

Condensation Risk of Mechanically Attached Roof Systems in Cold Climate Zones

Kehrer Manfred, Senior Researcher, Oak Ridge National Laboratory, TN, USA

Pallin Simon, LicEng., Chalmers University of Technology, Sweden

1. BACKGROUND

A white roof, or *cool roof*, is constructed to decrease thermal loads from solar radiation, therefore saving energy by decreasing the cooling demands. Unfortunately, cool roofs with a mechanically attached membrane have shown a higher risk of intermediate condensation in the materials below the membrane in certain climates (Ennis & Kehrer, 2011) and in comparison with similar constructions with a darker exterior surface (Bludau, Zirkelbach, & Kuenzel, 2009). As a consequence, questions have been raised regarding the sustainability and reliability of using cool roof membranes in northern U.S. climate zones.

A white roof surface reflects more of the incident solar radiation than a dark surface, making a distinguishable difference in the surface temperature of the roof. However, flat roofs facing a clear sky, with either a light or a dark surface, are constantly losing energy to the sky due to the exchange of infrared radiation. This phenomenon exists both during the night and the day. During the day, if the sun shines on the roof surface, the exchange of infrared radiation typically becomes insignificant. During nights and in cold climates, the temperatures of the roof surface and the sky can differ by as much as 20°C (Hagentoft, 2001), which could result in a roof surface temperature that is much colder than the ambient temperature. Further, a colder roof surface has increased energy loss and risk of condensation in the building materials below the membrane. In conclusion, both light- and dark-coated roof membranes are cooled by infrared radiation exchange during the night, though a darker membrane is heated more by solar radiation during the day, thus decreasing the risk of condensation.

The phenomenon of nighttime cooling from contact with the sky and the lack of solar gain during the day is not likely the exclusive issue affecting the risk of condensation in cool roofs with mechanically attached membranes. Roof systems with thermoplastic membranes are prone to be more affected by interior air intrusion into the roof construction, both from wind-induced pressure differences and from the flexibility and elasticity of the membrane (Molleti, Baskaran, Kalinger, & Beaulieu, 2011). Depending on the air permeability of the material underneath the membrane, wind forces increase the risk of fluttering (also referred to as billowing) of a flexible single ply thermoplastic

membrane. Expectably, the wind-induced pressure differences create a convective air flow into the construction (i.e., air intrusion). If the conditions are right, moisture from the exchanging air may condensate on surfaces with a temperature below the dew-point.

The definite path of convective air flows through the building envelope is usually very difficult to determine, so simplified models (Künzel, Zirkelbach, & Scfamaczek, 2011) help to estimate the additional moisture loads caused by air intrusion. The wind uplifting pressure in combination with wind gusts is an important factor for a fluttering roof. Unfortunately, the effect of fluctuating wind is difficult to estimate as this is a highly dynamic phenomenon and existing standards (ASTM, 2011a) take into account only a steady-state approach (i.e., there are no guidelines or regulations on how to estimate the air intrusion rate). Obviously, more detailed knowledge on the hygrothermal performance of mechanically attached cool roof systems is needed with regard to surface colors, roof airtightness, climate zones, and indoor moisture supply.

2. INTRODUCTION

The hygrothermal performance of the above-mentioned mechanically attached roof system has been investigated with numerical simulations. Measurements of the airtightness of the roof construction are necessary (see Section 3.2) to provide reliable input data for simulations. Studying these phenomena requires a tool capable of modeling heat and moisture transport in a transient simulation and with realistic boundary conditions. Long-wave (infrared) radiation must be considered at the exterior surface, otherwise nightly overcooling cannot be taken into account in the simulations of a cool roof. On account of these prerequisites, the hygrothermal software WUFI is used for computations of coupled heat and moisture transport (Künzel, 1995). WUFI, which has been validated repeatedly (Kehrer & Schmidt, 2008), features a detailed radiation model, based on physical fundamentals, which calculates the temperatures of the exterior surfaces, thus determining the risk of condensation. In consideration of the expected air intrusion underneath the thermoplastic roof membrane, the air exchange model of WUFI is applied to estimate the heat and moisture exchange of indoor air.

Figure 1 shows the modeled assembly, consisting of a traditional metal deck, 3-inch polyisocyanurate insulation boards, and a thermoplastic membrane (representing a flexible single ply membrane). Due to a supposedly air leaky roof construction underneath the thermoplastic membrane, an uplift of the exterior membrane will lead to indoor air intrusion. As a consequence of the air intrusion, an air layer is created underneath the membrane.

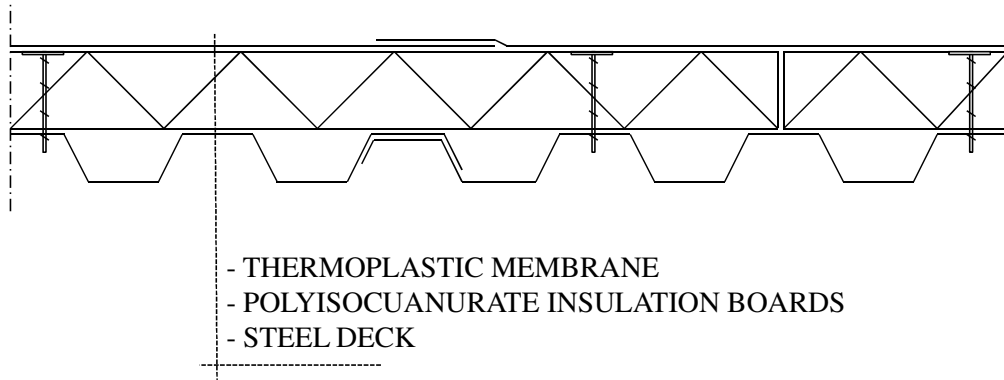


Figure 1 Model of the investigated mechanically attached roof system. The thermoplastic membrane has either a light or a dark surface that affects the hygrothermal performance of the roof.

The risk of condensation in the investigated roof system in Figure 1 depends on several parameters. Their influences on hygrothermal performance are analyzed in a systematic parameter study in which the following input parameters are varied:

- Climate, including wind and solar loads
- Indoor moisture supply
- Air intrusion rate

Varying the parameters leads to 128 different combinations (i.e., scenarios) that are simulated in WUFI. The composition of the combinations and the different variations of input parameters are discussed in Section 3.

Further, good workmanship is assumed, resulting in a tightly sealed thermoplastic membrane. The mechanical resistance of the membrane is neglected; that is, any applied pressure on top of the membrane is immediately, and without resistance, equalized underneath the membrane.

3. INVESTIGATION AND MEASUREMENTS

Air intrusion into a roof construction depends on the wind loads acting on the roof surface and the air permeability of the construction below the thermoplastic membrane. Subsequently, air intrusion is an important parameter to estimate when analyzing the hygrothermal performance of a roof. This section presents an approach to quantify this parameter.

3.1. Wind Forces

The airtightness of a roof construction, together with the existing pressure differences, determines the air leakage rate between the indoor and outdoor environment. In this study, the thermoplastic membrane is assumed to be sealed with satisfactory workmanship, thus minimizing exfiltration or infiltration air exchange; that is, air will not flow between the inner and outer surfaces of the roof. Instead, the exchange of air inside and between the roof materials is a consequence of indoor air intrusion (i.e., an exchange of indoor air in the materials of the building envelope). The air pressure differences influencing the intrusion rate are typically thermally driven (stack effect), with the ventilation system or wind loads acting on the building envelope (Hagentoft, 2001). The wind generally creates an uplifting force on the thermoplastic membrane. Due to the flexibility and elasticity of the membrane, it may easily deform in favor of pressure differences, causing the membrane to flutter and balloon (Baskaran & Molleti, 2010). This deformation, due to uplifting forces, is also referred to as billowing (Figure 2).

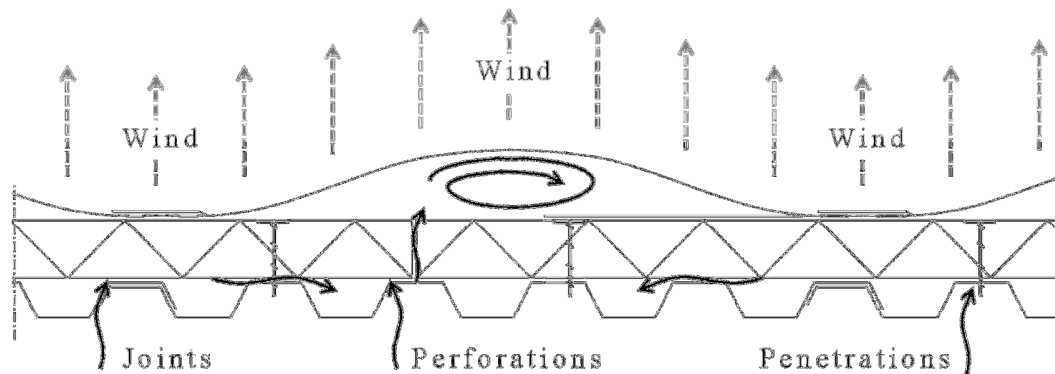


Figure 2 Wind forces inducing pressure differences on the outer roof membrane, causing the membrane to flutter and balloon. Depending on the condition and workmanship of the construction, air intrusion may arise in overlapping joints of the steel deck, penetrations, or perforations. Plausible locations of air intrusion are indicated with solid arrows. The uplifting forces, due to the wind, are indicated with dashed arrows.

Two essential parameters must be specified to estimate the air intrusion rate in a roof assembly. One is wind speed fluctuation, which causes a fluctuating pressure difference between the outdoor and indoor surfaces of the roof, and the other is airtightness of the roof construction below the outer membrane.

A negative wind-induced air pressure is typically acting on the exterior roof surface and can be estimated by use of ASCE Standard ASCE/SEI 7-10 (ASCE, 2010). The wind

pressure, P_w , for low-rise buildings is defined in Sections 28.3.2 and 28.4.1. Following the calculation steps of the ASCE Standard and determining the suitable coefficients for the roof construction, exposure and surrounding topography result in an uplift P_w as follows:

$$P_w = -0.273 \cdot V^2, \quad [1]$$

where V (m/s) is the wind speed parallel to the surface.

The wind speed is typically presented as an average speed for a defined period of time (e.g., 1 hour). Wind speeds that are based on measured averages at shorter time intervals are referred to as gusts, V_g (Harper, Kepert, & Ginger, 2010). Therefore, V can be expressed as

$$V = \frac{1}{m} \cdot \sum_{i=1}^m V_g^i, \quad [2]$$

in which m is the number of gust samples within 1 hour. In Figure 3, the variations of V and V_g are presented for a period of 6 hours, extracted from minute-based measurements of the wind speed in Holzkirchen, Germany from 2009 to 2010.

Hourly averages and one-minute gusts of wind speed

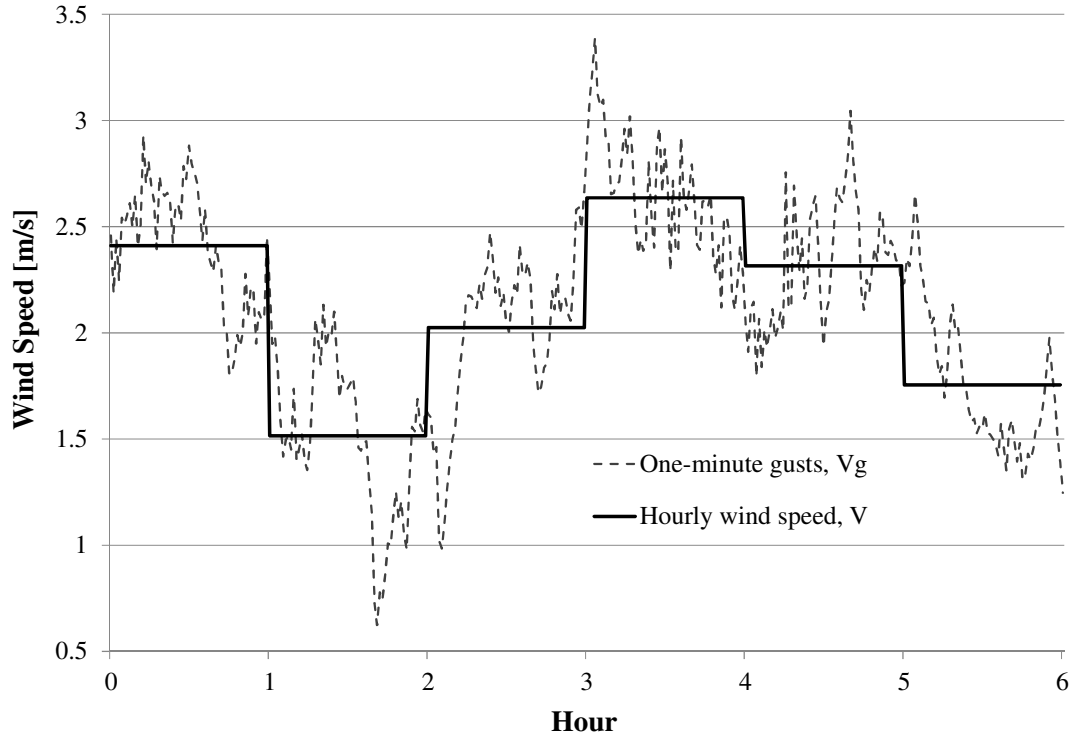


Figure 3 Variations of 1-minute wind gusts in Holzkirchen, Germany from 2009 to 2010 and the resulting hourly average wind speeds during the extracted measurements of 6 hours.

The difference in wind speed, ΔV , determines the pressure difference. A shorter time step between measured wind speeds is decisive for determining the fluttering effect of the roof membrane, and thus the air intrusion. Unfortunately, climate files usually consist of hourly averages of wind speed in which the differences between high and low wind speeds at shorter time periods are lost, as revealed in Figure 3. Therefore, the hourly averages of data used in this study are adjusted to a normalized minute-based variation of the wind speed. This procedure estimates a ΔV at a given hourly wind speed, intended to estimate the uplifting pressure difference, Δp_w , acting on the outer membrane surface. The minute-based gust measurements from Holzkirchen, because of their known reliability and continuity, serve as the template for such adjustments. In conclusion, the hourly averages of wind speed given from the four U.S. climate zones are adjusted to instead represent a plausible variation of wind speed, ΔV , at each given hour.

The hourly average of ΔV is defined as

$$\Delta V = \frac{1}{m-1} \cdot \sum_{i=1}^m |V_g^{i+1} - V_g^i|, \quad [3]$$

where m is the number of gust measurements during 1 hour. In this study, V_g is expressed each minute; hence $m = 60$ and i is the number of consecutive measurements.

Gusts typically decrease with increasing average wind speed (Davis & Newstein, 1968); thus ΔV , which also has been verified with the minute-based gust measurements from Holzkirchen, is taken into account in this study.

Finally, the wind-induced ΔP_w is expressed using [1] and [3].

$$\Delta P_w = -0.273 \cdot \left(\frac{1}{m-1} \cdot \sum_{i=1}^m |V_g^{i+1} - V_g^i| \right)^2. \quad [4]$$

3.2. Air Intrusion

The fluttering effect of the roof sheeting causes an exchange of indoor air underneath the membrane. This air intrusion is defined as an air exchange rate per hour, ACH , and can be defined as

$$ACH = \frac{Q}{V}, \quad [5]$$

where Q is the air flow rate (m^3/h) and V is the volume of air space that is ventilated (m^3), later assumed to be constant in the numerical model for practical reasons.

Q , in this study, depends on the pressure difference between the membrane and the indoor environment and also on the airtightness of the roof assembly, as given by

$$Q = A \cdot C \cdot \Delta P^n, \quad [6]$$

where A is the roof surface area (m^2); C is the air leakage coefficient (m^3/s , Pa); ΔP is the pressure difference (Pa), which in this study equals ΔP_w ; and finally n is the pressure exponent (-). The Q_{50} -value (l/s or l/s,m^2) refers to air flow rate at a pressure difference of 50 Pa, thus simplifying comparisons between different constructions and measurements.

Consequently, C and n are parameters related to the physical structure of the roof which are typically determined by measurements. Therefore, the roof construction defined in Section 2 is tested in accordance with the ASTM E2178-11 Standard for testing the air leakage rate (ASTM, 2011b). The specimen represents the roof construction as defined in Figure 1, except for the exclusion of the outer thermoplastic membrane. The reason for this approach is that the complete roof assembly is assumed to be very airtight and that the air intrusion rate between the indoor environment and underneath the membrane is to be estimated.

Figure 4 displays the constructed roof specimen. The steel deck includes one overlapping joint and has been screwed tight at three positions along the overlapping ridge, as indicated with solid arrows in the picture below. Further, two layers of overlapping 1.5-inch insulation boards are mounted on top of the wood-framed steel deck.

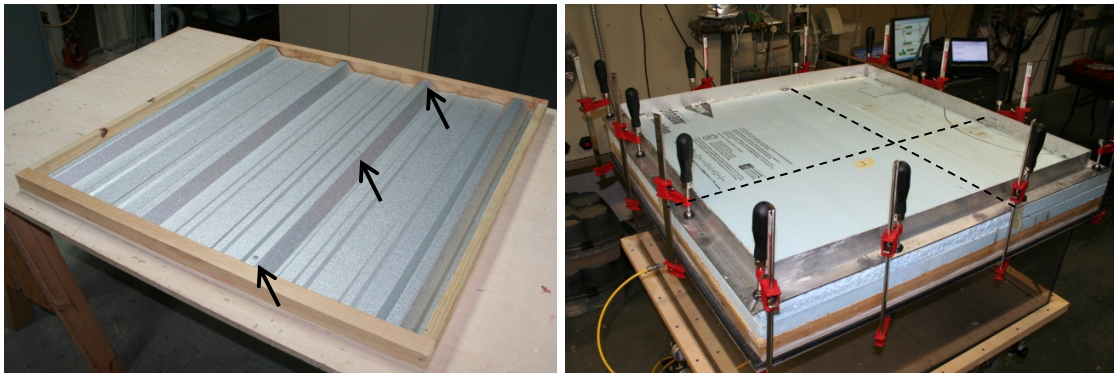


Figure 4 The airtightness of the materials below the thermoplastic membrane, which was tested by use of ASTM E2178-11. The specimen was constructed with a steel deck including a joint and, on top, two overlapping 1.5-inch insulation boards. The screws, ensuring a tight overlap, are indicated with arrows, and the joints between the overlapping insulation boards are indicated with dashed lines in the right-hand picture.

The roof specimen was tested in five different assemblies.

1. Sealed joints and sealed screw penetrations
2. Steel deck only
3. Full assembly
4. Full assembly, two to four 3/16-inch steel deck perforations
5. Full assembly, eight 3/16-inch steel deck perforations

The results of the measurements are presented in Table 1, in which the different assemblies were measured with various repetitions. The purpose of the first assembly (sealed joints and sealed penetrations) was to ensure a satisfactory seal between the steel

deck and the wooden framework, which is confirmed by the results in Table 1. Second, only the steel deck was tested, without the insulation boards mounted on top. This assembly was later compared with the full assembly with both steel deck and insulation boards, though without the thermoplastic membrane. The results from these two assemblies indicate that the airtightness of the steel deck is conclusive (i.e., the airtightness of the insulation boards is much less than that of the steel deck). Further, the steel deck was perforated with varying numbers of 3/16-inch drilled holes. The effects of a perforated steel deck are presented in Table 1, indicating the importance of intact steel sheeting.

Table 1 Results from measuring the air leakage coefficient, C , and the pressure exponent, n . Five different assemblies were measured with various repetitions and are presented as average values of the measurements.

Results from airtightness tests	C ($m^3/s, Pa$)	n (-)	Q_{50} (m^3/s)	Q_{50} (l/s)
1. Sealed joints and sealed screw penetrations	3.31E-07	0.99	1.74E-05	0.02
2. Steel deck only	6.45E-06	0.95	2.63E-04	0.26
3. Full assembly	6.19E-06	0.96	2.69E-04	0.27
4. Full assembly, 2–4 perforations	6.85E-05	0.54	5.61E-04	0.56
5. Full assembly, 8 perforations	1.25E-04	0.72	2.09E-03	2.09

The results from measuring the airtightness of the metal roof construction indicate that even small perforations of the steel increase the leakage rate significantly. A well-performed overlap of the steel deck sheets, screwed tight and without further sealing, has relatively high airtightness, however. Noteworthy is that the tested assemblies do not include any installation or structural penetrations that need to be sealed. The IECC-2012 Standard for Commercial Energy Efficiency declares the importance of sealing penetrations (ICC, 2011). Further, the IECC Standard provides three different approaches to determining the air barrier of different materials, construction assemblies, or the complete building, where the latter shall not exceed 2.0 l/s,m² at a pressure difference of 75 Pa. Assuming an n -value of 0.6, this regulation equals a maximum Q_{50} -value of 1.57 l/s,m². Naturally, the air leakage regulation includes all parts of the building envelope and not the roof solely. However, steel decks have been proven leaky, so sealing the joints of the steel sheets and ensuring a non-perforated steel deck is important for overall airtightness (Walsh, 2007). A literature study prepared for the California Energy

Commission in 2006 presented an average Q_{50} -value of 4.0 l/s,m² based on air leakage tests in 267 commercial buildings (Gadgil, Price, Shehabi, & Chan, 2006).

Another aspect of analyzing the results from the measurements of this study is their expected relationship to constructed roofs. The airtightness of the test specimens and the field measurements have been shown to deviate. Test results of a specimen representing a lightweight compact metal roof without a vapor retarder, like the roof construction presented in Figure 1, resulted in a Q_{50} -value of about 0.75 l/s,m², though field measurements varied between 2 and 6 l/s,m² (Hens, Zheng, & Janssens, 2003).

In the simulation model, the air layer is assumed to have an average thickness of 3 cm, representing the fluttering-induced air cavity.

Further, material properties from the hygrothermal model database are utilized, except for the metal trapezoidal construction where a vapor permeance of 1.0 (perm) is applied. The permeance represents a metal deck including air leakages from penetrations such as screws and is in accordance with earlier investigations done at Oak Ridge National Laboratory (Kyle & Desjarlais, 1994). The initial moisture content of the materials in the simulation model are in accordance with EMC80 (ASHRAE, 2011).

4. PARAMETERS

The results of this study are based on multiple iterations of the numerical simulation of the roof construction with varying input parameters. The varying parameters are presented briefly in Section 2 and are discussed in detail below.

4.1. Climate

Four different U.S. climates are used, representing climate zones 4 to 7:

- Climate Zone 4 – Baltimore, Maryland
- Climate Zone 5 – Chicago, Illinois
- Climate Zone 6 – Minneapolis, Minnesota
- Climate Zone 7 – Fargo, North Dakota

The chosen climate of each city represents the 10th percentile coldest climate and is presented with hourly values of temperature, relative humidity, wind speed, solar intensity, etc. These climates are applied to serve as design reference years for the estimation of hygrothermal performance in buildings (Sanders, 1996).

4.2. Surface Solar Reflectance

The solar absorptivity of a surface defines the ratio of solar radiation absorbed by a surface and varies between 0 and 1. The solar absorptivity used in the simulations of this study is set to either 0.3 or 0.85, which is representative of a white or a dark surface respectively. These values assume that a white roof reflects 70% of the sunlight and a dark surface reflects only 15%. The variation in solar absorptivity allows the hygrothermal performance of a cool roof color to be compared to that of a traditional darker roof color. The disparity between the chosen solar absorptivity for the light and dark surface in this study is less extreme than in the literature (Bludau et al., 2009), where 0.2 for a white and 0.9 for a black surface are assumed.

4.3. Indoor Moisture Supply

Four different variations of indoor relative humidity are used in the simulations. Due to the lack of specific design values for commercial buildings, equivalent rates for residential buildings are applied. The four different variations of indoor moisture supply are presented here:

- EN-15026, where the indoor relative humidity is assumed to vary with the outdoor temperature and is presented in two different classes, normal and high moisture load (Standardization, 2007). The high moisture load of EN-15026 is equivalent to the simplified default indoor design humidity method of ASHRAE 160 (ASHRAE, 2011). This study uses both the normal and the high indoor moisture load.
- ASHRAE 160 intermediate method, where the moisture load depends on the specified number of bedrooms and ventilation ACH . Two different scenarios are chosen for this study: two bedrooms with $ACH = 0.6$ and six bedrooms with $ACH = 0.2$, which supposedly are representative of a low and a high indoor moisture supply.

4.4. Air Intrusion

Typical air intrusion rates are defined in Section 3.2. The chosen rates are based on four different leakage rates of the roof assembly, presented below. The air intrusion rates used in the simulations of the roof are as follows.

- $Q_{50} = 0.27 \text{ (l/s,m}^2\text{)}$ A perfectly assembled roof construction with regard to both material properties and workmanship, according to measurements of the air leakage in the roof construction below the thermoplastic membrane in Table 1.

- $Q_{50} = 0.56 \text{ (l/s,m}^2\text{)}$ An assumed satisfactory assembly of roof construction, though with minor perforations in the steel deck; it is based on measuring the average leakage rate with a varying number of 3/16-inch holes (see Table 1).
- $Q_{50} = 1.0 \text{ (l/s,m}^2\text{)}$ Semi-leaky roof construction, arbitrarily chosen.
- $Q_{50} = 2.0 \text{ (l/s,m}^2\text{)}$ Leaky roof construction, based on both measurements presented in Table 1 and air leakage tests made on commercial buildings with similar roof assemblies (Gadgil et al., 2006; Hens et al., 2003).

The pertinent air leakage coefficient, C , and pressure exponent, n , values are taken from either Table 1 or are calculated by assuming $n=0.65$, which in lieu of provided values usually is a good assumption (Gadgil et al., 2006).

5. RESULT

A total of 128 different scenarios of the mechanically attached roof system are simulated, with varying input parameters as defined in Section 4. Each scenario is numerically simulated for a complete year.

The accumulation of moisture in the air layer between the thermoplastic membrane and the insulation board is evaluated since it is closely related to the amount of condensed water in the roof construction. The moisture content of the air layer is converted into a condensate layer thickness, d_l , in which the moisture content is assumed to be distributed over the complete surface area. The conversion is made to facilitate hygrothermal analysis of the roof construction and comparisons between the different simulated scenarios. The variations of d_l for each simulation are presented in Figure 5. Typically, d_l increases during the heating season, when the difference between the indoor and outdoor moisture content is the greatest.

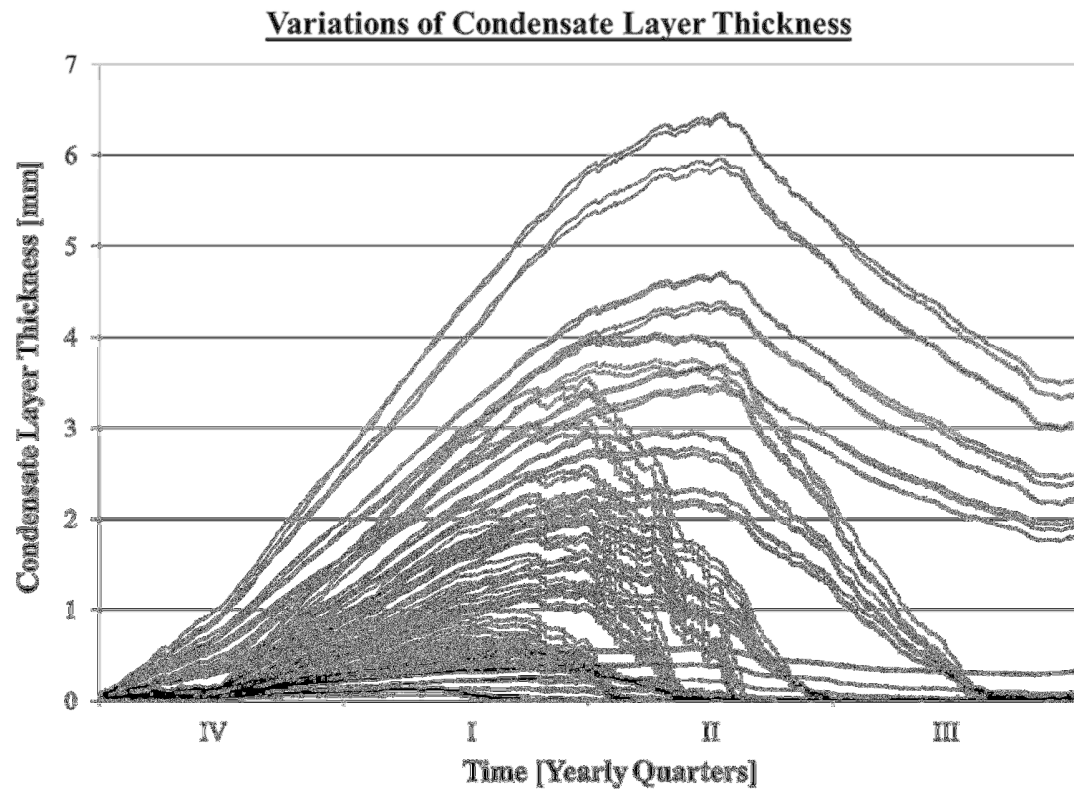


Figure 5 Condensate layer thickness, d_l , for the 128 simulated roofs with a mechanically attached outer membrane. Typically, the thickness increases during the heating season.

The variations of d_l , illustrated in Figure 5, give a range of different simulated roofs, without specifying the chosen input parameters of the simulations. The maximum values of d_l for the simulations are given in Figure 6 and Figure 7, as a function of the chosen indoor moisture supply. A curve, with either a black or a white surface, is presented for each moisture supply with varying climate zone and air intrusion rate.

**White surface - Maximum condensate layer thickness at
varying indoor moisture supply**

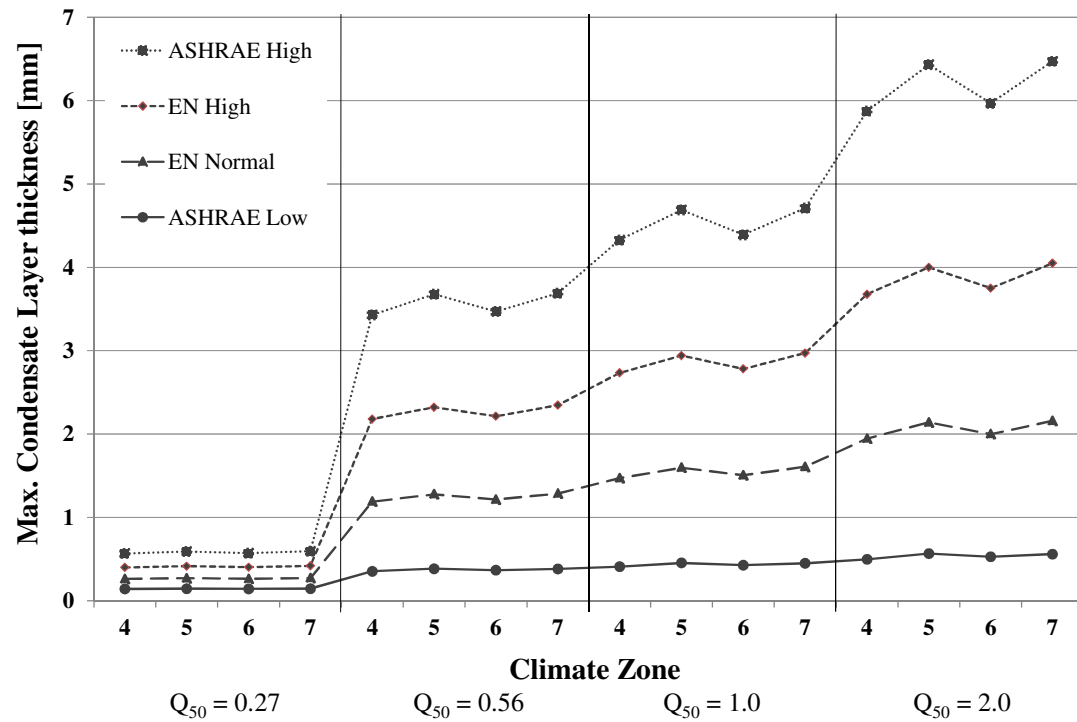


Figure 6 Maximum condensate layer thickness for each simulated roof construction with a white membrane surface. The curves represent the chosen indoor moisture supply with varying climate and air intrusion rate.

**Black Surface - Maximum condensate layer thickness at
varying indoor moisture supply**

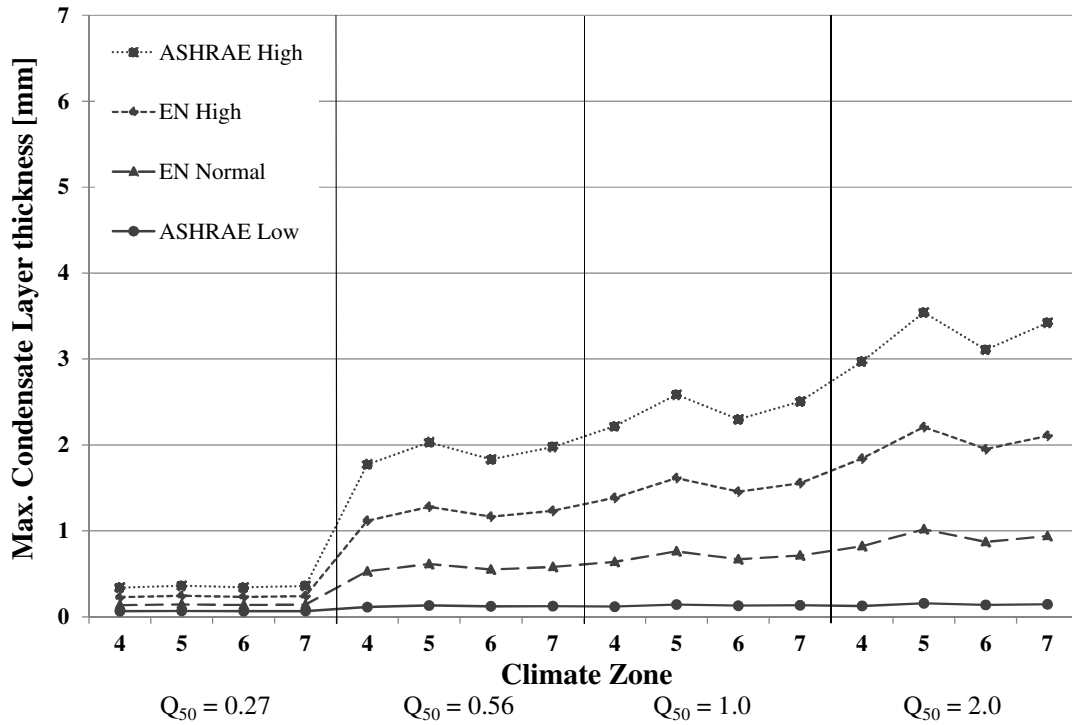


Figure 7 Maximum condensate layer thickness for each simulated roof construction with a black membrane surface. The curves represent the chosen indoor moisture supply with varying climate and air intrusion rate.

A critical d_l is commonly taken as 0.5 mm to avoid dripping (DIN, 2001; Hens et al., 2003), hence this value is considered an upper maximum for a safe and reliable roof construction. Additionally, a d_l between 0.5 and 1.0 is considered risky, and values beyond are rated as failures in terms of the risk for condensation. The 1.0 threshold is also recommended in German Standard (DIN, 2001); it is stated as an upper limit to avoid gravitational flow, but in presence of hygroscopic materials only. However, the standard is mainly used for the surfaces of walls with a sloped roof; consequently, water is more easily drained off compared to a flat roof. Hence the 1.0 threshold can be assumed conservative and thus applicable for this study.

The results of the risk evaluation for the 128 simulations are given in Table 2.

Table 2 Results from the 128 simulated scenarios, indicating the reliability of the roof construction at given conditions. Table cells with no background color indicate a safe roof construction, gray indicates risky construction, and black indicates an expected failure with respect to condensation. B stands for a black roof surface, and W stands for white.

Climate Zone 4								
Indoor moisture supply	Q ₅₀ = 0.27		Q ₅₀ = 0.56		Q ₅₀ = 1.0		Q ₅₀ = 2.0	
ASHRAE - Low	B	W	B	W	B	W	B	W
EN - Normal	B	W	B	W	B	W	B	W
EN - High	B	W	B	W	B	W	B	W
ASHRAE - High	B	W	B	W	B	W	B	W
Climate Zone 5								
Indoor moisture supply	Q ₅₀ = 0.27		Q ₅₀ = 0.56		Q ₅₀ = 1.0		Q ₅₀ = 2.0	
ASHRAE - Low	B	W	B	W	B	W	B	W
EN - Normal	B	W	B	W	B	W	B	W
EN - High	B	W	B	W	B	W	B	W
ASHRAE - High	B	W	B	W	B	W	B	W
Climate Zone 6								
Indoor moisture supply	Q ₅₀ = 0.27		Q ₅₀ = 0.56		Q ₅₀ = 1.0		Q ₅₀ = 2.0	
ASHRAE - Low	B	W	B	W	B	W	B	W
EN - Normal	B	W	B	W	B	W	B	W
EN - High	B	W	B	W	B	W	B	W
ASHRAE - High	B	W	B	W	B	W	B	W
Climate Zone 7								
Indoor moisture supply	Q ₅₀ = 0.27		Q ₅₀ = 0.56		Q ₅₀ = 1.0		Q ₅₀ = 2.0	
ASHRAE - Low	B	W	B	W	B	W	B	W
EN - Normal	B	W	B	W	B	W	B	W
EN - High	B	W	B	W	B	W	B	W
ASHRAE - High	B	W	B	W	B	W	B	W

In eight of the 128 roof scenarios, additional simulations were required for a risk evaluation. These eight roof scenarios accumulated moisture, indicating that the annual variation in moisture content will escalate. To confirm this assumption, the eight scenarios were simulated for 5 years, under the same condition but with an additional climate, instead representing the 10th percentile warmest climate. Four of the eight re-simulated roof scenarios reached risky levels, and the other four reached assumed levels of failure. These results are implemented in Table 2.

6. DISCUSSION AND CONCLUSION

This study focuses on the risk of condensation in cool roof construction with a mechanically attached outer membrane. The risk evaluation is based on 128 simulated scenarios of plausible roof conditions with varying indoor and outdoor climates. Four input parameters are chosen to vary: the outdoor climate, the solar surface properties, the indoor moisture supply, and the indoor air intrusion rate below the surface membrane.

The results emphasize the importance of solar reflectance at the roof surface. Comparing the maximum condensate layer thickness, d_l , in Figure 6 and Figure 7 reveals that the amount of accumulated moisture is almost doubled in a cool roof construction compared to a traditional black roof.

The indoor moisture supply is very much related to the expected hygrothermal performance of the roof. Referring to maximum d_l in Figure 6 and Figure 7, a low and a high moisture supply can cause as much as a 10× difference in condensate layer thickness. Another indicator is presented in Table 2, which reveals that only about 10% of the simulated roof construction is considered risky when the indoor moisture supply is at a low level. (Typically, a low indoor moisture supply is either attained by lowering the moisture production rate or by increasing the ventilation air exchange rate.) A distinction between a white and a black surface, for a low moisture supply, shows that only a white surface can be risky with a high air intrusion rate. Almost the opposite is valid for high moisture supply, where only about 13% of the roof constructions are considered safe. Hereby, the considered safe roof constructions have black surfaces only.

The different air intrusion rates show similar behavior in comparison with indoor moisture supply. An increased rate increases the maximum d_l , which also can be seen by the increased slope of the curves in Figure 6 and Figure 7 and by comparing the vertical sections of Table 2.

The fourth varying parameter, the climate, was proven to have the least influence on the amount of accumulated moisture. A slightly increased slope between each climate section

in Figure 6 and Figure 7 confirms a small increase in the maximum d_l . The low influence of the chosen climate is also obvious by comparing each climate section of Table 2.

In conclusion, both indoor moisture supply and air intrusion rate are critical parameters for hygrothermal cool roof performance. A low indoor moisture supply or a low air intrusion rate ensures a low risk of intermediate condensation. A safe upper limit of air leakage at 50 Pa, Q_{50} , is stated as 0.17 l/s,m² for metal roofs (Hens et al., 2003). This limit seems consistent with the low risks of the simulated lower air intrusion rate of 0.27 l/s,m², at least for the black roofs of this study. Further, a cool roof will accumulate approximately twice as much moisture below the surface membrane as a black surface. It is assumed that replacing a black surface with a cool membrane on an existing mechanically attached roof system could result in intermediate condensation.

The mechanical resistance of the roof membrane has not been taken into account in this study. Likely, this means that, at some lower limit of wind-induced pressure, the uplifting force is lower than the weight and flexible resistance of the membrane, thus preventing any air intrusion. Therefore, a complete depressurization analysis of a mechanically attached roof system is needed to fully analyze a cool roof assembly at realistic and fluctuating wind loads.

It is of great concern to emphasize that a single ply roof, including an interior vapor retarder, is not necessarily equivalent with an airtight construction. Either insufficiently sealed overlaps, perforations or penetrations of the vapor retarder, may cause high air intrusion rates.

Finally, the following practical conclusions can be stated:

- If a very low indoor moisture supply is assumed, no moisture problem is expected, except for white surfaces combined with high air intrusion rates.
- For black roofs, the joints of the steel deck do not necessarily need to be sealed to be considered safe, though penetrations and perforations must.
- The previous statement is valid for white roofs, only with a low or normal indoor moisture supply.
- For all other roof assemblies with varying indoor and outdoor climates, an interior air barrier is recommended.

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