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Hygrothermal assessment of north facing, cold attic spaces under the eaves with varying single sided passive ventilation strategies and infiltration scenarios, in a cool, temperate climate

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ABSTRACT

Relative humidity and temperature were measured in cold attic spaces under the eaves with diffusion-open roofing underlay to investigate different ventilation strategies, the influence of infiltration, and exterior insulated roofing underlay. The project was carried out as a full-scale experimental setup in the cool, temperate climate in Lyngby, Denmark. The objective was to test if the best practice recommendations concerning design of the cold attic space will prevent damaging moisture levels in the attics. Measurements do however indicate that complying with recommendations will not ensure satisfactory moisture levels in the attic spaces. A comparison of the passive ventilation strategies in combination with varying infiltration rates, for attic spaces fitted with diffusion-open roofing underlay, indicate that attic ventilation increases moisture levels. The exterior insulation of the attic space improved the hygrothermal performance.

KEYWORDS

Cold attics, ventilation, diffusion-open roofing underlay, insulated roofing underlay, moisture

INTRODUCTION

Recommendations regarding design of cold attics in cold, temperate climates are to ventilate moisture away using outdoor air, and to ensure air- and vapour tightness towards the conditioned spaces. Previous studies by the Technical University of Denmark (DTU) (Bjarløv et al., 2016) and other studies (Fugler, 1999; Harderup & Arfvidsson, 2013; Roppel & Lawton, 2014) do however indicate that moisture induced damages can be found in attics even when constructed in compliance with local best practice recommendations. Some studies (Essah et al., 2009; Harderup & Arfvidsson, 2013; Ojanen, 2001; Uvsløkk, 2005) have investigated the use of diffusion-open roofing underlay as an alternative to passive ventilation, indicating a lowering of the diffusion resistance may reduce moisture levels in the attic space. Single-sided passive ventilation with one or two ventilation valves have previously been investigated by DTU (Bjarløv et al., 2016; Pold, 2015) for attics with diffusion-open roofing underlay in a cool, temperate climate. Here reported results indicated that single-sided passive ventilation had a detrimental effect and led to an increase in humidity of air by volume. The authors hypothesized that the observed detrimental effect was a result of a lower air tightness allowing for more air to infiltrate from the conditioned interior. Simulations by Essah et al. (2009) for attics with diffusion-open roofing underlay suggests an increase in moisture levels due to eave-to-eave ventilation. Meanwhile experimental studies by Hagentoft & Sasic Kalagasidis (2010) have investigated attics fitted with adaptive ventilation, indicating superior performance compared to eave-to-eave ventilation. Simulations by Nik et al. (2012) support these indications for adaptive ventilation, as well as suggest superior performance compared to attics with eave- and gable ventilation, and insulated roofing underlay. Furthermore, experimental studies including (Harderup & Arfvidsson, 2013) have investigated the influence of long-wave radiation, and observed lower temperatures in the attic construction than in the outdoor air, increasing the risk of condensation on the roofing underlay.

The objective of the research project was to test the best practice recommendations concerning design of the cold attic space. Especially whether compliance with the Danish building regulations (TBST, 2018) regarding the airtightness of the building envelope (less than 1 l/s per m^2 heated floor area at 50 Pa pressure difference) will prevent damaging moisture levels. According to official Danish guidelines, appropriate ventilation of the attic is recommended and this may be achieved with attic using "pressure equalization" (based on stack effect ventilation) (Brand et al., 2009). However, (Brand et al., 2013) state "It cannot be expected that a diffusion-open roofing underlay (Z-value < 3 GPa m^2 s/kg) will to a sufficient extent remove moisture from the attic rooms and attic rooms under the eaves (when the floor width > 1 m). Unless the vapour retarder toward the indoor climate is perfectly installed, these attics will need some degree of ventilation." Therefore, the guidelines suggests to ventilate the attic using two ventilation valves. Measurements of relative humidity and temperature will be presented for different attic designs, as well as temperatures in the roofing underlay. Results are expected to contribute to enhancing the current best practice recommendations for design of cold attic space under the eaves, to reduce the risk of moisture induced damages.

METHODS AND MATERIALS

The experimental setup consisted of a 45° single sided pitched roof, constructed on top of a 40-foot reefer container, conditioned to 20 °C and 60% relative humidity (corresponding to an indoor climate class 3 (Brand et al., 2013)). The roof was subdivided into nine attics with the interior dimensions (LxWxH) 1.25 m x 1 m x 1 m, each with different design variations, of which seven are presented in this paper. Special care was taken to reduce potential sources of error like unintentional transport of heat, air, moisture and mould spores. Thus, hygric- and thermal decoupling were established between the attic spaces and to the conditioned spaces, using vapour retarders and thick layers of mineral wool. The attic spaces were fitted with a diffusion-open roofing underlay, with a vapour diffusion resistance, Z, of 0.1 GPa·s·m^2/kg.

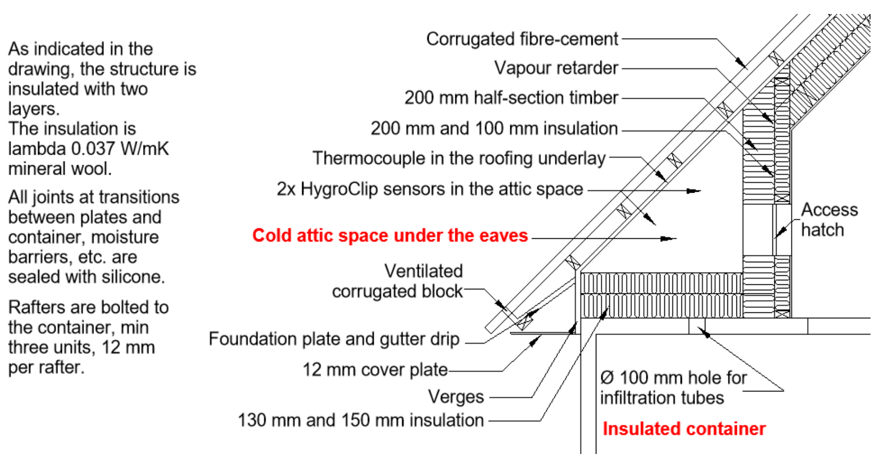

Figure 1 Vertical section of the cold attic space under the eaves

The attics were constructed as north facing, cold attic spaces under the eaves, as this represents the worst-case scenario, since the roof surface receive only a limited amount of solar radiation. A conditioned loft corridor was constructed on the southern side. The experiment was conducted at the test site of the Department of Civil Engineering at DTU in Lyngby, Denmark (55.79°N, 12.53°E). The experiment consisted of three series of variations, representing different structural roof scenarios. The series were infiltration rate, single-sided passive ventilation strategies, and exterior insulation. Two different infiltration scenarios were investigated: 1) 3.4 l/s at 50 Pa pressure difference; 2) No infiltration from the conditioned spaces. It is easier to construct tight walls, ceilings and floors than it is to construct tight joints. Leaks are therefore often found where the ceiling meets the walls. This means that attic spaces under the eaves are in risk of being subjected to (local) infiltration rates well above 1 l/s per square meter attic space at 50 Pa pressure difference over the building envelope that is allowed by BR18. The 3.4 l/s at 50 Pa pressure difference used in this experiment is used to approximate the effects of infiltration in an assumed worst-case scenario. Infiltration was established by fitting several attics with PVC tubes connecting the attics and the conditioned spaces. Three different ventilation strategies: 1) Un-ventilated (UV), in which attic spaces were not fitted with ventilation valves; 2) Pressure equalization (PE), in which attic spaces were fitted with a valve in the top corner. 3) Single-sided ventilation (SSV), in which attic spaces were fitted with two valves, diagonally in the top and bottom corners. The third series compared an unventilated attic space with infiltration, to an identical attic, fitted with a 50mm polystyrene insulation on the exterior side of the ventilated cavity. This series investigated the influence of long-wave radiation. An overview of the attic variations is presented in **Table 1**.

Table 1 Overview of attic variations

Attic space	B1	B2	B3	B4	B5	B6	B7
Infiltration rate at 50 Pa	-	-	-	3.4 l/s	3.4 l/s	3.4 l/s	3.4 l/s
Ventilation strategy	UV	PE	SSV	UV	PE	SSV	UV
Exterior insulation	-	-	-	-	-	-	+

Temperature and relative humidity sensors were installed in the attic spaces (two in each), outside, and inside the conditioned container, while temperature sensors were installed in the roofing underlay (see Figure 1). The presented results are based on measurements logged every 10 minutes from November 2014 to May 2017. Note that measurements from the two sensors in the attic spaces were averaged. The accuracy of the sensors is shown in **Table 2**.

Table 2 Accuracy of sensors

Instrument	Measurement	Accuracy	Range
Rotronic HygroClip	Temp.	± 0.1 K at 23 °C and 10, 35 and 80% RH	-50 to 100°C
2 S	RH	± 0.8 % at 23 °C and 10, 35 and 80% RH	1 to 100 %
Thermocouple type T	Temp.	± 0.5 K at 0 °C	-200 to 350 °C

RESULTS

In the following, the measured temperature and relative humidity in the attic spaces are presented as 15-days moving average of the derived daily average values, using 7 days before and after the current date (Figures 2-3). Figure 2 shows the relative humidity for attics without infiltration (B1-3) and with infiltration (B4-6), where higher relative humidity is seen for the cases with ventilation and/or infiltration. The highest relative humidity is seen for the PE attic (B5). Figure 3 shows the temperatures in the attic spaces. Since the measured temperatures were almost identical for attics B1-4, the measurements are shown in combination, against the PE attic (B5) and the SSV attic (B6). Slightly higher temperatures were seen for B5 and B6 during the cold periods (highest for B5,) and slightly lower during the warm periods.

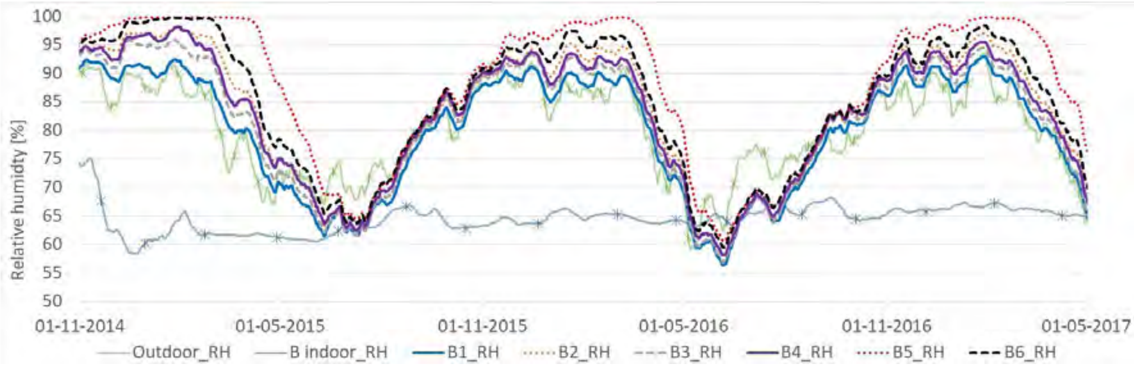

Figure 2 Relative humidity in the attics spaces, indoor, and outdoor.

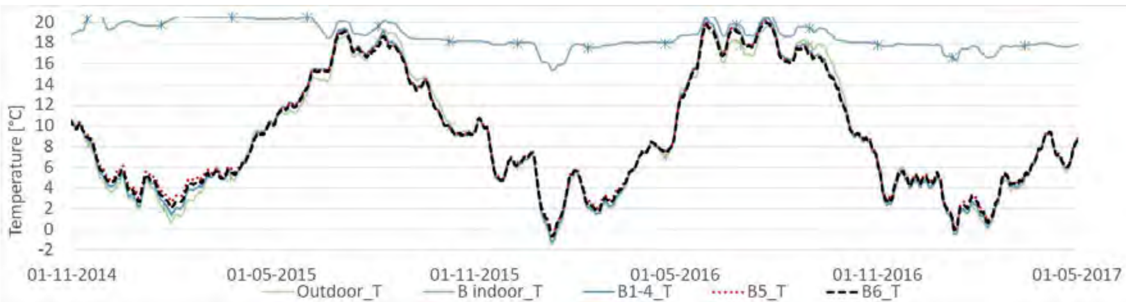

Figure 3 Temperatures in selected attic spaces, indoor, and outdoor.

Figure 4 shows the difference in temperatures measured in the roofing underlay and outdoor air, when the temperature in the roofing underlay is lower than the outdoor air. Temperatures are presented as hourly averages of the logged data. The difference in temperatures is the effect of the exterior insulation mounted on attic room B7 preventing heat loss by long-wave radiation. Heat losses from radiation will be greatest during cold nights with clear skies. Focus in the presented data is therefore on cold periods. November 1st, 2016 to May 1st, 2017 was chosen, as the lowest temperatures were observed during this winter period. Tendencies were similar for the other winter periods. In Figure 4 the roofing underlays are seen to experience temperatures several degrees below that of the outdoor air. The uninsulated underlay (B4) is seen to frequently experience the largest temperature difference to the outdoor air (when B4 > B7). Furthermore, the humidity of air by volume was calculated for the attics, and the insulated attic was seen to experience an increase of up to 0.35 g/m^3 during the winter periods.

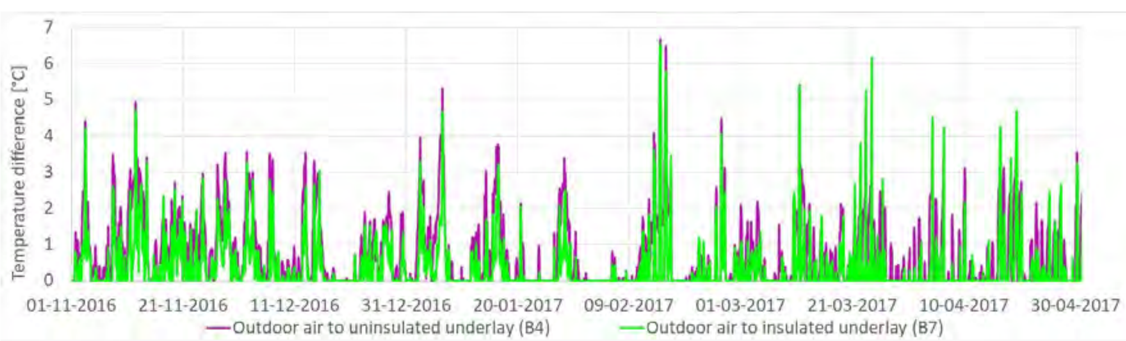

Figure 4 Temperature in the roofing underlay relative to the outdoor air.

DISCUSSIONS

Considering the humidities of B1 and B4 in comparison to B2-3 and B5-6 in Figure 2, measurements seem to indicate that ventilation of diffusion-open attic spaces under the eaves in a cool temperate climate using PE or SSV will increase the relative humidity. While a comparison of B1 to B4, B2 to B5, and B3 to B6, indicate that the relative humidity also will increase in case of infiltration from the conditioned spaces. Lastly, a comparison of B1 to B4 and then to B5-6 show the compounding effect of infiltration and the tested ventilation strategies for the attic spaces with diffusion-open roofing underlay, where the relative humidity was observed to increase even further. The PE attic experienced the largest increase in temperature and relative humidity (B4 to B5). A smaller increase in relative humidity was observed for the SSV attic (B4 to B6). We believe that the observed increase in moisture levels is due to untight ceiling and roof constructions allowing a stack effect to cause an updraft of infiltration air.These indications correlate with findings of previous experimental studies by DTU (Bjarløv et al., 2016; Pold, 2015). However, in contrast to Bjarløv et al. (2016) but in agreement with Pold (2015), the ventilation strategy PE (B2 and B5) was shown to result in the largest increase in the moisture levels, compared to SSV (B3 and B6). Simulations by Pold suggested that PE will exacerbate infiltration from the indoor spaces due to negative pressure under the roof cladding, resulting in increased moisture levels. Polds simulations also suggested that SSV increase moisture levels in attic spaces just to a smaller extent. Findings concerning lowered moisture levels due to reduced attic ventilation for attics with diffusion-open roofing underlay in cool temperature climate, correlate with the experimental studies by Harderup & Arfvidsson (2013) and Ojanen (2001), as well as the simulation results by Essah et al. (2009). Furthermore, as it was the case for these attic spaces, Harderup & Arfvidsson also observed relative humidity favorable for mould growth during the cold periods. In this study, relative humidity favorable for mould growth, was observed between mid-August to mid-April, when considering 75% relative humidity as critical limit as suggested in the best practice recommendations (Brand et al., 2013).

Considering the temperature difference between the outdoor air and the roofing underlays in Figure 4, measurements indicate that externally insulating the roofing underlay reduces the heat loss due to long-wave radiation for these attics. The roofing underlay temperatures in the externally insulated attic (B7) were seen to increase by up to 2.5 °C compared to the uninsulated attic (B4), and 0.5 °C on average. This difference between the two roofing underlays occurred around midnight on May 18th, 2017. The roofing underlays were observed to experience temperatures below that of the outdoor air (Figure 4); and despite the focus on clear, cold nights, the largest temperature difference between the roofing underlays and the outdoor air occurred around 14:00 on February 14th, 2017: a difference of 6.7 °C for the uninsulated attic and a difference of 6.6 °C for the insulated attic. Roofing underlay temperatures below that of the outdoor air and attic space air is a potential risk, as movement of warmer, moister air to the roofing underlay could lead to condensation on the interior surface. In the summer periods the attic spaces were almost identical. These findings correlate with Harderup & Arfvidsson (2013), who during the cold periods observed the highest temperatures in the externally insulating attics, compared to the uninsulated; also, a small increase in the moisture levels was observed. Finally, our measurements thus seem to indicate that the exterior insulation has both positive and negative effects on the moisture balance in this attic space with the temperature increase in the roofing underlay being good while the increase in the humidity of air by volume in the attic space is not.

CONCLUSIONS

Measurements from different cold attic spaces under the eaves fitted with diffusion-open roofing underlay, indicate that following the current best practice recommendations regarding passive ventilation does not guarantee safe moisture levels in attic spaces. Ventilation of these attic spaces seems to lead to an increase in moisture levels, and so does infiltration from the conditioned spaces. Allowing for infiltration in combination with ventilation allows for even higher levels of moisture. From this, the results indicate that the assessed ventilation strategies under similar physical conditions does not mitigate moisture problems but may instead exacerbate moisture problems. Furthermore, exterior insulation of the attic spaces reduces the risk of condensation on the interior surface of the roofing underlay slightly. However, more data and analysis about other construction scenarios are needed for more general conclusions.

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