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Study of ventilated low-slope and large span wooden element roofs in the current and future climate

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Abstract. Finland's building regulations and guidelines rely on ventilation to ensure the hygrothermal performance of structures. For wooden roofs, height of ventilation cavity and area of ventilation openings have been determined depending on roof slope and roof area in guideline. This causes difficulties in practical implementation in low-slope roofs with large span, because the guideline leads to large ventilation openings that can be challenging to be implemented. In practice, roof element suppliers have produced roofs with slightly smaller height of ventilation cavities and areas of ventilation openings. This study examined the hygrothermal behavior of the ventilated wooden roof, where the role of airtightness of vapor barrier and ventilation rate were investigated. The ventilation rates of the simulation model were set based on the results of long-term continuous measurement. First, to ensure the applicability of used model, the mold index calculated from measurements was compared to simulated with the design weather data. Next, hygrothermal behavior was evaluated based on mold index using the design climate data (current and future) for airtight and 'loose' structure with various ventilation rates. Results shows that focusing on airtightness is important. However, the larger ventilation rate has an unfavorable effect on mold index which is emphasized in future climate. Thus, revision of the design guidelines is proposed to restrict the ventilation openings and unnecessarily effective ventilation. In addition, air tightness guidelines should be set more precisely from the perspective of moisture safety.

1. Introduction

Examining the hygrothermal performance of structures with ventilated cavities is a complex problem at the theoretical level. Climate models have been developed to describe temperature, humidity and the radiation factors in building physic design years [1], so that hourly based simulation can be conducted. In practice, the simulation is simplified to a one-dimensional (1D) analysis and utilize a constant ventilation rate, because simulating the ventilation flow in the structure in two- or three-dimensional (2D/3D) is too laborious and the results are uncertain, often to unknown extent. When considering the structure itself, assumptions about airtightness and the possible wetting effect of an air leakage due to the overpressure is required. Thus, varied results are obtained in the sensitivity analysis of the studied structure, and based on the results, it has to be stated that the structure works under certain assumptions, which can be challenging to verify in practice. Furthermore, one has to consider whether the simulation has been able to assess the structure's hygrothermal performance sufficiently.

There has been some interest in studying the hygrothermal performance of ventilated structures in the Nordic countries. Ingebretsen et al. presented a review of the recent studies of the ventilated roof and façade systems in Nordic climate [2]. The review states that several different factors have a great influence on ventilation ranging from the details of a structure to climatic factors such as temperature and wind speed. The studies presented suggest recommended theoretical values for air change rate (ACH [1/h]) for the considered situations such as 20 1/h [3] and values applied in simulation for similar structures such as 30 1/h [4]. However, values presented in these studies cannot be directly applied for the evaluation of the ACH of the ventilation gap in studied large span roofs.

Finland's building regulations and guidelines rely on ventilation in the moisture safety of the roof structures. Especially for wooden roofs, the required height of the ventilation cavity and the areas of the ventilation openings have been determined precisely, depending on the roof slope and the roof area. The first guidelines for heat and moisture insulation of structures were given by Association of Civil Engineers RIL in 1948. Later, the primary guidebook - the RIL107 [5] *Guidelines for waterproofing and moisture insulation of buildings* (first edition in 1976) has been updated regularly. In the early stages only simple calculation instructions and principles for achieving a suitable hygrothermal performance were presented. In the edition of RIL107-1989, a guideline table corresponding to the current form was included with slightly different design values. The sources for the values are not presented in RIL107-1989, but Mikko Vahanen, who was the chairman of the committee for RIL107-1989, published the corresponding values in a self-published instruction booklet in 1985 and marked the sources as DIN 4108 and German flat roof guideline (Flachdachrichtlinie). Some minor changes to the original design values were introduced in editions 2000 and 2012. The values in the 2012 edition remain still in the current RIL107-2022. Table 1 shows the design values proposed in RIL107-1981 and RIL107-2022. Although the design values of the guidelines have been imported from Central Europe without a detailed study of its applicability, the guidelines still emphasize the experience-based idea of the importance of ventilation. FRAME [6] report in 2013 shows that a low ventilation rate of a roof (0.5-1 1/h) is advantageous in terms of hygrothermal performance, based on the current and future climate at that time. Nevertheless, the report recommends that ventilation rate should not be limited, because the simulation does not include moisture sources that occur in real structures, such as moisture during construction, air leaks from the interior or rain leaks that require the 'adequate' ventilation.

In terms of the hygrothermal performance of ventilated structures, the airtightness of the vapor barrier has been identified as a significant factor, as Viljanen has summarized [3]. This is taken into account in the Finnish guidelines [5], stating that maximum air infiltration must be less than 4 (q_{50} [$m^3/(m^2h)$]) and the recommendation is 1. It can be concluded that the 'normal' q_{50} ranges from 1 to 4.

In Finnish requirements, it is stated that if the structure does not comply with the guidelines, a hygrothermal performance must be demonstrated. However, current requirements do not specify any methods that should be used [7]. The previous guidelines required a statement based on simulation or experimental tests of the hygrothermal performance [8]. In the recent guidelines, it is mentioned that there should be a study carried out by a research institute [5]. Regard to microbes, indications of damage are considered to be exceeding the action level, when the damage is on internal surfaces or in internal structures, or in other premises and structures from which the people inside may be exposed to the released pollutants [9]. However, in Finland there is still debate about what the criteria limits concerning for example the cold attics. Consequently, the criterion for the calculated mold growth index (MGI) allowed in the ventilation cavity of the roof is somewhat unclear.

Table 1. Design guidelines for ventilated roof cavities [5].

Slope		Minimum cavity height [mm]		Inlet opening [‰] from roof area		Outlet opening [‰] from roof area	
1989	2022	1989	2022 [a]	1989	2022	1989	2022
≤ 1:20	≤ 1:40	200	300	5.0	2.5	5.0	2.5
1:20-1:3	1:40-1:10	100	200	2.0	2.5	2.5	2.5
≥ 1:3	≥ 1:10	50	100	2.0	2.0	2.5	2.0

[a] Minimum ventilation gap, taking into account thermal insulation deformations and work tolerances. On small roofs or parts of the roof, the ventilation gap can be smaller than the value in the table, if the inlet and outlet openings have a sufficient height difference (at least 500 mm) and the air flow distance in the ventilation gap is short (less than 3 m). Even then, the ventilation gap must be at least 50 mm on steep roofs (≥ 1:20), and at least 100 mm on slope ≤ 1:20.

This study investigates the hygrothermal performance of the low-slope with large span wooden element roof structure in two case buildings, in which the ventilation cavity and openings are clearly below the required values. Role of airtightness of vapor barrier and ventilation rate are studied to evaluate the current design guidelines. The study utilizes the results of experimental measurements and simulation. These experimental results are used to ensure the suitability of the simulation model, and to visually assess the condition of the structures. Finally, the hygrothermal performance is investigated based on the mold index using the current and future design climate data.

2. Material and methods

2.1. Investigated structure and measuring points

Case buildings were built 3-4 years ago. Schematic drawings of the roof plan, the section and the eaves details of the investigated buildings are presented in figure 1. Slope of the roof in both cases (a) and (b) is 1:40. Buildings are located in (a) Southern and (b) Southeastern Finland respectively. Ventilation is assumed from lower to upper eaves due to temperature difference [5]. Prevailing wind direction is south in both cases, however the prevailing wind direction (W) is in case (a) towards the main facade with upper eaves and in case (b) towards lower eaves.

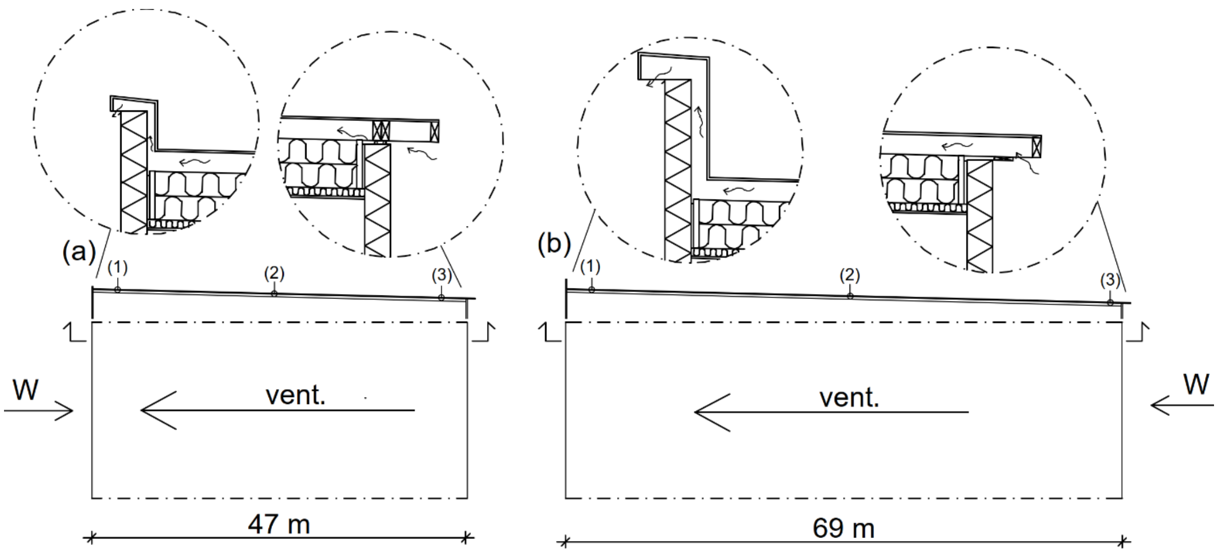

Figure 1. Schematic plan drawings of the investigated roofs (case a and b) and the sections showing measuring points (MP) 1-3. Vent. represents the assumed ventilation direction based on the slope.

According to guidelines, the minimum ventilation cavity height is 300 mm and inlet/outlet opening area 2.5 ‰ from roof area. In both cases, the guided values are not achieved. The cavity height of the structure is only 120 mm for both cases. In case (a) roof area is around 2735 m^2 and ventilation gap at lower and upper eaves 18 mm and 48 mm thus openings at lower and upper eaves are 0.4 ‰ and 1.0 ‰ from roof area (gap length ~ 60 m). Limited ventilation gap at lower eaves is due the fire regulations; Securo FB 36 mm fire break has been utilized. Conventional fiberglass insect nets (# 2 mm) on other eaves are used. In case (b) roof area is around 19222 m^2 and ventilation gap at lower and upper eaves 120 mm and 100 mm thus openings at lower and upper eaves are 1.7 ‰ and 1.5 ‰ from roof area (gap length ~ 280 m). Eaves are at height around (a) 6 to 7 and (b) 7 to 10 meters.

2.2. Experimental measurements

Measurements for T and RH was conducted using Vaisala's HUMIGAP HMP110 probes and Delta Ohm HD4V3TS2 Active Hotwire air speed transmitter (range 0.1…5.00 m/s). Devices were combined with

Mira's wireless DLS system. Instruments were installed into the ventilation cavity through the side of the beam of the adjacent cavity as presented in figure 2.

Outdoor T and RH were measured near the lower eaves of the case buildings. Also, the open weather data (T, RH and wind (w), later Ext. referring to external source of data) from weather station near the case buildings from [10] was utilized in the analysis. A visual inspection was performed during the installation of the measuring devices, and no indication of moisture damage was found.

Figure 2. Installation of the measuring devices and overview of the air cavity.

2.3. Simulation model

WUFI PRO 6 was applied for simulation, in which the heat and moisture transport processes are described by the coupled differential equations (1) and (2) [11].

$$\frac{\partial H}{\partial T}\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + h_v\frac{\partial}{\partial x}\left(\frac{\delta}{\mu}\frac{\partial p}{\partial x}\right) \tag{1}$$

$$\rho_w\frac{\partial u}{\partial \phi}\frac{\partial \phi}{\partial t} = \frac{\partial}{\partial x}\left(\rho_w D_w\frac{\partial u}{\partial \phi}\frac{\partial \phi}{\partial t}\right) + \frac{\partial}{\partial x}\left(\frac{\delta}{\mu}\frac{\partial p}{\partial x}\right) \tag{2}$$

where H is enthalpy of moist building material [J/m^3], T temperature [K], λ thermal conductivity [W/mK], h_v evaporation enthalpy of water [J/kg], δ water vapor diffusion coefficient in air [kg/(msPa)], μ vapor diffusion resistance factor of dry material [-], ρ_w density of water [kg/m3], Cp specific heat [J/kgK], u water content [m^3/m^3], ϕ relative humidity [-], D_w liquid transport coefficient [m^2/s] and p water vapor partial pressure [Pa].

Structure layers and materials used for the simulation of the case buildings are shown in table 2, in which the properties of utilized materials are also listed. Material values are obtained from the WUFI database, except bituminous felt.

Table 2. Material layers and hygrothermal properties.

Layer	Material	Thickness [mm]	λ [W/(mK)]	ρ [kg/m^3]	c_p [J/kg]	μ [-]	DWS/DWW[a] [m^2/s]
1	Bituminous felt	2x3	0.23	1100	1000	50000	0
3	OSB3 board	18	0.105	595	1400	165	3e-10/3e-11
4	Ventilation cavity	120	0.723	1.3	1000	0.11	0
5	Mineral wool	330	0.037	30	840	1	0
6	Vapour barrier PE	0.2[b]	2.3	130	2300	40000	0
7	Mineral wool	48	0.037	30	840	1	0
8	Gypsum board	13	0.2	850	850	8.3	4.5e-6/1e-6

[a] DWS = D_w for suction and DWW = D_w for redistribution which are depended on the water content

[b] 1 mm in model

Design climate data for heat and moisture simulation in current (Jokioinen 2011) and future (Jokioinen RCP85-2080) climate [12] is applied as exterior boundary condition. Interior boundary conditions are set to 21 °C and relative humidity varies according to the humidity and temperature (Te) of the outdoor air, so that the moisture excess Δv is 5 g/m3 when Te ≤ 5 °C and 2 g/m3 when Te ≥ 15 °C (intermediate values are interpolated). The heat transfer coefficient inside and outside of the structure were 0.125 and 0.0588 [m2·K/W], respectively. In addition, the mode "Explicit Radiation Balance" was applied and pre-selected values for "Roofing, bituminous felt" was utilized. Ventilation cavity is modelled using Air Layer 120 mm; without additional moisture capacity from WUFI material database. Additional 1 mm thick layers are used in cavity boundaries using Air Layer 120 mm; with additional moisture capacity as a buffer material (no ventilation). Ventilation is modelled as a WUFI feature called "Air change source" [11], in which a long-term continuous measurements were used to assess the range of ventilation rates. The effect of air leakage was taken into account by utilizing moisture source term "Air Infiltration model IBP" in WUFI with stack height of 8 m and overpressure of 10 Pa for whole insulation layer (5). The sealing solutions for the joints of studied element roofs are highly developed. Thus, q_{50} of 1 or less are usually achieved in the buildings with considered roof element type. To ensure the applicability of the used model, the MGI calculated from measurements was compared to simulated with the design weather data. Also, the boundary conditions were compared based on the MGI. The mold growth index was estimated applying the Finnish mold growth model [13]. The analysis is based on MGI comparison because MGI combines T and RH into single comparable numerical value. Parameter for mold sensitivity class MSC1 (sensitive) was applied to ventilation cavity which corresponds to OSB in WUFI Mould Index VTT [14].

Differences between the current and the future climate was studied in the three years period for airtight (q_{50} of 1) and 'loose' (q_{50} of 4) structure with various ventilation rates from theoretical minimum 0.5 to 25.

3. Results and discussion

3.1. Experimental

The average results and estimated ACH of measuring period is presented in table 3. The velocity in case (a) is partially below the measurement range of the device, which slightly reduces reliability especially in MP 2. Flow measurement from all three points would also have be desired. However, the results show the effect of prevailing wind direction indicating increase in absolute humidity [g/m^3] (AH) in windward side. The ACH of case (b) is more effective and thus a greater effect on the temperature is observed at the lower eaves, while in case (a) the temperature of the ventilation gap is more uniform.

Table 3. Average results from measuring points.

Case: MP	v [m/s]	ACH[a, b] [1/h]	T [°C]	RH [%RH]	AH [g/m3]
a: 1	0.153	7.9-11.9	13.9	62	7,09
a: 2	0.08	4.1-6.2	14.3	54	6.44
a: 3	-	-	13.7	53	6.25
b: 1	0.43	14.6-21.9	13.7	63.6	6.95
b: 2	0.45	15.3-22.9	13.2	61.8	6.72
b: 3	-	-	11.4	68.5	7.13

[a] ACH = v[m/h]*ventilation cavity cross section area/ventilation cavity volume

[b] Measured v is concerned to be v_{max}. Depending on the flow intensity the average v_{avg} is somewhat lower. Lower limit is set based on fully developed laminar flow between two parallel plates $v_{avg} = 2/3*v_{max}$

Numerous factors from measurement data can be observed that affect the hygrothermal performance of the roof. As an example of the effect, the wind direction in the summertime is presented in figure 3. Arrow (1) shows the effect of the wind on temperature during sunny day; T decreases on the windward side. In case (a) the arrow (2) shows that the AH at MP3 follows exterior AH when the wind is towards to upper eaves, and at the same time the AH in MP1 is at lower level. This indicates that the part of the ACH in windward side can be assumed to be the 'pumping' effect of uneven air flow on eave, which, however, does not generate flow through the ventilation cavity. When the wind is towards to lower eave the AH in MP3 is at the same level or only slightly above MP1 and MP2, however below the exterior AH as shown with arrow (3). This demonstrates that the ACH is minimal, but the ventilation air flow passes through the cavity from lower to upper eave. Similar findings were discovered in case (b). However, the differences in AH between measuring points were found to be minor compering to case (a).

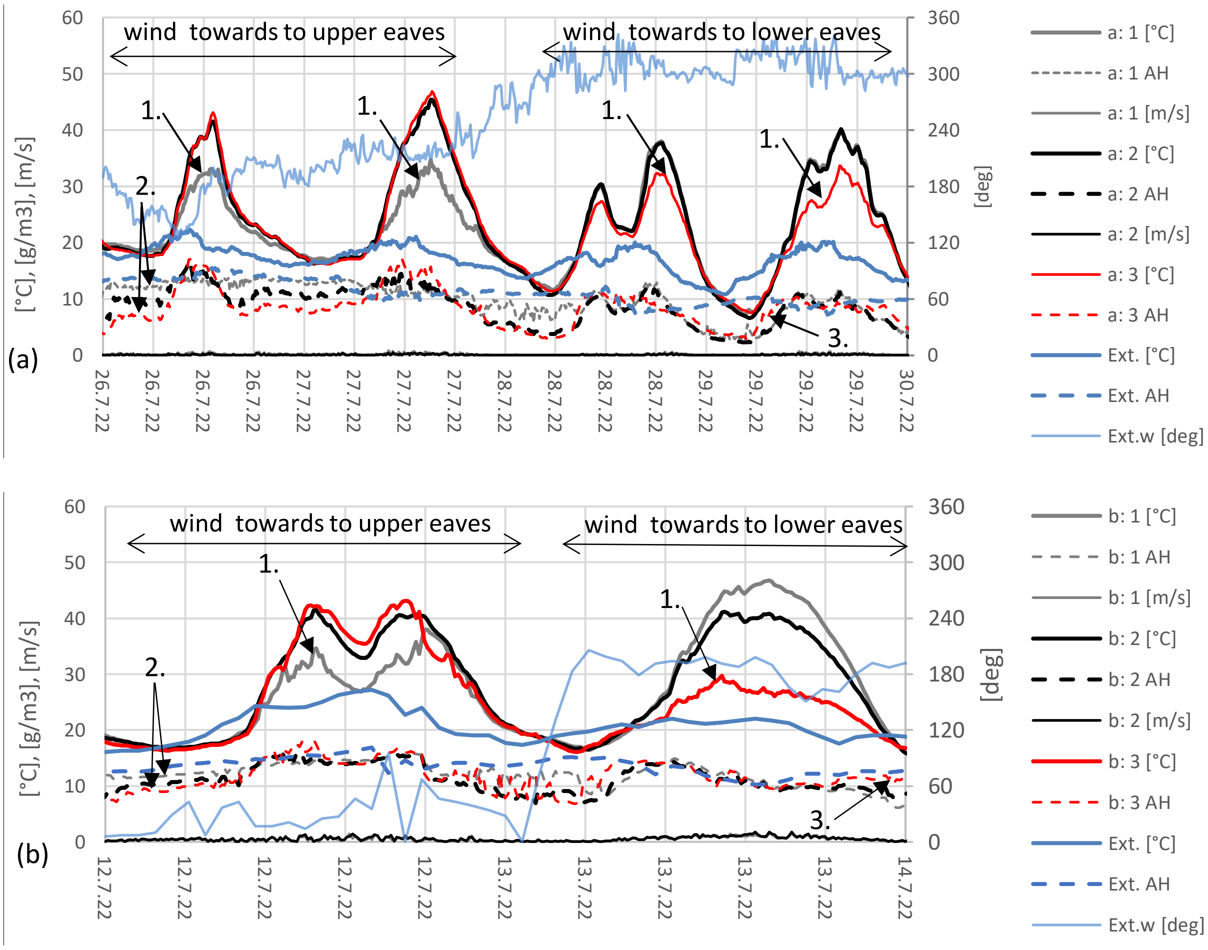

Figure 3. Results in case (a) and (b). a:1, a:2, a:3 and b:1, b:2, b:3 is referring to measurement points in the setup shown in figure 1. Ext. refers the data from weather station.

In addition, an interest finding from the results that is in relation to temperature variation was observed. Results shows the increasing effect of the daytime temperature rise on the air velocity. Moreover, the AH of the air in the ventilation cavity increases significantly due to temperature rise. On the other hand, the AH decreases below the outdoor air AH at night when the temperature decreases. These observed changes in AH clearly originate from the temperature dependence of the sorption of building materials; Increasing T in material causes moisture release into the ventilation cavity and, correspondingly, the cold material absorbs moisture. Considering the hygrothermal analysis, WUFI model does not take into account the temperature dependence of the sorption of materials. However, the temperature dependency of sorption of wooden materials is widely studied [15] and there are presented simulation models to investigate temperature dependence of sorption in structural level e.g. [16]. Therefore, taking temperature dependence into consideration in the simulations would be an interest for further studies.

3.2. Computational analyse

The applicability of used model is assessed in figure 4. Comparison of the MGI between continuous measurements and model are shown in figure 4 (a). In case (a), the measured ventilation rates correspond to the values ACH 5 and 10 and the MGI values for MP a:1 and a:2 correspond to the results of the model respectively. Regarding point a:3, the ventilation rate is unknown. Since the potentials causing the ventilation air flow the temperature difference and the wind are affecting to opposite directions, the ventilation is assumed to be 'pumping' and highly dependent on the wind. In this case the effect of the wind increases the ACH at the upper eave and decreases at the lower eave. Based on the measurements and assumption of the ventilation behavior, it can be estimated that the ACH is slightly lower in MP a:3 than in MP a:1 and a:2. Referring to this assumption, lowest MGI in MP a:3 is consistent. Case b represents almost an ideal implementation of the building and the ventilated roof, such that the temperature difference and the wind are affecting to same direction. Therefore, the ventilation rate is higher and consistent between MP b:1 and b:2. The measured ventilation rates of case b correspond to the value ACH 20. Air velocity was not measured in the windward eave in MP b:3, but ACH is assumed being at least same as in MP b:1 and b:2. The AH difference in measuring points is minor. However, the ventilation causes decrease in temperature near the lower eave and therefore causes higher MGI in MP b:3. Figure 4 (b) presents the comparison of the boundary conditions which shows that the measured conditions are slightly less challenging than the design climate.

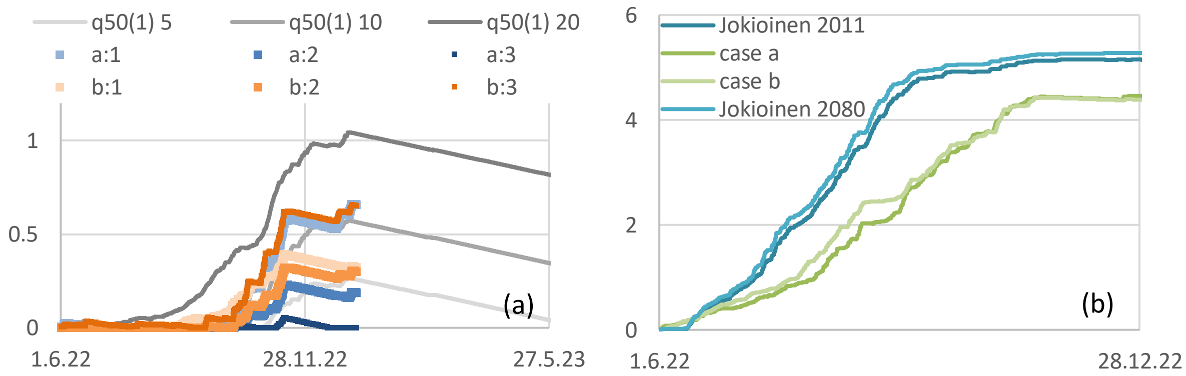

Figure 4. (a) MGI in ventilation cavity based on experimental (points, referring to figure 1) and based on simulation (lines) in which q50 refers to q_{50} and number in brackets to the rate and second number to ventilation rate [1/h]. (b) Calculated MGI based on design climate / weather data (exterior air).

It can be concluded that in case (b) when the structure is well and consistent ventilated the result of the model is slightly more critical than the experimental results. On the other hand, in the case (a) with lower ACH, especially near the eaves on the windward side, the situation can be more critical in practice. Nevertheless, the MGI results corresponds in magnitude to visual observation that no mold was detected in the inspection, as MGI < 3 indicates mold growth visible only under a microscope [13]. Thus, the simulation model with design climate boundary conditions gives a promising estimate of the hygrothermal performance of the structure.

In the analysis of hygrothermal performance of the structure in current and future climate, the effect of airtightness and ventilation rate was studied. Results in the current climate condition are shown in figure 5, which indicates that higher ventilation rate and more 'loose' case produce increase in the MGI. The preferred situation is obtained with $q_{50} = 4$ if ACH is 5 and with $q_{50} = 1$ if ACH ranges from 0.5 to 10.

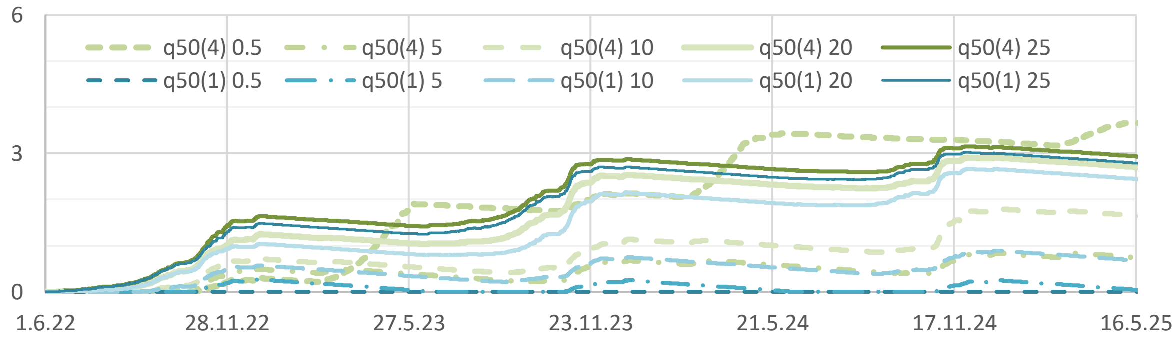

Figure 5. MGI with different q_{50} (1 and 4) and ventilation rates (0.5 to 25).

Figure 6 shows the results in the future climate condition. The results are more radical and show that, according to the utilized scenario, the structure must be airtight, and no significant ventilation should be allowed. The optimal solution would be an airtight structure with $q_{50} \leq 1$ and a very limited theoretical ACH of 0.5 1/h.

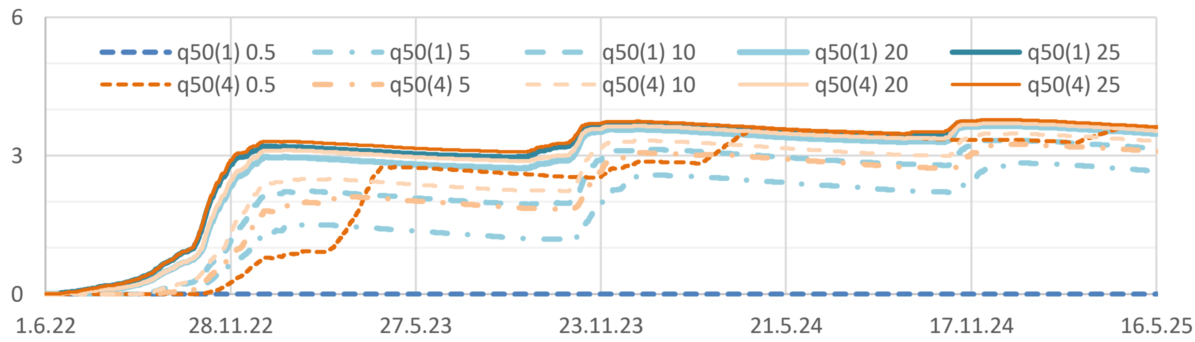

Figure 6. MGI in future climate. MGI with different q_{50} (1 and 4) and ventilation rates (0.5 to 25).

Examining the MGI is a straightforward method to evaluate hygrothermal performance of structures. However, acceptable limit of the MGI is still uncertain in the long-term analysis. Thus, setting the criterion for MGI as low as < 1 that [6] suggests may be too critical for ventilated roof cavities, when the fact that the cavity is connected to the outside air but outside of the air barrier is taken into account. MGI results using the design climate data was in the range of 0.5-3, when corresponding values of the investigated cases were utilized ($q_{50} = 1$ and ACH = 5-20). In our opinion, the MGI criterion that should be aimed for in design could be MGI < 3, so that the results at the end of the period is no longer increasing. However, this puts the recommendation of conducting hygrothermal behavior by using the future climate conditions [1] in a difficult question, because our results for the MGI in future climate were mainly around 3-4 and still rising ($q_{50} = 1$ and ACH = 0.5 as an exception). This finding suggest that only very minor ACH is acceptable in future climate.

Measurements show that the ventilation rate in the cavity might vary especially if openings are restricted. Thus, the effect of different ACH can be studied as a computational sensitivity analysis if measured values are not available. However, estimating the magnitude of the ACH can be difficult, thus measurements are recommended, though measuring the ACH can be challenging for several roof types. In these cases, the field investigations including T/RH measurements might be more reliable for ensuring hygrothermal performance, compared to a computational analysis.

With the examined roof type, sufficient ventilation was achieved in terms of hygrothermal performance, even though the ventilation openings were significantly smaller than in the guidelines. The MGI results also indicates that ventilation gap could be beneficial to constrict on the windward side.

4. Conclusions

The hygrothermal performance of the low-slope with large span wooden element roof structure were studied. The current design guidelines for airtightness and ventilation were evaluated based on experimental and computational study.

The Finnish design guidelines for roof ventilation have so far mostly emphasized the need for vigorous ventilation, regardless of the fact that the roof absorbs moisture from ventilation air in certain seasons. The results of the computational study show that the higher ventilation rate has an unfavorable effect on the mold index which is emphasized in future climate, and focusing on airtightness is important for ensuring the hygrothermal performance. Thus, revision of the design guidelines is proposed to rather restrict the ventilation openings and unnecessarily effective ventilation. In addition, air tightness required in the design guidelines should be set more precisely considering the moisture safety.

The results show that the examined roof elements can be built with significantly smaller ventilation gaps and ventilation cavity height than those required in guidelines, however, what are the more adequate design values of the ventilation gaps and cavities are worth further study. Experimental results show that the practical challenge is the site-specific microclimate differences, which are affected by the prevailing wind directions, as well as the shape and size of the ventilation gaps. Thus, it is necessary to conduct further field studies for assisting the revision of guidelines, in which the effect of these parameters on actual ventilation rate should be examined, in addition to the temperature and relative humidity in air cavity.

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