# Hygrothermal Conditions in Ventilated Cathedral Ceilings: Influences on Roof Ventilation and Emissivity— Field Study and Analysis

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## ABSTRACT

*Scenarios of the future climate in Scandinavia point to a more humid climate, which will give traditional, well-tried constructions new challenges. Ventilated cathedral ceilings are exposed to the changing weather conditions on the site, and it is important to secure the long-term moisture durability of the construction.*

*Measurements in the airway in two ventilated cathedral ceilings with different roof covering materials were performed during the spring of 2009. The results show a difference in the thermal and moisture performance of the construction. Calculations of the mold growth potential have shown that a roof with black asphalt shingles has a greater risk of being attacked by mold growth than a roof covered with ventilated hot-dip galvanized steel (painted black).*


## INTRODUCTION

Higher demands on the energy performance in the building sector have increased the demand for extra thermal insulation in different parts of the building envelope. The extra insulation in ventilated roof constructions reduces the heat transfer from the interior of the building through the roof, reducing the temperature in the cold parts of the construction. An unchanged moisture transfer through the roof increases the risk of high relative humidity in the materials of the cold parts during periods of colder weather. Mold grows on organic materials where sufficient temperature and relative humidity is present. The natural resistance to degradation towards other species of fungi is reduced once the mold growth has started on a material (Mattsson 2004).

The ventilated cathedral ceilings in Swedish single-family houses are most often wooden constructions, sensitive to the influence of high moisture contents. Excess moisture is ventilated out through an airway in the construction where the airflow is governed by the stack effect and outdoor wind conditions. Different materials in the roof covering can have an influence on how the roof construction behaves under different weather conditions. The solar absorption coefficient and the long-wave radiation emissivity of the materials are parameters that can contribute to keeping the moisture conditions on a safe level.

The moisture supply into the ventilated cathedral ceiling can arise from a number of different sources, varying in size in different conditions. Moisture transfer through the ceiling varies, depending on the vapor permeability of the construction and the internal moisture production in the building. No information on the moisture transfer through the ceilings of the houses in this study is available. External moisture sources can be precipitation, such as driving rain and melting snow, and air movement into the airway.

## OUTLINE OF VENTILATED CATHEDRAL CEILINGS

Two similar houses built during the 1990s in close vicinity to each other close to Gothenburg, on the Swedish west coast (Figure 1), have been studied. The houses are exposed to the same weather conditions and have similar residential patterns. The orientation of the roof ridge is east-west and the measurements were performed in the airway facing north. The roof construction of the houses is a ventilated cathedral ceiling with 18° roof pitch and 3.7 m distance from roof eave to ridge.

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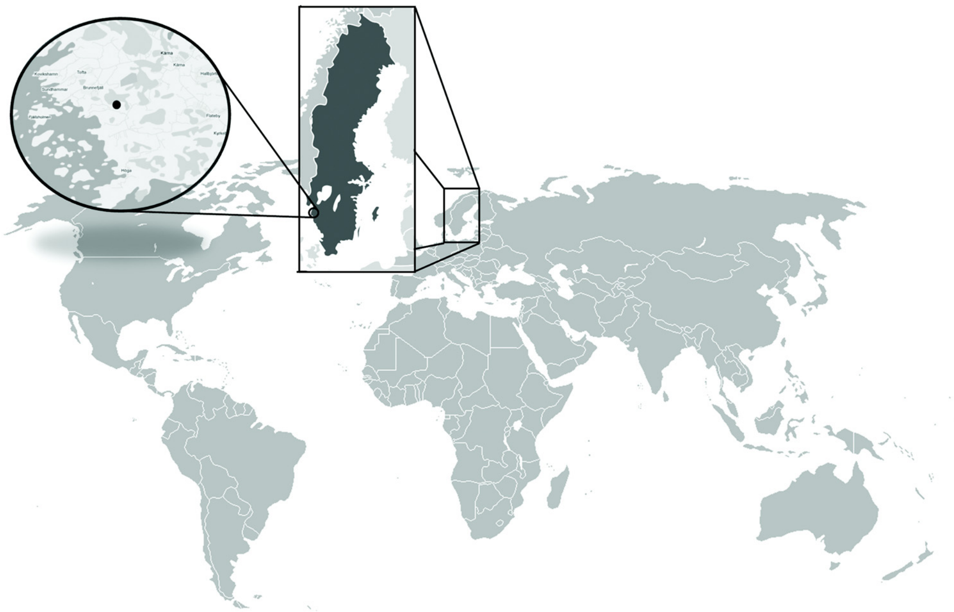

*Figure 1* *Map of location of the two studied houses, on the Swedish west coast. The black dot in the circle to the left marks the location of the houses.*

The ventilation openings at the bottom of the roof have a net free area of 0.046 $m^2$ and are covered with a fly screen. There are no openings at the roof ridges.

The materials used in the two studied roofs are identical, apart from the outermost material, which in the first case is black asphalt shingles and in the second case hot-dip galvanized steel (painted black) covering a 45 mm ventilated airway. Both studied constructions include an inner ventilated airway of 38 mm. The center-to-center distance of the main support beams is 1.2 m, and the distance between the supports in the airways is 0.6 m. A cross section of the studied object with hot-dip steel roof covering is shown in Figure 2. The construction with shingle roof covering is shown in Figure 3.

Asphalt shingles are made of a frame of glass fiber, impregnated and covered with oxidized asphalt, and the surface is covered with granules of black shale. The material in itself is not sensitive to high moisture contents. This is also the case for the hot-dip galvanized steel.

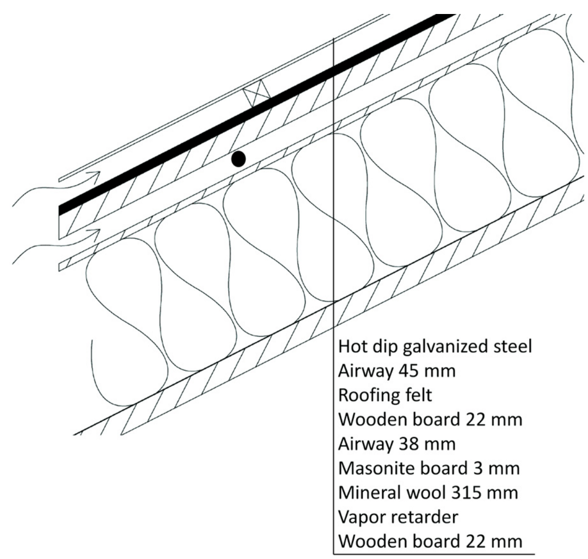


*Figure 2* *Cross section of material layers in the ventilated cathedral ceiling with steel roof covering. The black dot in the inner airway shows the sensor location.*

### Measurements in Airway of Ventilated Cathedral Ceilings

The Swedish west coast has a fairly mild and humid climate. The annual mean temperature in Gothenburg in 2008 was 9.5°C and the mean relative humidity was 80.5%. It is mostly during the spring and autumn when the humid periods dominate, and these are the critical periods for mold growth. The measurements presented in this paper were performed during the spring of 2009. During the measurement period, the weather was mostly clear and sunny, and the maximum wind speed is 7 m/s (Johansson 2009).

Testo 175-H2 sensors were used for the measurements in the ventilated cathedral ceilings. The temperature measurement range is –20°C to 70°C, with an accuracy of ±0.5°C. Relative humidity can be measured between 0% and 100%, with an accuracy of ±3% (Nordtec Instrument AB 2009). The sensors were attached to a stick and placed 1 m into the airway

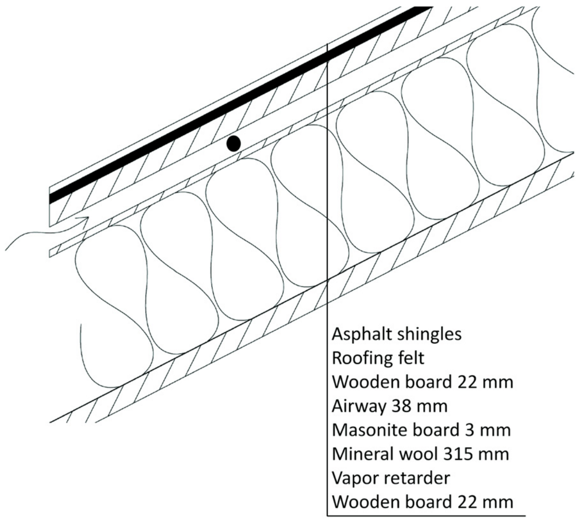


***Figure 3*** *Cross section of material layers in the ventilated cathedral ceiling with shingle roof covering. The black dot in the airway shows the sensor location.*

from the wall, as shown in Figures 2 and 3. The measurements started on March 4, 2009, and ended on May 19, 2009.

This study is based on measurements from sensors located close to the roof eaves. The influence of different location of sensors is not considered. However, a previous study by Rose (2001) has shown that the temperature differs greatly between sensors located close to the roof eave and at the ridge. The influence of sensor location on the measured relative humidity is unknown for this case.

The influences of long-wave radiation and the addition of an extra ventilated airway on the temperature in the inner airway have been studied for the two constructions. During the measured period, the owner of one of the houses observed the weather and the cloudiness of the sky. These data, together with the measurements, have been used to identify results from a clear and a cloudy week.

### Mold Growth Potential

Temperature and high relative humidity in the materials of the construction can lead to mold growth. A period of beneficial conditions for mold growth can be interrupted by less humid or cooler periods than demanded for growth, which will lead to a decay of the mold. Researchers in the field of mold growth have developed calculation models for when the conditions for mold growth are present for sufficient time to induce the germination of spores in the material. The mold growth index, developed by Hukka and Viitanen (1999), is one of the commonly used models. The prerequisites required for mold growth are described by Viitanen (2001). Beneficial conditions for mold growth can be described by the dimensionless mold growth potential $m$:

$$m = \frac{\varphi}{\varphi_{crit}} \tag{1}$$

where $\varphi_{crit}$ is the dimensionless critical relative humidity dependent on temperature (°C), according to Equation 2:

$$\varphi_{crit} = \begin{cases} 100\%,\ T < 0°C \\ -0.00267 \cdot T^3 + 0.160 \cdot T^2 - 3.13 \cdot T \\ +100\%,\ 0°C \le T \le 20°C \\ 80\%,\ T > 20°C \end{cases} \tag{2}$$

There is a risk for mold growth when the mold growth potential is larger than 1 (i.e., when the relative humidity in the air exceeds the critical relative humidity).

## RESULTS FROM MEASUREMENTS

The results from the measurements are presented in duration graphs over the measured period. In Figure 4, the relative humidities of the airways in the ventilated cathedral ceilings and the outdoor air are shown.

If the critical moisture level of a material is unknown, the Swedish regulations on moisture safety in materials demand that the relative humidity in the construction should not exceed 75% (Boverket 2007). The airway of the roof with shingle covering exceeds the relative humidity of 75% during 1211 hours, which corresponds to 67% of the measured period. The relative humidity is above 75% in the roof with hot-dip galvanized steel covering during 421 hours, 23% of the time. In the outdoor air the relative humidity exceeds 75% during 912 hours, which is 51% of the measured period. This indicates that there is a larger risk for moisture damage in the inner part of the roof covered with asphalt shingles than in the roof with hot-dip galvanized steel.

The temperatures in the airways of the ceilings and in the outdoor air are shown in Figure 5.

The average temperatures were 10.2°C for the airway in the shingled roof, 10.7°C for the steel roof, and 7.3°C for the outdoor air. The airways had higher temperatures than the outdoor air during most of the studied hours, probably caused by the insolation on the roof covering. The measurements show that the shingled roof reaches higher temperatures than the steel roof for more hours, but still the average temperature is higher for the steel roof.

In this study, the shingle surface was black, which led to a high emissivity and higher temperatures during warm days than it would be if a brighter color was used. Rose (2001) studied the temperature in a number of roof constructions with different preconditions. In two roofs with comparable conditions, the reduction in surface temperature caused by different shingle color was 22.7%. Thus, a darker shingle color causes a warmer surface temperature.

The duration of the mold growth potential in the roofs has been calculated and is presented in Figure 6.

When the mold growth potential is larger than 1, there is risk for mold growth in the construction. In the shingled roof,

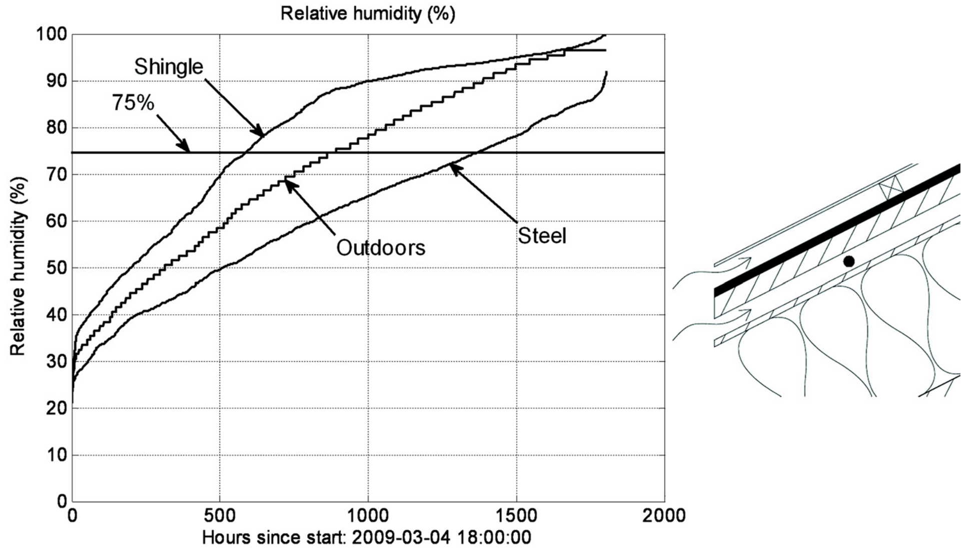


***Figure 4*** *Duration graph for relative humidity in the airways in the ventilated cathedral ceilings and the outdoor air during the spring of 2009; the critical relative humidity of 75% is indicated. The relative humidity is higher in the roof with shingled surface than in the outdoor air. The roof with steel surface has a lower relative humidity than the outdoor air. The black dot in the roof section to the right represents the location of the sensor in the steel roof.*

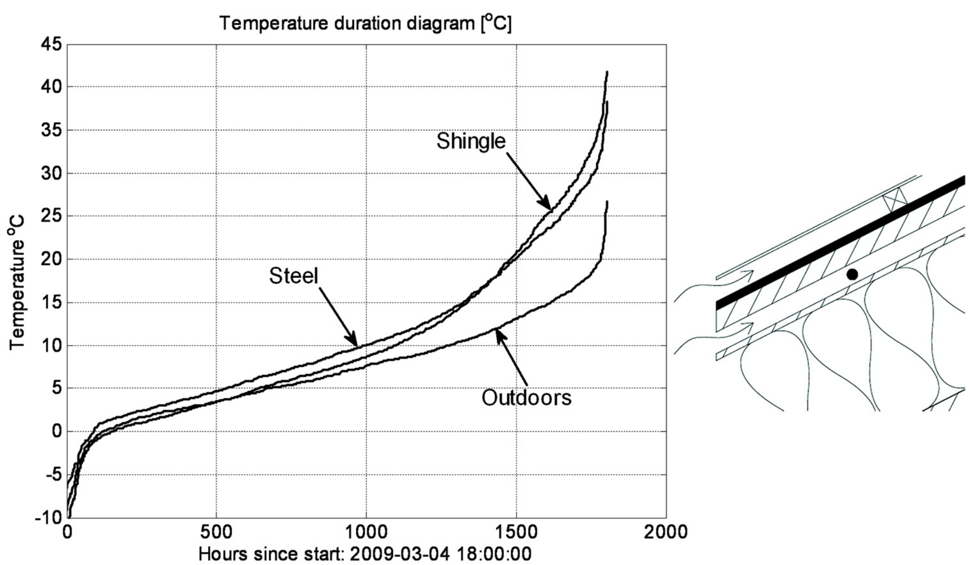


***Figure 5*** *Duration graph for temperature in the airways in the ventilated cathedral ceilings and the outdoor air during the spring of 2009. The temperature is similar in the roofs with steel and shingle coverings. Both roofs have warmer average temperatures than the outdoor air. The black dot in the roof section to the right represents the location of the sensor in the steel roof.*

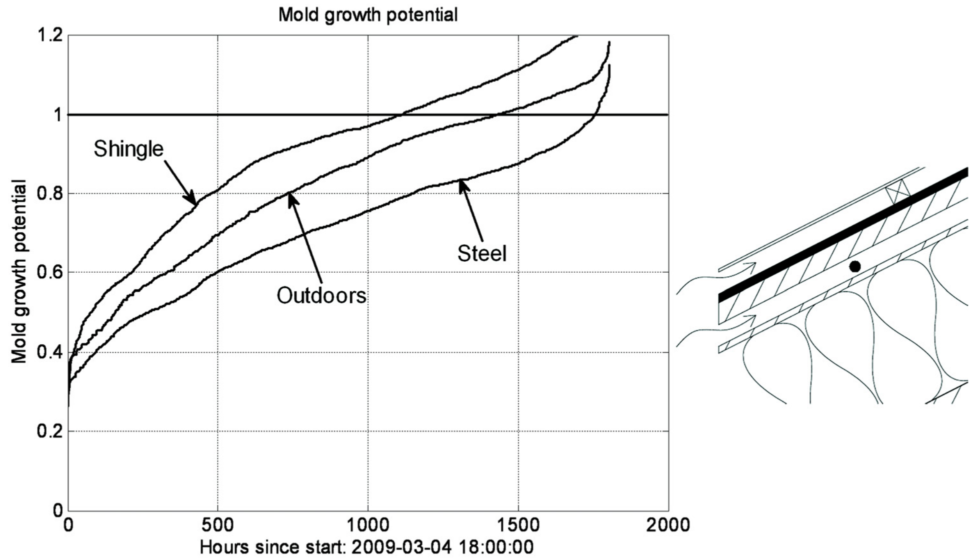


***Figure 6*** *Duration graph for mold growth potential in the airway in the ventilated cathedral ceilings and in the outdoor air during the spring of 2009. The mold growth potential is higher in the roof with shingled surface than in the roof with steel surface. The black dot in the roof section to the right represents the location of the sensor in the steel roof.*

beneficial conditions for mold growth are present during 689 hours, 38% of the measured period; the average mold growth potential during the period is 0.94. The beneficial climate for mold growth in the roof with hot-dip galvanized steel covering is present during 49 hours, 3% of the period; the average mold growth potential is 0.72.

### Influence of Long-Wave Radiation

The light hours of the day have been excluded to allow study of the influence of the long-wave radiation exchange between the roof surface and the sky at night. Figure 7 shows the mold growth potential in the airway in the two roofs during the cloudy week.

There is a lower mold growth potential in the airways than in the outdoor air for a large part of the cloudy week. The mold growth potential in the shingled roof was higher than in the steel roof. The mold growth potential in the airways during the clear week is shown in Figure 8.

During the clear week there is a larger difference between the roof constructions compared to the cloudy week. The risk for mold growth was higher in the airway in the shingled roof than in the roof with steel roof covering for most of the clear period.

To study the influence of the specific conditions in the two different houses, the water vapor content for the shingled roof and the temperatures for both roofs were used to calculate the mold growth potential (Figures 9 and 10).

The mold growth potential in the airways in the ventilated cathedral ceilings is now more similar in the two roofs. The higher temperature in the roof with steel surface than in the shingled roof lowers both the relative humidity and the critical relative humidity of the air in the airway. A part of the difference can be explained by the differing temperatures in the two roofs, but there is still a larger mold growth potential in the shingled roof than in the steel roof. No regard is given to the possible differences in indoor temperature and indoor moisture production. A difference between the two houses concerning these issues could be a part of the explanation to the differences in the measured mold growth potential.

## CONCLUSION

Measurements were performed in the 38 mm thick airway of two similar ventilated cathedral ceilings with different black roof coverings. It was shown that it is almost always warmer in the airway of the roof with hot-dip galvanized steel covering than in the roof with shingles. The interior temperatures of the houses are unknown, but assumed to be similar since both houses have similar heating systems and occupational patterns. Based on the assumption that heat loss from the living compartment is similar in both houses, the conclusion is that the shingled roof is influenced more by the long-wave radiation and insolation than the ventilated steel roof covering. The inner airway in the roof with steel covering is less closely linked to the temperature in the roof surface than the shingled roof is. This property gives a buffering effect on the temperature shifts in the airway in the steel roof during day and night, reducing the risk of condensation and high relative humidity.

Selection of the roof covering material facing the outdoor air should be made with great care in respects to thermal and moisture properties. Influence by the solar radiation and long-wave radiation should be studied to avoid condensation and high relative humidity in the construction. The peaks and sinks

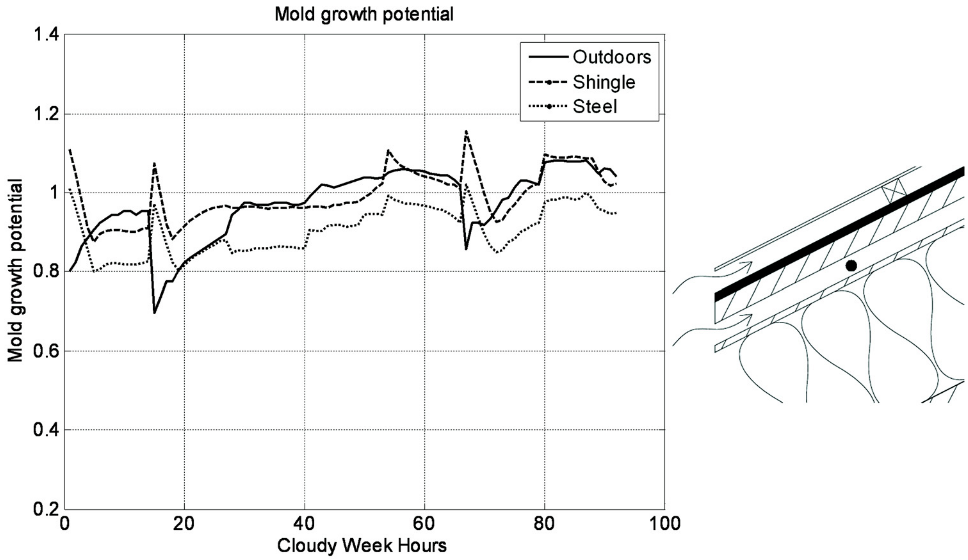


***Figure 7*** *Mold growth potential in the airway in the ventilated cathedral ceilings during the cloudy week. The roof with shingled surface has a higher mold growth potential than the roof with steel surface. The black dot in the roof section to the right represents the location of the sensor in the steel roof.*

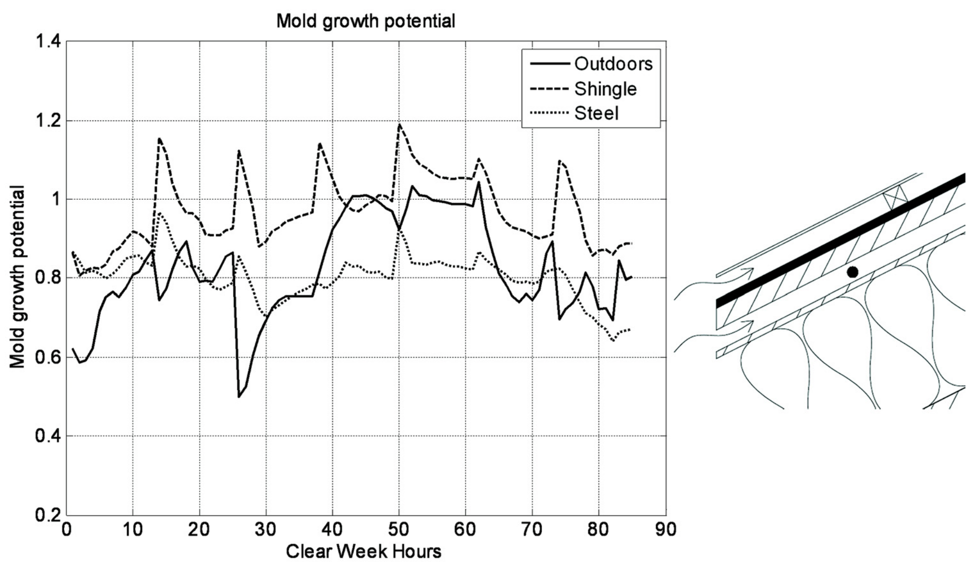


***Figure 8*** *Mold growth potential in the airway in the ventilated cathedral ceilings during the clear week. The roof with shingled surface has a higher mold growth potential than the roof with steel surface. The black dot in the roof section to the right represents the location of the sensor in the steel roof.*

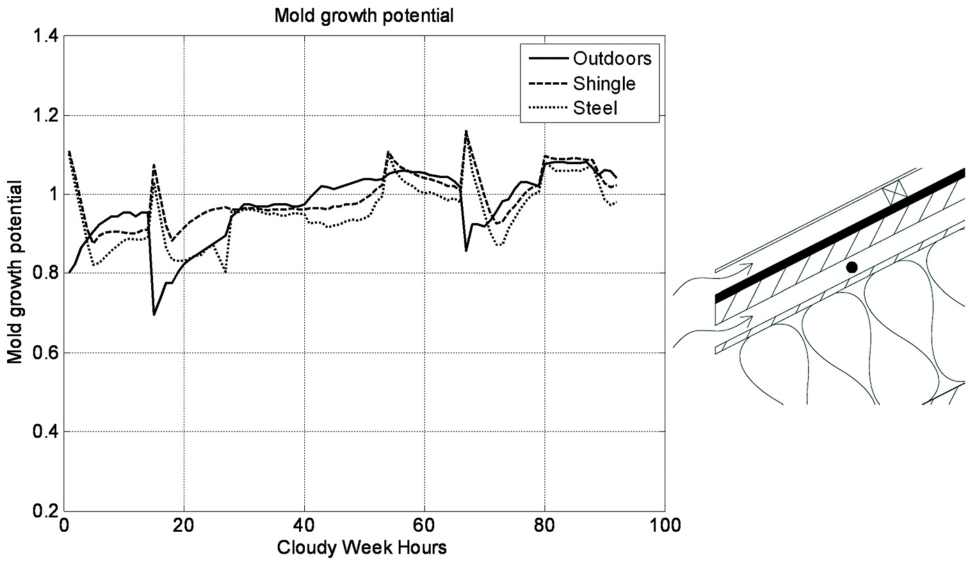


***Figure 9*** *Mold growth potential in the ventilated cathedral ceilings with the water vapor content of the shingled roof during the cloudy week. The black dot in the roof section to the right represents the location of the sensor in the steel roof.*

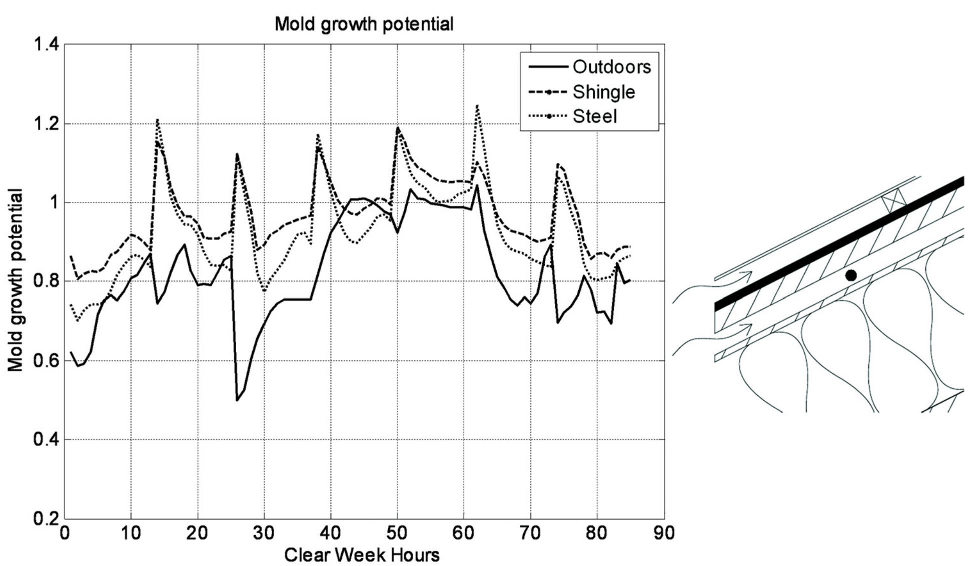


***Figure 10*** *Mold growth potential in the ventilated cathedral ceilings with the water vapor content of the shingled roof during the clear week. The black dot in the roof section to the right represents the location of the sensor in the steel roof.*

in the temperature behavior in the airway are higher on clear days than on cloudier ones. This causes the temperature in the construction to be more stable during the cloudy days.

The mold growth potential is higher in the shingled roof than in the steel-covered roof. The difference between the airways lies in the temperature changes in the outer roof, the water vapor content in the airway, or a combination of both. Since the influence of the activities indoors on the temperature and relative humidity in the airways are unknown, it is hard to make further conclusions on the influence of the choice of roof covering material on the mold growth potential from this study. However, the results suggest that a ventilated outer roof covering leads to a lower mold growth potential of the airway than a nonventilated roof covering does.

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