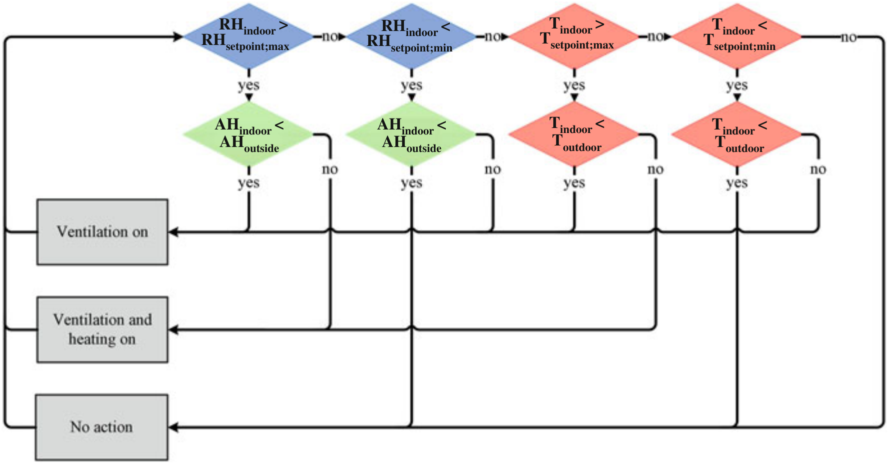


Fig. 7.27 Schematic representation of the ventilation control system for ‘smart’ ventilation (Taken from: Peters 2007)

higher than the indoor absolute humidity, if the indoor relative humidity is too low, and vice versa. This concept is called smart ventilation. For Museum Muiderslot in the Netherlands this strategy (Fig. 7.27) was successfully used to improve the indoor climate. Although the indoor climate sometimes still fell outside the climate specifications of 5 °C < T < 25 °C (41 °F < T < 77 °F) and 40 % < RH < 65 % (±10 %/day). In winter the indoor climate fell within the specifications 69 % of the time instead of 25 % and in summer 83 % instead of 49 % (Peters 2007).

Moisture, both as a liquid or as a gaseous vapor can be damaging to the building fabric. When the moisture content of a building material is high for a long period of time the risk of mold or rot increases significantly. In cold climates high moisture loads of the building envelope will also increase the risk of frost damage. But even when a building is designed to prevent water from entering, some moisture will be transported into the building; by diffusion of water vapor and capillary suction of liquid water. To successfully mitigate water accumulation within the building and its fabric some knowledge on the moisture transport mechanism is essential. For a good understanding of moisture transport mechanisms it is important to know whether liquid water or its vapor is involved. The driving forces behind the transport mechanisms are different, see Table 7.8.

Table 7.8 Driving forces behind the transportation of moisture

State of aggregation	Mechanism	Driving force
Water vapor	Diffusion	Difference in partial vapor pressure
	Convection	Difference in total air pressure
Water	Capillary	Difference in capillary suction
	Gravity	Mass
	Pressure	Difference in total external air pressure

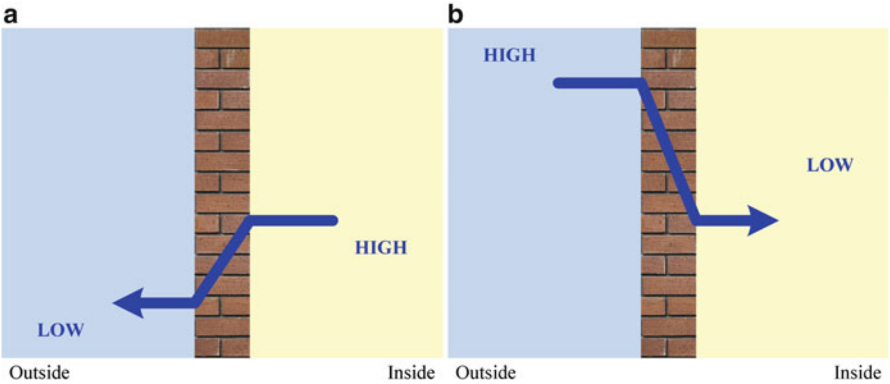


Fig. 7.28 A schematic representation of vapor diffusion through a wall in the northern hemisphere in winter (**a**) and summer (**b**)

7.5.1 *Vapor Transport by Diffusion*

The driving force of vapor diffusion is the partial pressure differences of water vapor. Note that this pressure difference only refers to the water vapor and thus is related to the absolute humidity of the air. Water vapor will move from areas with high water vapor pressure, i.e. high absolute humidity, to areas with low vapor pressure.

A museum with an indoor relative humidity of 50 % and a temperature of 20 °C (68 °F) will have an absolute humidity of 8.66 g/m^3. The partial water vapor pressure will be about 1,170 Pa. During cold periods in the northern hemisphere low outside temperatures, e.g. −5 °C (23 °F) and a relative humidity of about 85 % will result in an absolute humidity of 2.91 g/m^3. The partial vapor pressure will then be about 340 Pa. As a result moisture will flow from the inside to the outside, see Fig. 7.28a. In summer with temperatures of 30 °C (86 °F) and 70 % relative humidity outside, the absolute humidity will be 21.3 g/m^3 and the partial water vapor pressure will be about 3,190 Pa. The water vapor will flow from the outside to the inside, see Fig. 7.28b. Note that the partial pressure difference for water vapor in summer is significantly larger than in winter. Resulting in a larger moisture flow in summer.

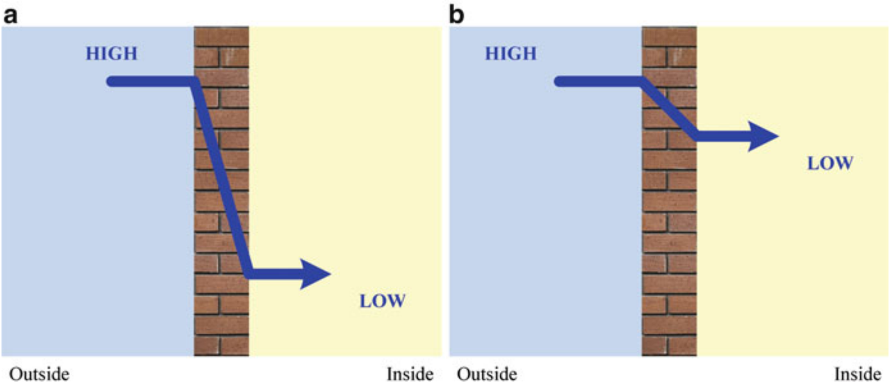


Fig. 7.29 A schematic representation of vapor diffusion through a wall in the tropical region in wet season (**a**) and dry season (**b**)

If the building is located in a tropical region the situation is slightly different. Outdoor temperatures will be high. In the wet season the outdoor temperature decreases a little e.g. to 27 °C (81 °F) but the relative humidity will increase to 80 or 90 %. The absolute humidity will be somewhat higher: 19.5 g/kg. The water vapor pressure will be around 3000 Pa. The indoor temperature can be estimated and will be lower than outdoors: 24 °C (75 °F). The indoor relative humidity decreases to 55–65 %. The absolute humidity will be around 11.5 g/kg and the water vapor pressure will be around 1,800 Pa. Water vapor will flow from the outside to the inside, see Fig. 7.29a. During the dry season, outdoor temperatures of around 30 °C (86 °F) and a relative humidity of around 70–80 % can be measured. The absolute humidity would be around 20.5 g/kg and the water vapor pressure would be around 2,900 Pa. Indoor conditions for traditional buildings can be estimated for the dry season with an indoor temperature of around 27 °C (81 °F) and relative humidity of around 72 %. The absolute humidity would be around 16.4 g/kg and the water vapor pressure would be around 2,600 Pa. Water vapor will still flow from the outside into the building, see Fig. 7.29b.

One of the key factors that determine the rate in which vapor diffuses through materials is the water vapor resistance factor (abbreviated as wvrf, symbol: μ, unit: dimensionless ratio). This factor characterizes the resistance of materials to vapor transport compared to one meter of air, which is indexed as 1. This μ-value is relative and helps to indicate the relative water vapor permeability of different materials. Materials with vapor barrier characteristics that reduce vapor diffusion obviously have very high numbers, ranging from 9,000 to 150,000 (see Sect. 7.5.3). Metals, glass and cellular glass insulation are vapor and watertight. In Table 7.9 some wvrf's are provided for some common building materials.

Table 7.9 Water vapor resistance factor (wvrf) of different building materials

Material		Wvrf
Insulation material	Mineral wool and capillary active panels	1–6
	Petro chemicals (PS, PUR, PVC, etc.)	15–250
	Foamglas	∞
Gypsum board		5–6
Plaster		6
Brick		9–13
Concrete		25–33
Wood		100
Glass		∞
Metals		∞

7.5.2 Vapor Transport by Convection

Convective vapor transport is in many cases the most important cause of moisture related damage in the northern hemisphere (Janssens and Hens 2003; Rousseau 2003; Said et al. 2003). In cold climate regions the building envelope has a low temperature during winter. When warm, humid indoor air is allowed to penetrate into the building envelope, the water vapor will condensate inside the construction. There are several pathways that can lead to surface condensation as can be seen in Fig. 7.30.

In winter the building envelope in the northern hemisphere becomes colder moving from inside to the outside. Especially when buildings are insulated on the inside, or when the cavity is filled with an insulation material, the outer leaf of the building envelope will get colder increasing the risk of surface condensation. So, once warm humid indoor air penetrates the building envelope it will cool the air down. As a result water vapor will condense on, or inside, the building structure, known as surface condensation.

Vapor diffusion through materials plays a minor role when compared to convective vapor transport. The amounts of moisture transported by convection typically far exceeds those of diffusion (Anonymous 1997). Convective moisture transport is driven by the difference in total air pressure (see Sect. 7.4: Air), which is primarily related to the air tightness of the zone.

7.5.3 Water Transport by Capillary Sorption

Materials that allow moisture transport are referred to as being hygroscopic. These materials have pores with a wide range of sizes. The smaller the pore size, the larger the capillary suction. Furthermore small pores can absorb water from large pores but not the other way around. Pores can be classified by size as micro-pores

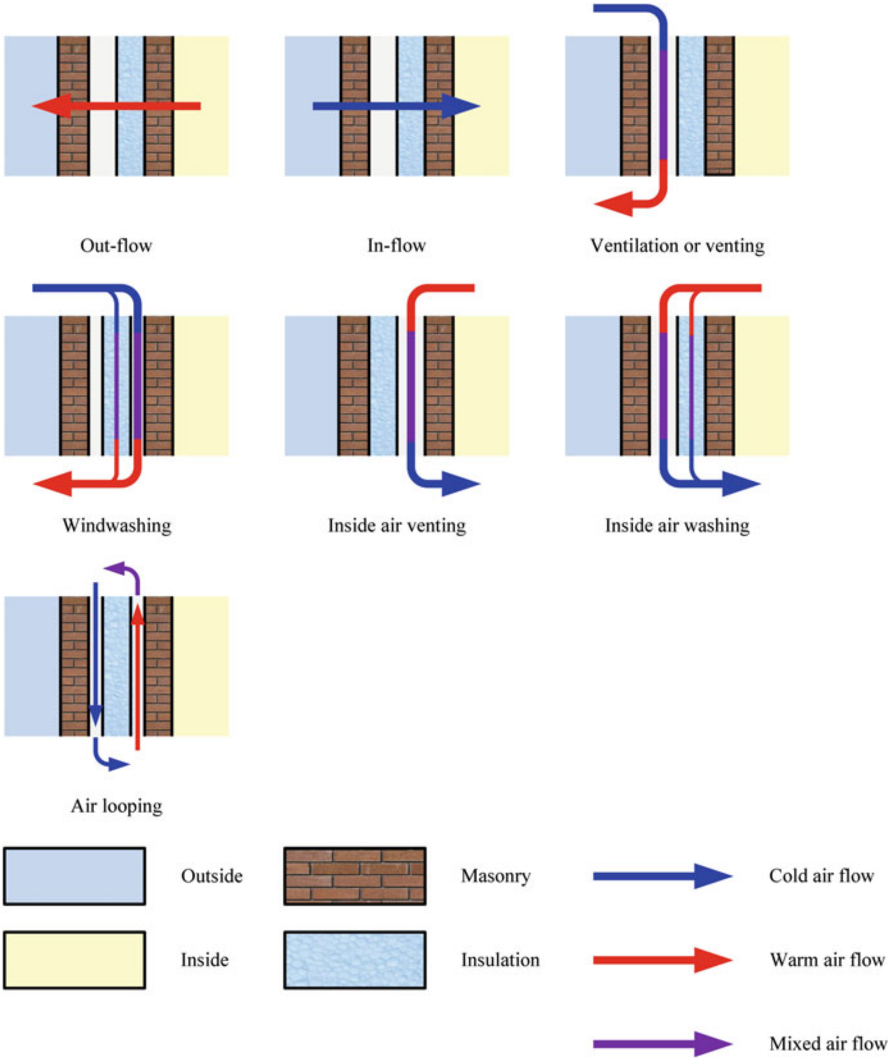


Fig. 7.30 Different air flow modes in cavity walls. If warm humid air (*red*) penetrates the structure it will cool off (*purple*). If the temperature of the cold air (*blue*) drops below dew point condensation will occur (Taken from: Hens et al. 2007)

(diameter <10 nm), meso-pores (diameter between 10 and 100 nm) and macro-pores (diameter larger than 100 nm) (Van Hees and Lubelli 2012). Most materials will have both large and small pores. Large pores have a radius of 1–100 μm, small pores have a radius of 0.01–1 μm (Fig. 7.31).

When a material is wetted, the large pores quickly absorb water, while small pores take more time to be filled. The drying rate of large pores is obviously also quicker than the small pores. The pore size distribution determines the wetting and drying behavior of a material. The most important water transport by capillary

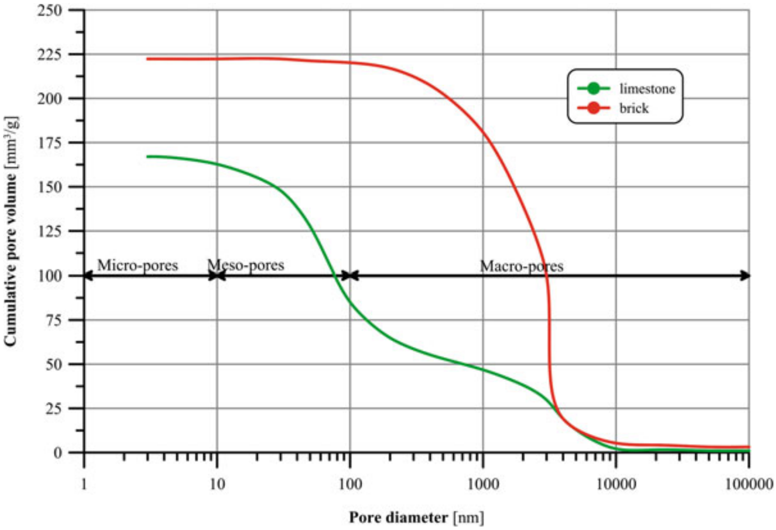


Fig. 7.31 Pore size distribution of two typical building materials: brick (*red*) and limestone (*green*) (Taken from: Brocken 2012)

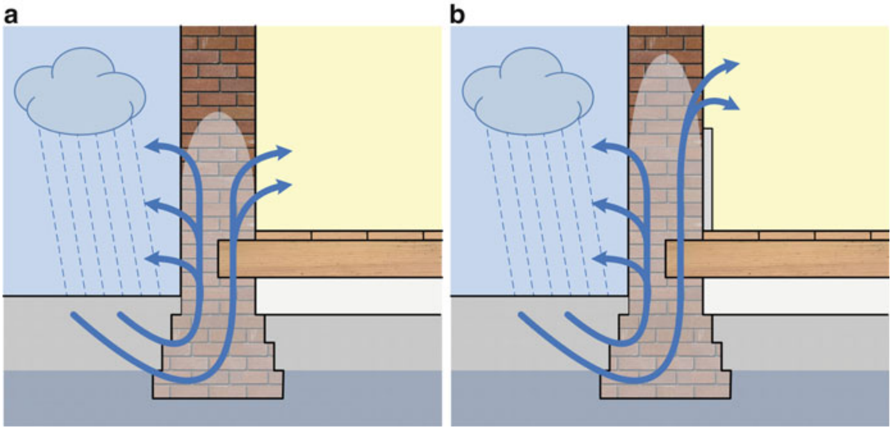


Fig. 7.32 Rising damp in an outer wall without interior finishes (**a**) and rising damp in an outer wall with a vapor impermeable layer causing capillary water to rise higher (**b**)

sorption is rising damp. This phenomenon can manifest itself on the inside as well as the outside of buildings, see Fig. 7.32.

When a building or building material is wet or moist, and the environmental conditions are right, drying will occur in two stages. The first stage occurs when all the pores in a material are full of water. At the surface, water will evaporate. This will continue as long as there is liquid water present near the surface, for instance when a wall is connected to groundwater. This first drying stage is relatively fast. The second stage occurs when there is no more liquid water available at the surface, for instance when the evaporation rate is larger than the supply of liquid water from the inner core. In this case the evaporation front will be inside the material. At this front, liquid water will become water vapor. This water vapor then has to be transferred out of the material by diffusion, which is a relatively slow process. These differences in drying rates are the cause of building defects like frost damage and crypto efflorescence. Because of the slow drying process of the second stage, hygroscopic building materials like brick will stay wet for a long period of time after absorbing water during a rain shower. In cold climates where temperatures are below 0 °C (32 °F) absorbed rain water can freeze leading to frost damage. In building materials like brick it is very common that salts are present. When those salts are dissolved in water and drying occurs, whether to the outside or inside, salts will migrate. At the point where water evaporates salts will form crystals. Thus during the first stage the crystals will be formed on the surface (efflorescence) causing aesthetic loss but no actual damage to the brick. During the second stage crystals will be formed inside materials (crypto efflorescence). These crystals can cause crystallization pressures that might cause the face of the bricks to crumble and disintegrate.

7.5.4 *Interstitial Condensation*

Depending on the differences in the partial pressure of water vapor, water vapor will be transported from the outside to the inside or vice versa. In cold climates a specific risk can occur when warm moist air penetrates into the building structure. This process is facilitated when building materials, gypsum and brick with a low water vapor resistance factor are used. In cold climates, during periods with low outdoor temperatures, the buildings structure is cold on the outside but can be heated on the inside (Fig. 7.33). When insulation materials are used with a low wvrf

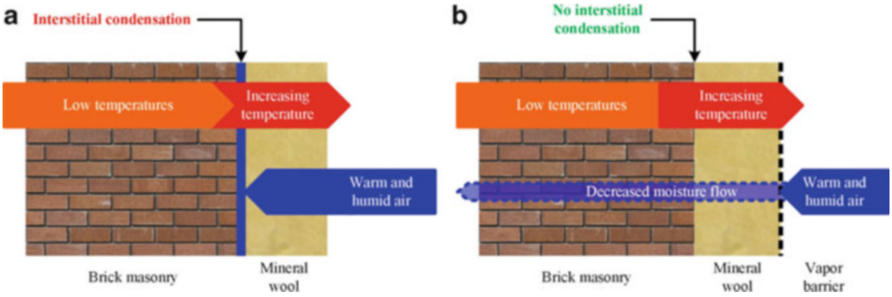


Fig. 7.33 A schematic presentation of interstitial condensation (**a**) and how to prevent this (**b**)

the temperature difference can be quite large (see also Table 7.9) and moist air can penetrate into the building structure to the point where the structure's temperature is below the dew point and water vapor will condensate (Fig. 7.33a). At this point the partial vapor pressure exceeds the maximum vapor pressure. This is called interstitial condensation, and it occurs within the materials of the building structure. To prevent interstitial condensation, vapor barriers can be applied (Fig. 7.33b). These are located on the side with the highest temperature i.e. on the inside in cold regions and on the outside in hot and humid regions. This vapor barrier will prevent high vapor concentrations from penetrating into the structure thus decreasing the risk of interstitial condensation (Quirouette 1985).

The so-called equivalent air layer thickness (symbol: Sd, unit; m) is a measure to describe the effectiveness of any given material to prevent interstitial condensation. It can be calculated by multiplying the thickness (d) and water vapor resistance factor (wvrf) of a material. To prevent interstitial condensation the equivalent air layer thickness needs to be 0.5 m or more (Borsch-Laaks 2006). In Table 7.10 this value for various vapor barriers is provided.

The main purpose of an air barrier is to stop outside air from entering the building or vice versa through seams and cracks in the building fabric. The purpose of a vapor barrier is preventing diffusion through the building fabric. The latter is perfectly suited to prevent surface condensation inside the structure by stopping infiltration and exfiltration (Quirouette 1985). In practice both types of barriers are combined into one layer (foil). Care should be taken to ensure that seams of this foil are also air tight. Applying barriers in practice in such a way that air tightness in achieved, is very difficult. Extreme care should be taken when applying these foils and closing the seams (Fig. 7.34a, b).

Lime plasters or sprayed foam insulation will also reduce in- and exfiltration, but especially the foam insulation is obviously much less suitable in most historic buildings.

Table 7.10 The equivalent air layer thickness of various vapor retarders and barriers

Material	Thickness [mm]	Water vapor resistance factor (μ) [−]	Equivalent air layer thickness (Sd) [m]
Tar paper (single sided)	0.15	580	0.087
Tar paper (double sided)	0.30	3,000	0.9
Glass fleece	2.0	4,000–60,000	8–120
Polyvinylchloride foil	0.1	9,000–45,000	0.9–4.5
Polyethylene foil	0.1	45,000–140,000	4.5–14
Polyethylene foil	0.3	34,000	10.2
Polyester	0.1	4,000	0.4
Roofing felt (2×) and bitumen layers (3×)	5.0	700,000	3,500
Latex paint	0.1	1,500	0.15
Oil paint	0.03	3,000–8,000	0.09–0.24

Fig. 7.34 The application of vapor barriers is an import but sometimes difficult job: (**a**) a vapor barrier with very small overlap and weakly glued seems, this can become problematic in future and needs adjustment (Photo: Van der Wal, Cultural Heritage Agency of the Netherlands), (**b**) a properly executed vapor barrier with a sufficient overlap and properly glued seems as part of a wall closing protocol

7.5.5 Hygric Mass

Fluctuations of the indoor relative humidity can sometimes be buffered by the hygroscopic mass of the building. For air exchange rates less than one per hour, hygroscopic walls and ceilings can stabilize the indoor relative humidity significantly (Padfield 1999). The larger the ability to absorb or desorb moisture from the surrounding air, the higher the hygric mass or storage capacity (specific hygroscopic moisture capacity: symbol: ξ, unit: kg/m^3). This capacity is easily readable from a hygroscopic curve. The steeper the curve, the higher the specific hygroscopic moisture capacity, see Fig. 7.35. In general all building materials have a higher moisture capacity at high relative humidity levels. But since most indoor climates in museums will have a relative humidity between 40 and 60 %, see the grey area in Fig. 7.35, gypsum plaster and wood are comparatively good buffers. From this figure it is also evident that (fired) brick, a common building material, has a rather poor storage capacity.

But even materials with high moisture capacity become useless as a hygric buffer when the rate at which they absorb or desorb is too fast or too slow. For materials the buffer efficiency depends not only on the specific hygroscopic moisture capacity but also on the resistance to water vapor transport, characterized by the water vapor permeability coefficient (symbol: δ, unit: s). The rate at which vapor is absorbed or desorbed is given by the water vapor diffusivity (symbol: D_v, unit: m^2/s). The effective depth is a measure for the thickness of the wall that is actually used for buffering. The effective depth depends on the water vapor diffusivity and the length of a certain periodical fluctuation. The hygric buffer

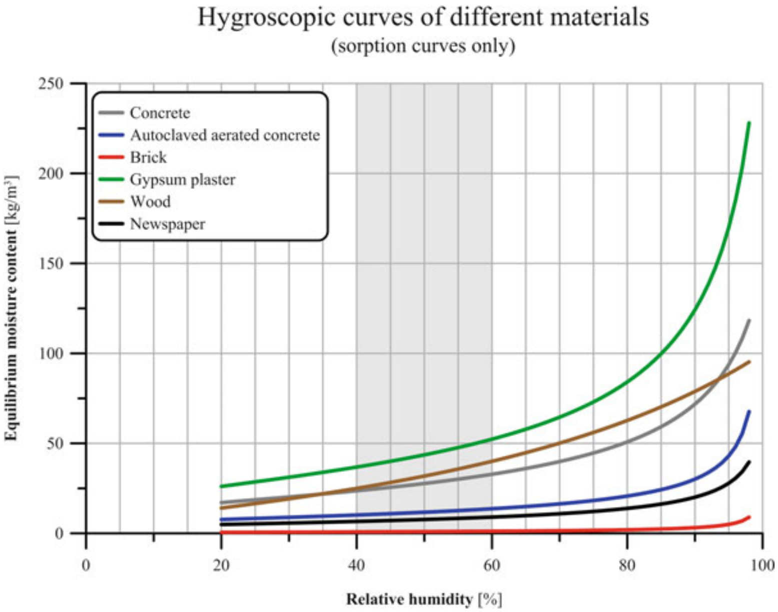


Fig. 7.35 Hygroscopic sorption curves for different materials, the steepness of the curve is a good indicator for hygric storage: a steeper curve indicating better hygric storage (Based on data taken from: Hens 2003)

capacity is the product of the hygric mass and the effective depth. A material that is very thin will simply not have sufficient storage capacity, i.e. has a low hygric mass. A material that has a large hygric storage capacity but is a bad hygric conductor, i.e. a low vapor diffusivity, will absorb and desorb moisture too slowly for this property to be useful and vice versa. This relation is presented in Fig. 7.36. In general, the higher the water vapor permeability coefficient (or lower the water vapor resistance factor) the higher the effective depth and the better the overall hygric buffering performance. Note that the hygric buffer capacity is very similar to that of the thermal buffer capacity.

In Table 7.11 the effective depth is given for a diurnal cycle (24 h) for different building materials and for concrete also a 3 month (2,160 h) cycle. It shows that slow fluctuations will penetrate deeper into the building fabric. The effective depth of concrete changes from 0.3 to 2.4 cm comparing a diurnal and 3 month cycle. This is very small when compared to the effective depth for temperature. This means that the complete buffering of a diurnal or 3 months hygric cycle would require a thickness which is readily available in unfinished concrete walls. On the other hand, other materials require a thickness varying from 0.1 to 18.1 cm to buffer daily cycles. The materials with these thicknesses can be found in almost any building. The exception would be mineral wool, where the required depth of material is unlikely to be used. As can be seen from Table 7.11 concrete, lime plaster (best) and wood are good hygric buffers (high hygric buffer capacity). The

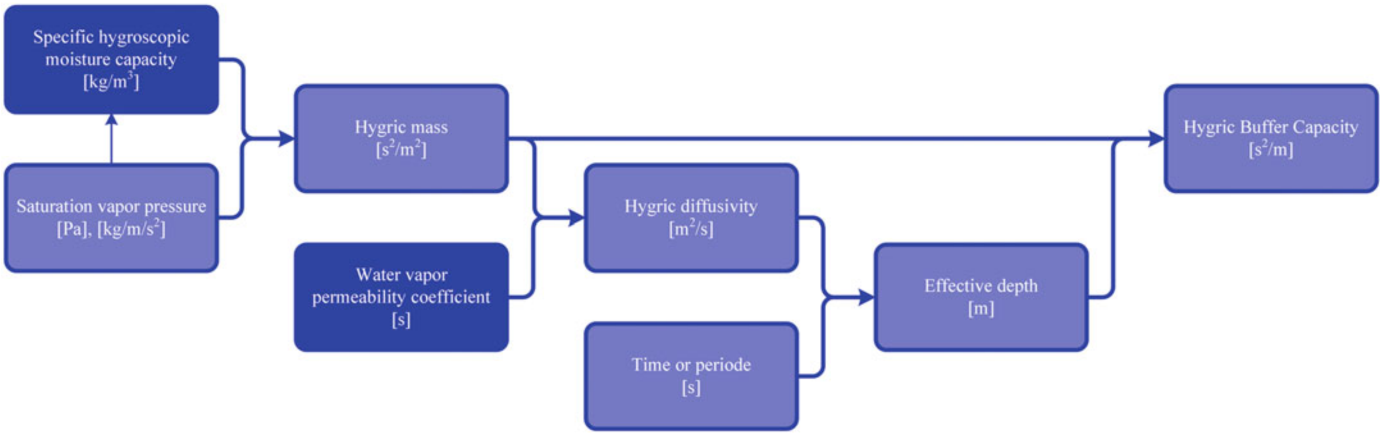


Fig. 7.36 The relation between hygric properties (*solid boxes*), the hygric buffer capacity and the derived physical quantities of building materials

Table 7.11 Effective depth calculated for different periods and building materials

Material	Period t [h]	Water vapor resistance factor μ [−]	Specific hygroscopic moisture capacity ξ_{40-60} [kg/m^3]	Effective depth d* [cm]	Hygric buffer capacity $\times 10^6$ [s^2/m]
Concrete	24	25	76.2	0.3	81.35
	2160	25	76.2	2.4	771.72
Brick	24	10	1.8	2.6	19.85
Lime plaster	24	6	74.9	0.5	164.71
Wood	24	100	73.1	0.1	39.85
Mineral wool	24	2	0.2	18.1	14.04

correspondence with the specific hygroscopic moisture capacity is large. Fired brick and mineral wool are unsuitable. Table 7.11 also shows that the thickness needed to buffer daily fluctuations in general is small (less than 0.5 cm). It should be noted that when the practical available depth is smaller than the theoretical effective depth, the hygric buffer capacity will be the product of the hygric mass and the available depth.

The best and most common buffering materials are wood, cut across the grain, and unfired clay brick (Padfield 1999). Not all of those materials are traditional building materials and some of them have other disadvantages. Note that good thermal buffer materials are not necessarily good hygric buffer materials and vice versa.

7.6 Conclusion

In the past decades the tendency in the heritage field was to gain control over the indoor climate primarily by mechanical equipment. Buildings were adapted to this new hygrothermal balance by making them more airtight and sometimes by applying water vapor barriers. More and more the characteristics of the materials used are chosen based on their ability to positively influence the indoor climate and thereby reduce the capacity of mechanical systems. To make the right choices it is important to know what the current indoor climate is, and how this is influenced by the building fabric and construction. The next seven steps might serve as a guide to start understanding the indoor climate:

1. Determine the orientation of the building and solar gains, wind speeds and wind directions for the building location. These parameters can be measured independently or obtained from a local weather station;
2. Inspect the building on the outside and inside for possible defects. Several visually observable phenomena can help identify problems in the building

envelope: salt efflorescence, algae growth, wet areas, cracks, seams, surface or interstitial condensation, mold growth etc.;

3. Take measurements of the outdoor and indoor climate. The temperature and relative humidity over a period of time give insight in the possible climate risks for the building, interior or collection as presented in Chaps. 4 and 5. Comparison with the outdoor climate gives insight in to how the building affects the indoor climate. The outdoor climate can be measured independently or obtained from a local weather station. The indoor climate also can be measured independently as described in Appendix 4, Fig. A4.1 or can be outsourced to a commercial company;
4. Make an assessment of the hygrothermal properties of the building envelope as described in Sects. 7.3, 7.4, and 7.5 to understand why there is a difference between the outdoor and indoor climate. Gather information on the building envelope regarding: the type of building materials, dimensions of transparent and non-transparent surfaces, layers of building construction from outside to inside, connections between different building parts, etc.;
5. Make an assessment of the air exchange rate;
6. Make an assessment of internal heat and moisture sources and sinks, considering both dynamic and static sources and sinks. Estimate how each zone is influenced by these sources, or sinks, for how long and at which interval. Typical static sources are electrical equipment, plants, etc. Typical dynamic sources are climate systems, people, etc.;
7. Make an analysis of the gathered data. Keep in mind when looking at climate data whether or not these form an actual threat to the building, interior, or collection. Establish whether any indoor climate parameter is a threat: temperature, relative humidity, or their fluctuations. Be precise. Then try to understand why this parameter differs from the optimal. Use the first barrier principle as described in Sect. 7.2 to find the aspects of the building that play a role in how the indoor climate is formed.

The results of this step can be manifold, varying from climatic data presented in figures to a full analysis of the building physics in a comprehensive report. Once the indoor climate is understood in more detail, any optimization of the indoor climate can start with improving the building physics. Depending on the decision to be made a choice should be made on which of the above steps will provide enough information to make an well informed decision. It can be very helpful to use a floor plan in which the climate zones are presented to indicate e.g. moisture and temperature sources and sinks.

References

Anonymous (1997) Wärmetechnische Sanierung schützenswerter Gebäude (seminarheft). Energieegentur NRW, Wuppertal

Borsch-Laaks R (2006) Innandämmung – Wo ist das Risico? WTA-J 1:19–42

Brocken H (2012) Vochttransport tussen steen en mortel: het grijze gebied tussen de stenen. In: Historisch Metselwerk. WBOOKS, Zwolle

Cairns Regional Council (2011) Sustainable tropical building design: guidelines for commercial buildings. Cairns Regional Council, Cairns

De Wit M (2009) HAMBASE part II input and output heat air and moisture model for building and systems evaluation. University of Eindhoven, Eindhoven

Department of Industries (2014) Your home Australia's guide to environmentally sustainable homes. Department of the Environment, Water, Heritage and the Arts, Canberra

Ferrari S (2007) Building envelope and heat capacity- re-discovering the thermal mass for winter energy saving. In: Proceedings of the 2nd PALENC conference and the 28th AIVC conference on building low energy cooling and advanced ventilation technologies in the 21st Century. Greece, 27–29 Sept 2007, pp 346–351

FLIR Systems Inc (2011) FLIR user's manual FLIR Bxxx series FLIR Txxx series. FLIR Systems, Wilsonville

Halwatura RU, Jayasinghe JWR (2008) Thermal performance of insulated roof slabs in tropical climates. Energy Build 40:1153–1160

Häupl P (2007) Energetische Sanierung denkmalgeschützter Bebäude mit kapillaraktiver Innendämmung. WTA-Almanach 2007:131–168

Häupl P et al (2005) Hygrothermal 2-dimensional analysis of critical constructive details of the Rijksmuseum Amsterdam. Institute for Building Climatology, Dresden University of Technology, Germany

Hens H (2003) Randvoorwaarden, prestaties, materiaaleigenschappen. Acco, Leuven

Hens H et al (2007) Brick cavity walls: a performance analysis based on measurements and simulations. J Build Phys 31(95):95–124

Hermans J (2008) Energie survival gids. BetaText, Bergen

ISSO 33 (1996) Kengetallen en vuistregels, hulpmiddel bij het ontwerp van gebouwinstallaties. Stichting ISSO, Rotterdam

Janssens A, Hens H (2003) Interstitial condensation due to air leakage: a sensitivity analysis. J Therm Envelope Build Sci 27:15–30

Maekawa S, Ankersmit B, Neuhaus E, Schellen H, Beltran V, Boersma F (2007) Investigation into impacts of large number of visitors on the collection environment at Our Lord in the Attic. In: Museum microclimates, contributions to the Copenhagen conference 19–23 Nov 2007, pp 99–105. Available at: http://natmus.dk/fileadmin/user_upload/natmus/bevaringsafdelingen/billeder/far/Museum_Microclimate/Proceedings/musmic150.pdf. Accessed 12 Jan 2015

Morelli M et al (2010) Internal insulation of masonry walls with wooden floor beams in northern humid climate. In: Proceedings at thermal performance of the exterior envelopes of whole buildings XI

NPR 2068 (2002) Thermische isolatie van gebouwen- vereenvoudigde rekenmethoden. NEN, Delft

Olsen L, Radisch N (2002) Thermal bridges in residential buildings in Denmark. KEA energeticka agentura s.r.o, Brno

Padfield T (1999) On the usefulness of water absorbent materials in museum walls. In: 12th triennial meeting preprints (ICOM Committee for Conservation): 83–87. France Lyon, 29 Aug–3 Sept 1999

Peters M (2007) Grote binnenklimaatverbetering door klimaatregeling in het Muiderslot. Bouwfysica 21:15–21

Pilette CF, Tayler DA (1988) Thermal stress in double-glazed windows. Can J Civ Eng 15:807–814

Quirouette RL (1985) The difference between a vapour barrier and an air barrier. National Research Council Canada, Ottawa

Rode C (2005) Moisture buffering of building materials. Department of Civil Engineering Technical University of Denmark, Denmark

Rousseau MZ (2003) Heat, air and moisture control strategies for managing condensation in walls. In: Proceedings of BSI 2003, Canada

Said MNA et al (2003) Hygrothermal performance of a masonry wall retrofitted with interior insulation. In: Carmeliet J et al (eds) Research in building physics. Swets & Zeitlinger B.V, Lisse, pp 445–454

Schellen HL et al (2008) The use of finite-element software to solve hygrothermal building physical problems related to insulating high rise building façades. In: Proceedings of the 8th Nordic symposium on building physics, Copenhagen, Denmark, 16–18 June 2008

Song SY, Kim KW (1997) The optimal insulation detail of the thermal bridge adjacent to hot water pipes in apartment building slabs. In Proceedings of BS'97, Prague, Czech Republic, 8–10 Sept 1997

Tammes E, Vos BH (1984) Warmte- en vochttransport in bouwconstructies. Kluwer Technische Boeken B.V, Deventer

Tersteeg R (2009) Verbetering door isolatie, na-isolatie aan de binnenzijde van bestaande woningen. Technische Universiteit Delft, Delft

Van Hees R, Lubelli B (2012) Van bindmiddel en zand tot mortel: samenstelling en gedrag. In: Historisch Metselwerk. WBOOKS, Zwolle