BUILDING ENVELOPE DESIGN BY HYGROTHERMAL SIMULATIONS – EXPERIENCE AND GUIDELINES –

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PROJEKTOWANIE PRZEGRÓD BUDOWLANYCH POPRZEZ OBLICZENIA HIGROTERMICZNE – DOŚWIADCZENIA I WYTYCZNE –

Dla oszacowania stopnia ryzyka wewnętrznego zawilgocenia ścian i dachów były dotychczas stosowane proste, stacjonarne metody obliczeniowe. Obecnie, procesy cieplno - wilgotnościowe zachodzące w przegrodach, mogą być dokładnie przewidywane za pomocą zweryfikowanych narzędzi obliczeniowych, których praktyczne zastosowanie jest w Europie normalizowane. Zamiast dążyć do uzyskania idealnie szczelnych izolacji przeciwwilgociowych można, poprzez zbilansowanie dobowych i sezonowych przepływów wilgoci za pomocą symulacji higrotermicznych, projektować bardziej tolerancyjne wilgotnościowo a przez to trwalsze komponenty budowlane. Badania symulacyjne mogą nawet spowodować poszukiwania innowacyjnych materiałów jak inteligentna folia adaptacyjna, której rozwój przedstawiono w tym artykule.

ABSTRACT

In the past simple steady-state calculation methods were employed to assess the risk of interstitial condensation in wall and roof constructions. Today the hygrothermal performance of building envelope systems may accurately be predicted by validated simulation tools whose practical application is going to be standardized in Europe. Balancing diurnal and seasonal moisture fluxes by hygrothermal simulations instead of striving for a perfect seal helps to design more moisture tolerant and hence more durable building components. Simulation studies may even trigger the search for innovative products such as the smart vapour retarder whose development is summerized in this paper.

1. INTRODUCTION

Moisture protection of building structures often concentrates solely on controlling interstitial condensation caused by diffusions of indoor air humidity into the building enclosure during winter time. In most countries the problem of interstitial condensation is dealt with by employing a simple steady-state calculation method based on Glaser [1]. However, this method does neither account for hygroscopic sorption nor for liquid transport. Therefore its application is more or less limited to light-weight structures. Other moisture loads, such as construction moisture, precipitation, summer condensation or rising damp are beyond the scope of the Glaser-method. The limitations of the Glaser-method can be overcome by using modern simulation models such as Match [2] or WUFI [3]. An extensive compilation of hygrothermal simulation tools can be found in an IEA-Annex 24 report from 1996 [4].

In this paper the temporal variations of the temperature and humidity conditions in the building envelope is analyzed by applying hygrothermal simulations according to existing guidelines. By way of an example case it is also demonstrated how such simulation tools may be used for innovative building envelope design.

2. DYNAMIC BUILDING ENVELOPE CONDITIONS

The main function of the building enclosure is to protect the indoor spaces from natural weather. Besides precipitation and wind that occur only sporadically the solar radiation and the outdoor air conditions are essential. In Figure 1 those hygrothermal loads, their directions and their influence on the vapour diffusion process within the thermal envelope are represented schematically for an insulated cathedral ceiling. Usually, the loads show mainly diurnal variations at the exterior surface and seasonal variations at the interior surface of the building enclosure. During the daytime the roof surface heats up by solar radiation: this leads to an increase in temperature until there is a balance with the transfer of heat to the interior through thermal conduction and to the exterior through long-wave radiation and convection. Even before sunset, when the solar radiation decreases, the long-wave (infra-red) emission may lead to an overcooling (cooling down below air temperature) of the exterior surface which means that condensation of the ambient humidity may occur.

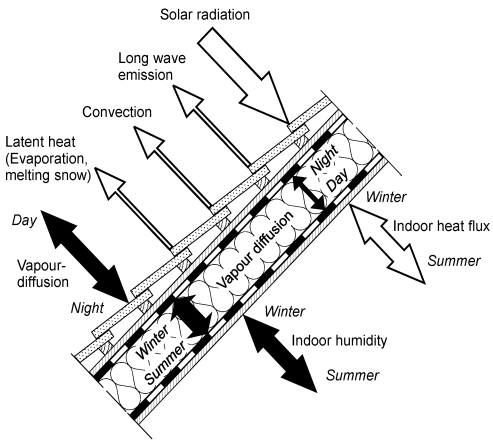

Fig. 1: Schematic representation of the hygrothermal effects and their alternating diurnal or annual directions in an inhabited attic (unvented cathedral ceiling insulation).

The hygrothermal loads bear consequences for the transient temperature and humidity conditions in the construction. When the exterior surface temperature rises during daytime it may cause vapour diffusion out of the exterior layers to the interior side of the envelope. The possible extent of moisture transport to the interior side can be estimated from results in Figure 2 which were recorded in a sheet-metal cathedral ceiling (orientation: south, inclination: 50°). The measured variations of the exterior surface temperature and the relative humidity between the vapour retarder and the mineral wool insulation during a bright winter day show a very large range. Here the temperature of the sheet-metal covering rises from -15°C during the night to 70°C at noon. This strong increase in surface temperature drives the moisture of the wooden sheathing (bearing of the sheet-metal) to the interior side. For that reason the relative humidity between the vapour retarder and the insulation increases with a small delay from less than 10% to more than 90%. During the next night, when the exterior surface temperature falls again below the temperature of the conditioned space the direction of the vapour diffusion flow changes and the relative humidity behind the vapour retarder goes back to its initial state. These experimental results show clearly the diurnal humidity variations that may appear in the building enclosure due to vapour diffusion processes. In general the balance between nighttime and daytime diffusion fluxes results in a seasonal net flux to the exterior side in winter and to the interior side in summer.

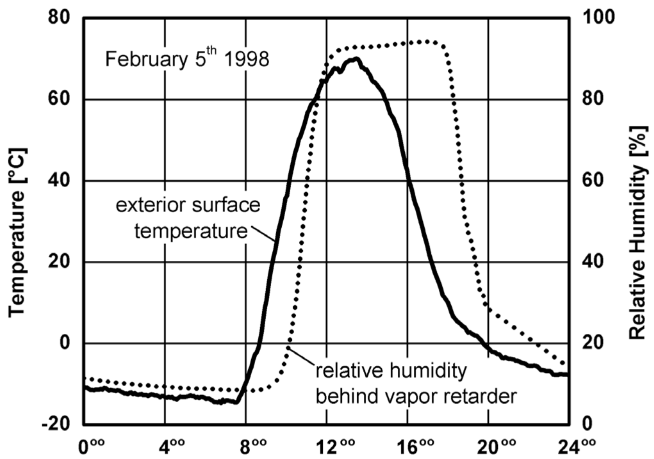

Fig. 2: Diurnal fluctuations of surface temperature and RH between the vapour retarder and the fiber glass insulation measured at a south facing cathedral ceiling during a sunny winter day in Holzkirchen [5].

3. MOISTURE CONTROL STRATEGY

The modern moisture control strategy takes account of the real conditions at a construction site. Unfavourable weather during construction and small imperfections in the building enclosure can never be entirely excluded. Therefore some moisture as vapour or liquid may get into a construction assembly. Vapour barriers are generally installed to prevent the indoor air humidity from penetrating into the building enclosure during the heating season. However, in summer the vapour flux may come from outdoors especially in cases where the exterior layer has some moisture storage capacity (e.g. brick veneer). The so-called summer condensation occurs when the sun hits a wet façade driving the evaporating moisture inwards as long as the exterior layer contains precipitation water [6].

A second moisture source is air convection. In contrast to vapour diffusion which is acting on the whole area of the enclosure, air convection follows a small path created by cracks, imperfect joints or other flaws in the air barrier. Air-tightness of the building enclosure is very important because air convection can move more moisture than vapour diffusion. However, the most efficient way of getting moisture into the building enclosure is liquid water penetration. Minor flaws in the exterior seal of the enclosure may therefore have detrimental effects unless the drying potential of the enclosure assures a sufficiently forgiving construction.

The use of vapour tight barriers in building envelope systems subjected to the hygrothermal loads described above has caused a lot of problems in the past. Many damage cases originate from the deficiency of such barriers because of inadequate workmanship or a lack of durability. Instead of striving for a perfect seal modern vapour control strategies aim at a tailored balance of all moisture supplying and removing processes. That means that a limited moisture entry is accepted when a sufficient and quick drying is assured later on. The admitted quantities of moisture in the building enclosure depend mainly on the materials' capacity of storing moisture without harmful side effects. After a characteristic moisture supply and removal cycle a building component should not contain more moisture than before. This means, the condensate accumulated during the heating period has to dry out in early summer. Infiltrating precipitation water must drain and dry away before the next rain period. This can be achieved by carefully balancing the moisture fluxes in both directions, e.g. with tailor made vapour retarding layers as suggested in [7]. Employing hygrothermal simulations is probably the most efficient way of doing this.

4. APPLICATION OF HYGROTHERMAL SIMUATION TOOLS

Today, some of the hygrothermal simulation tools developed at universities or other research institutions are also available for the practitioner. The specifications and applications of such tools are described in the ASTM Manual 40 "Moisture Analysis and Condensation Control in Building Envelopes" [8] and in the ASHRAE Handbook of Fundamentals 2001 [9]. Recently (Oct. 2004) an English version of the WTA-Guideline 6-2-01/E "Simulation of Heat and Moisture Transfer" has been published. This guideline contains the following items:

- fundamentals of heat and moisture transfer processes for building purposes
- definition of hygrothermal material properties
- boundary conditions (indoor and outdoor climate, surface resistance)
- initial conditions (e.g. construction moisture)
- accuracy of numerical solution (grid spacing, time steps)
- documentation of results.

Its purpose is to help the practitioner to successfully apply hygrothermal simulations and demonstrate to the public that moisture protection involves much more than control of interstitial condensation. In the meantime the European draft standard prEN 15026 "Hygrothermal performance of building components and building elements – Assessment of moisture transfer by numerical simulations" which is largely based on the WTA-Guideline is in its final stages. This development proves that also in Europe hygrothermal simulations can be considered state-of-the-art.

For the simulations in this paper, the most widely used tool in Europe and North-America called WUFI® [3] will be employed. This model has been validated by a number of common exercises [4] and by well-defined benchmark cases. The reliability of this software has also been confirmed by independent authors who compared experimental data with WUFI® predictions, e.g. [10, 11].

5. EXAMPLE CASE: DEVELOPMENT OF A SMART RETARDER

Hygrothermal simulation tools are usually applied to assess the moisture protection of building envelope systems and sub-systems in order to prevent unhygienic conditions or damage. However, they may also be used to create new and innovative envelope components or building materials by running parametric studies with virtual assemblies or material layers. Such an example is the development of the smart vapour retarder, a humidity controlled PA-film described in [12]. The development of that vapour retarder would have been impossible without a hygrothermal simulation model. Therefore the process leading to this product will briefly be summarized here.

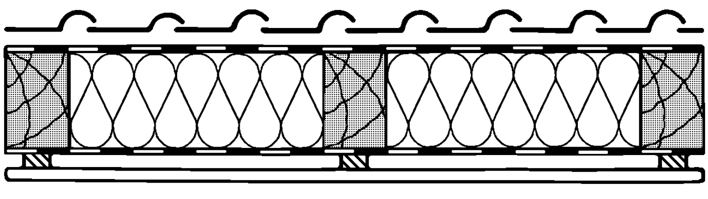

Fig. 3: Typical construction of an unvented cathedral ceiling with glass fibre insulation between roofing membrane and vapour retarder (bottom).

The development was inspired by moisture accumulation problems in unvented roof constructions found in practice such as the one depicted in Figure 3. Because most of these assemblies have a rather vapour tight roofing membrane (e.g. bituminous felt or reinforced plastic film), vapour barriers were installed to protect them from interstitial condensation. However, in the case of minor imperfections with subsequent moisture intrusion this assembly would fail because it cannot dry out to either side. In existing roofs, the top layer is difficult to change without replacing all tiles. Therefore a better solution to this problem is to find a vapour retarder that is tight enough to prevent excessive interstitial condensation while still allowing some moisture penetration to provide a sufficient drying potential towards the interior.

The first stage of the development process aimed at the optimization of the vapour diffusion resistance of the retarder by simulating the moisture behaviour of timber-framed cathedral ceiling constructions exposed to Central European climate conditions. The vapour diffusion resistance of a material layer is commonly defined by the equivalent diffusion resistance of a stagnant air layer with the thickness s_d. It turned out that a vapour retarding layer of sd = 2 m is a good compromise between the requirement to prevent excess interstitial condensation and the need to provide a better drying potential of these constructions to eliminate moisture damage during the summer period. Starting from equilibrium water content at 80% R.H. Figure 4 shows the calculated moisture balance after a typical meteorological year (recorded at Holzkirchen weather station) for different orientations and inclinations of the roof surface. A negative moisture balance indicates that the assembly dries out. A positive balance, however, is a warning sign. It may be an indication for moisture accumulation. It seems that especially the northern orientation combined with an inclination of more than 40° is rather unfavourable for this roof.

While the drying potential is clearly better than with a traditional polyethylene or aluminium vapour barrier, the drying by vapour diffusion towards the interior is not sufficient for shaded orientations. Therefore the vapour diffusion characteristics of the retarder have to be tailored in a way that enhances the drying potential of the assembly during the summer season. This can be achieved by reducing the retarder's resistance during the evaporation period (summer time) while keeping the resistance up the condensation period (winter time). The resistance should be variable with the variation being a function of a parameter that differs distinctly between the condensation and evaporation period. As explained above, the relative humidity at both sides of an installed vapour retarder is such a parameter. The simulations show that a virtual material layer having a vapour diffusion resistance which is diminished by a factor of 10 during the summer period solves the moisture problems for all orientations and inclinations of the considered construction. After this parametric study the only remaining item was to find a material whose properties matched the virtual retarder.

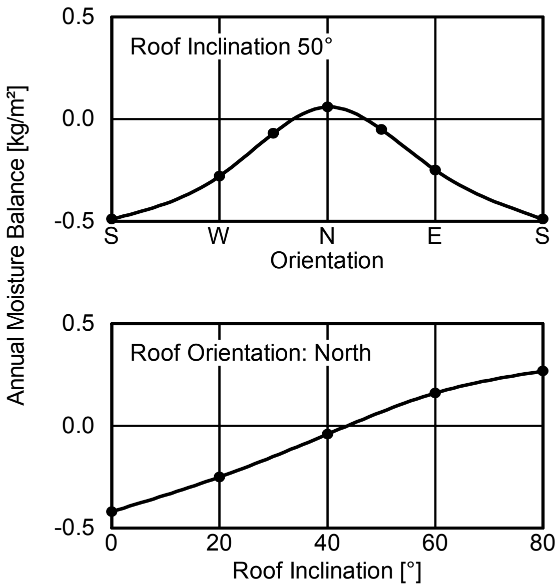

Fig. 4: Annual moisture balance in a cathedral ceiling with vapour tight top and a slightly permeable vapour retarder (s_d = 2 m) determined for different orientations and inclinations of the roof.

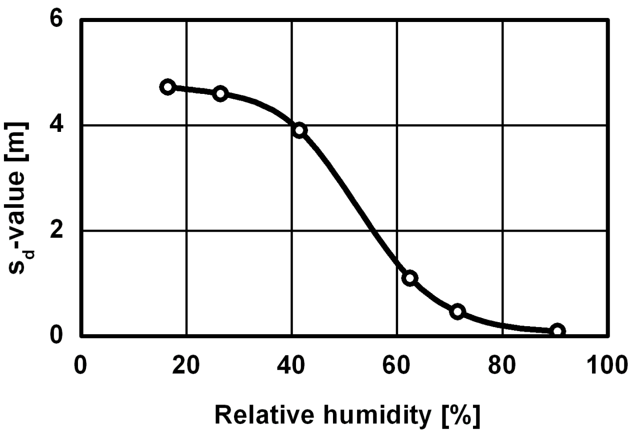

Fig. 5 Variation of vapour diffusion resistance s_d of a film (thickness = 50 µm) made from polyamide (PA) with ambient humidity conditions.

Several plastic films were tested in the laboratory and a polyamide film whose vapour transport characteristics are shown in Fig. 5 was chosen because its humidity depending diffusion resistance corresponds with the properties of the virtual layer defined by the hygrothermal simulations. The resulting temporal fluctuation of the water content in the roof assembly of Fig. 3 with a vapour retarder having a constant diffusion resistance (sd = 2 m) and the polyamide film (see Fig. 5) is shown in Fig. 6. In this example the roof surface is facing North with an inclination of 50°. The interior climate has been chosen according to the recommendations of the WTA-Guideline 6-2-01/E, with low (30% r.F. indoor air humidity in January), medium (40% r.F.) and high (50% r.F.) interior moisture load. While the constant vapour retarder is doing fine when the interior moisture load is low, the situation is becoming critical for higher indoor air humidity because the drying rate in summer is too small to prevent moisture accumulation in the construction. When this retarder is replaced by the smart PA-film (variable s_d) the drying rate in summer is increased considerably. Therefore the roof construction will dry out in the long run even when the interior moisture load is high due to excessive vapour production by the occupants. Experimental results [13] confirmed the positive results of the simulations. Since its market introduction in 1997 the smart retarder is successfully applied in Europe and North-America. This proves the benefits of hygrothermal simulations concerning building performance predictions and innovative product development.

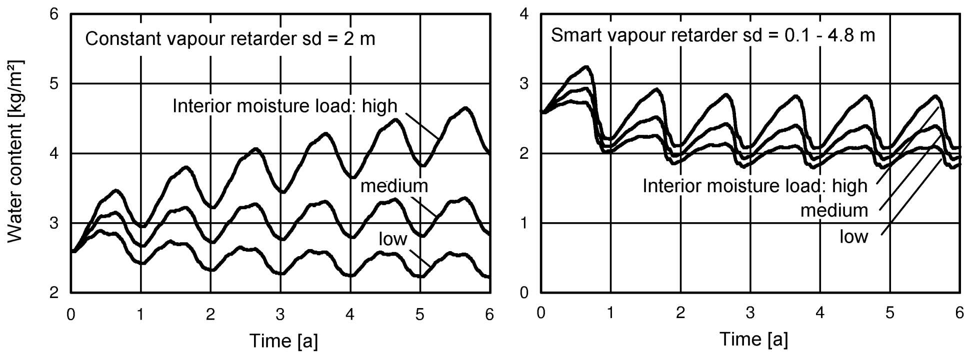

Fig. 6 Seasonal water content fluctuations in a north oriented roof assembly with the constant vapour retarder respectively the smart retarder.

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