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PREVENTING MOISTURE PROBLEMS IN RETROFITTED PITCHED ROOFS

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Abstract. Retrofitting the thermal insulation of pitched roofs, especially those equipped with an impermeable sheathing membrane, may cause problems by moisture accumulation in the roof. As a non-ventilated insulation makes use of the whole cavity between the rafters and can be realized much more easily it should be preferred over a ventilated construction if possible. However, this requires that the roof assembly can dry out to the interior side, so that any moisture penetrating into the roof by accident will not be trapped permanently. The influence of the local climate, roof orientation and inclination as well as the interior conditions on the hygrothermal performance of an unventilated pitched roof has been determined by numerical investigations. The results show that a north orientation combined with a strong inclination is the least favourable situation for the drying potential of the roof. The application of a humidity-controlled vapour retarder offers the best solution against moisture related problems under all investigated conditions. However, under favourable boundary conditions also a moderate vapour retarder provides a working alternative.

Key words: vapour diffusion, adaptive vapour retarder, pitched roof, thermal insulation

INTRODUCTION

The greatest potential for reducing the CO_2 output in Germany lies, as already explained by Gertis [1991], in the improvement of heat insulation for old buildings. This also represents an increasing challenge for the field of building physics since insulating measures as applied in new buildings often cannot be implemented here because of the construction situation, or because they are too expensive. One example is the post cathedral ceiling insulation for pitched roofs. In southern Germany these roofs often hale

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a relatively vapour-tight underroof (e.g. bituminous felt on wood sheathing), so that the insulation could either be ventilated, or the vapour diffusion processes must be analyzed more precisely. Ventilation should be avoided if possible because this not only reduces the thickness of the insulating layer, but also requires the use of chemical wood preservatives due to insect access [DIN 68800-3, 1990]. Cathedral ceiling insulation using a vapour barrier (μd > 100 m) (μd-value: diffusion-equivalent air layer thickness, also referred to as vapour diffusion resistance) may conform with standards [DIN 4108-3, 2001], but not with practical experience, because initial moisture or moisture penetrating through imperfections or via interior walls gets trapped in the roof and causes damage in the long term [Schulze 1996, Künzel 1996]. It is therefore preferable to work with vapour retarders with a diffusion resistance clearly under 10 m so that any possible moisture can dry out to the room side.

However, one has to make sure that the condensation which arises in the wintertime can be removed again in the summer, i.e. the moisture balance must be such that evapouration exceeds condensation, and therefore no moisture can accumulate in that section of the building. The standard calculation method according to Glaser [DIN 4108-3, 2001] is only partially suitable for such an examination because the simplified boundary conditions are too different from the actual conditions. In addition, contrary to popular opinion the results obtained with this method are not always on the safe side, as [Künzel 1995] shows. For this reason, the moisture behavior of such a roof with cellulose fiber insulation in dependency of the external and internal climatic conditions is examined using a modern transient calculation method.

NUMERICAL INVESTIGATIONS

The roof under examination is a pitched roof, typical of those on old buildings, the construction of which is shown in Figure 1. It has 160 mm strong rafters and 16 mm thick wooden sheathing covered by a vapour-tight membrane (μd = 1000 m). The roofing comprises roofing tiles with a short-wave absorptivity of 0,6. This roof is completely insulated by blowing in cellulose fibers (material properties from Künzel [1992]) following the addition of a vapour retarder and vapour permeable paneling on the room side. From a hygrothermal viewpoint, the insulating material with a thermal conductivity of 0,04 W/mK and a μ-value of 1,5 only differs from mineral fiber material in its water vapour sorption capacity. The equilibrium moisture contents at 80% and 95% relative humidity are 0,8 and 2,7 vol.-%, respectively, for a density of 60 kg/m^3. The capillary conductivity of the insulation material can be neglected for the moisture conditions under examination here. The μd-value of the conventional vapour retarder is independent of the ambient conditions. For the investigation, it is varied between 0.5 m and 5 m and is 2 m in the standard case. Alternatively, the calculation can be performed using the vapour diffusion characteristics of the humidity-controlled (smart) vapour retarder [Künzel 1997a]. Its diffusion resistance adapts to the surrounding conditions and has an average value of 4 m under winter conditions, and of approximately 0.4 m in summer. The measured dependency of its vapour diffusion characteristics on the relative humidity is depicted in Figure 2. The humidity-controlled (smart) vapour retarder is a 50 μm thick nylon-based membrane, a material which is being used primarily for food packaging.

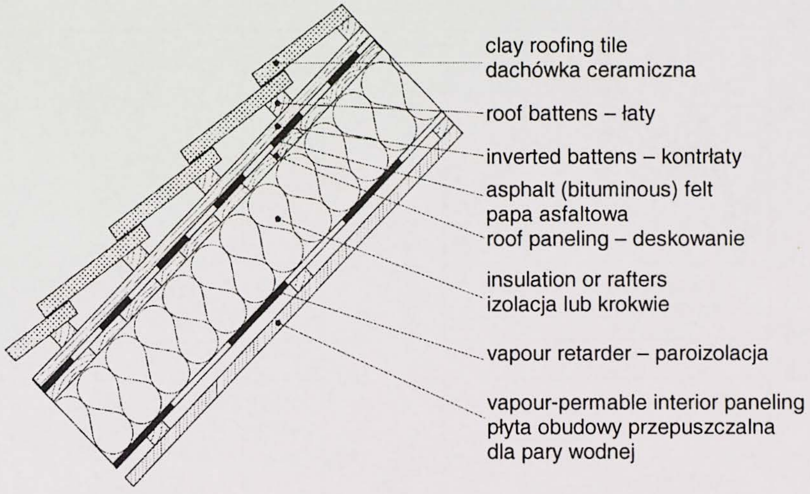


Fig. 1. Construction of the roof under examination
Rys. 1. Budowa badanego dachu

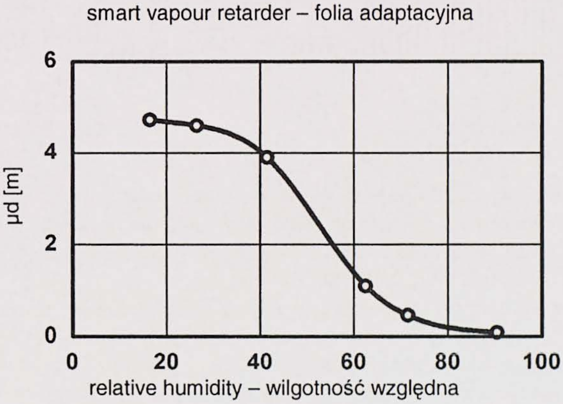


Fig. 2. Vapour diffusion resistance of the humidity controlled retarder depending on the environmental humidity
Rys. 2. Zmienny opór dyfuzyjny folii adaptacyjnej w zależności od otaczającej wilgotności

The calculations for the hygrothermal behavior of this roof under natural climatic conditions are conducted with the aid of the PC program WUFI® [Künzel 1994] which has repeatedly been verified by comparison with experimental results. Assuming an initial moisture level in the roof which corresponds to the equilibrium moisture of the building material stored at 80 % relative humidity, the influences of the outdoor and indoor climates and the orientation and slope upon the long-term moisture situation in the roof are calculated in parametric studies. For exterior conditions, meteorological records based upon the hourly mean values of a typical year in Holzkirchen (see Fig. 3)

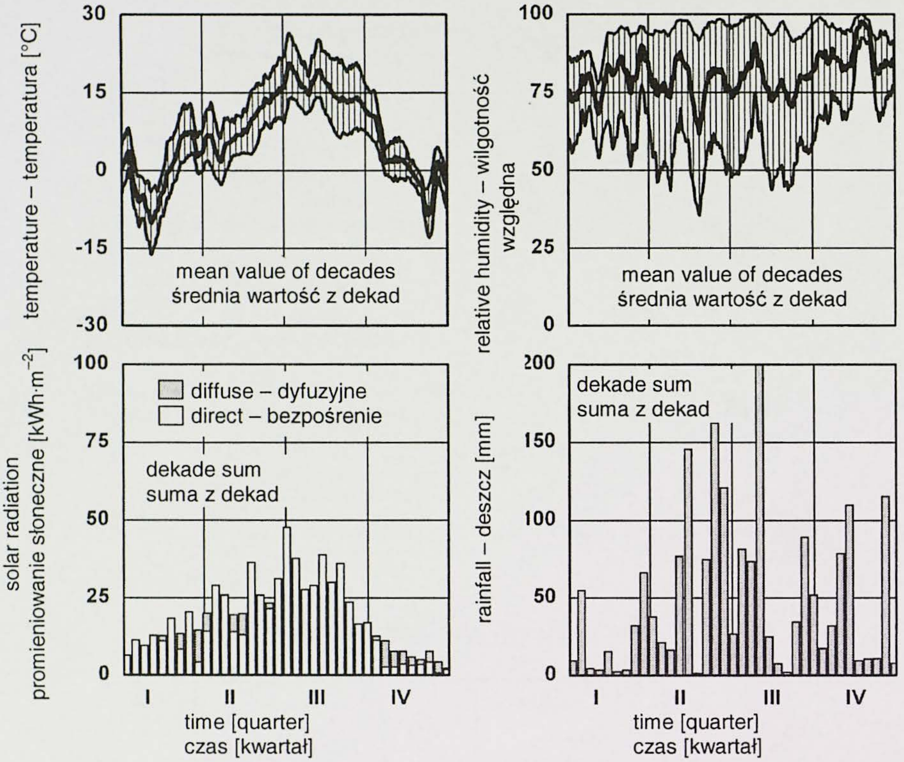


Fig. 3. Climatic boundary conditions based on measured hourly mean values in Holzkirchen (680 m above sea level, in front of the alps). Outdoor temperature and humidity are shown as mean values of decades together with its daily range. The short wave radiation and the rainfall are given as decade sum

Rys. 3. Klimatyczne warunki brzegowe opracowane na bazie pomiarów godzinowych w Holzkirchen (680 m nad poziomem morza, przed Alpami). Temperatura i wilgotność powietrza zewnętrznego pokazują średnie wartości z dekad łącznie z dobowymi wachaniami. Promieniowanie słoneczne oraz deszcz pokazano jako sumy dekadowe

are used, as well as the German Test Reference Years [Blümel et al. 1986]. Since the nightly long-wave emission of the roof is of significance for the surface temperatures, the Holzkirchen records must be complemented with the atmospheric counter-radiation, which is derived from the temperature, the relative humidity and the cloud cover similarly to the Test-Reference-Years. The intensity of short-wave radiation on the non-shaded roof surface is determined according to [Künzel 1994], depending upon the pitch and the orientation of the roof. The external air humidity conditions are of no importance for the calculation due to the vapour-tight underroof. The influence of the ventilated roof covering on the surface temperature of the underroof can be determined by comparison with outdoor measurements. A good conformity between the measured and the calculated underroof surface temperatures is achieved, as Figure 4 shows, with an external heat transfer coefficient of $19\ W/m^2 \cdot K$, a short-wave absorption number of 0.6 and

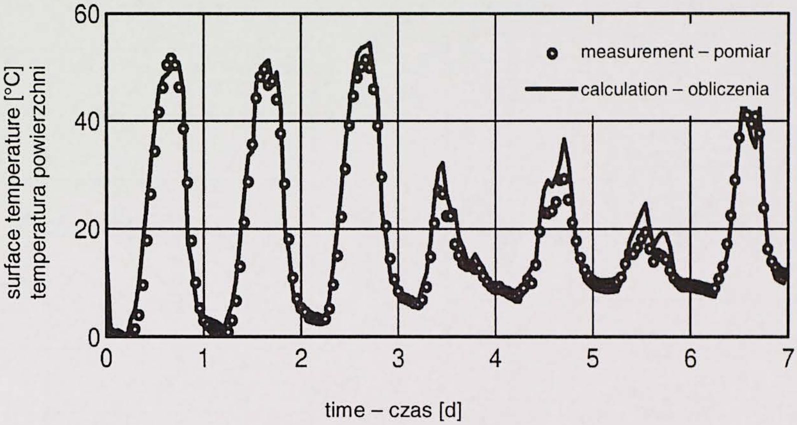


Fig. 4. Run of the curve for measured and calculated surface temperature of the westward orientated underroof. Exemplary displayed is one week in the end of May with bright and cloudy days

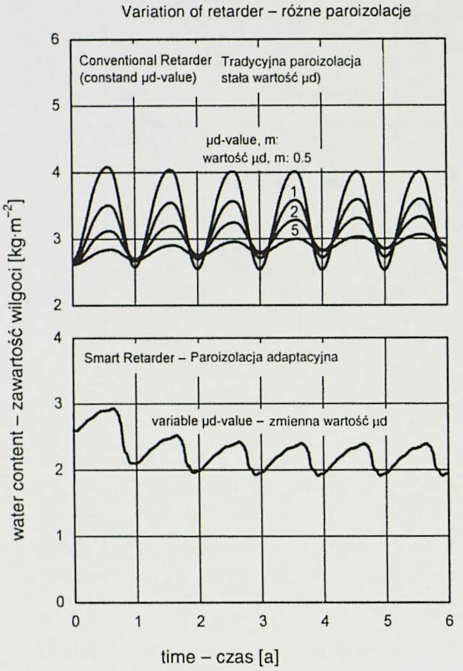
Rys. 4. Przebieg pomierzonej i obliczonej temperatury powierzchni dolnej dachu. Przykładowo pokazano wyniki z jednego tygodnia z końca maja przy słonecznych i zachmurzonych dniach

a long-wave emissivity of 0.3 (long-wave emission of the roof covering also leads to a certain under-cooling of the lower roof). The short-wave absorption and the long-wave emission numbers used here are effective characteristics which immediately refer to the underroof and incorporate the effect of the roof covering.

Based on these preliminary experimental and calculative investigations, the standard case used for this survey, from which the individual parameters are then varied, is a north-facing roof with a pitch of 50°. The Holzkirchen weather data and the indoor air conditions for a normal moisture load derived according to WTA-Guideline, 6-2-01/E [2001] are applied as the standard climate for outdoor and indoor conditions. Each of the calculations begins in October and is conducted over a six-year period for the typical cross section of the roof assembly. The influence of possible snow coverage is not taken into account.

RESULTS

The roof's moisture behavior in the standard case with different vapour retarding films is depicted in Figure 5 over a six-year period using the total moisture content courses in the roof. If the course of the maximum wintertime moisture level is monitored, or if the initial and final moisture level in the roof are compared, then it becomes apparent that – with the exception of the case with a room-side μd-value of 0.5 m – a slight moisture accumulation takes place in the roof, which becomes more pronounced as the μd-value increases. The seasonal moisture amplitudes are, however, greater than the difference in final moisture levels when the different vapour retarders are used. While the wintertime condensation levels with a room-side μd-value of 0.5 m and 1 m exceed



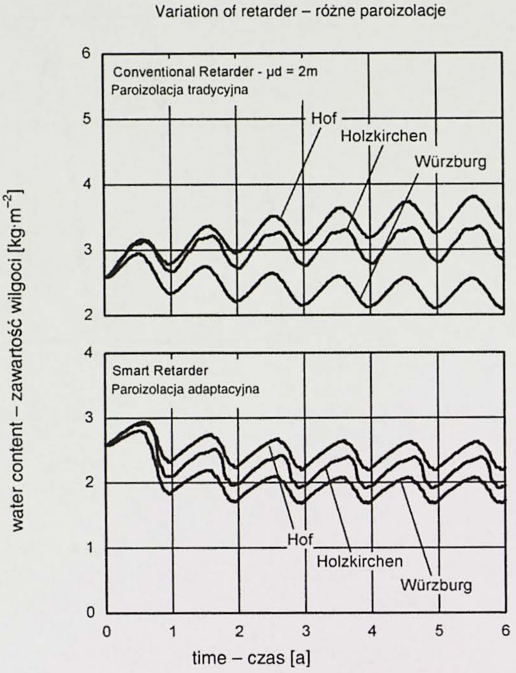


Fig. 5. Development of the total water content by using conventional vapour retarders with a different diffusion resistance and by using a moisture adaptive vapour retarder

Rys. 5. Zmiana całkowitej zawartości wilgoci przy użyciu tradycyjnych paroizolacji o różnych oporach dyfuzyjnych oraz przy użyciu folii adaptacyjnej

Fig. 6. Development of the total water content by different outer climate conditions due to the position

Rys. 6. Zmiana całkowitej zawartości wilgoci przy różnych klimatach zewnętrznych w zależności od położenia

the limit specified in [DIN 4108, Teil 3, 2001], they are lower when the tighter vapour retarders are used. Although the vapour retarder with a μd-value of 5 m lets less moisture into the roof in the wintertime, it appears sensible to favor the vapour retarder with a μd-value of 2 m because in the present case it provides sufficient protection against condensation and at the same time offers a relatively high drying potential. A room-side vapour diffusion resistance of 2 m for the conventional vapour retarder is therefore used for the remaining calculations. Under the same conditions, employing the humidity-controlled (smart) vapour retarder causes the roof to dry out below the initial moisture levels, as shown in Figure 5 (bottom).

The influence of the outdoor climate on the roof is depicted in Figure 6 showing the moisture courses which are calculated with the Test Reference Years for Würzburg and Hof in comparison to the standard example which is based upon the Holzkirchen climatic data. The roof with the conventional vapour retarder dries out under Würzburg climatic conditions, while there is an increase in moisture levels over a six-year period for Holzkirchen and Hof. The humidity controlled vapour retarder leads to a drying-out under all climatic conditions, so that no critical moisture conditions in the roof need to be feared in any of the cases. Because the moisture accumulation using the conventional vapour retarder is relatively even over the years, whereby it is apparent after one year whether or not the water content in the roof increases or decreases in the long term, it seems to make sense to judge the moisture behavior of a building element using the annual moisture balance (the difference in water content after one year in comparison to the initial level). If the balance is positive then moisture is being accumulated; if it is negative then the building component is drying out. If the annual moisture balances from calculations with the 12 different Test Reference Year records are plotted against the annual mean temperatures of the respective climatic regions, then the result is, as Figure 7 shows, an approximately linear correlation. A critical moisture balance only arises in Hof (climatic regions: Black Forest, Swabian and Franconian Jura) and also in Holzkirchen when the conventional vapour retarder is used. The warmer the climatic region, the stronger the decrease in water content in the roof. So the moisture behavior of the roof system can be transferred to other regions with similar climatic conditions.

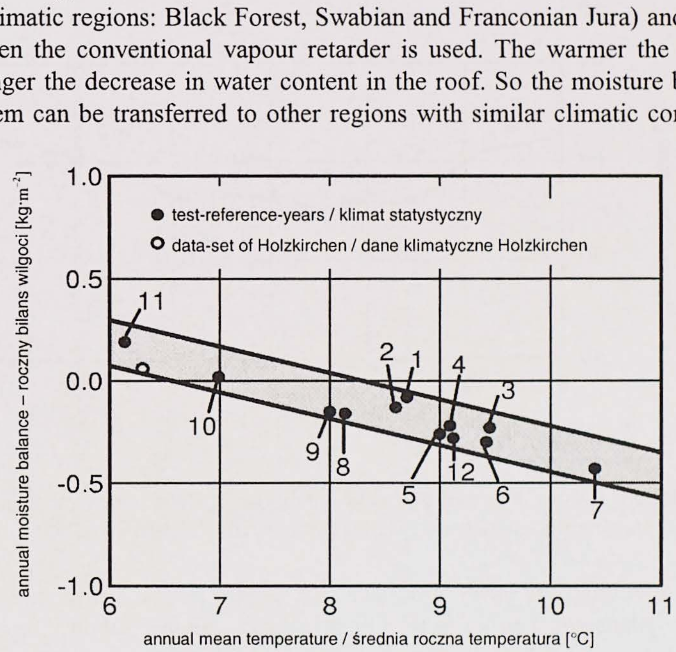


Fig. 7. Correlation between the calculated annual moisture balance and the annual average air temperature of the used climatic data sets: 1 – Bremerhaven, 4 – Trier, 7 – Freiburg, 10 – Stötten, 2 – Hannover, 5 – Würzburg, 8 – Augsburg, 11 – Hof, 3 – Essen, 6 – Frankfurt / Main, 9 – München, 12 – Friedrichshafen and data-set of Holzkirchen

Rys. 7. Zależność między obliczonym bilansem wilgoci oraz średnią, roczną temperaturą powietrza klimatów statystycznych: 1–Bremerhaven, 4 – Trier, 7 – Freiburg, 10 – Stötten, 2 – Hannover, 5 – Würzburg, 8 – Augsburg, 11 – Hof, 3 – Essen, 6 – Frankfurt / Main, 9 – München, 12 – Friedrichshafen oraz klimatu Holzkirchen

As we can see in Figure 8 the temperature of Holzkirchen is very similar to that of Cracow. Merely the relative humidity in Cracow is a little bit lower than in Holzkirchen. Nevertheless it is to be expected, that identic roof constructions in Holzkirchen and in Cracow behave in nearly the same manner.

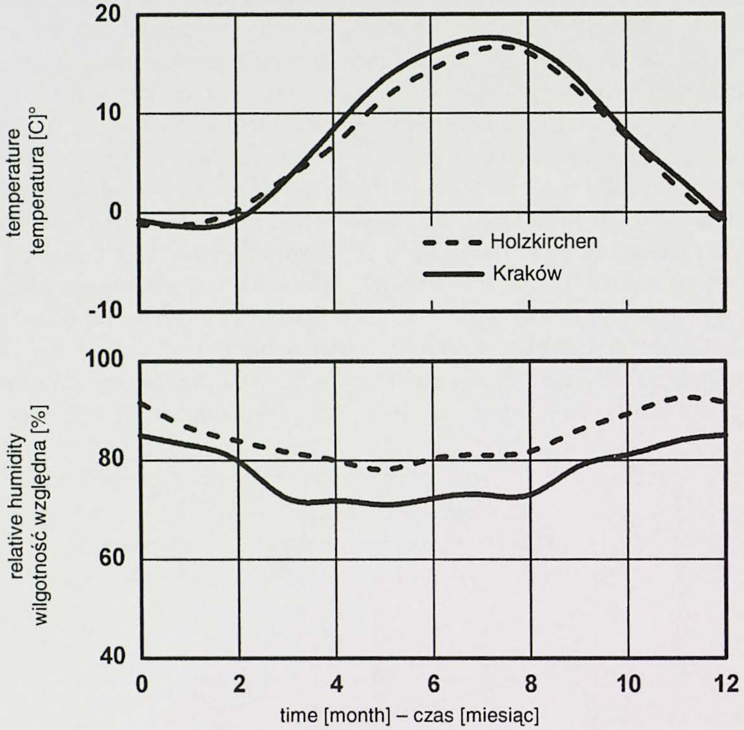


Fig. 8. Monthly mean values of the climatic conditions of Holzkirchen and Cracow
Rys. 8. Średnie miesięczne parametry klimatyczne w Holzkirchen i Krakowie

The orientation of the roof surface has at least as much influence upon the annual moisture balance of the roof as the climatic region. Figure 9 shows the influence of orientation (top) and pitch on the moisture behavior taking the standard example as a basis. Due to the higher surface temperatures arising from the increased irradiation, a reduction in the roof pitch or the azimuth leads to significantly more favorable drying conditions with the consequence that moisture cannot accumulate in south-oriented or in relatively flat roof constructions, as long as there is no shade from trees or neighboring buildings. The danger of moisture accumulation is also relatively low with unshaded roofs facing west or east, with the west side slightly more favorable than the east side due to the higher outdoor air temperatures in the afternoons. In the case under examination here, moisture problems can only arise with north-facing and relatively strongly sloped roofs because when conventional vapour retarders are used there is insufficient drying

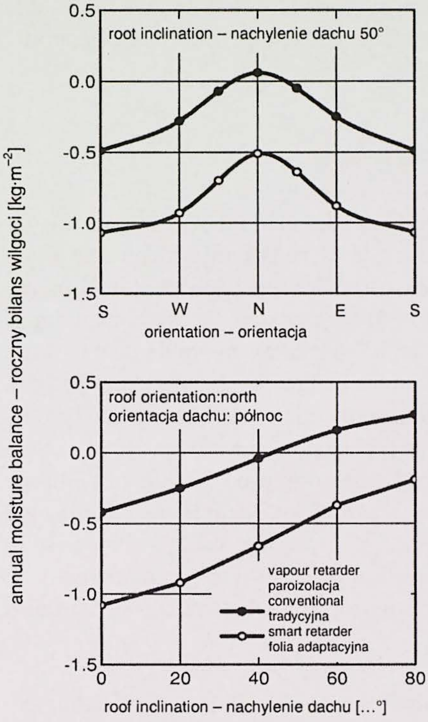


Fig. 9. Annual moisture balance by different orientations of the roof surface. Values above zero indicate the risk of moisture accumulation

Rys. 9. Roczny bilans wilgoci przy różnej orientacji połaci dachowej. Wartości dodatnie wskazują na ryzyko akumulacji wilgoci

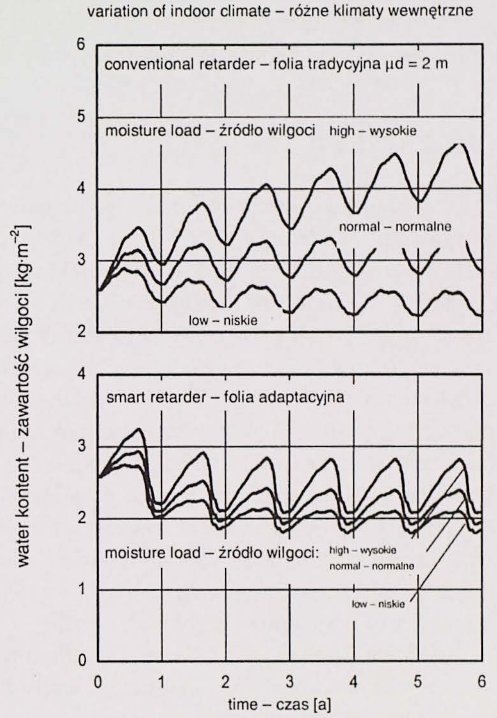


Fig. 10. Development of the total water content with different moisture loads indoor according to WTA-Guideline 6-2-01/E

Rys. 10. Kształtowanie się zawartości wilgoci przy różnej wydajności zgodnie z wytycznymi WTA 6-2-01/E

potential due to the low surface temperatures. This drying potential can, however, be significantly improved with the aid of the humidity controlled (smart) vapour retarder's special characteristics so that the annual moisture balance always stays negative, i.e. no moisture accumulation arises.

The effects of the room climate on the moisture situation in the roof for the standard case are demonstrated by the courses of the water content in Figure 9. While a low moisture load in the room does not result in an increase in water content in the long run, a high moisture load quickly results in critical levels if a conventional vapour retarder is applied. If the influence of the indoor climate is compared with that of the outdoor climate in Figure 6, then it is apparent that the air humidity conditions in the room have still greater effects on the moisture balance in the roof than the difference between one of the warmest and the coldest regions in Germany. However, it must be taken into consideration that high moisture loads will only arise in extremely rare cases in habitable attic rooms, because in most occupied living rooms the air humidity levels are generally within those defined here as normal moisture load.

CONCLUSIONS

The boundary conditions investigated here (outdoor climate, indoor climate and orientation) are affecting the long-term moisture behavior of non-ventilated pitched roofs with vapour-tight underroof to comparable degrees, so that none of them should be neglected if the moisture tolerance of such a roof is to be assessed. These constructions appear quite safe if two or three of these factors can be judged as favorable. If this is not the case, then an exact evaluation of the individual case should be undertaken or another construction chosen. The influence of the insulating material's sorption capacity only plays a subordinate role for the moisture issue, as a comparison with similar investigations shows in [Künzel 1997b], for which mineral wool was used instead of cellulose fibers. It is, however, important that the insulating material and the interior paneling are sufficiently vapour permeable because otherwise a similar drying blockage can arise as with the less permeable vapour retarders discussed above. Despite the complexity of the different influencing factors, it always seems possible to implement a non-ventilated pitched roof with vapour-tight underroof:

– for flat-pitched (< 20°) roofs (ventilation is problematic here anyway),

– hor pitched roofs which are not mainly north-facing and without shade for long periods from the surrounding buildings,

– for proven low moisture loads in a converted attic storey e.g. for usage as an office or bedroom,

– when an humidity controlled vapour retarder is used in connection with a vapour--permeable interior paneling.

If one of these conditions is fulfilled then an increased risk of damage in a carefully executed construction can be excluded. Generally, it is therefore not necessary to ventilate the insulation layer, which in turn leads to more space for the insulation (higher thickness) and to lower costs for the renovation of old buildings. The use of chemical wood preservatives should also be avoided in favorable conditions. Similar considerations could also lead to an improvement of the moisture tolerance and the cost-benefit relation of insulating measures with other building components and hence make a contribution to the efficient renovation of old buildings.

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ZAPOBIEGANIE PROBLEMOM WILGOTNOŚCIOWYM W MODERNIZOWANYCH DACHACH ZE SZCZELNYM POSZYCIEM

Streszczenie: Ze względu na łatwość wykonania, docieplenie połaci dachowych wykonuje się często bez uwzględnienia warstwy wentylacyjnej, umieszczając izolację termiczną w całej, wolnej przestrzeni pomiędzy krokwiami. Rozwiązanie takie może powodować akumulację wilgoci w dachu ze szczelnym, nieprzepuszczającym pary wodnej, poszyciem. Ewentualne zawilgocenie może w takim przypadku wysychać jedynie do wnętrza poddasza. Za pomocą obliczeń numerycznych analizowano zjawiska cieplno-wilgotnościowe zachodzące w niewentylowanych dachach ze szczelnym pokryciem. Uwzględniano wpływ klimatu zewnętrznego, orientacji, nachylenia jak również wewnętrznych warunków mikroklimatycznych. Obliczenia pokazały, że najmniej korzystny, ze względu na możliwość wysychania, jest stromy dach o wystawie północnej. Zastosowanie wilgotnościowej folii adaptacyjnej rozwiązuje w pełni problem zawilgocenia we wszystkich analizowanych przypadkach. Stwierdzono również, że w niektórych sytuacjach, zadawalającym rozwiązaniem może być również zwykła paroizolacja o małym oporze dyfuzyjnym.

Słowa kluczowe: dyfuzja pary wodnej, paroizolacja adaptacyjna, dach ze szczelnym poszyciem, izolacja cieplna

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