Influence of local weather conditions on ventilation of a pitched wooden roof

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Abstract

This paper investigates the influence of temperature and wind conditions on ventilation of the air cavity beneath the roofing in a full-scale pitched wooden roof construction. The potential for condensation in the air cavity is studied. The relevant roof construction is equipped with 81 thermocouples and four air velocity measurement devices. A weather station at the site records outdoor temperature and wind conditions. Five periods between 2016 and 2018 are investigated. The findings show distinct periods of below-ambient temperature and positive condensation potential in the ventilated air cavity of the roof. A relation between low wind speed and positive condensation potential is shown. Difference in size of periods with below-ambient temperature and periods with positive condensation potential implies that the materials in the roof regulate the humidity in the air cavity. Large negative peaks in the condensation potential indicate dry-out of the construction.

Key words: Pitched roof; Wood construction; Air cavity; Ventilation; Condensation

1. Introduction

The Norwegian climate is characterized by extreme variations and large geographical and seasonal differences. This results in considerable weather strain, which puts large demands on Norwegian building envelopes (Lisø & Kvande, 2007). As an exposed element of the building envelope, the roof must be constructed to stand local weather loads. Pitched wooden roofs, defined as roofs with a wooden load bearing system, is a widely used roof structure in Norway (Edvardsen & Ramstad, 2014). These roofs are constructed with ventilation by providing airflow through an air cavity beneath the roofing. The purpose of the ventilation is 1) to remove excessive moisture from the roof construction to avoid damages and mould growth, and 2) to remove heat in order to prevent melting of snow on the roof and subsequent formation of ice on the eaves (Bøhlerengen, 2007). Performed this way, ventilated pitched wooden roofs are considered climatic robust constructions. The risk of condensation inside the air cavity is, however, dependent on local weather conditions and the consequences are dependent on the roof design and materials used.

Measurements performed by Gullbrekken et al. (2017) showed large periods of below-ambient temperature in the ventilated air cavity in a pitched wooden roof. During three periods in spring, summer and autumn 2016, it was found that the temperature at the rear side of the roofing was lower than the outdoor temperature 51%, 14% and 56% of the time, respectively. A strong correlation between wind speed and air velocity in the air cavity was observed. However, the conclusions were based on hourly averaged data and periods during winter were not studied. The effect of the wind direction towards the building was neither analysed. The condensation potential was not investigated, and the study only included the south face of the roof.

This paper is a continuation of the study performed by Gullbrekken et al. (2017). The aim of the study is to investigate the influence of temperature and wind conditions on ventilation of the air cavity in the same full-scale wooden roof construction as previously studied by Gullbrekken et al. (2017). One of the main goals is to examine the risk of condensation in the ventilated air cavity. The following research questions are addressed:

- How is the temperature in the air cavity depending on the outdoor climate?
- What is the condensation potential that follows below-ambient temperature periods in the air cavity?
- What consequences do the risk of condensation imply?

The study includes pitched wooden roofs and focus on roofs insulated in the entire cross section. Roofs with cold attics, ventilated or unventilated, are not studied. Neither are air cavities with cross-ventilation, nor flat roofs and compact roofs.

2. Theoretical framework

Air contains moisture in the shape of water vapor. At every temperature there is an upper limit for water vapor content in air, denoted the saturation pressure. Saturation pressure increases with increasing temperature, i.e. air may contain more water vapor at higher temperatures (Thue, 2016). Saturation curves are found empirically and may vary depending on the reference. As a result, different formulas for calculating the saturation curve as a function of temperature exist (Hens, 2007). The formulas have varying accuracy and are usually valid within certain temperature intervals. In this study, saturation pressure is calculated with Equation (1a) and (1b) (Geving & Thue, 2002. Hens, 2007). Partial vapor pressure is given by Equation (2) (Thue, 2016).

$$p_{sat} = 611 \cdot \exp(72.5 \cdot 10^{-3} \cdot \theta - 288.1 \cdot 10^{-6} \cdot \theta^2 + 0.79 \cdot 10^{-6} \cdot \theta^3,\ [0℃ \leq \theta \leq 40℃] \tag{1a}$$

$$p_{sat} = 611 \cdot \exp(82.9 \cdot 10^{-3} \cdot \theta - 288{,}1 \cdot 10^{-6} \cdot \theta^2 + 4.403 \cdot \theta^3,\ [-30℃ \leq \theta \leq 0℃] \tag{1b}$$

Where: p_{sat} saturation pressure of water vapour (Pa)
θ air temperature (°C)

$$p_v = 461.4 \cdot v \cdot (\theta + 273.15) \tag{2}$$

Where: p_v partial pressure difference of water vapour (Pa)
v absolute humidity in air (kg/m^3)

Condensation potential, denoted CP_i, can be expressed as the difference between partial vapor pressure and saturation pressure. The risk of condensation remains zero as long as CP_i remains negative, i.e. as long as the partial vapor pressure is lower than the saturation pressure.

3. Methods

The study was carried out on a full-scale experimental laboratory building, ZEB Test Cell Laboratory, situated in Trondheim, Norway. See Figure 1. The building has a wooden roof construction with a roof angle of 40°. The roof has eaves-to-eaves ventilated air cavities below the roofing, with 48mm wide inlets and outlets along the eaves. The air cavities are 10.8m long, 552mm wide and 48mm high. The lower surface of the cavities consists of a flexible roof underlay mounted on an oriented strand board (OSB). The upper surface is an OSB covered by a bitumen-based roofing membrane on the weather exposed side. See Figure 2.

The air cavities of the roof are equipped with instrumentation for temperature and air velocity measurements (Figure 2). 81 thermocouples are shared evenly on nine parallel cavities. In each cavity, three thermocouples are located 0.5m above the eaves, three are found between the eaves and ridge, and three are located 0.5m below the ridge. In each triplet, one sensor is installed on the roof underlay, one is installed in the middle of the air cavity, and one is mounted on the rear surface of the roofing. In two of the air cavities, two air velocity measurement probes are installed. The accuracy and range of the sensors are ±0.10°C and -20°C–60°C for the thermocouples, and 0.05m/s and 0.05–5m/s for the air velocity probes. Outdoor temperature and wind exposure are recorded at a weather station located 1.5m above the ridge of the roof. The equipment has a measuring interval of one minute. The data is saved on a server, derived manually and analysed with the software MATLAB.

Four of the cavities on the roof were studied, described in the plan drawing in Figure 1, showing the building from above. Two cavities on the southern side of the roof, denoted SA and SE, and two cavities on the northern side of the roof, denoted NA and NE, were included in the study.

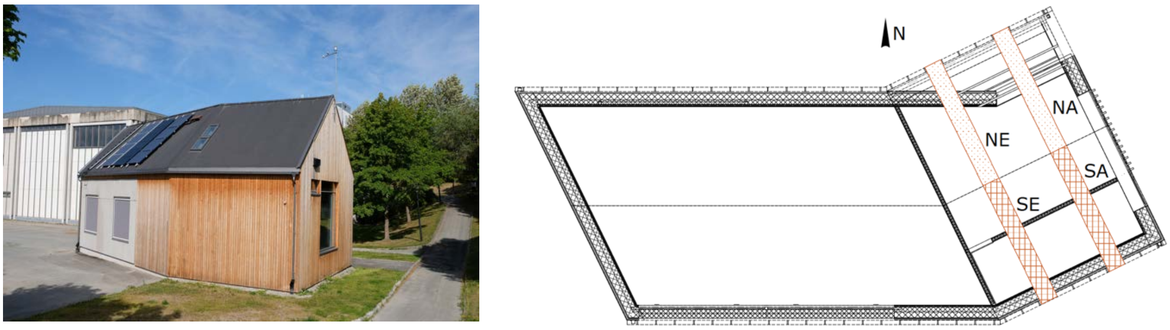

Figure 1 The ZEB Test Cell Laboratory (left). Position of the air cavities included in the study (right). The figure is based on a plan drawing created by Luca Finocchiaro.

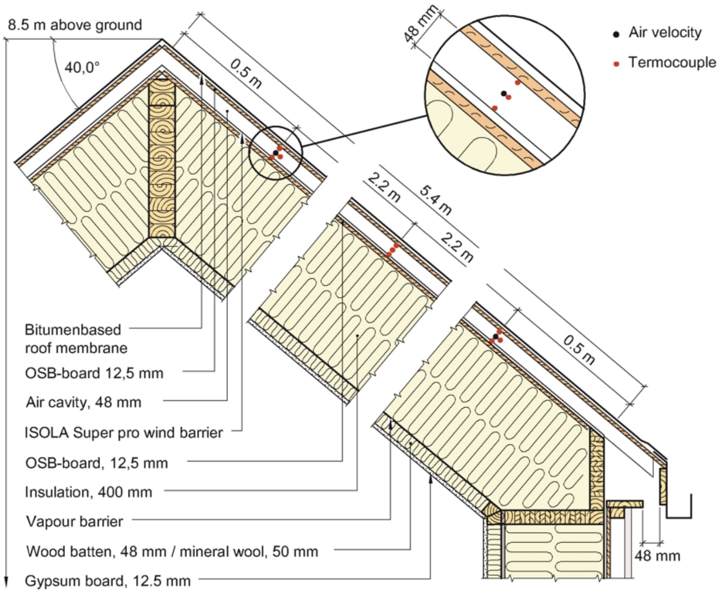

Figure 2 ZEB Test Cell Laboratory roof structure.

The periods of measurement presented in this paper represent different seasons in 2016-2018, including spring (22.3-31.3.16), summer (3.7-14.7.16), autumn (21.9-27.9.16) and winter (21.12-31.12.17 and 24.2-7.3.18). The selection of the periods is based partly on the preference of studying different seasons, and partly on the access to longer measurement periods with complete data. The stability of the outdoor climate during the periods also was of importance. Two different winter periods were chosen in order to compare the situation with and without snow covering the roof (December 2017 without snow and February/March 2018 with snow).

4. Results

All results are based on data with a one-minute measuring interval. Due to different duration of the periods, the number of measurements in each period varies. Temperature, condensation and wind conditions are presented for the five given periods. Temperature conditions in the air cavities, as well as wind conditions are described in Figure 3. The temperature data used is an average of measurements given by the three triplets of sensors in each air cavity. Wind directions are divided into eight wind approach zones, A-H, described by the following angles: 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315° ± 22.5°. The angle of 0° corresponds to wind approaching perpendicular to the wall on the northern side of the building (zone A). Figure 4 shows CP_i in the air cavity and wind speed as a function of time. Figure 5 compares the risk of condensation in the different periods. Results are not given for February/March 2018, as no positive CP_i was found in this period.

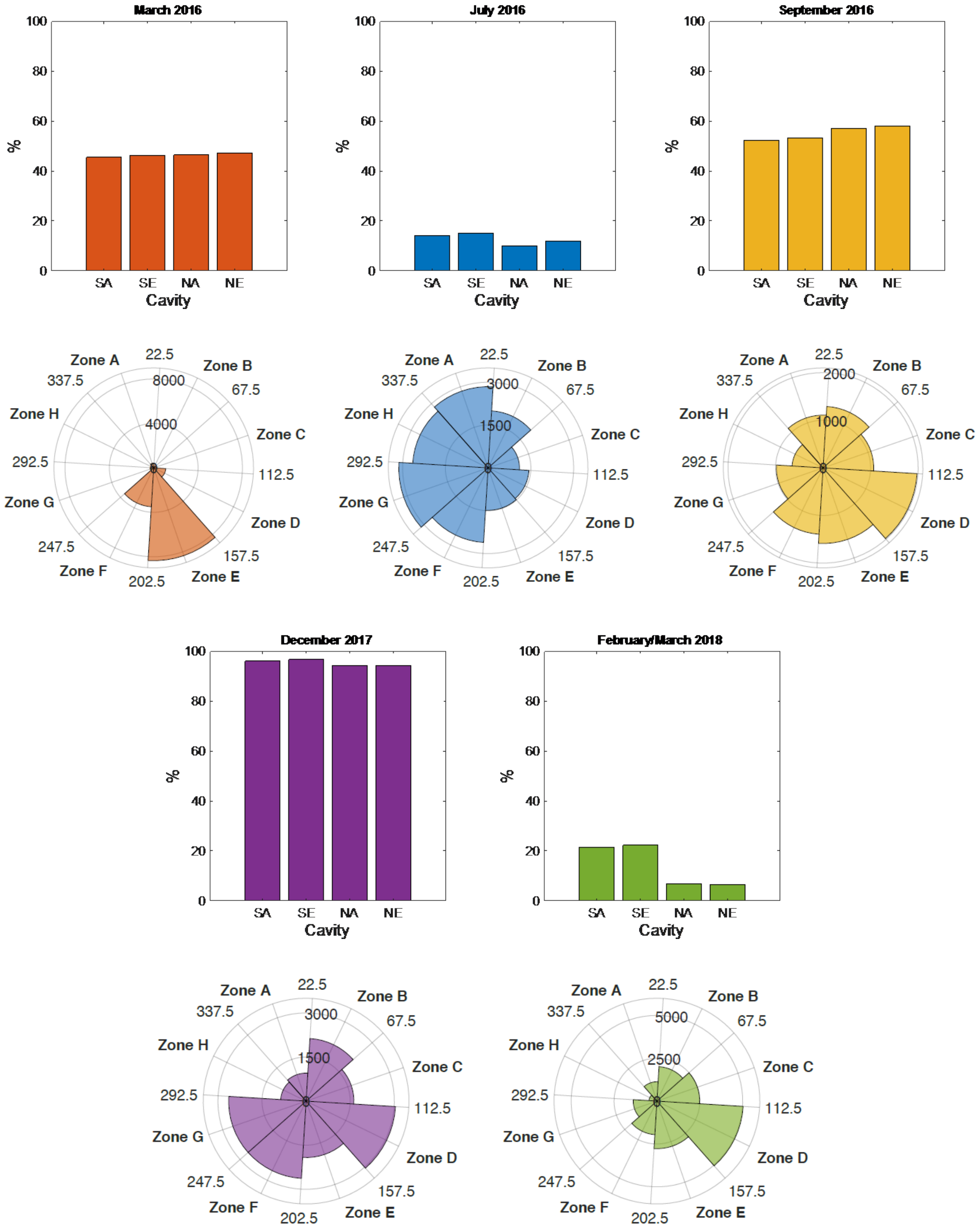

Figure 3 The bar charts present the percentage of each period with lower temperature on the rear side of the roofing than in the outdoor air. The polar charts show the occurrence of wind from different directions towards the house. The radial axes in the polar charts represent the number of measurements within a zone. Note that the scale of the radial axes varies between the different periods.

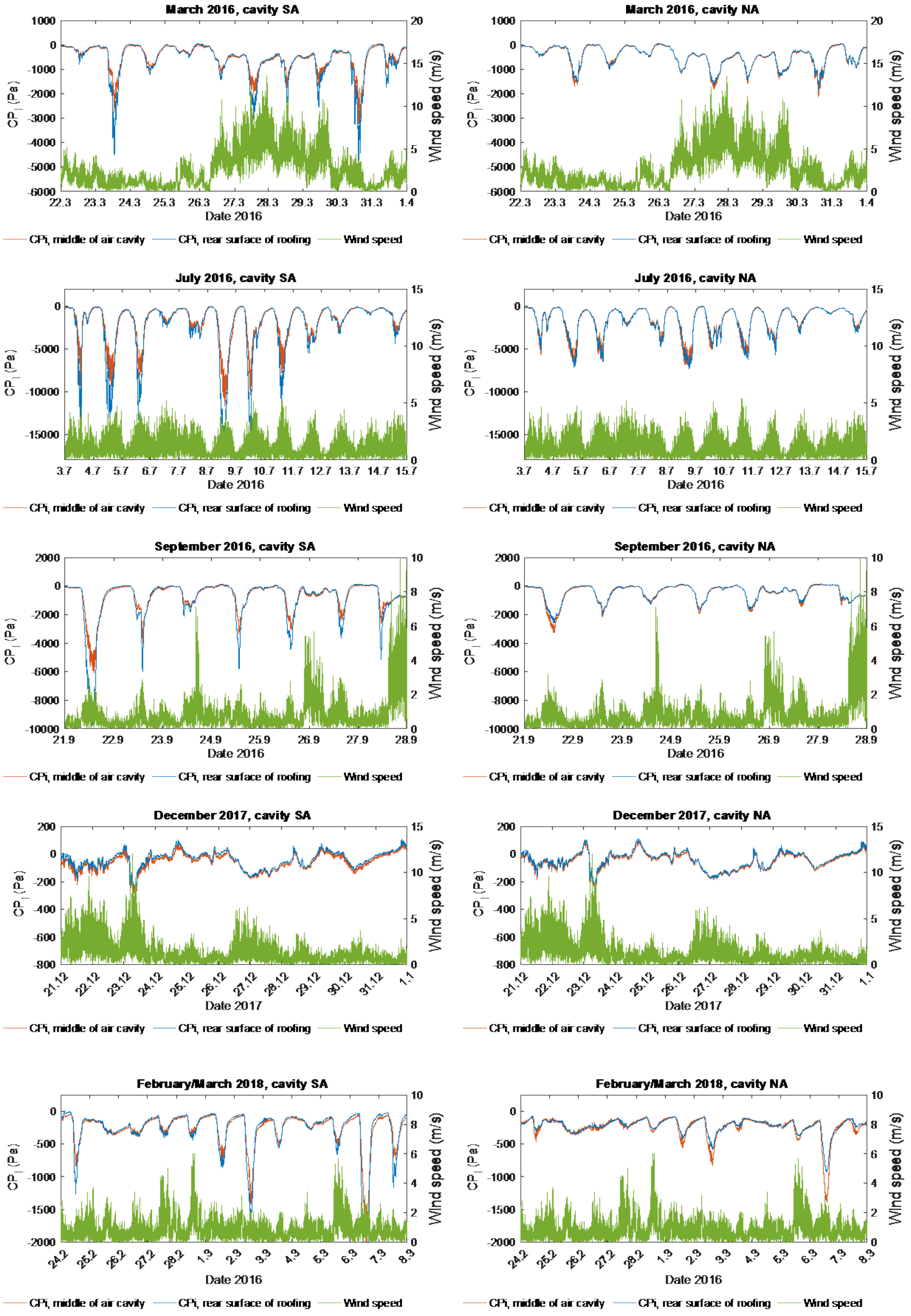

Figure 4 Variation in CP_i and wind speed in the five periods. Results for cavities SA (left) and NA (right) are presented. Note different axes scales.

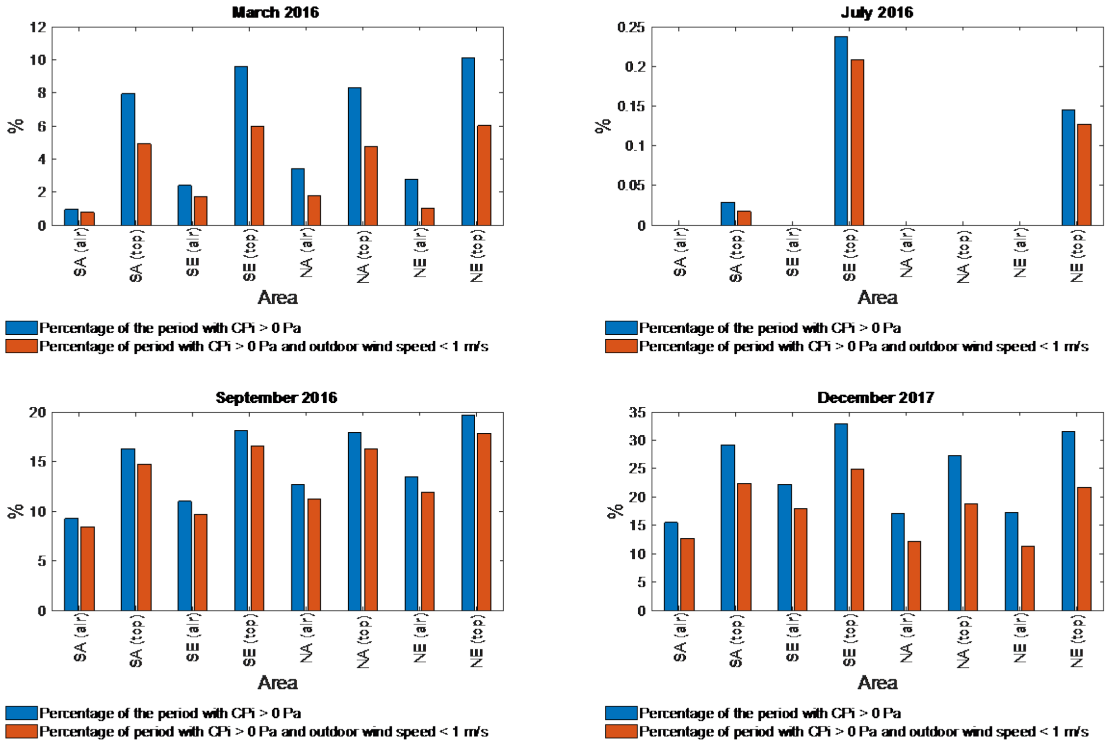

Figure 5 Percentage of each period with positive CP_i, and percentage of each period with positive CP_i at the same time as the wind speed is < 1m/s. Note different axes scales.

5. Discussion

In this paper, the temperature and condensation conditions in the ventilated air cavity of a full-scale pitched wooden roof have been investigated. Five periods between 2016 and 2018 were included in the study. How the temperature in the air cavity depends on the outdoor temperature and wind is presented in Figure 3. The subsequent CP_i in periods with below-ambient temperature in the air cavity is examined in Figure 4 and Figure 5.

5.1. Temperature conditions

The measurements from the roof at ZEB Test Cell Laboratory demonstrated long periods of below-ambient temperature in the ventilated air cavity beneath the roofing. During the spring and autumn periods, the one-minute interval measurements at the rear side of the roofing showed temperatures below the ambient temperature for approximately 50% of the time. This is in line with the results found by Gullbrekken et al. (2017). In the December period, below-ambient temperature was measured close to 100% of the time. There was no snow on the roof in this period. Low outdoor temperatures and periods with clear sky may have contributed to large cooling of the roof and the subsequent below-ambient temperatures at the rear side of the roofing. During the second winter period, in February/March 2018, smaller intervals with below-ambient temperature were found. Snow, which covered the roof in this period, has an isolating effect, hence protecting the roof from the low outdoor temperatures and subsequent undercooling. Undercooling was still present for approximately 20% of the time on the southern part of the roof.

5.2. Temperature influence on CP_i

As recorded in Figure 4, differences in CP_i were found when comparing the southern and the northern side of the roof. Due to heating by the sun, the negative peaks in CP_i was much larger on the southern side. The large negative peaks in CP_i correspond to the points of time with high temperatures in the air cavity found by Gullbrekken et al. (2017). The periods of positive CP_i were larger on the northern side of the roof. Together with the smaller size of negative peaks, this implies that the risk of condensation is higher at the northern side. A higher CP_i was also seen for the rear side of the roofing than for the middle of the air cavity. However, the rear side of the roofing also had a larger dry-out potential because of greater heating of the roofing during the day. This decreases the risk of long-term moisture deposit on the OSB. Both during the spring and autumn period, the local climate gave high temperatures during the day and shifts to low temperature during the night. The high temperatures give the large negative CP_i during daytime, while the shifts to low temperatures during night contribute to the positive CP_i. The winter period in 2017 gave positive CP_i in up to 33% of the time as a result of the long periods of undercooling. The summer period in 2016 and the winter period in 2018 showed very little and no positive CP_i, respectively. This agree with the smaller periods of below-ambient temperature on the rear side of the roofing found in these periods. To summarise, the observations showed that CP_i in the air cavity was very dependent on the temperature and radiation conditions present.

5.3. Wind influence on CP_i

A relationship was also shown between variation in wind and CP_i. Periods with larger wind speed corresponded to periods with low CP_i, and the opposite. However, it is not unambiguous that high wind speed leads to small CP_i. The reason is that large negative CP_i to a great extent is influenced by the temperature conditions in the air cavity. Yet, Figure 4 shows that the positive peaks of the CP_i decreased when the wind speed increased, and the opposite. It was also found that the wind speed was very low, i.e. below 1m/s, during most of time when the CP_i was positive. This implies that wind speed is of importance for the condensation situation in the air cavity. Gullbrekken (2018) showed that most weather stations in Norway had a daily average wind speed larger than 1m/s more than 250 days of the year. This indicates good conditions for ventilation of roofs. However, this paper found that when looking at data with a one-minute measuring interval, the studied periods had wind speeds less than 1m/s during 27-75% of the time. Accordingly, in cases with condensation risk it is important to study the local climate conditions in order to make sure ventilation of the air cavity is satisfactory.

A strong correlation between wind speed and air velocity in the ventilated air gap was found by Gullbrekken et al. (2017) for the spring, summer and autumn periods studied. This show how high wind speed may induce good ventilation of the roof. Even though good ventilation of the air cavity is supposed to avoid condensation (Bøhlerengen, 2007), this study found that the risk of condensation was not eliminated. However, a very close relationship between undercooling and CP_i was seen. Undercooling may cause large changes in the partial vapor pressure in the air close to the rear side of the roofing, hence increasing the CP_i. If the undercooling is very strong, i.e. the temperature differences are large, the outside air may become a humidity source and increase the moisture at the rear side of the roofing in a ventilated roof. Ideally, the ventilation should be closed in periods with below-ambient temperature in the air cavity in order to avoid moistening of the cavity.

5.4. Consequences of condensation

The periods with below-ambient temperature in the air cavity were longer than the periods with positive CP_i. This implies that the OSB at the rear side of the roofing was absorbing moisture due to its hygroscopic properties, hence regulating the humidity content of the air in the cavity. Accordingly, there is low risk of visible condensate on the rear side of the roofing and hence low risk of condensate dripping onto the roof underlay. Due to the large negative peaks in CP_i, especially at the south side of the roof, the surface will experience dry-out. Consequently, there is little concern that moisture absorbed will lead to damages in the OSB. With other roofing materials, the risk of condensation and following consequences may be larger. Hens et al. (2002) found that the CP_i in a flat metallic roof with ventilated cavity was positive 47% of the time at the rear side of the roofing. The study also measured that timber laths and rafters in the roof absorbed moisture.

Equations (1a) and (1b) were used to calculate the saturation pressures in the studied air cavities. As the equations are empirical, other results than those found in this study may be obtained if using equations from other references. In addition, the CP_i can only be utilised to evaluate the risk of condensation on a given surface. To be able to evaluate the amount of condensate, the integral of all positive CP_i with time must be considered. This is not studied in this paper and could be done in further research.

6. Conclusions

The study of the roof on the ZEB Test Cell Laboratory shows distinct periods with below-ambient temperature in the ventilated air cavity. Large differences between seasons are found. Positive CP_i is measured during long periods, especially in spring, autumn and winter without snow. Large proportions of the periods with positive CP_i have wind speeds less than 1m/s. The periods with below-ambient temperature in the air cavity are larger than the periods with positive CP_i. This implies that the materials in the roof absorb moisture and regulate the humidity in the air cavity. However, large negative peaks in CP_i indicate dry-out of the construction.

7. Acknowledgements

To be added in the final version.

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