MODELLING THE EFFECT OF AIR LEAKAGE IN HYGROTHERMAL ENVELOPE SIMULATION

Hartwig M. Künzel, Dr.-Ing. [1]
Daniel Zirkelbach, Dipl.-Ing. [2]
Beate Schafaczek, Dipl.-Ing. [3]

ABSTRACT

Vapour-tight wooden structures such as unvented flat roofs have acquired a bad reputation in Europe due to frequently reported moisture problems caused by vapour convection. While better detailing and workmanship may considerably improve the air-tightness of a roof assembly, field observations indicate that it is impossible to achieve a perfect air barrier under practice conditions. Therefore, a new European standard draft on wood protection specifies a convective moisture source for vapour control design analysis of building assemblies. This convective source is added as a safety margin to the amount of condensate caused by vapour diffusion when dew-point calculations are performed.

The paper describes how this concept of convective moisture source is translated into an air-leakage model for hygrothermal simulation tools. Since the bulk of exfiltrating air is flowing straight through larger gaps and joints, it is unlikely to do any harm because the flow channels will generally become to warm for vapour condensation. Therefore, the model assumes that only small leaks with tortuous paths contribute to the convective moisture source. The challenge is to determine the flow rate through the small moisture-relevant leaks. Based on field tests and theoretical assumptions a small leak air permeance is defined that serves to calculate the convective moisture entry. The resulting flow rate depends on the air pressure differentials due to stack effect and mechanical ventilation. Wind induced pressure differentials are neglected because they are very transient in nature (changing force and direction) and more complex to determine. After specifying the most likely position for convective condensation within the building assembly, the moisture source is calculated hourly depending on the indoor and outdoor climate conditions.

The convective moisture source model has been validated by comparison with field tests. Applying the model offers the possibility to assess the risk of moisture damage caused by vapour convection. It demonstrates that flat roof assemblies

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[1] Hartwig M. Künzel, Dr.-Ing.is head of department of Hygrothermics, Fraunhofer-Institute for Building Physics, Holzkirchen, Bavaria, Germany
[2] Daniel Zirkelbach, Dipl.-Ing. is deputy head of department of Hygrothermics, Fraunhofer-Institute for Building Physics, Holzkirchen, Bavaria, Germany
[3] Beate Schafaczek, Dipl.-Ing. is scientist in the department of Hygrothermics, Fraunhofer-Institute for Building Physics, Holzkirchen, Bavaria, Germany

with vapour barriers are more prone to moisture problems than those with moderate vapour retarders, which is in line with practical experience. The model also indicates the limits of moisture removal by vapour diffusion of building assemblies subject to vapour convection.

1. INTRODUCTION

Despite increasing efforts to seal building envelope assemblies against airflow and moisture intrusion, the potential of failure remains unaltered. Vapour infiltration, that means the convective flow of humid indoor air into a construction, may introduce more moisture into the building envelope than can safely dry-out. In contrast to well-known vapour diffusion processes, convection effects have been underestimated for a long time. As a consequence moisture problems occurred in practice, although the assemblies passed all requirements established by the dew-point method which evaluates only the seasonal diffusion fluxes.

While current standards on building envelope performance assessment by transient hygrothermal simulations either do not consider convection (e.g. EN 15026-2007), or do not specify exactly how to deal with air flow (ASHRAE 160-2009), a quantitative evaluation of the consequences of vapour convection would be desirable. Based on an extensive literature research a simplified model to quantify the moisture entry by vapour infiltration has been presented by Zirkelbach (2009). The background and assumptions leading to this model are summarized and the results are compared to those of a back-ventilation model where outdoor air is replaced by indoor air.

2. QUANTIFICATION OF MOISTURE ENTRY DUE TO VAPOUR INFILTRATION

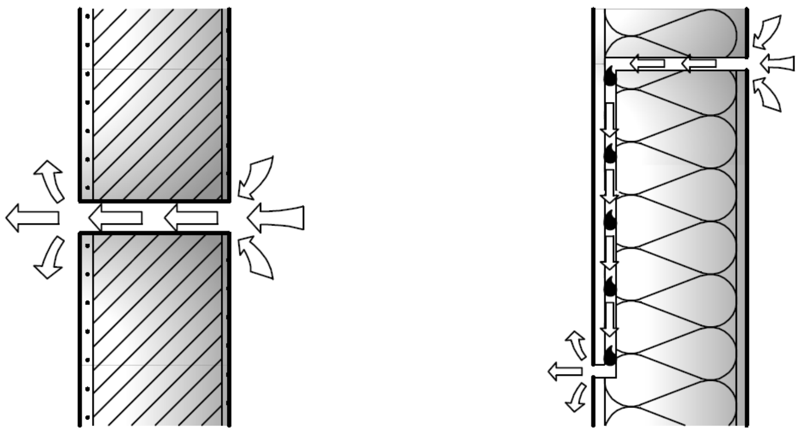
The convective moisture entry due to defects in the vapour respectively air control layer is a multidimensional effect, which cannot be captured directly by a one-dimensional calculation. However, also a multidimensional simulation tool hardly solves the problem, because the exact configuration of leakages is generally unknown and the complexity of relevant flow paths is out of scope for most approaches. Therefore it makes sense to develop a model, which doesn’t simulate the flow itself, but concentrates on the effects of vapour infiltration and subsequent condensation by introducing a moisture source inside the construction.

A first attempt to quantify the moisture entry due to vapour infiltration under German climate conditions was proposed by the IBP for the assessment of interstitial condensation in wooden constructions by dew-point calculations (Künzel 1999). It introduces a convective moisture source of 250 g/m² during the heating period which has to dry out during the summer together with the amount of condensate caused by vapour diffusion. The quantity of this convective moisture source was derived from results of investigation of air-tight light weight constructions with vapour barriers (TenWolde 1998). In the meantime the inclusion of vapour infiltration by introducing a moisture source seems to gain acceptance in practice. One example is the requirement in the new draft for the German wood protection standard DIN 68 800-2 (2009) to consider a moisture source of 250 g/m² to account for air flow through small leakages and defects when dew-point calculations are performed. As already explained by Zirkelbach (2009), there are very few studies, which can provide reliable information on moisture entry due to vapour convection. This is the reason why the convective moisture source to consider the leakages, which was established for a north orientated exterior wall, acts as reference case for the development of a transient vapour infiltration model for hygrothermal simulation tools.

2.1 Air flow paths through building envelope components

Leakages of the building envelope can be quantified with the help of a blower door test. But not every leaky joint or crack in the construction represents a moisture problem. Figure 1 depicts two exemplary flow channels through the building envelope, whose consequences are very different for the moisture conditions in the construction. The left channel is a typical situation for a connection detail, where the indoor air flows directly form the inside to the outside. In this case the air usually takes along enough thermal energy to warm up the flow path. This keeps its temperature above the dew-point, which means that there will be no condensation. Such leakages are thermal shorts (“energy leaks”) of the building envelope. They form the major part of all leakages, but they play a minor role for the moisture source in the construction.

FIGURE 1: Flow channels in constructions – on the left hand side a channel which goes directly form the inside to the outside (“energy leak”) and on the right a channel with extended path at the cold side, so that the air cools down and vapour condenses (“moisture leak”).



In contrast, there are narrow and warped flow channels, as displayed on the right hand side of Figure 1. Here, the indoor air creeps in a tortuous way to the outside giving it time to cool down, until part of the air humidity condenses at the cold side of the construction assembly. Only such leakages are important for the moisture conditions and have to be considered in a vapour convection model. According to estimation by Zirkelbach (2009), the volumetric flow through moisture leaks represents only 5 – 10 % of the total air flow through the building envelope.

In cold and moderate climates the vapour concentration of the interior (and with it also the partial pressure of water vapour) is generally higher than that of the outdoor air. Only high temperatures and simultaneous precipitation or the operation of AC-systems can inverse these conditions for a short period of time. A significant flow through leaky structures only occurs, when the pressure gradient over the building envelope permits it, for example under wind pressure or due to buoyancy forces caused by temperature differences between indoors and outdoors. Whilst a flow from the outside contributes to the drying process, the inverse flow leads to wetting of the construction, when the temperature drops below the dew-point temperature along the flow path. Therefore, only periods with low outdoor temperature coinciding with air pressure gradients from inside to outside may cause a convective moisture source in the building assembly.

2.2 Air pressure differences between inside and outside

The pressure difference across the construction is the driving force for air flow. Such pressure differences can have the following reasons:

- Buoyancy (stack effect)
- Wind forces
- Total pressure differences due to mechanical ventilation systems, kitchen hoods and open fireplaces

Ventilation fans in bathrooms, kitchen hoods and open fireplaces normally induce a negative pressure in the building and therefore pose no problem during the heating season. Central ventilation systems should be pressure equalized with the exception of those used in clean rooms which would require special consideration.

Pressure differences due to wind are of erratic nature and therefore more difficult to determine. The stagnation pressure at the building envelope depends on wind speed, direction and gustiness as well as on building geometry, height and the neighboring environment (topography). Typical air flow pattern and resulting pressure coefficients are shown in the ASHRAE Handbook (2009). The air pressure gradient over the envelope assembly is also a matter of indoor pressure which may not be equal to the air pressure in the upstream free field, because of interior partitions and external pressure imbalance. Thus, it is very challenging to determine the correct transient pressure differentials across a building component. This is the reason why the simulation of ventilated cavities is often performed independent of the current wind situation by selecting a constant air change rate which represents the average outdoor air convection through an external wall cavity. Despite this rather crude simplification the results appear to correspond well with field measurements (Karagiozis & Künzel 2009, Hägerstedt & Harderup 2011).

Very important for pressure differences over the building envelope is the stack effect because of its permanent impact during the heating period. Since the building acts like a captive balloon when it is cold outside, the heated air in the room tends to rise up and is displaced by the colder and therefore heavier inflowing air. This results in a higher pressure gradient in the upper zone of the building envelope and causes exiting air flow. On the other hand there is an inverse pressure gradient in the lower zone of the building, which poses no problem because cold and dry air comes in. If the leakages are distributed evenly over the building envelope, the neutral pressure level will be in the middle of the building. If this is not the case, the neutral level moves to the zone with the greatest leakages. Over roof assemblies and over the upper zones of walls of a heated building, there is always a pressure drop from the inside out in winter. The pressure differences caused by the stack effect can be calculated with equation 1. Here, the neutral pressure level is supposed to be in the middle of the connected airspace:

$$\Delta P = \rho \cdot \frac{T_e - T_i}{T_i} \cdot g \cdot \frac{h}{2} \tag{1}$$

where

ΔP = pressure difference between inside and outside (Pa)
p = density of the outdoor air (ρ = 1.3 kg/m³)
T_e , T_i = exterior, interior air temperature (K)
g = gravitational constant (g = 9.81 m/s²)
h = height of the connected airspace in the building (m)

The stack pressure increases proportional to the building height and to the temperature difference between inside and outside. This means, that tall buildings with a connected airspace and those with a high indoor air temperature experience the highest pressure differences. For example: the maximum pressure difference acting on the roof of a two-story single family house (indoor air 20 °C, outdoor air 0°C) amounts to little more than 2 Pa. In comparison, the pressure difference almost quadruples over the roof of an indoor swimming pool in a 15 m tall building with an indoor air temperature of 30 °C. In summer time (outdoor air 20 °C) the pressure difference decreases to 3 Pa in the indoor swimming pool and approaches values around zero in buildings with normal indoor air temperature.

2.3 Vapour infiltration model

The wind-induced and the thermal pressure differences, which come into consideration as driving force for air convection, reach on average often a similar magnitude. Nevertheless only the stack effects are considered for the infiltration model, for the following reasons: The wind-induced pressure differences are subjected to great variations and when they peak a “moisture leak” can become a less critical “energy leak” because the increased flow rate may even heat up a tortuous path. Furthermore wind induced pressure differences show no seasonal asymmetry. Therefore, condensate caused by convection in winter may dry out the same way in summer, also when the air flows from inside to outside.

In contrast, the buoyancy flows through the envelope in winter cause a rather continuous moisture source while there is no equivalent driving force for convective drying in summer. This is the reason why the stack effect is assumed to be a critical parameter for the hygrothermal behaviour of a construction. Additionally it can be modelled more easily, so that it makes sense to focus first of all on buoyancy driven air flows when developing a vapour convection model.

The main principle of the proposed model is its strong simplification and its sole concentration on the moisture related effect of air convection. That means all thermal effects of air flowing through the building envelope component are neglected. This is necessary in order to stay on the safe side when the influence of a 3D flow pattern is introduced into a 1D calculation. Another simplification represents the selection of the position within the building assembly that receives the condensable humidity carried in by convection. The position of this condensation plane or layer has to be defined by common sense before starting the hygrothermal simulation. The right choice depends on the construction. It must be cold enough for condensation to occur and it must be easily accessible for the indoor air that has penetrated the interior lining or air barrier. Examples are the exterior sheathing of wood frame walls or roofs and the interface between the interior insulation and the original wall after thermal retrofits of plastered masonry structures.

The convective moisture source is equal to the amount of condensate that forms when the indoor air temperature is cooled down to the temperature of the selected condensation layer in the building assembly. Any increase in sorption water content that could occur in reality by the temperature drop is neglected. In the current model, the heat of condensation resulting from convective flow is disregarded, because this is more consistent with the main principle of the model. Assuming that there will be laminar air flow in the small cracks and channels within the building component – a reasonable assumption according to test results in Maref (2009) – the volume flow q_{CL} (CL=component leakage) is described by:

$$q_{CL} = k_{CL} \cdot \Delta P \tag{2}$$

where

q_{CL} = air flow through the “moisture leaks” of the envelope component (m³/(m²h))

k_{CL} = moisture specific air permeance of the component (m³/(m²·h·Pa))

The amount of condensation (moisture source S_{CL}), which results from vapour convection, is determined by the difference between the indoor vapour concentration and the vapour saturation concentration at the selected convective condensation position p according to equation 3:

$$S_{CL} = q_{CL} \cdot (c_i - c_{sat,p}) \tag{3}$$

where

S_{CL} = moisture source due to vapour infiltration into the component (kg/(m²h))

c_i = water vapour concentration of the indoor air (kg/m³)

$c_{sat,p}$ = water vapour saturation concentration at position p, where condensation due to indoor air penetration is expected (kg/m³)

Thus the model allows a transient consideration of the convective moisture sources depending on the specific air permeance of the component k_{CL}, on the height of the connected airspace, on the selection of the potential condensation layer within the building component and on the transient exterior and interior climate conditions. The unknown variable is the component’s moisture specific air permeance k_{CL} that sums up exclusively the moisture leaks. Component permeance estimates in the ASHRAE Standard 160 (2009) range from 0.01 m³/(m²·h·Pa) for airtight buildings to 0.06 m³/(m²·h·Pa) for standard constructions. Recent laboratory tests of air leakage rates of wood frame walls with glass fibre or spay foam insulation carried out in Canada (Maref 2009) have shown air permeances of well-constructed envelope components which were lower than 0.004 m³/(m²·h·Pa). However, when the air barrier was penetrated by ducts and fasteners it increased to 0.02 – 0.03 m³/(m²·h·Pa). The values for the permeance in the ASHRAE Standard and those measured by Maref (2009) differ approximately by a factor of three but they show similar spreads in the air-tightness e.g. a factor of about six between standard (including penetrations) and air-tight assembly.

Since it is unknown what percentage of the published North American air permeance values represent those flow paths belonging to the group of “moisture leaks” and because there is still a lack of results for European assemblies, an alternative approach to determine k_{CL} is proposed. As mentioned above, the German standard for wood protection DIN 68800-2 (2009) assumes that air convection is responsible for 250 g/m² of condensation in insulated wooden structures during winter. Originally this amount has been determined by hygrothermal simulations of a north facing cathedral ceiling structure and a stud wall insulated with 20 cm mineral wool under the climate conditions of Holzkirchen (Bavarian alpine region at 760 m a.s.l.). Following the interpretation of the experimental results in TenWolde (1998) that the amount of condensation due to air convection is approximately equivalent to the integral vapour diffusion flux through a vapour retarder with s_d = 3.3 m (1 US perm) the calculated amount of condensation has been determined to be 250 g/m² for German climate zones by Künzel (1999). Applying the new model to the benchmark case of a stud wall and considering the wall’s top section results in a component permeance k_{CL} of 0.007 m³/(m²·h·Pa) for a single family home (2 storeys, h = 5 m). This shows that moisture leaks represent approximately 10% of the total component air permeance published in ASHRAE 2009 for standard building assemblies.

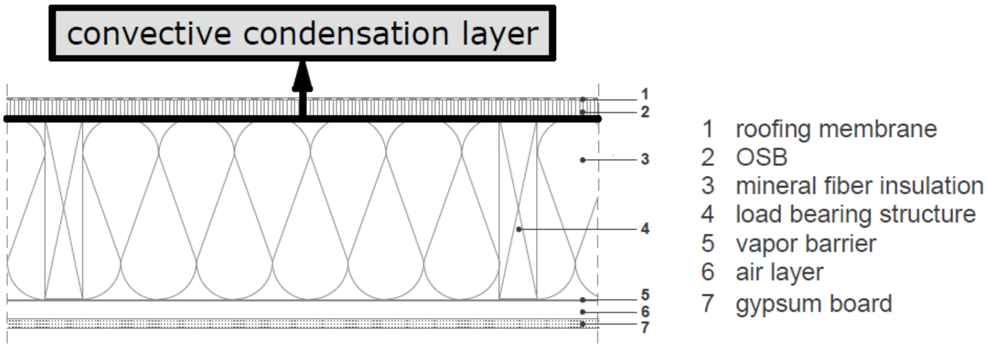
3. APPLICATION EXAMPLE

The influence of vapour convection on the hygrothermal performance evaluation of an envelope assembly is illustrated by applying the new infiltration model to a roof construction. The flat roof assembly depicted in Figure 2 is quite common in Europe and has already been subject to an investigation including the air infiltration model under European climate conditions (Künzel 2011). It is supported by rafters with 240 mm glass fibre insulation in the cavities and an exterior OSB sheathing. The roofing membrane has a diffusion resistance s_d = 300 m (approximately 0.01 US perm) and a short-wave radiation absorptivity of 0.6. The absorption coefficient of 0.6 represents the lower limit for a conventional roofing membrane or additional covering (exception green roofs or cool roofs). Bituminous and other dark roofing membranes typically have an absorption coefficient of 0.8 to 0.95. On the interior side, there is either a vapour barrier with 0.1 perm (s_d = 33 m) or a moderate vapour retarder with a permeance of 1.0 perm (s_d = 3.3 m). The stack pressure is calculated for the flat roof of a house with a height of 5 m.

As exterior climate a cold year for the location of Chicago is selected. The calculation of the roof’s surface temperature includes short and long wave radiation exchange which may lead to considerable undercooling of the roof during clear nights. The interior conditions are determined from the daily mean outdoor temperature by employing the simplified method (Fig 4.3.1) in ASHRAE Std. 160 (2009).

The simulations are performed with WUFI® 5, a model to calculate the simultaneous heat and moisture transport in building components under real climate conditions. The convective moisture source is calculated according to equation 3, where the position p describes the condensation layer assumed indicated in Figure 2. Since the OSB sheathing is the most exposed and vulnerable structural layer in the assembly its moisture content is evaluated to check the overall hygrothermal performance of the considered flat roof.

FIGURE 2: Analysed flat roof assembly with selected position for the convective moisture source.



The results of the simulations including vapour infiltration are compared to those without convective moisture source. They are also compared to calculations simulating the influence of wind without buoyancy driven infiltration in a very simplified way. This is done by assuming a constant flow of indoor air between exterior sheathing and roofing membrane as it could occur due to wind induced pumping effects when the membrane is only mechanically attached. The calculation approach of this effect is the same as that of a ventilated cavity described in Karagiozis & Künzel (2009) with the difference that the cavity between sheathing and roofing membrane is very small and ventilated by indoor air instead of outdoor air. In reality, this cavity will be discontinuous and varying in width when the wind is blowing. For the simulation it is assumed to be of constant thickness (1 mm). Also the ventilation rate is constant and amounts to 16 ACH. This air change rate has been determined by assuming that the indoor air circulation through the cavity results in the same moisture excess of 250 g/m² during the heating season under the same conditions used to calibrate the air infiltration model explained above. The major difference between the indoor air ventilation model and the vapour infiltration model is the convective drying potential. While convective drying is excluded when employing the vapour infiltration model, the ventilation model may result in convective drying as soon as the temperature beneath the roofing membrane rises above the dew-point of the indoor air.

The calculation starts in October, and is continued with the same data set over a period of five years. Initially, the moisture content of all materials is in equilibrium with 80% RH, The resulting temporal variations of the sheathing moisture content of the flat roof assembly (MW insulation incl. 0.1 perm retarder) with and without air infiltration are compared to the simulation results with indoor air convection in Figure 3. While there is no problem in the air-tight case, the air infiltration model indicates slow moisture accumulation resulting in 20 % by mass sheathing moisture content during the fifth year. The case with constant indoor air circulation beneath the roofing membrane shows a higher moisture load in winter which dries out completely in summer. The maximum OSB moisture content stays below 18% by mass which means the structure will be considered to be safe.

FIGURE 3: Calculated water content of the roof's exterior OSB sheathing by considering diffusion only (air-tight) and by including air convection with two different approaches as air infiltration and indoor air convection (indoor air circulating continuously through a layer of 1 mm below the roofing membrane at 16 ACH).

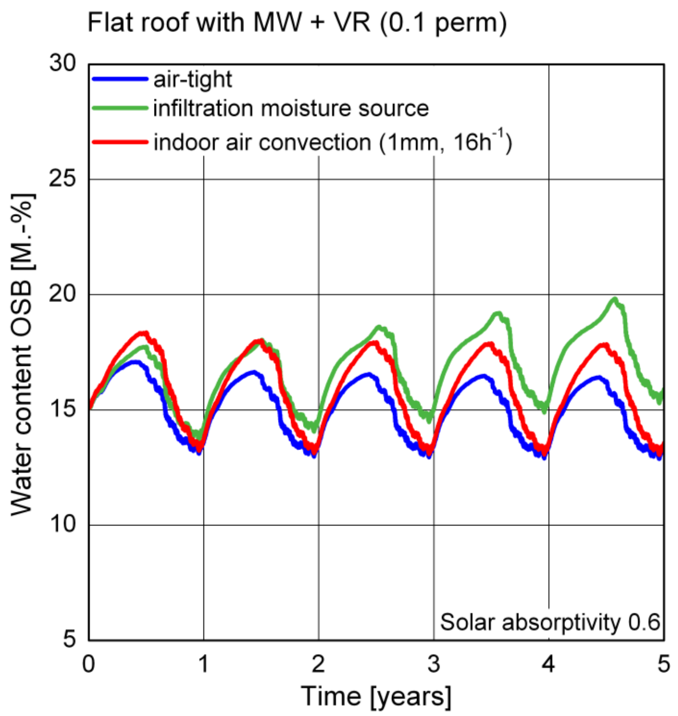
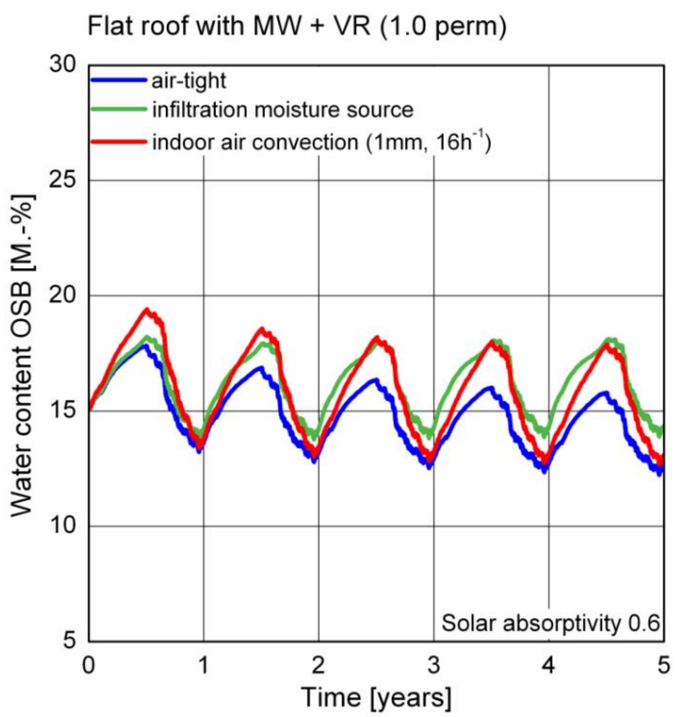
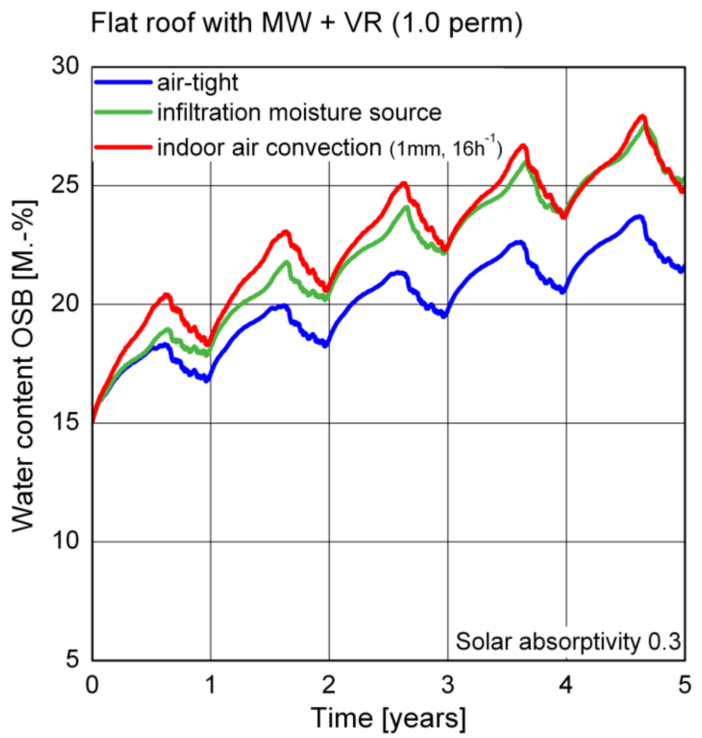


FIGURE 4: Calculation results as in Figure 3 with the difference that the permeance of the vapour retarder has been increased by a factor of 10.



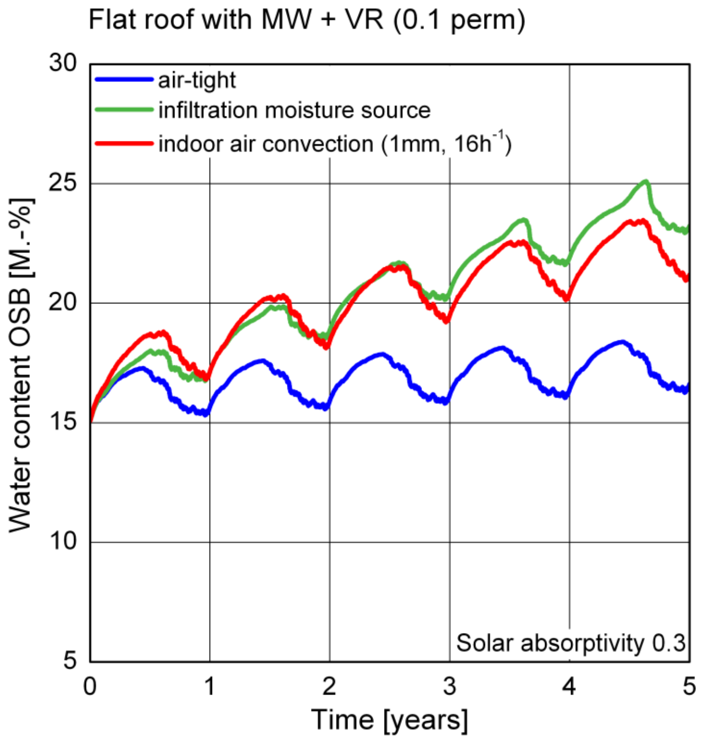
Since European experience has shown that flat roof structures like this one are vulnerable to moisture damage, the simulation with air infiltration model appears to be more appropriate then the other two assumptions. In the meantime it has been recognized that replacing the low-permeance vapour retarder by a moderate retarder of 1.0 perm is a simple way of increasing the moisture tolerance of flat roofs. Repeating the simulations with such a moderate retarder proves that this solution also works for the considered roof assembly in Chicago (Figure 4). Even with air infiltration the construction dries out effectively due to solar vapour drive (diffusion process) in summer.

FIGURE 5: Calculation results as in Figure 4 with the difference that the solar absorptivity of the exterior surface has been decreased from 0.6 to 0.3.



However, if the drying conditions during the warm season are worsened through lower surface temperatures e.g. by applying a reflective membrane or coating on top of the roof (a_s = 0.3), the moisture tolerance of the roof assembly may vanish as demonstrated in Bludau (2009). The simulation results obtained for the same roof as in Figure 4 but this time with a reflective surface (Figure 5). In all cases even without any air convection, moisture is accumulating in the roof. Comparing the results with those in Figure 4 indicates that the summer drying potential has become too small to compensate the moisture entry during winter. If diffusive moisture entry is prevented by choosing a less permeable vapour retarder, the situation improves as shown in Figure 6. However, this is a rather risky solution because as soon as air convection is included in the simulation the construction fails. In this case both convection approaches result in approximately the same moisture accumulation.

FIGURE 6: Calculation results as in Figure 5 with the difference that the permeance of the vapour retarder has been decreased by a factor of 10.



4. DISCUSSION AND CONCLUSIONS

The consideration of air infiltration (vapour convection) into the building envelope and its moisture related consequences improves the prediction performance of hygrothermal simulation tools. This increases the safety of moisture control design analysis for light-weight structures, and allows assessing their moisture tolerance with respect to different construction details and climatic parameters. Moisture risks caused by inadequate drying potentials, e.g. due to vapour tight layers on both sides of the construction, will be disclosed and measures to improve the assembly can be evaluated. Finally, the balance between wetting in winter and drying in summer can be determined more accurately when convective moisture sources are included in the hygrothermal simulation model. Especially for roofs with reflective surface layers (cool roofs), a more realistic risk assessment is very important because their drying potential appears to be limited in cold and moderate climate zones.

A degree of uncertainly remains, concerning the permeance k_{CL} representing the sum of all “moisture leaks” and its percentage of the building component’s total air permeance, the quantity that is usually measured. If the value for k_{CL}= 0.007 $m^3/(m^2 \cdot h \cdot Pa)$ derived here for standard air-tight structures can be considered as conservative, then a more thorough and detailed air-sealing design combined with onsite inspections could lead to more air-tight envelope components. Anticipating such improved wooden structures Zirkelbach (2009) proposed a new air-tightness classification where k_{CL} is lowered to 0.004 $m^3/(m^2 \cdot h \cdot Pa)$ or even 0.0015 $m^3/(m^2 \cdot h \cdot Pa)$ for buildings whose measured q_{50} value (total air flow rate at 50 Pa pressure difference) is smaller than 3 $m^3/(m^2h)$ respectively 1 $m^3/(m^2h)$.

Another uncertainty is the lack of conclusive investigations with references to the influence of wind-induced air flows on the moisture behaviour of constructions, both concerning the transient pressure differences over individual components and their contribution to the convective moisture sources as well as concerning their influence on the drying process in summer and in transition periods. In contrast to the buoyancy forces which are rather easy to determine, wind induced pressure differences depend on a variety of parameters including local topography and exposure. This complexity makes it difficult to capture wind related air convection by a simplified approach which can be widely applied in building practice.

Although there is a considerable need for further research and analyses concerning the air pressure conditions acting on different parts of a building and the specification of the air tightness of components, the application of the presented vapour infiltration model describes a step forward towards a more realistic risk assessment compared to the currently standardized calculation methods. The results have shown that it can differentiate between envelope assemblies with more or less favourable track records. This is why it is currently being supported by many building experts in Germany. It may be assumed that the vapour infiltration model is also appropriate for cold and moderate climate zones of North America. However, it is unsuitable for the evaluation of structures that are less airtight than should be expected when installed according to best practice.

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