Condensation Problems in Cool Roofs

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ABSTRACT

In some regions of the United States so called cool roofs have become mandatory in order to save cooling energy in summer and it is expected that these roofs will also become more widespread in other parts of the world. A cool roof uses a bright surface to reflect incident solar radiation which significantly lowers the day-time surface temperature compared to conventional roofs with bituminous felt. However, since most energy savings measures involve some sort of moisture related issue, the question is whether the widespread application of these roofs may lead to durability problems. There are already rumors that the so-called self-drying roofs that do not have a vapor barrier might face moisture accumulation when equipped with a reflective surface, because the solar vapor drive helping to dry out the roofs during summer time is diminished.

In order to clarify this important durability issue experimentally verified hygrothermal simulations have been carried out on light-weight flat roofs with and without reflective surface layer. Because the long-wave radiation to the sky is an important factor for the night-time roof temperature and thus also for the risk of interstitial condensation, the sky radiation has been measured as part of the meteorological data collection at the field test site in Holzkirchen. Together with continuous surface temperature recordings of different roofs these meteorological data have been used to validate the new radiation exchange model of a hygrothermal simulation tool. Afterwards a typical light-weight cool roof has been selected and its moisture behavior simulated under different outdoor conditions. The results show that severe moisture accumulation will only occur in colder regions of Europe and North-America. However, among these regions there are also some where cool roofs could be beneficial for cooling energy savings.

KEYWORDS

Cool roof, Interstitial condensation, Nightime radiative cooling

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1 INTRODUCTION

In order to build energy efficient buildings nowadays it is very important to optimize the building envelope. The roof provides a large part of the envelope so it is obvious to try saving energy at this area. There are already some approaches and solutions to save energy by building a so called 'cool roof'. A cool roof uses a bright surface to reflect incident solar radiation which significantly lowers the day-time surface temperature compared to conventional roofs with bituminous felt. Cool roofs bring along the risk of moisture accumulation in colder regions of Europe and North America due to the reduced surface temperature during the day. Furthermore the long wave radiation can lead to overcooling of the surface beneath the ambient temperature. Such low temperatures during the night can cause the temperature to drop beneath the dew point followed by condensation of moisture in the construction. New simulation models are able to consider this effect.

2 FUNDAMENTALS

2.1 Cool Roofs

The temperature occurring on a roof depends on several factors. When the solar radiation hits the roof's surface, a part is reflected, another is absorbed. A part of the received energy is emitted back to the sky as infrared radiation. Another part of the heat is exchanged with the environment by convection. The remaining heat flows through the roof and interacts with the room. This heat flow depends on the temperature gradient between the roof surface and the interior temperature, the thermal conductivity and the thickness of the construction materials (e.g. insulation) of the roof. Unlike conventional roofs, cool roofs keep a moderate temperature even during hot summer days by having a higher solar reflectance and higher thermal emittance than conventional roofs. Many publications, especially from the United States, talk about cooling energy savings of up to 25%.

2.2 Self Drying Roofs

Self-drying roofs are designed to eliminate accumulation of moisture in the construction. The occurring moisture can dry out to the interior of the building (downward drying). The construction is usually sealed to the outside by a roofing membrane acting as water and vapor barrier. In the interior the construction consists of an insulation core made from materials which do not rapidly degrade mechanically in the presence of moisture. To the inside no vapor retarder is used to guaranty the possibility to dry out. The interior finish can be formed for example by a gypsum board in habitations or profiled sheeting in industrial buildings. A widespread research about self-drying roofs was performed by Dejarlais [Desjarlais *et al.* 1995 and 1998].

3 CALCULATIONS

3.1 Climatic Data

For the studies performed at the Fraunhofer Institute for Building Physics in Holzkirchen measured climatic data are used. The climate at Holzkirchen is representative for a critical climate situation in Germany. At the institute's weather station many kinds of metrological data are collected. To carry out these investigations the following data have a significant influence. The surface temperature on black and white surfaces (measured since 1998), the global, diffuse and west radiation (measured since 1987) and the atmospheric counter radiation (measured since 2002). A further experimental setup was built up in 2007, to research the influence of the night time long wave radiation in detail.

3.2 Hygrothermic Simulations

A validated method for simultaneous calculation of heat and moisture transport in building components WUFI® [Künzel 1994] was used for the simulations in this paper. As boundary conditions the climatic reference data (hourly values) from the investigated location was used. This file contains hourly values for temperature, humidity, rain, wind, solar-, atmospheric radiation etc.. For the interior climate the specifications from EN 15026 [2007] for 'normal moisture load' was used. The interior conditions are shown exemplary for Holzkirchen in Fig. 1. In this standard the indoor conditions are derived from the outdoor climate. Depending on the outdoor air temperature the indoor conditions vary between 20 and 25°C, respectively 30 and 60% RH. The material properties needed to perform the calculations are taken from the WUFI material database.

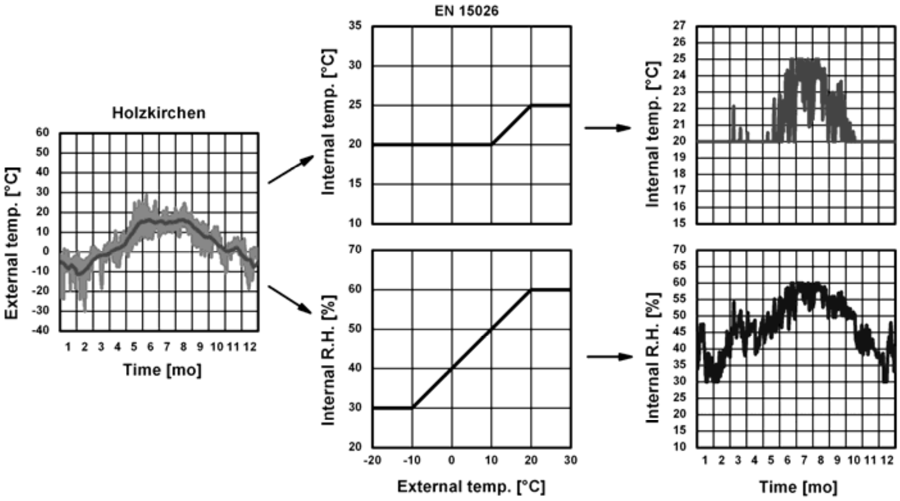

Figure 1. Example of the used interior conditions for the calculation in Holzkirchen derived from the outdoor temperature according to EN 15026 [2007].

3.3 Comparision of Measurement and Calculation Using An Explicit Long-Wave Radiation Model

For validating of an explicit long-wave radiation model in WUFI® [Kehrer and Schmidt 2006] many calculations where performed. This model considers an explicit exchange of the long wave radiation while in earlier applications the radiation effects were only lumped together with the convective heat transfer coefficient. In this section only one example is shown comparing measurement with calculation. In this case a flat roof is considered, built up with mineral wool insulation and sealed with an elastomeric bitumen roofing sheet covered with dark red colored mineral granules.

In Fig. 2 the measured surface temperature of the flat roof is displayed in blue. The red line is the temperature calculated by WUFI® using the measured ambient air temperature (green graph) as boundary conditions and the radiation values collected by the weather station. The surface temperature values are in a range of -10°C to 50°C while the air temperature only show values between -3°C and 20°C. Surface temperatures below ambient air temperature are due to long-wave radiation to the clear sky at night. The calculation shows a good accordance to the measured values; the lower temperatures during night time as well as the higher temperatures during day are captured. The days between the second and fifth November during which the calculation shows a much higher temperature than the measurement, the roof was covered with snow. The model does currently not take into account the effect of snow.

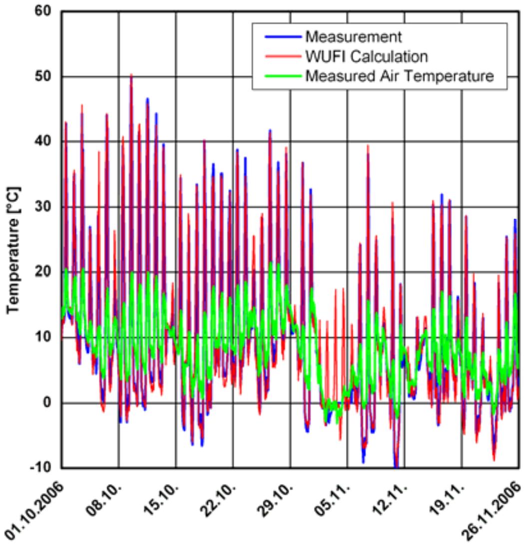

Figure 2. Comparision between measuremnet and calculation.

3.4 Self-Drying Flat Roofs in North America

The considered self-drying roof is built up as shown in Fig. 3. To the outside it is sealed by a roofing membrane, to the inside the construction is completed with profiled sheeting. The interior is filled with foam insulation (Polyisocyanurate).

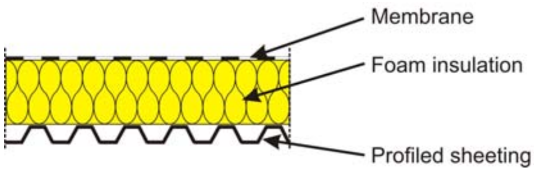

Figure 3. Composition of the self-drying roof.

The simulations were carried out for different locations in North America to find out, if there is a problem using a reflective layer on a self-drying roof. Phoenix (Arizona) was selected as warm location, Chicago (Illinois) as temperate location and Anchorage (Alaska) as cold location. The following parameters were used for the calculation: Vapor permeability of the profiled sheeting was set to s_d=3.3m (1US perm – equivalent diffusion resistance considering perforations and joints) according to Desjarlais [1995] and for the roofing membrane to s_d=1000m. The short-wave absorption factor for a white surface is 0.2 and for a black surface is 0.88. For the long-wave emission ε=0.9 is used. The calculation starts at the first of October and is continued for five years to see if a moisture accumulation will occur. The simulations results are compared by examining the total water content in the construction. If a water content of more than 0.5kg/m^2 occurs there is a risk of water dripping out of the construction. Furthermore the annual average of the moisture content should not increase over time.

The temperatures at the examined locations are shown in Fig. 4. The curves displayed in gray are hourly values of the temperature; the black curve is the floating monthly average. Comparing the average curves, in Phoenix the temperature ranges between 10 and 35°C with minimum temperatures of 0°C and maximum values of about 45°C. In Chicago the average temperature fluctuates between -9 and 23°C with minimum values of about -22°C and maximum values of about 34°C. The average temperature in Anchorage lies between -12 and 15°C with minimum values of -29°C and maximum values of 24°C.

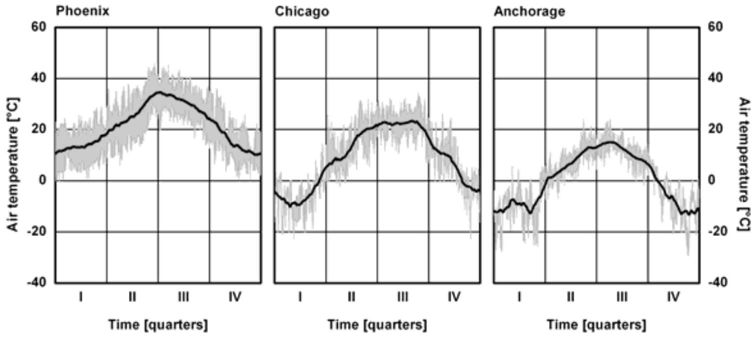

Figure 4. Air temperature in Phoenix, Chicago and Anchorage. The gray line are hourly values, the black line shows the floating monthly average.

The temporal variations of the total moisture content in the construction are displayed in Fig. 5. For the warm location Phoenix the total water content reaches up to 0.05 kg/m^2 in case of the white surface. The roof with the black surface stays dry almost all year. Concerning the roof in Chicago, a difference between the black and the white surface is recognizable. The bright roof reaches a total water content of about 0.3 kg/m^2, the dark roof about 0.1 kg/m^2. At the cold location Anchorage the roof with the dark surface shows maximum total water content of 0.35 kg/m^2 while the roof with the white surface is not able to dry out during the summer time. An accumulation of water over the years is clearly visible.

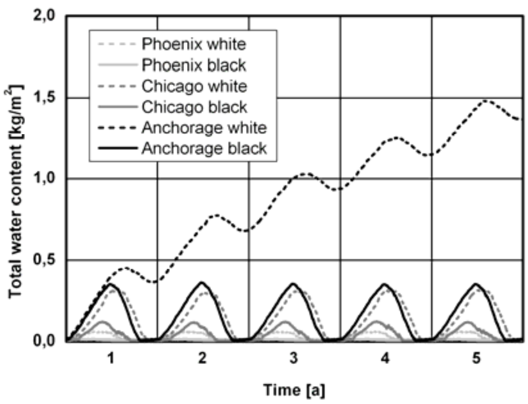

Figure 5. Total water content flat roof at different locations with white and black surface.

The self-drying roof works in most locations independent of the applied surface color under the conditions that the only source of moisture is vapor diffusion from the interior. Only in locations with low average temperatures moisture accumulation due to a bright surface color cannot be ruled out.

3.5 Bright and Dark Flat Roof in Holzkirchen

For the following comparison of the influence of the different surface colors on the moisture behavior a flat roof which is typical for European constructions is considered.

The composition is shown in Fig. 6. The roof is constructed with mineral insulation between wooden rafters, sheeted by an OSB panel and is sealed with an elastomeric bitumen roofing sheet. This roofing sheet is calculated with a radiation reflecting white surface (absorption factor 0.2) and a typical used black surface (absorption factor 0.88). The long-wave emission factor ε=0.9. To the inside the construction is closed using a vapor retarder (s_d=2m) and a gypsum board. In this example the insulation layer has a thickness of 200mm.

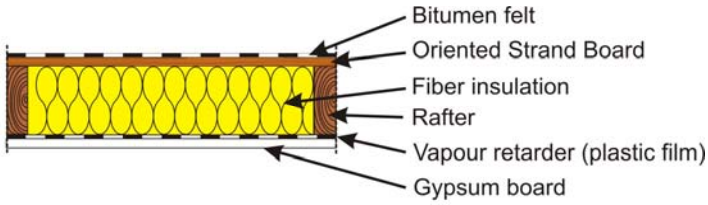

Figure 6. Composition of the flat roof.

For the calculations the Holzkirchen climate data are used. For the interior conditions 'normal occupacy' is assumed according to EN 15026 [2007] (see also paragraph 3.2). The calculation starts at the first of October and is performed for five years to see if a moisture accumulation will occur.

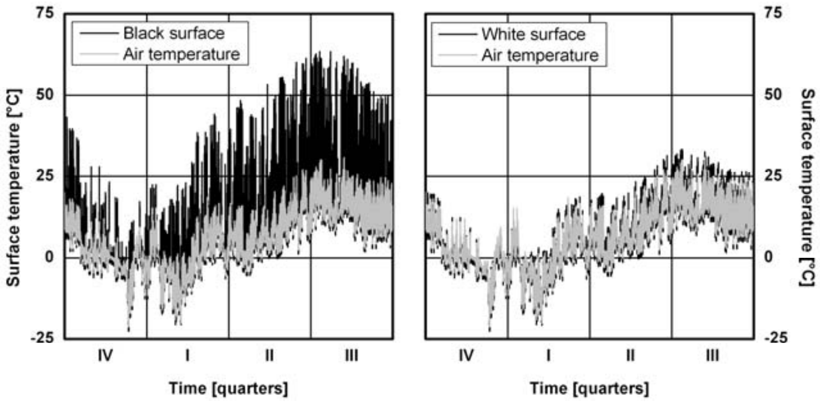

Figure 7. Comparision of black and white roof surface temperature and air temperature in Holzkirchen.

The calculated surface temperatures are shown in Fig. 7. On the black surface maximum temperatures of about 60°C develop. The fluctuation of the white roof temperature is similar to that of the ambient air temperature, with maximum values of about 30°C. On both roofs there is some overcooling below the outdoor temperature.

The cold time during night and winter is the crucial factor for vapor diffusion into the roof. If there is no sufficient drying during daytime or summer moisture accumulation can occur.

Fig. 8 shows the development of moisture in the OSB layer beneath the roofing membrane. Using a bright roof membrane the construction cannot dry out due to the reduced temperatures during the day. During night time moisture is permeating into the construction and leads to an increasing accumulation of water in the OSB layer. The moisture penetrating during winter cannot dry out during the summer time due to the reduced solar heat gain.

After five years a water content higher than 26M.-% will occur and it is still increasing. The moisture content in the wood over 20M.-% is considered to be critical because it may lead to degradation of the material. The roof with the dark sheeting shows a much better behaviour, the moisture content of the OSB layer varies between 11 and 16M.-%.

These calculations show the problems of using bright, energy saving roof sheeting in areas with cold winters. Before using such bright membranes for this kind of construction the moisture behaviour should be checked by hygrothermal simulations using the regional climate conditions.

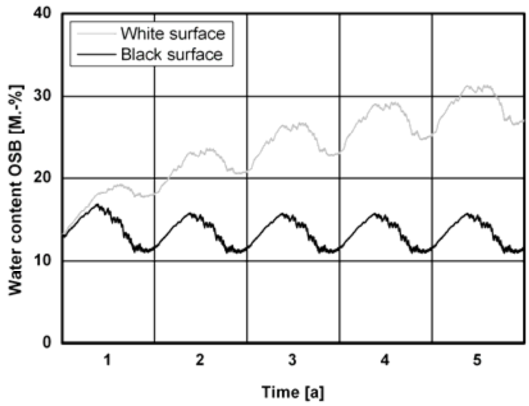

Figure 8. Comparision of the development of moisture in the OSB layer under a black and white roof sheeting in Holzkirchen.

3.6 Bright and Dark Flat Roof at North American Locations

The same construction shown in chapter 3.5 was investigated using North American climate conditions. As locations Phoenix, Chicago and Anchorage are selected again (annual temperature variations see Fig. 4). The calculations were performed for white surfaces and only if the moisture content in the OSB layer exceeded the limit of 20M.-% the simulations were repeated for black surfaces.

Figure 8 shows the water content developing in the OSB layer depending on the surface color. The white surface in Phoenix shows moisture contents between 11 and 16M.-%. In this warm region the flat roof works with every surface color.

The flat roof in Chicago reaches values between 17 and 23M.-% in the OSB sheet. For this reason the roof with the black surface is simulated as well. The black surface in Chicago leads to a water content of 10 to 15M.-%. In Chicago such a construction should be built up with a dark surface to avoid damage by accumulating moisture.

In Anchorage the white roof shows a fast increase of the average moisture content in the OSB layer signifying that such a roof will fail. If a black roofing membrane is used the moisture in the OSB layer ranges between 14 and 20M.-% which is just below the critical limit. A brighter color can not be recommended for this location.

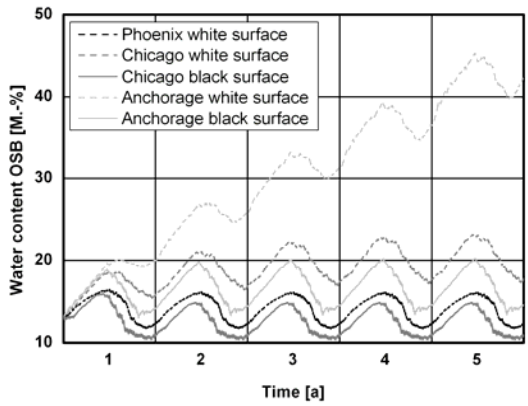

Figure 9. Comparision of the development of moisture in the OSB layer roof sheeting in North America.

3 CONCLUSIONS

Self drying roofs with foam insulation can be applied with all kind of surface colors in most parts of Northern America. Only in regions with very cold ambient temperatures there is a risk of moisture accumulation especially in case of using a bright surface. Bright roof sheeting is saving cooling energy during hot summer days. Using this sheeting at temperate climatic locations an accumulation of moisture can occur in constructions where a vapor retarder is applied at the interior side.

If a cool roof is designed for a temperate or cold climate its moisture behavior should be analyzed by hygrothermal simulations in order to avoid critical water content in the construction. If necessary a darker color of the roof surface should be considered.

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