Chapter 2
Long-Term Thermal Performance of Insulations Under Moisture Loads

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Abstract The performance of thermal building envelope insulation systems may be severely impaired by moisture. The best solution would be to keep insulation materials dry at all times. Alas, building practice has proven time and again that this is wishful thinking. Even if the insulation materials are enclosed by vapor barriers on both sides, there is a fair chance that moisture will get inside eventually through imperfections and small leaks emerging during normal use. Once inside, moisture will be trapped there for a long time. Thus, understanding the long-term performance of insulation materials is vital for sustainable and energy efficient building design. This chapter analyzes and quantifies the impact of moisture on the thermal resistance of insulation systems and explains the interdependece of heat and moisture transfer. This hepls to develop durable envelope solutions and appropriate test methods for insulation materials.

2.1 Theoretical Background

Under dry conditions, heat transfer in insulation materials is mainly governed by conduction in the solid and gas phase as well as by thermal radiation within the pore space. Convection by external pressure or buoyancy effects should be minimized by air and wind barriers and the pore structure of the insulation material. If the gas phase is partly replaced by water with its rather high thermal conductivity (0.6 W/(m·K)), the thermal transmittance of the whole system will increase accordingly. This is called the sensible heat effect of moisture. However, there is a second moisture impact on thermal transmittance, the so-called latent heat effect. It is caused by water evaporation and condensation at different location of the assembly. In vapor permeable materials, this effect may transfer more energy than the sensible heat flux by conduction, at least for short periods of time.

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Both effects are relevant to quantify the impact of moisture on the thermal performance of insulation systems. There may be other effects such as heat transfer by liquid flow or thermal storage by ice formation. However, they are usually of minor importance in insulation materials and therefore not considered here. This does not mean that liquid flow has no impact at all, but it is mostly more indirect, e.g. in mineral, capillary active insulation materials whose particular properties enhance vapor diffusion, which will be addressed later.

While sensible heat flux is a linear phenomenon and proportional to temperature gradient and thermal conductivity of the material, the latent heat flux is non-linear and depends only indirectly on the temperature gradient, because it is proportional to the vapor pressure gradient and the vapor diffusion coefficient of the material. Since variations in vapor pressure depend strongly on the moisture stored in the insulation layer but also in the adjacent layers, the latent heat flux may become very dynamic, and a precise analysis requires hygrothermal (heat and moisture transfer) considerations. To quantify its impact in relation to thermal conductance under realistic practice conditions, means to carry out a more long-term investigation to evaluate its dynamic behavior. Short snapshots as in Hedlin (1988) may demonstrate peak values but not necessarily the mean impact over the whole heating or cooling period. In contrast to thermal conduction which also depends on stationary moisture in the insulation layer, the dynamic latent heat effect is only significant in very vapor permeable insulation materials. In vapor retarding materials, such as closed cell foam insulation, there is only very little vapor transport and thus hardly any latent heat contribution to the total heat flux. However, over several years vapor diffusion and interstitial condensation may lead to moisture accumulation in the insulation layer and therefore also to a considerable increase in its thermal conductivity—Zirkelbach (2011).

Independent of the kind of insulation material, it is important to assess the long-term thermal performance of the whole system in response to environmental moisture loads. Short-term investigations and those that consider only parts of the entire building system may be misleading because of the complex nature of the interaction between energy and moisture. Therefore, it is not enough to consider the relevant heat transfer phenomena in insulation materials individually, as in most guarded hot plate tests. To grasp the whole picture, it is crucial to do a long-term hygrothermal analysis of the entire building envelope system subject to real climatic boundary conditions. This may be achieved by an elaborate field test or more cost-effectively by validated hygrothermal simulation models.

The following section summarizes the background of the coupled heat and moisture transfer mechanisms that determine moisture dependent heat transmission through insulated envelope systems. It identifies the relevant material properties and explains how they should be measured. Finally, the importance of moisture related effects is demonstrated by two practice cases with vapor retarding and vapor permeable insulation materials.

2.2 Analysis of Moisture Effects on Heat Transfer in Thermal Insulation Materials

Heat transfer in dry insulation materials is a mixture of thermal conduction in the solid and the gas phase as well as radiation exchange and some convection effects within the gas phase. The latter is usually very small and may only become relevant if there are external air pressure differences or large temperature gradients. Thus, under normal conditions the term thermal conduction in insulation materials includes only physical conduction and internal thermal radiation exchange in the solid matrix and the gas-filled voids. The type of gas and the size of the voids has also an influence on the thermal resistance of the material. Small pores and heavy gases decrease the thermal conductivity because the momentum propagation between gas molecules and the solid matrix, respectively between the individual gas molecules is reduced. Evacuating the voids inhibits thermal conduction in the pore space altogether, leaving only the conduction in the solid matrix and thermal radiation as heat transfer mechanisms. Adding compounds that absorb radiation and/or reduce the emissivity of the solid matrix increases the thermal resistance by reducing the radiative heat transfer.

The presence of moisture will always lower the thermal resistance of porous materials by adding another phase to the material with a considerable thermal conductivity (liquid water $\approx$ 0.6 W/(m·K), ice $\approx$ 2.1 W/(m·K)), water molecules adsorbed by the solid matrix). The thermal conductivity of water in the adsorbed phase is not really known, however, this doesn't really matter because the thermal conductivity of insulation materials is measured as a lumped quantity of different heat transfer phenomena anyway. The impact of moisture on the internal radiation exchange is largely unknown. As long as the moisture in the material is stationary, i.e. not moving about by vapor diffusion or liquid flow (capillary flow and surface diffusion—see Künzel, 1995), the impact of moisture on the heat flux by effective thermal conduction can be described by:

$$q = -k(w) \cdot \Delta\theta / \Delta x \tag{2.1}$$

where,

q [W/m^2]	heat flux
$k(w)$ [W/(m·K)]	moisture dependent effective thermal conductivity
θ [K]	temperature

Equation (2.1) describes the steady state heat flux through a homogenous insulation material subjected to a constant temperature difference, a common situation under winter conditions. As long as the exterior and interior surface temperatures do not change, this heat flux doesn't change either, provided that the moisture distribution within the insulation layer remains the same. If the boundary conditions change over time, the heat flux becomes dynamic and its size changes not only with time but also with the position within the insulation layer due to thermal inertia. This transient process may be described by the following partial differential equation:

$$\frac{\partial H}{\partial t} = -\nabla \cdot q + S_h \tag{2.2}$$

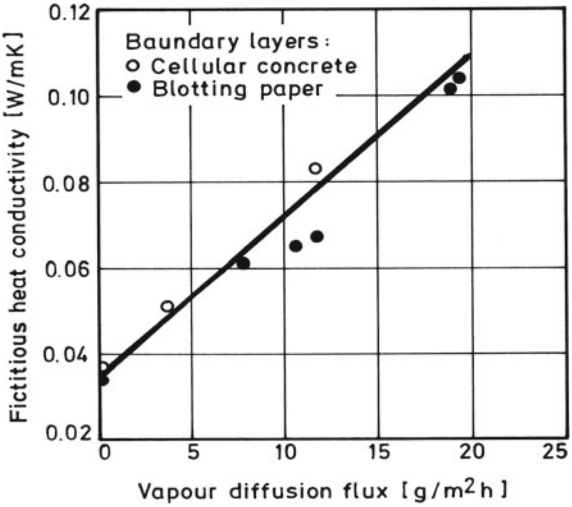
where,

H [J/m^3] enthalpy of the material and the moisture inside
S_h [J/(m^3·s)] heat source/sink related to moisture movement

For insulation materials with very low vapor permeability such as closed cell organic foams, the term S_h on the right-hand side is negligible, i.e. close to zero. In this case we get Fourier's heat transfer equation. In materials with high vapor permeability, however, another heat transfer effect, the so-called enthalpy flux or latent heat flux may become dominant. This phenomenon is caused by water evaporating at the warm side and moving by vapor diffusion through in the gas phase to the cold side where it condenses again. It has nothing to do with thermal conduction and the driving force is only indirectly the temperature gradient. In reality it is a diffusion flux driven by vapor pressure differentials and fed by evaporating water and condensing vapor within the insulation material or in resp. on the material layers adjacent to the insulation layer.

An experiment using a modified guarded hot plate apparatus measuring the heat transfer through a mineral wool insulation slab between two wet layers of either blotting paper or cellular concrete (AAC) in Achtziger (1984), demonstrated the mechanism of latent heat transfer and its importance for the overall thermal performance of insulation systems. Figure 2.1 shows the "fictitious" thermal conductivity of the insulation layer (determined from measuring the total heat flux and the surface temperature difference over the mineral fiber insulation slab) as a function of the vapor flux calculated from the weight changes of the respective boundary layer

Fig. 2.1 Apparent thermal conductivity of mineral fiber insulation slabs between wet layers of porous materials, determined form heat flux and surface temperature measurements, as function of vapor diffusion flux through the insulation—Achtziger (1985)



materials. The thermal conductivity increases almost linearly with the vapor diffusion flux, reaching values that are three times as high as the thermal conductivity of the dry material.

These results of Achtziger (1985) are in line with the findings in Hedlin (1988). However, in this case the moisture was initially not in the insulation material itself but in the adjacent boundary layer materials. This demonstrates that the latent heat transfer is neither part of thermal conduction, nor is it a specific material property but rather the response of a whole system to certain boundary conditions. In contrast to thermal conduction, it is also highly dynamic. While the conduction heat flux remains almost constant for a long period of time—as long as the boundary conditions are left unchanged—the latent heat flux decreases to zero as soon as the wet layer at the warm side has dried out.

Since vapor diffusion in building envelope systems can have such an important influence on heat transfer, it must be accounted for, to understand and quantify the relevant thermal phenomena in insulated building assemblies—see: EN 15026 (2007), ANSI/ASHRAE Standard 160 (2016), and ASHRAE Handbook of Fundamentals (2017). The enthalpy flows through vapor movement and phase transition can be described by specifying the source term in the heat balance equation:

$$S_h = -h_v \nabla \cdot g_v \tag{2.3}$$

where,

S_h [J/m^3·s]	heat source/heat sink caused by condensation/evaporation
h_v [J/kg]	latent heat of phase change
g_v [kg/m^2·s]	vapor diffusion flux density

The latent heat of phase transition consists of the evaporation enthalpy of pure water ($h_v \approx 2500$ kJ/kg) and the material specific sorption enthalpy which is negligible for most building materials compared to the evaporation enthalpy of water if RH $\geq$ 50%. To determine S_h, the remaining unknown is the vapor diffusion flux density g_v which can only be calculated by solving the transient moisture transfer equation.

2.3 Interaction Between Heat and Moisture Transfer—Hygrothermal Phenomena

As soon as moisture is present in porous materials, its migration in building envelope systems has an influence on heat transfer that must be accounted for. Analogous to heat transfer, transient moisture transfer can be described by the following partial differential equation—Künzel (1995):

$$\frac{\partial w}{\partial t} = -\nabla(g_w + g_v) \tag{2.4}$$

where;

W [kg/m^3]	water content of the building material layer
g_w [kg/(m^2·s)]	liquid transport flux density
g_v [kg/(m^2·s)]	vapor diffusion flux density

Liquid transport flux has generally only a minor effect on heat transfer—see: Künzel (1995), Gawin et al. (2004). Most conventional insulation materials such as organic foams or mineral fibers do not support liquid flow. However, there are also exceptions, e.g. capillary active insulation materials. They have been developed for interior wall insulation applications that work without a vapor retarder. Their capacity to support liquid flow helps to wick any water back from the condensation plane, because vapor and liquid flow are driven by different potentials (vapor pressure vs. capillary pressure respectively RH). These driving forces are generally opposed to each other in the insulation layer when condensation occurs (Binder et al., 2010) as shown in Fig. 2.2. In this case, the liquid flux may be relevant because it enhances the vapor diffusion flux. This happens by wicking back condensation water from the cold to the warm side, a bit like a low performing heat pipe—Gawin et al. (2004). However, this effect should not be overestimated because it is only relevant in materials whose structure is dense enough to support liquid flow, which means the thermal resistance is usually not that large anyway. Since liquid flow is absent or insignificant in most conventional insulation materials, only vapor diffusion is considered here by the

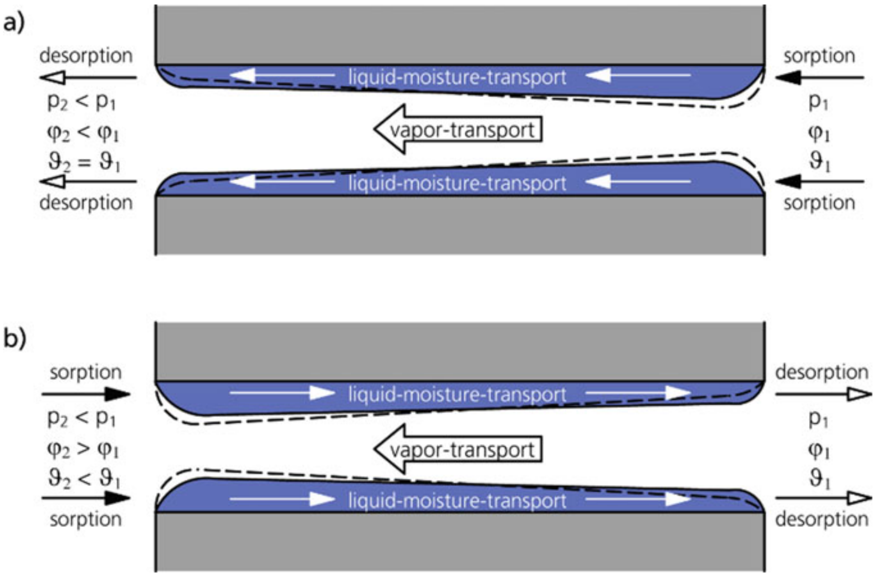


Fig. 2.2 Moisture transport phenomena in pores of hydrophilic media under **a** isothermal and **b** non-isothermal boundary conditions. In case (**b**) the driving potentials and thus the related moisture fluxes of vapor diffusion and liquid transport in the surface water layer (aka surface diffusion) are often opposing each other—Binder et al. (2010)

following gas diffusion equation:

$$q_v = -\delta \cdot \nabla_{pv} = -\delta \cdot \nabla_{\varphi p_{sat}} \tag{2.5}$$

where:

δ [kg/(m·s·Pa)]	water vapor permeability of building material
p_v/p_{sat} [Pa]	water vapor partial/saturation Pressure. φ [–]relative humidity (RH)

According to Eq. (2.5), the vapor diffusion flux through porous materials depends on the RH in the pores and the saturation pressure which is an exponential function of the local temperature. This means, heat transfer is also affecting moisture transfer and vice versa and it also demonstrates that both transfer mechanisms are strongly coupled. Therefore, we talk about hygrothermal transfer, because one doesn't exist without the other, as long as moisture is present, and in real buildings, moisture is always present.

The fundamentals and working principles of these hygrothermal transfer models have been standardized in EN 15026 (2007), as well as in ANSI/ASHRAE Standard 160 (2016), and ASTM E3054/E3054M (2016) for wider application, i.e. many national moisture control standards refer to them. Neglecting transfer by air convection in porous insulation materials—if convection effects occur, more sophisticated approaches would be necessary that take account of joints and imperfections—the one-dimensional heat and moisture transport through the building envelope components may be represented by the following partial differential equations:

$$(\rho\_s\, c\_s + \rho\_w\, c\_w) \cdot \partial\theta/\partial t = \nabla \cdot [k(w)\nabla\theta] + h\_v\nabla \cdot [\delta\nabla(\varphi \cdot p\_sat)] \tag{2.6}$$

$$dw/d\varphi \cdot \partial\varphi/\partial t = \nabla \cdot [D\_w\, dw/d\varphi + \delta\nabla(\varphi \cdot p\_sat)] \tag{2.7}$$

where

ρ_s, ρ_w	density of solid matrix, water [kg/m^3]
c_s, c_w	specific heat of solid matrix, water [J/kg K].
w	moisture content, [kg/m^3]
k(w)	moisture dependent thermal conductivity, [W/(m·K)].
D_w	liquid diffusivity, [m^2/s]

Equations (2.6) and (2.7) are strongly coupled. The stationary water in the material pores increases the thermal storage ρ_w c_w and the thermal conductivity k(w) in Eq. (2.6). The divergence of the vapor transport from in Eq. (2.7) multiplied by the heat of evaporation, represents the latent heat transfer in Eq. (2.6). The temperature distribution calculated by Eq. (2.6) has a small effect on the liquid flux in Eq. (2.7) due to changes in water viscosity (part of D_w) but a significant impact on the vapor transport term because the saturation pressure increases exponentially with temperature, while the relative humidity in the pore air changes only slightly as long as enough sorption moisture is present on the pore surfaces to compensate the effect of temperature fluctuations.

An important aspect of the exponential increase of saturation pressure with temperature concerns the magnitude of the latent heat effect. Under winter conditions with 20 °C indoors and 0 °C outdoors it can be of the same size as the heat flux due to thermal conduction in a fibrous insulation layer of 10 cm as long as there is enough moisture on the warm side. In the temperature range between 20 °C and 40 °C there is only a slight increase in the conduction heat flux, however, the latent heat flux can be almost three times as high. However, the moisture in the assembly will also dry out much faster, unless it is trapped between two vapor tight layers, e.g. vapor barrier and roofing membrane.

This may challenge our common sense, but the good news is, we possess the tools that show us what is really going on, when heat and moisture intertwine. Until now, hygrothermal simulation tools were mainly employed to predict the moisture conditions in building assemblies, e.g. to avoid moisture related damage like mold growth, rot, corrosion, etc. There are only very few studies that employed these tools for heat transfer investigations such as interpreting guarded hot plate measurements, e.g. Gawin et al. (2004), Kehrer et al. (2003). In those tests only the total heat flux density can be measured. To separate the latent heat flux from the sensible heat flux resulting only from thermal conduction in the solid, liquid, and gaseous phase is very difficult. Comparing the measured heat flux to hygrothermal simulation results that mimic the course of the guarded hot plate test is a possible way out, because hygrothermal models calculate both heat fluxes independently. Therefore, their sum must coincide with the measured heat flux as long as material parameters, boundary and initial conditions are the same for measurement and simulation. Since the latent heat flux is not part of thermal conduction, the only remaining unknown—the moisture dependent thermal conductivity—can be determined that way.

2.4 Measuring Thermal Conductivity of Moist Materials

As already mentioned above, there must be a clear separation between thermal conduction in wet materials and heat transfer by vapor diffusion and evaporation/condensation. This has already been recognized several decades ago, e.g., by Sandberg (1986). While the true thermal conductivity of a moist material can be seen as a material property, the latent heat flux is neither part of it, nor is it a thermal property at all. It is true that the latent flux is usually a function of another material property, the vapor permeability, however, since the driving force for vapor diffusion is partial vapor pressure which is not directly related to temperature, there is no way of combining sensible and latent heat transfer in one single transfer equation. For this reason, it is impossible to measure the true moisture dependent thermal conductivity in highly vapor permeable materials independent of moisture transfer. In materials with low vapor permeability the latent heat transfer becomes so small that its impact falls within the measuring accuracy. Therefore, a standard guarded hot plate test will provide reliable results for most closed cell insulation materials (Fig. 2.3).

Many solutions have been proposed to get around the latent heat dilemma with thermal conductivity measurements of vapor permeable insulations materials. In the ISO Standard 10051 (1996) the moisture effects on heat transfer during guarded hot plate measurements have been analyzed and the test period has been divided into 3 phases. The initial Phase A is characterized by a rather uniform moisture distribution in the carefully sealed test sample (moisture is not allowed to dry-out during the test—moisture loss should be below 0.01 kg/(m^3·h)), when there is still an over hygroscopic water content at the warm side of the sample. Phase A is followed by the transition Phase B when the heat flux decreases because the warm side is slowly drying out until a dynamic moisture equilibrium is reached in Phase C. This moisture equilibrium results from opposing vapor and liquid flow processes in hygroscopic and capillary active insulation materials as explained in Fig. 2.2. These fluxes are in balance with each other when a constant moisture profile is achieved which is characterized by zero net moisture movement under the prevailing boundary conditions. It should be noted that care must be taken to avoid liquid flow due to gravity. Therefore, the standard states that downward heat flow is preferred. However, before doing the thermal transmissivity test on a moist material in the downward direction, we propose to first make sure that there is no difference in results between upward and downward direction when testing the same material in dry state, unless buoyancy and edge effects can be totally excluded.

To evaluate Phase A, the standard recommends A for materials with low vapor permeability because the effects of moisture movement are small. For all other materials Phase C is the preferred evaluation range and the moisture distribution at the beginning and at the end of the test should be measured and if possible, the rate of moisture redistribution should be determined by calculation. Alas, the standard does not present a comprehensible explanation on how to calculate k(w) for highly vapor permeable materials exactly. Therefore, we propose to accompany the heat transmission tests of materials with high vapor permeability by hygrothermal simulations and determine the true k(w) by comparing the measured and the calculated dynamic heat flux results, e.g. as demonstrated in Gawin et al. (2004) and Kehrer et al. (2003).

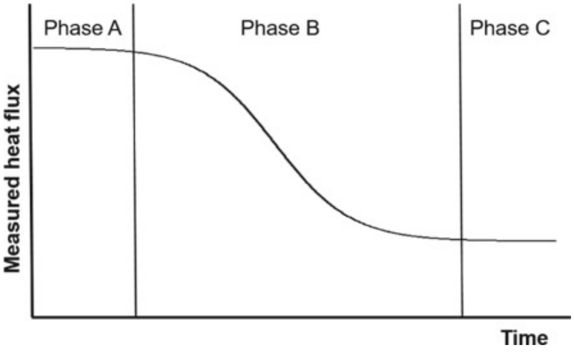


Fig. 2.3 Evolution of the measured heat flux during thermal transmissivity tests of moist materials according to ISO 10051 (1996)

2.5 Practice Case: Water Accumulation in Closed-Cell Foam Insulation of an Inverted Roof

Garden roofs are on the rise because they provide some natural space in an urban environment and my help to alleviate the urban heat island effect. Since gardening activities may damage the waterproofing membrane so-called inverted or protected membrane roofs appear to be a good solution. This type of flat roof where the waterproofing membrane is directly attached to the concrete deck, covered by extruded polystyrene insulation (XPS) and ballasted by gravel has been applied in Europe for decades. Because precipitation water penetrates the insulation layer before it is drained off on the roofing membrane there is a risk of interstitial condensation in the insulation slabs.

While numerous investigations have shown that there is no moisture accumulation when extruded polystyrene is used as insulation material, there has been some doubt whether replacing the gravel ballast by plant substrates will not lead to critical conditions. From practical experience it is known that the bottom surface of the insulation is permanently in contact with water. While the extrusion skin of the insulation slabs is impermeable to liquid water, its vapor permeability is not zero. This means some vapor will enter the insulation layer and if it cannot leave through the upper surface, long-term moisture accumulation may occur which results in a reduction of the roof's thermal resistance.

Based on field tests and hygrothermal simulations on inverted flat roofs with plant cover, the long-term moisture uptake of XPS insulation slabs of 60 mm thickness has been determined for Central European climate conditions. Figure 2.4 shows the measured water content in the XPS insulation as dots compared to the simulated water accumulation (solid lines) over a period of 30 years. The simulations were performed, because the measured results were questioned, and it was hoped that the moisture accumulation would level off after some years.

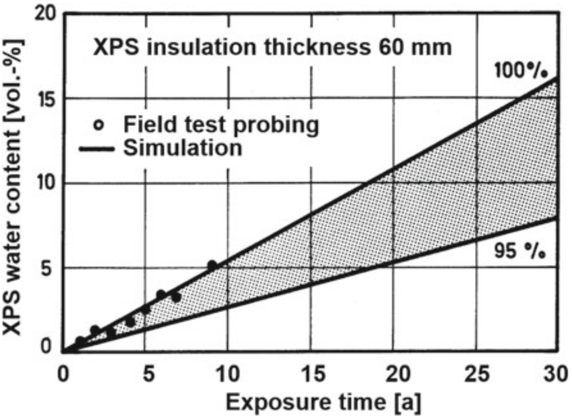


Fig. 2.4 Water content due to vapor condensation in the insulation layer of an inverted roof over time as a function of the relative humidity in the substrate above the insulation—Künzel and Kießl (1998). The dots show the measured values and the solid lines the simulated annual increase, assuming average substrate moisture of 95% and 100% RH

As boundary conditions for the simulations the controlled indoor conditions during the field test and the outdoor temperature variations of an average year at the test location were employed. The moisture conditions beneath and above the insulation layer have not been monitored during the field test. Therefore, they had to be estimated from observations during probing. There had been ample of proof that the lower surface of the insulation was always in contact with residual precipitation water, therefore RH was set to constant 100% at this position. The upper surface covered by the plant substrate also appeared to be wet most of the time according to observations during probing. Therefore, an average RH of 95% respectively 100% was selected for the simulation. The comparison between measurement and simulations demonstrated that the relative humidity in the substrate layer above the insulation remained around 100% all year round at that location. Since most plants need liquid water to survive, the relative humidity in the soil must be on average at least 99%. In later field tests this result has been confirmed by monitoring the dewpoint and the surface temperature at the top of the insulation layer—Künzel and Kießl (1998).

The consequences for the thermal performance of the observed long-term moisture accumulation are significant. According to Achtziger and Cammerer (1984), the thermal conductivity of the XPS insulation rises from 0.03 W/(m·K) in dry state to about 0.045 W/(m·K) at 16 vol.-% water content after 30 years. This increases the heat transfer through the insulation layer by about 50%. Over the estimated 30-year service life of the roof, the additional conduction heat transfer due to moisture in the XPS amounts to 25%. This could be easily compensated by installing insulation slabs that are 20 mm thicker. The moisture uptake is a function of the vapor pressure gradient (which is proportional to the temperature gradient in this case). Thus, inverted roofs designed to have a higher R-value (insulation thickness) will pick-up moisture more slowly and hence increase their thermal conductivity less quickly.

2.6 Practice Case: Latent Heat Effect Caused by Water Trapped in the Mineral Fiber Insulation Layer of a Light-Weight Flat Roof

In order to study the hygrothermal behavior of envelope assemblies with mineral fiber insulation, a light-weight flat roof has been installed at the Fraunhofer IBP open-air test site in Holzkirchen—see: Bludau et al. (2010). The 90 mm thick insulation layer, installed between an aluminum vapor barrier and a vapor-tight roofing membrane was equipped with temperature and humidity sensors at the bottom (on the vapor barrier) at the top (underneath the roofing membrane) and half-way between top and bottom within the mineral fiber insulation slabs. To simulate the effect of moisture trapped during the installation process, about 2 kg/m^2 of water was added on top of the insulation before enclosure. With the temperature variations during changing seasons or during a night and day cycle, the moisture was expected to migrate between bottom and top of the insulation slabs which could be monitored by the humidity sensors.

During the test period from August until January, the indoor temperature was kept at 20 °C, while the recorded roof surface temperature cycled between minimum and maximum values of −20 °C and 20 °C in winter, respectively, between 0 °C and more than 60 °C in summer. The resulting RH recordings within the roof are shown in Fig. 2.5. The overall agreement between measured and calculated curves is rather good and justifies further evaluations based solely on simulation results. In summer the RH at the top position varies between 20% at noon (when the sun shines and heats up the exterior surface) and 100% at night. With lower temperatures and shorter days in autumn and winter the RH at noon stays higher and remains from midmonth of November permanently at 100%. At the bottom of the insulation layer, the relative humidity stays at 100% during the whole summer until the middle of November. Afterward, it cycles between maximal 10% at night and 100% on sunny days.

The position in the middle of the insulation layer shows cycles with smaller amplitudes compared to the other two positions, but most importantly, there is almost no time period with constantly 100% RH all day round. This means the bulk of the water in the flat roof is either stored at the top of the insulation layer (winter situation) or at the bottom (summer situation), but not somewhere in between. It also shows that there are two separate cycles overlapping each other, a daily and a seasonal cycle.

The thermal consequences may only be evaluated by hygrothermal simulation since no heat flux transducers had been installed for this test. However, there had been another roof set-up with moisture introduced in the insulation layer before, that did not show the expected increase in heat transfer measured at the bottom of the concrete roof deck. For that reason, the thermal consequences of the roof described above was analyzed in more detail. Figure 2.6 shows the simulated heat flux densities including and excluding the latent heat effect determined for the bottom of the insulation layer, plotted as daily and weekly mean values over one year. Excluding the latent heat effect means here, that the heat of evaporation is set to zero in the simulations, i.e., the resulting heat flux is only due to thermal conduction. From the difference, it

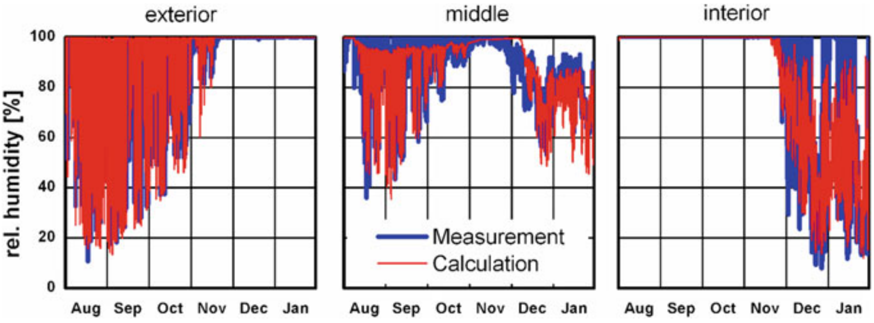


Fig. 2.5 Comparison of measured and calculated relative humidity variations at the three sensors' position in the mineral fiber insulation layer of the investigated flat roof

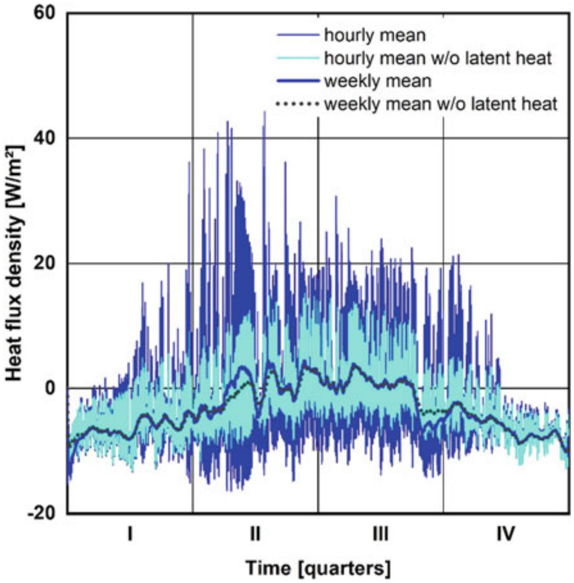


Fig. 2.6 Hourly and weekly means of the heat flux density calculated for the indoor surface of the flat roof with latent heat effect and without (heat of evaporation set to zero)

becomes obvious that the latent heat effect plays an important part leading to heat flux peaks in summer that are three times as high as the conduction heat flux. However, in the winter month the latent heat effect may still be significant, but it is not dominating the total heat flow anymore.

The most important energetic consequences for the building can be derived from the net heat losses and gains. Since most buildings have a rather high thermal inertia, the daily heat flux fluctuations through the building envelope are reaching the indoor spaces with a phase shift compared to the solar radiation input through the windows. The thermal storage also helps to dampen indoor temperature swings. Therefore, the energy balance of the building depends more on daily or even longer averages of the envelope heat fluxes. In order to clearly see the net effects of sensible and latent heat transfer through the roof, weekly averages of the heat flux with and without latent effects have also been plotted in Fig. 2.6.

During the cold winter month with a rather high negative heat flux density (heat loss through the building envelope), there is no difference between the mean heat flux densities with and without latent heat effect. Thanks to the reversible nature of the latent effect (night-time losses are compensated by daytime gains), moisture in the insulation layer does not have any significant impact on the energy consumption. During the hot summer month with net heat gains through the roof, the same results can be observed.

Only during the swing seasons, when the heat flux density is close to zero, both curves diverge slightly. In spring, the latent heat effect seems to increase the heat gains, and in fall it increases the heat losses. However, the net influence of the latent heat effects last only about a month and appears to be rather small. An explanation for the impact of the latent heat effect in spring and fall could be the bulk of condensate migrating from top to bottom respectively from bottom to top of the insulation layer. While the water during the heating and cooling season remains either at the top or the bottom with only little moisture moving back and forth during daily cycles, there seem to be two periods per year when the whole water in the roof moves mainly in one direction—up or down—which has a net effect on the average heat flux. Luckily, in the investigated case, this happens during the seasons when the thermal performance of the building envelope is of minor importance, because the indoor and outdoor temperatures are not far apart from each other.

It should be noted, however, that this positive view of the latent heat effects in vapor permeable insulation materials is only valid for insulated building assemblies without liquid counterflow in any form, e.g., due surface diffusion, capillary action or gravity. Also, the consideration of the net fluxes integrated over several days is only appropriate for buildings with high thermal storage capacity. Buildings with light-weight structure and well insulated envelope may not benefit from the reversing latent heat fluxes and suffer net heat losses, because intermediate heat gains are only partly or not at all usable without overheating the building.

2.7 Conclusions

Excessive moisture in building assemblies is always a matter of concern, because it may not only degrade the thermal performance but more importantly it represents a hazard for the hygienic conditions in the building and the durability of its structure. From a purely energetic point of view, temporary or localized moisture peaks are generally not a big issue. Construction moisture may affect the initial thermal performance of building assemblies but only the long-term moisture conditions have a lasting impact and should be considered in more detail. Laboratory and field tests may help to assess the long-term hygrothermal performance to some extent, however, they are expensive and not generally applicable—insulation manufacturers are hardly inclined to sponsor tests that may demonstrate thermal degradation of their products over time. Therefore, hygrothermal simulations are usually the simplest and most efficient way of predicting the long-term thermal performance of building envelope insulation systems for the climatic design loads.

Hygrothermal models that comply with the existing standards treat heat transfer by thermal conduction and latent heat flow separately and comprehensively, which means they also take the moisture in neighboring materials and the dynamic changes in boundary conditions into account. As an input, they require thermal storage capacity as well as thermal conductivity including its dependence on stationary moisture k(w) without any latent heat contribution. Further necessary input are the moisture transfer characteristics of all the materials involved, the so-called hygrothermal properties. Since most of the hygrothermal simulation tools on the market have been broadly experimentally validated, their application can be regarded as state-of-the-art for moisture control design purposes. However, there are only limited applications where the main focus has been on thermal performance rather than moisture safety issues. Therefore, the focus on the thermal properties in the hygrothermal databases has been less pronounced, which means, the actual data may contain all sorts of safety margins. The tabled thermal conductivity may also contain some contributions of latent heat effects resulting from standard thermal conductivity tests performed on moist materials.

Despite these shortcomings, rather accurate thermal performance predictions seem feasible at least in relative terms, i.e., the impact of moisture in building envelope assemblies on latent heat transfer may be quantified. To assess the overall effect of latent heat transfer in building assemblies on the energy performance of buildings, hygrothermal whole building simulation analysis is recommended. In cases of stationary moisture effects in materials with low or moderate vapor permeability, hygrothermal component simulation seems sufficient. For these materials which are present in many building components, it would be helpful to define limits for the allowable water content based on acceptable thermal performance degradation margins. Similar limits already exist for timber and timber-based products to prevent rot or other forms of material degradation. However, exceeding moisture limits to safeguard design thermal resistance should not necessarily signal failure but could be remedied during the design process by adding more insulation to compensate for performance degradation during the expected service life of the building assembly.

In practice, moisture in foam insulation has become a controversial issue. Most concerned are flat roofs—inverted and conventional—where moisture has accumulated either naturally or due to unintended leaks. But similar problems have also been reported form externally insulated walls, where rainwater leakage occurred. Obviously, this impairs the thermal performance of the assembly concerned. However, in most cases the remaining thermal resistance is still significant and costly removal of the wet insulation may be unnecessary. Some experts even recommend leaving the old insulation material in place and top it up by a new insulation layer. Long-term monitoring of roofs retrofitted this way has demonstrated that this works very well regarding thermal performance and sustainability aspects—see: Spilker and Oswald (2003), Zöller and Sprengard (2018).

In summary, it may be concluded that moisture in insulation materials has an impact on thermal performance, but it is predictable and mostly less dramatic than often assumed. The presence of moisture in building assemblies is mostly unavoidable but it can be controlled by good design that focusses on minimizing the loads and maximizing the drying potential. Because heat and moisture transfer are always coupled, it makes little sense to analyze heat transfer individually. This holds for measuring the thermal conductivity of moist materials, but it is equally true for evaluating the consequences for the thermal transmissivity under practice conditions.

Since moisture may have more severe implications than just increasing heat transfer, hygrothermal simulations are often performed anyway. Including an energy performance evaluation would, therefore, not require much additional effort. One important prerequisite is the availability of thermal conductivity data of insulation materials being determined excluding latent heat effects. Otherwise, the impact of moisture may be counted twice which would penalize vapor permeable insulation materials.

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