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 daytime surface temperature compared to conventional roofs with bituminous membrane. 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 summertime is diminished.

In order to clarify this important durability issue, experimentally verified hygrothermal simulations have been carried out on lightweight flat roofs with and without reflective surface layers. Because the long-wave radiation to the sky is an important factor in nighttime 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, Bavaria, Germany. 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 lightweight 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, there are some regions where cool roofs could be beneficial for cooling energy savings.

INTRODUCTION

Nowadays, in order to build energy-efficient buildings, 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 saving energy by building so-called “cool roofs.” A cool roof uses a bright surface to reflect incident solar radiation, which significantly lowers the daytime surface temperature compared to conventional roofs with bituminous membrane. Cool roofs bring along the risk of moisture accumulation in colder regions of Europe and North America, due to the reduced surface temperatures during the day. Furthermore, the long-wave radiation can lead to overcooling of the surface below ambient temperature. Such low temperatures during the night can cause the temperature to drop beneath the dewpoint, followed by condensation of moisture in the construction. New simulation models are able to consider this effect.

FUNDAMENTALS

Cool Roofs

The temperature on a roof depends on several factors. When solar radiation hits the roof’s surface, a part is reflected, and 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 rooms below. 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 maintain 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%.

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 a water and vapor barrier. In the interior, the construction consists of an insulation core made from materials that do not rapidly degrade mechanically in the presence of moisture. To the inside, no vapor retarder is used to ensure the dry-out potential. The interior finish can be formed, for example, by a gypsum board in residential buildings or steel decking in industrial buildings. Extensive research about self-dry roofs was performed by Desjarlais *et al.* from 1995 to 1998.

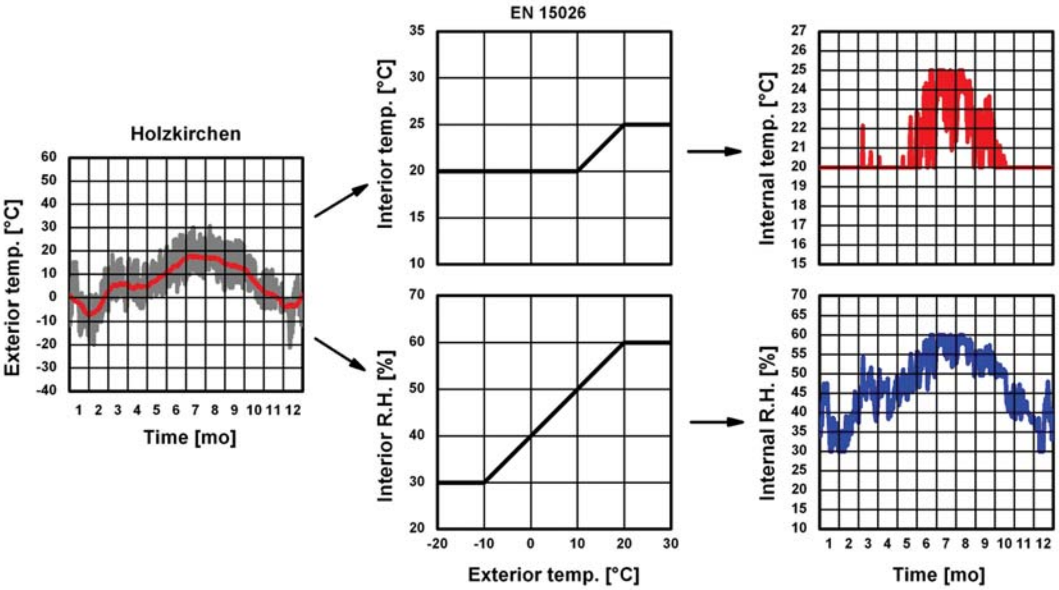


Figure 1 – Example of the used interior conditions for the calculation in Holzkirchen derived from the outdoor temperature according to EN 15026 [2007].

CALCULATIONS

Climatic Data

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

Hygrothermic Simulations

WUFI® [Künzel, 1994] was used for the simulations in this paper. [WUFI®, which stands for *Wärme Und Feuchte Instationär* – Transient Heat and Moisture – is a validated software program for simultaneous calculation of the coupled heat and moisture transfer in building components.] As boundary conditions, the climatic reference data (hourly values) from the investigated location were used. This file contains hourly values for temperature, humidity, rain, wind, solar and atmospheric radiation, etc. For the interior climate, the specifications from EN 15026 [2007] for "normal moisture load" were used. The interior conditions for Holzkirchen are shown in *Figure 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 (68 to 77°F), respectively, and between 30 and 60% RH. The material properties needed to perform the calculations are taken from the WUFI® material database.

Comparison of Measurement and Calculation Using an Explicit Long-Wave Radiation Model

For validation of an explicit long-wave radiation model in WUFI® [Kehrer and Schmidt, 2006], many calculations were 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 mineral granules.

In *Figure 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 to 50°C (50 to 122°F), while the air temperature only shows values between -3 and 20°C (26.6 and 68°F). Surface temperatures below ambient air temperatures 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 nighttime, as well as

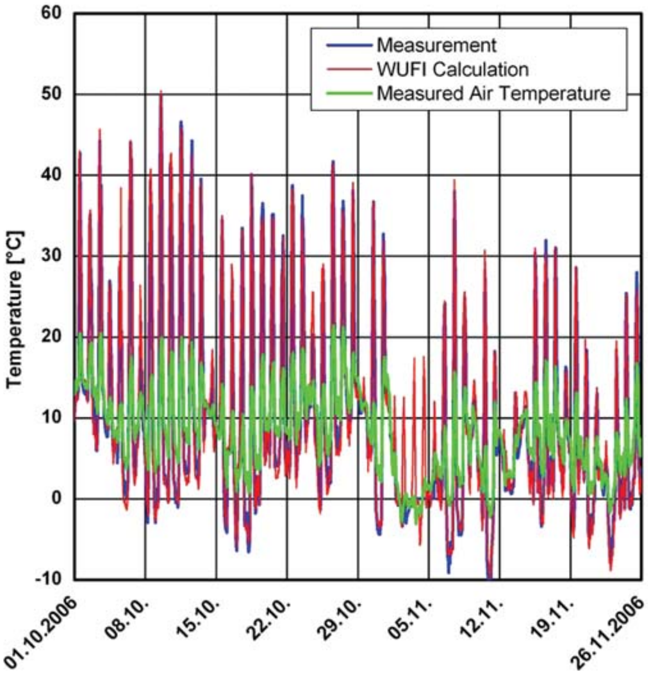


Figure 2 – Comparison between measurement and calculation.

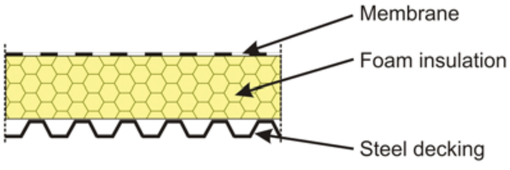


Figure 3 – Composition of the self-drying roof.

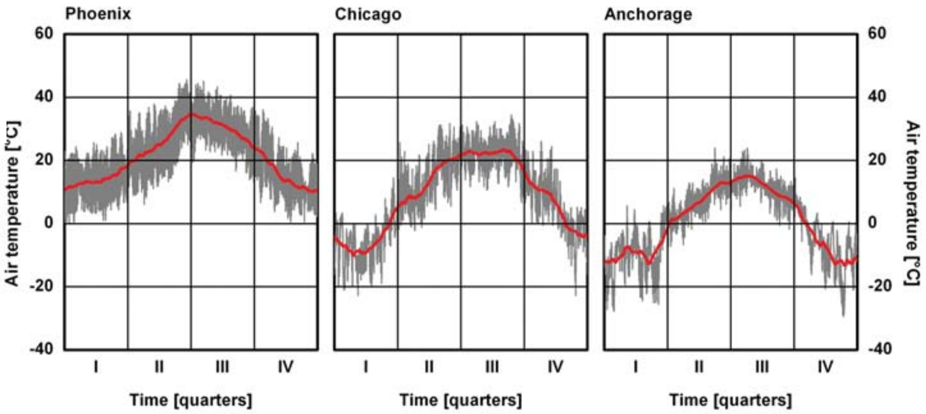


Figure 4 – Air temperature in Phoenix, AZ; Chicago, IL; and Anchorage, AK. The gray lines are hourly values; the red line shows the floating monthly average.

the higher temperatures during the day, are captured. Between November 2 and 5, during which time the calculation shows a much higher temperature than the measurement, the roof was covered with snow. The model does not take into account the effect of snow.

Self-Drying Flat Roofs in North America

The considered self-drying roof is built-up, as shown in *Figure 3*. It is sealed to the outside by a roofing membrane and attached to steel decking. The center is filled with foam insulation (polyisocyanurate).

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, AZ, was selected as the warm location; Chicago, IL, as the temperate location; and Anchorage, AK, as the cold location. The following parameters were used for the calculation: Vapor permeability of the steel decking was set to sd = 3.3 m[1] (1 U.S. perm – equivalent diffusion resistance considering perforations and joints), according to Desjarlais [1995]; and for the roofing membrane, to sd = 1,000 m. The short-wave absorption factor for a white surface is 0.2; and for a black surface, it is 0.88. For the long-wave emission, e = 0.9 is used. The calculation started on the first of October and was continued for five years to see if a moisture accumulation would occur. The results of the simulation were compared by examining the total moisture content in the construction. If a moisture content of more than 0.5 kg/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 *Figure 4*. The curves dis-

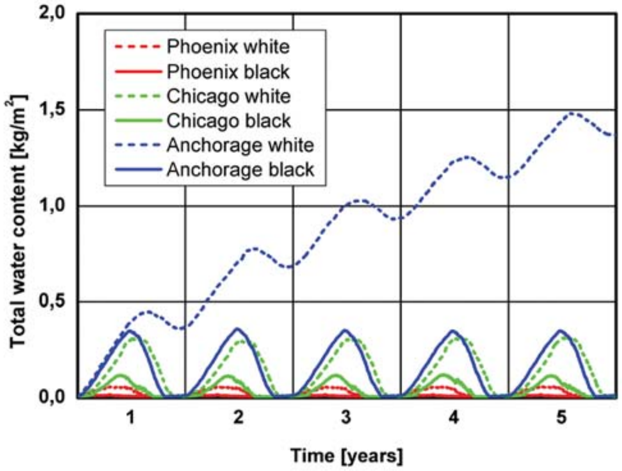


Figure 5 – Total water content of flat roofs with white and black surfaces at different locations .

played in gray are hourly values of the temperature, and the black curve is the floating monthly average. Comparing the average curves:

- In Phoenix, the average temperature is between 10 and 35˚C (50 and 95˚F), with minimum temperatures of 0˚C and maximum values of about 45˚C.
- In Chicago, the average temperature fluctuates between -9 and 23˚C (16 to 73˚F) with minimum values of about -22˚C and maximum values of about 34˚C (-8 to 93˚F).
- The average temperature in Anchorage falls between -12 and 15˚C (10 and 59˚F), with minimum values of -29˚C and maximum values of 24˚C (-20 to 75˚F).

Figure 5 shows the temporal variations of the total moisture content in the construction. For warm-weather Phoenix, total water content reaches as much as 0.05 kg/m^2 in the case of the white surface. The roof with the black surface stays dry almost all year. For the Chicago roof, a difference between the black and the white surface is recognizable. The white roof reaches a total water content of about 0.3 kg/m^2; the dark roof, about 0.1 kg/m^2. In cold-weather 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 summertime. An accumulation of water over the years is clearly visible.

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

Bright and Dark Flat Roofs in Holzkirchen

For the following comparison, the influence of different surface colors on the moisture behavior of a typical European flat-roof construction was considered. The composition is shown in *Figure 6*. The roof (in Holzkirchen, Germany) is constructed with mineral insulation between wooden rafters, sheeted by an OSB panel, and sealed with an elastomeric bitumen roofing sheet. This roofing sheet was calculated with a radiation-reflecting white surface (absorption factor 0.2) and a typical black surface (absorption factor 0.88). The long-wave emission factor e = 0.9. To the inside, the construction was closed using a vapor retarder (sd = 2 m) and gypsum board. In this example, the insulation layer had a thickness of 200 mm.

For the calculations, the Holzkirchen climate data were used. For the interior conditions, "normal occupancy" was assumed, according to EN 15026 [2007, paragraph 3.2]. The calculation began October 1 and was performed for five years to see if moisture accumulation would occur.

The calculated surface temperatures are shown in *Figure 7*. On the black surface, maximum temperatures of about 60°C (140°F) developed. The fluctuation of the white roof temperature is similar to that of the ambient air temperature, with maximum values of about 30˚C (86°F). On both roofs, there is some overcooling below that of 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.

Figure 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, moisture is permeating the construction and leads to an increasing accumulation of water in the OSB layer. The moisture penetrating during winter cannot dry out during the summertime, due to the reduced solar heat gain.

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

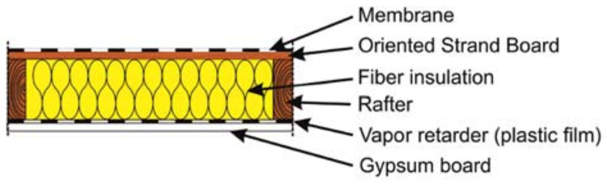


Figure 6 – Composition of the flat roof.

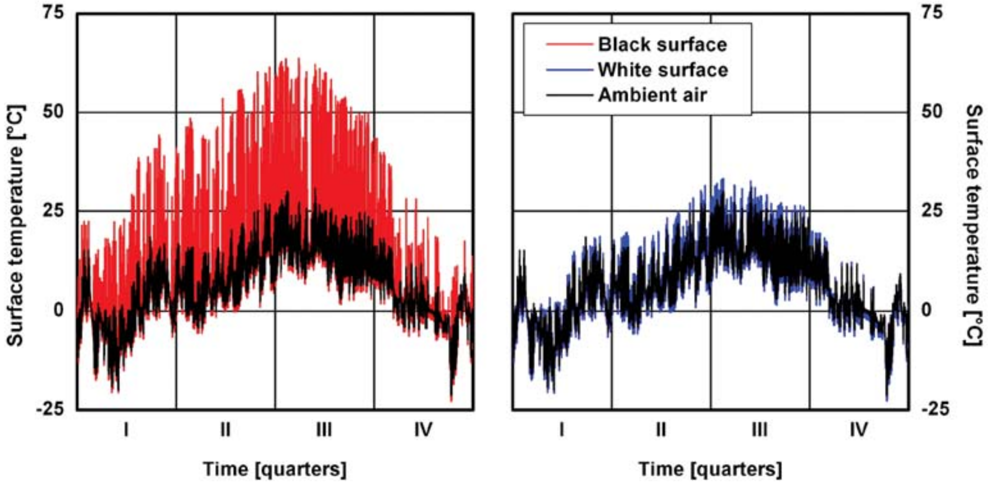


Figure 7 – Comparison of black and white roof surface temperature and air temperature in Holzkirchen.

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 behavior should be checked by hygrothermal simulations using the regional climate conditions.

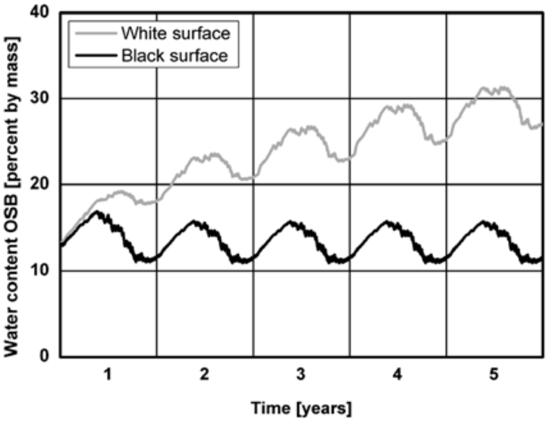


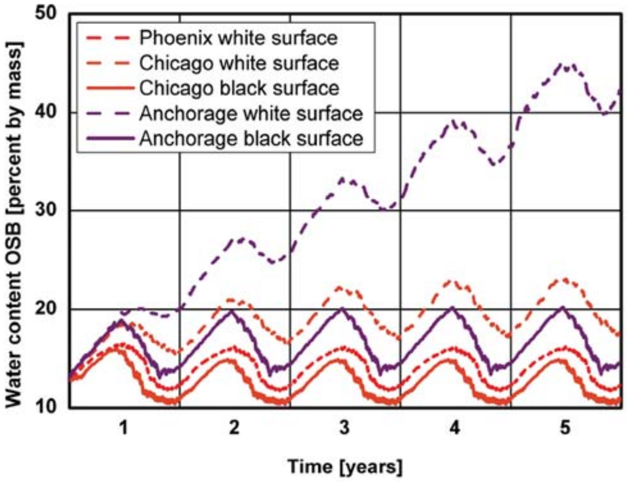
Figure 8 – Comparison of the development of moisture in the OSB layer under a black and white roof sheeting in Holzkirchen.

Bright and Dark Flat Roofs at North American Locations

The same construction shown in Holzkirchen was investigated using North American climate conditions. Phoenix, Chicago, and Anchorage were again selected (for annual temperature variations, see *Figure 4*). The calculations were performed for white surfaces and only if the moisture content in the OSB layer exceeded the limit of 20% by mass. 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 16% by mass. In this warm region, the flat roof works with every surface color. The flat roof in Chicago reaches values between 17 and 23% by mass 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 15% by mass. In Chicago, such a construction should be built up with a dark surface to avoid damage from 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

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



will fail. If a black roofing membrane is used, the moisture in the OSB layer ranges between 14 and 20% by mass, which is just below the critical limit. A brighter color cannot be recommended for this location.

CONCLUSIONS

Self-drying roofs with foam insulation can be applied with all kinds of surface colors in most parts of North America. Only in regions with very cold ambient temperatures is there a risk of moisture accumulation, especially if using a bright surface. Bright roof sheeting saves 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 on 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.

FOOTNOTE

1. sd = vapor diffusion resistance, measured in meters (equated to an equivalent layer of air with the same permeability).

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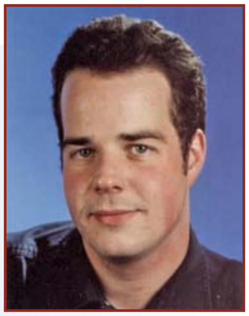

Christian Bludau earned his diploma in civil engineering from the Technical University in Munich, Germany, in 2001 and became a research assistant at the Institute for Building Materials and the Institute for Structural Engineering at the University of the German Armed Forces in Munich. Since 2005, he has been a PhD student with IBP, focusing on the hygrothermic conditions in wall and roof constructions with special interest in the thermal behavior of flat roofs.

Daniel Zirkelbach

Daniel Zirkelbach received his diploma in civil engineering at the Technical University in Munich in 2000, after which he joined IBP. In 2003, he was promoted to group manager, and in 2007, he became deputy head of his department. His scope of work includes hygrothermal simulations, moisture protection and management, and climate-adapted design.

Hartwig M. Künzel

Hartwig M. Künzel is department head at IBP. His department specializes in hygrothermal simulation and laboratory and field testing. The heat and moisture transport model WUFI® was developed as part of his PhD thesis, defended at the University of Stuttgart in 1994. He has been active in many international projects (e.g., IEA Annex 14 and 24), standard committees (ASHRAE, CEN), and continuing education seminars. Dr. Künzel has published over 200 scientific articles in trade journals and textbooks.