Research paper

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Analysis of Hygrothermal Performance of Low-energy House in Nordic Climate

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Abstract

Analyses of hygrothermal conditions in low-energy houses is important because of their likely sensitivity for excessive moisture. The presented work deals with real-time measurement of temperature and relative humidity at multiple locations inside a low-energy house envelope. The measured data allows diagnosing approaches towards building design and understanding and evaluating the house performance. Suitability and accuracy of numerical computation was analysed. The Finnish mould growth model was used to monitor risk and extent of mould growth under measured and computed conditions. The measured conditions represent more favourable environment to avoid mould growth than the design values recommended by national and international guidelines. There was no mould growth indicated at any monitored points of the envelope. Monitoring the hygrothermal conditions provides valuable information about the performance of structural elements, building material and the house envelope and it helps to predict moisture related risks during the building's service life.

Keywords

Hygrothermal analysis, measurement, numerical simulation, mould risk, low-energy design

Acknowledgement

This work was achieved within the Increasing Energy Efficiency in Buildings (IEEB) project supported by the European Union Interreg 4A Nord programme.

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We are grateful for support for this project through funding from the European Union Interreg 4A Nord programme (Increasing Energy Efficiency in Buildings (IEEB)) and from the Academy of Finland (Climate Change and Health (CLIHE) project 329885, awarded to Filip Fedorik).

Introduction

Residential and commercial buildings consume about 40% of EU's energy consumption and produce some 36% of EU's CO_2 emissions (Directive (EU) 2018/844, 2018). Design of low-energy buildings is a key element to create a sustainable society. Building energy demands bring changes in house design that can influence the indoor environment and overall building performance. The concept of energy efficient buildings incorporates, for example, suitable architectural and building technology design and use of passive energy sources, and requires careful and functional design from the early stages of the design and during construction. Current international codes (ISO 6946, 2017 and ISO 10211) and Finnish decree (FME, 2017) define the thermal properties of envelope assemblies. However, there is lack information about moisture performance associated with envelopes and how moisture changes during the service life of the structure.

A key design consideration with low-energy houses is their likely sensitivity for excessive moisture because a building with high thermal resistance requires thick layers of thermal insulation. Type and amount of thermal insulation material has a great impact on energy loss. Conductive heat losses in small houses represent significant part of the total energy loss. The lower the energy consumption target is set, the more important is the thermal insulation. However, depth of the envelopes has significant impact on current practices in terms of mass transfer. Hygrothermal performance of highly energy efficient buildings should be analysed to determine whether the design creates a damp risk and conditions suitable for biological growth. All layers must be chosen with respect to the others to provide a functioning building envelope (Radon et al., 2017). For instance, thermal resistance of a wind barrier and water vapour permeability of a vapour barrier have significant effect on moisture safety of highly insulated houses (Pihelo et al., 2016). Experts' knowledge and numerical simulations usually control the moisture safety inside structural elements during the design phase of a building (Boudreaux et al., 2018). Numerical simulations represent a cost-efficient approach to measure the hygrothermal performance of building components with high accuracy (Glass et al., 2015). Yet, numerical simulations require authentic material properties and actual and predicted boundary conditions, which might be difficult to obtain (Rouchier et al., 2016).

Besides analysis during the design phase, on-site continuous temperature and humidity measurement can provide real-time information about a building hygrothermal performance. Monitoring the hygrothermal conditions across the envelopes' assemblies allows evaluation of the wall system performance. Real-time measurement provides authentic information about hygrothermal performance because the moisture transfer mechanisms occurring on and inside the structure is complex and, in many cases, numerically unpredictable. The systems providing the main source of moisture inside the building envelopes are precipitation, condensation, vapour diffusion, built-in moisture, capillary uptake from ground and moisture carried by air leakages (Saber and Maref, 2019, Vinha et al, 2018, Vinha, 2012, Kalamees, 2007). Especially, the initial conditions considered in the design phase may significantly differ from conditions during the construction. For example, building materials often are stored at the site of construction and can be exposed to local climate for some period of time, potentially impacting the moisture content of installed elements (Mjörnell and Olsson, 2019). Therefore, providing good quality building work can avoid risks in the future and assure house performance as designed (Singhaputtangkul and Low, 2015). Measurement of the hygrothermal conditions during construction phase can allow elimination of potential faults during the building life cycle. Varying temperature and relative humidity in time influences material properties and there are expected changes in the properties during the building lifespan. Measuring hygrothermal conditions helps the future development for ageing of construction material (Riahinezhad et al., 2019) and building sustainability.

The aim of this study was to analyse the measured temperature and relative humidity inside low-energy timber-frame house envelope. The measurement and numerical simulation agreement was analysed to determine whether the actual design approach meets the requirements for moisture safety. The moisture safety is described by application of the Finnish mould growth model (Viitanen et al., 2008, Ojanen et al., 2011) that allows to monitor and identify the risk of mould growth. The study brings an overview for analyzing measured and simulated hygrothermal data in assessment of a house hygrothermal performance that meets commonly obtained data from highly insulated timber-framed detached houses in cold climates (Vinha et al., 2018).

Analysed house

Hygrothermal conditions and numerical simulations were made for a two-storey detached (single-family) house (Figure 1) located in Oulu (North Ostrobothnia, Finland). Oulu has a continental subarctic climate with long, cold winters with low humidity and short warm summers with high humidity. The house is a timber-frame house of net area 160m^2, air volume 480m^3 and ratio of building envelope to volume 0.8m^2/m^3. Thermal transmittance (U-value) of the envelope is

$0.110W/m^2K$. Windows' orientation is mainly southeast and northwest. The energy needs of a building are covered by household systems: this complex system includes all present energy consumers and sources, such as energy providing heating and cooling, heat transfer from inhabitants and household equipment, solar radiation, etc. However, the house energy consumption dependency can be reduced by the house own energy production. For instance, a significant part of energy consumption is a building's ventilation system. The energy consumption is reduced by a heat recovery which can be further decreased by pre-heating and pre-cooling of supply air. The energy needed for hot water can be covered by using renewable energy. The ventilation unit operating the building has annual heat recovery efficiency of 76.5%. The specific fan power (SFP) is 1.56 $kW/(m^3/s)$. The final inspection was provided at the end of 2012, shortly after measured data started to be recorded.

The total energy consumption of the house obtained by simulation is $112kWh/(m^2a)$. The Decree of the Ministry of the Environment from 2012 defined the E-value (calculated energy performance reference value) for detached houses of $150m^2<A_{net}<600m^2$ by $173-0.07 \cdot A_{net}$. Therefore, E-value=$161.8kWh_E/(m^2a)$. The current valid decree from 2017 (FME, 2017) defines the E-value limit by $200-0.6 \cdot A_{net.}$ Hence, E-value=104 $kWh_E/(m^2a)$. The annual heat demand was calculated using Passive House Planning Package (PHPP) and it is $64kWh/(m^2a)$. Thus, the house meets requirement for E-value from the 2012 decree, but it does not meet requirements for the 2017 decree nor passive house, which is $15kWh/(m^2a)$ (PHI, 2016).

Figure 1. Timber-frame single family house subjected to temperature and relative humidity measurement during construction.

Methodology

Monitoring system

Hygrothermal monitoring of the house's northeast envelope was achieved using 16 temperature (Dallas DS1820) and 16 relative humidity (HoneyWell HIH4021) sensors, analog-to-digital converter (ADC), mini PC, power supply and 3D router. Sensors were installed during construction (hence the structure was not disturbed to place the sensors), with wires connecting sensors and ADC installed along the monitored structural elements for approximately 40-50 cm to minimize effect of interstitial heat and moisture transfer through the envelope (Figure 2). The HoneyWell HIH4021 is a covered, condensation-resistant, integrated circuit humidity sensor that operates under a 4-5.8V voltage supply and has an accuracy of ±3.5% φ in range 0-100%. The Dallas DS1820 is a single-wire digital thermometer with accuracy ±0.5^{0}C between -10 and +85^{0}C.

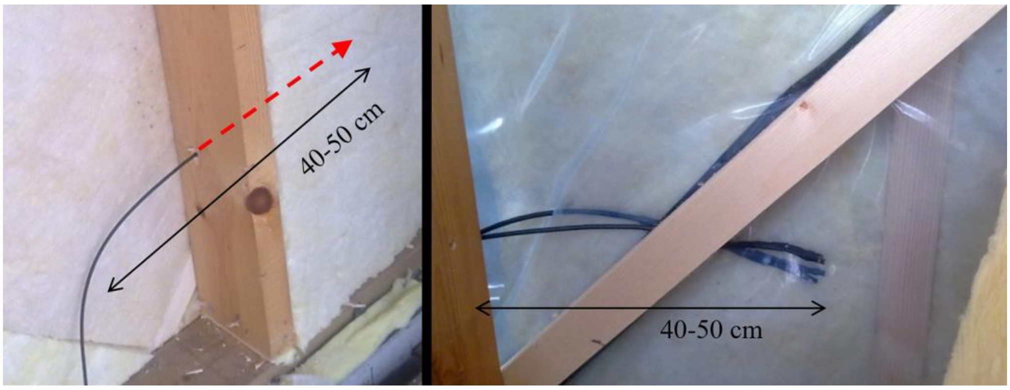

Figure 2. Temperature and relative humidity sensors/installation inside envelope.

The temperature data are transferred straight to digital output and the analog relative humidity data are converted with the DS2438 AD-converter. The θ and φ sensors are joined together for simpler installation, improving durability while construction and more precise location of both measurements (Figure 3).

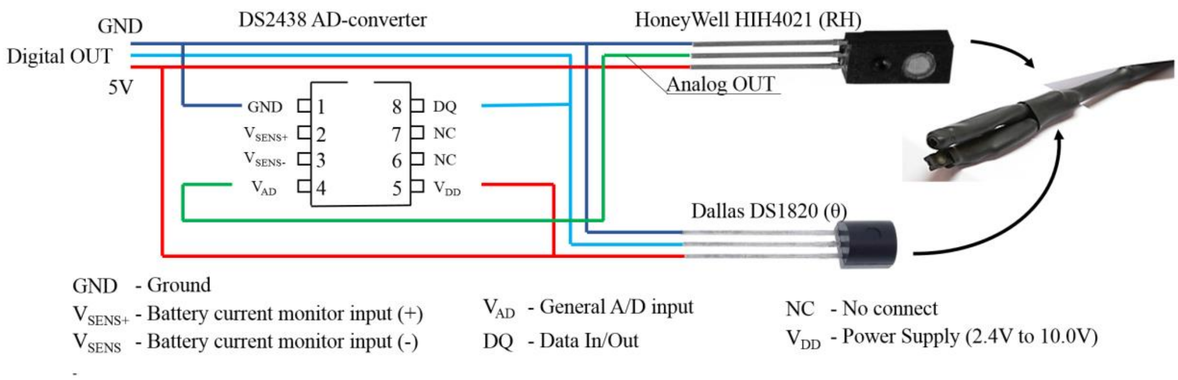

Figure 3. Schema of measurement system - thermometer Dallas DS1820, analog humidity sensor HoneyWell HIH4021 and analog-to-digital converter DS2438.

Measured data

The locations of sensors must be chosen carefully to achieve planned goals. More important is to measure surface temperature and space air moisture content than wood moisture content because they allow to understand the building assembly hygrothermal conditions. The study combines temperature and relative humidity measurement from which the absolute water content can be calculated (Straube et al., 2002). Temperature and relative humidity inside the building envelope was recorded from

1.10.2012 to 31.7.2017 at 1 hour intervals (i.e. 42,336 time-steps) for 16 locations that span important details within an envelope (Figure 4).

The bottom of the building envelope is monitored by temperature and humidity sensors 6-10 that are located 300 mm above the floor level. The same placement of sensors (sensors 1-5) throughout the envelope is controlled at height of 2,000 mm. Then, the data provides reliable information about effect of natural convection in the ambient of indoor and outdoor surfaces on hygrothermal performance of the envelope. Besides the part of the envelope that could be mainly described by one-dimensional heat and mass transfer mechanism, the focus of hydrothermal measurements was the sill plate (points 11 and 12) and a building corner (points 14 and 15) (Figure 4). These represent locations of thermal bridge where excessive humidity without effect of any water damage inside the structure can occur and lead to higher damp risk (Brzyski et al., 2019). In particular, the bottom of a timber-frame envelope is of great importance because of its risk of damp, despite being protected by capillary barrier from the foundation. Then, the sensors 11 and 12 monitor temperature and relative humidity on top of external and internal corner of the sill plate (about 10 mm above the floor). Sensors 14 and 15 are installed on outdoor and indoor surface of a vapour retarder in the building corner where is the higher risk of condensation (Starakiewicz, et al., 2019), at a height of 1,500 mm above the floor.

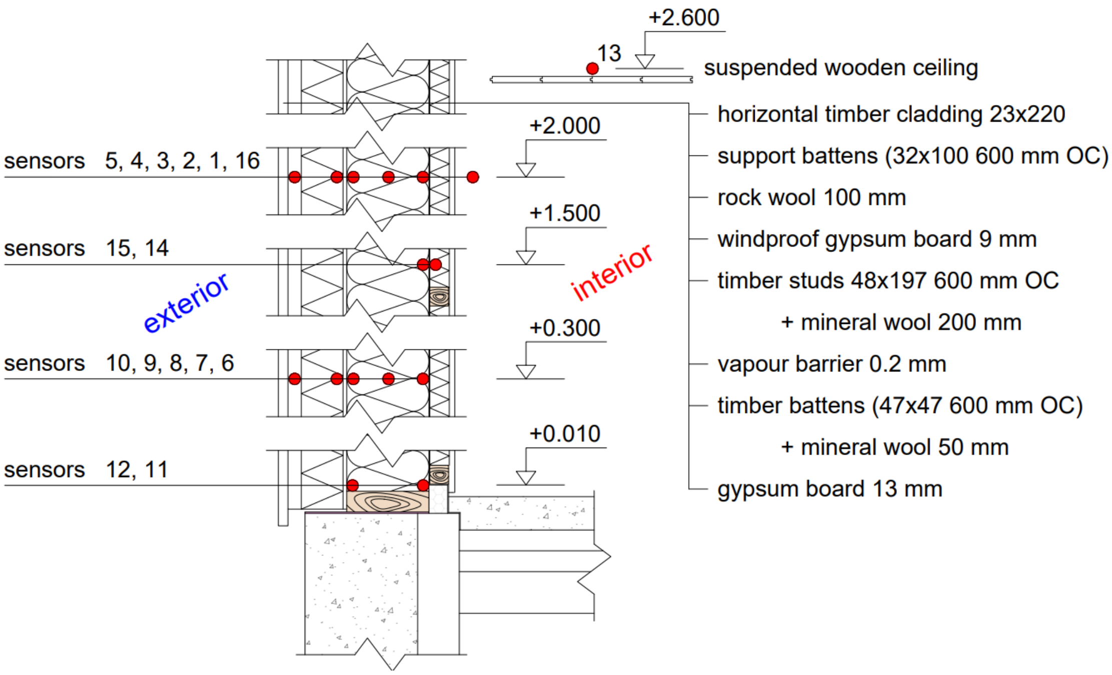

Figure 4. Assembly of envelope with illustration of the locations of the temperature and relative humidity sensors.

Numerical simulation

The calculation was provided by numerical tool Wufi®2D that allows hygrothermal simulation in one and two-dimensional environment inside building components. The simulation was performed for the period of measurement (1.10.2012-31.7.2017) initiated with conditions θ=20°C and φ=80% for each modelled component. Indoor boundary conditions represent temperature measured at point 13 and relative humidity from point 16 (Figure 4). The reason is that the data at point 14 is limited in the period from 1.3.2015 to 31.7.2017 because of late installation. However, during this period the temperature between the point 13 and 14 achieves average temperature difference 0.23°C. Therefore, it is assumed that the indoor temperature copies the trend of temperature inside the ceiling air space from 1.10.2012. The indoor relative humidity during the entire analysed period is assumed to be the same as the measured period indoors, although, the other measured data shows slightly decreasing tendency. Hence, the relative humidity data is fitted to corresponding date since 1.10.2012. The external boundary conditions are described by measurement inside the outdoor air gap (sensor 10) (Figure 4). Therefore, the conditions inside the outdoor air gap are protected from the solar radiation and driving rain. The northeast orientation of the wall and short height of the building is assumed by the Wufi simulation. The heat transfer via building component is characterized by thermal conductivity λ, heat capacity Cp and density ρ of the material. The mass transfer depends on moisture storage function W, liquid transport coefficient DW and water vapour diffusion resistance factor μ. Where λ and DW depends on W and W and μ depends on φ. The composition of the model from outdoor is: rockwool, gypsum board, mineral wool, vapour retarder, mineral wool, and gypsum board; therefore, the external cladding is not considered. Temperature and relative humidity from points 9-6 (Figure 4) were validated. Thus, the simulation represents one-dimensional heat and mass transfer. Additionally, two-dimensional hygrothermal simulation was performed to monitor heat and moisture transfer through the sill plate. The material properties were obtained from manufacturers' catalogues and missing data were taken from the most matching material defined in Wufi®2D material library. (Table 1) (see in detail Appendix 1).

Table 1. Material properties used in numerical calculation.

Properties Material	ρ [kg/m^3]	C_p [J/kgK]	λ [W/mK]	DW [m^2/s]	μ [-]	W [kg/m^3]
Rockwool	120	850	0.034	0	1.3	0-258
Windproof gypsum board	800	850	0.194-0.214	0-1·10-6	8.0	0-400
Vapour retarder	83	1800	0.994-1.014	0	4000-140	0-110
Mineral wool	60	850	0.038-0.057	0	1.2	0-44.8
Gypsum board	625	850	0.194-0.214	0	8.3	0-400

Finnish mould growth model

During the last two decades, there have been developed models that allow to identify risk of microbial growth. The mould growth prediction can be evaluated by experimentally validated Finnish mould growth model (Viitanen et al., 2008, Ojanen et al., 2011), mould resistance design (MRD-model) model (Thelandersson and Isaksson, 2013) and the IBP-biohygrothermal model (Sedlbauer, 2002). Especially, the Finnish mould growth model has significant impact on current building physics design. For instance, ASHRAE 160-2016 (2016) suggests that the hygrothermal conditions should not exceed mould index 3. The model allows to identify the real performance of the buildings with good agreement between the predicted and observed mould growth (Jensen et al., 2019, Glass et al., 2017). The Finnish mould index was also applied in identifying microbial level with other models in probabilistic-based methodology for more systematic approach to evaluate wall construction (Gradeci et al., 2018).

A risk of mould on and in the building envelope was estimated using the Finnish mould growth model. The model evaluates the possibility and development of the mould growth principally based on suitable temperature and relative humidity. As a material sensitivity has an essential role in the Finnish mould growth model, four material sensitivity classes are defined, MSC1 – very sensitive, MSC2 – sensitive, MSC3 – medium resistant and MSC4 – resistant, which differ by favourable hygrothermal conditions for the mould growth and maximum achievable mould index. The speed of mould growth is also associated to speed of mould decline. Where MSC1 corresponds to HTL1 (strong decline), MSC2 to HTL2 (significant decline), MSC3 to HTL3 (relatively low decline) and MSC4 to HTL4 (almost no decline). The favourable temperature for mould growth is defined between 0 and 50 ^{0}C and the minimum relative humidity for the mould growth initiation is considered to be 80% for MSC1 and MSC2, and 85% for MSC3 and MSC4. The Finnish mould growth model is expressed by equation (1):

$$\frac{dM}{dt} = \frac{1}{168 \cdot \exp(-0.68 \ln \theta - 13.9 \ln \varphi + 0.14W - 0.33SQ + 66.02)} k_1 k_2 \qquad (1)$$

Where W is timber species, SQ surface quality (neglected for other materials than wood), t is the time, k_1 and k_2 are coefficients for growth. The mould index M describes amount of mould occurring on building material surface in the range 0-6 (M=0 for no mould to M=6 for mould covering full surface).

Results and discussion

Boundary conditions

The real-time measured boundary conditions at 1 hour intervals were evaluated monthly and annually. The annual data obtained in 2012, 2013 and 2017 are excluded because the 2012 consists of period from 1st October to 31st December and 2017 is from 1st January to 31st July only and the beginning of 2013 was influenced by finishing construction work and occupants' move in. Hence, these impacts would significantly influence the annual data and make them incomparable.

The air gap behind outdoor cladding is 32 mm thick, containing support battens (32x100mm) with opening between the air layer and exterior conditions exceeding 30,000 mm^2 per 1 m of length. Hence, the air gap is well-ventilated via natural convection (ISO 6946) and the outdoor conditions are assumed to correspond data at points 5 (2000 mm above floor) and 10 (300 mm above floor) (Figure 4) whose values are similar (average difference of 0.09^{0}C and 0.17%). There are factors that may influence the temperature difference and/or air exchange inside the air gap. For instance, depending on outdoor cladding paint treatment, the solar radiation may cause heating the outdoor layer leading to warm the air gap. The surrounding environment also may affect the convective heat transfer, with features such as trees, neighbourhood buildings, garage, etc., providing a potential wind barrier. However, the house's surrounding and outdoor cladding paint do not show any sign of significant influence on hygrothermal conditions inside the air gap. Hence, data obtained at point 5 were chosen for further analysis.

The outdoor conditions correspond to costal cold humid climate with mean humidity over 80%, in range of 14-100% and temperature between -30 and 31^{0}C (Figure 5a). Monthly average temperature is between -13 and 22^{0}C and relative humidity 40-100% (Figure 5b). The annual outdoor conditions slightly differ from each other. The temperature decreases and relative humidity increases from 2014 to 2016 (Table 2).

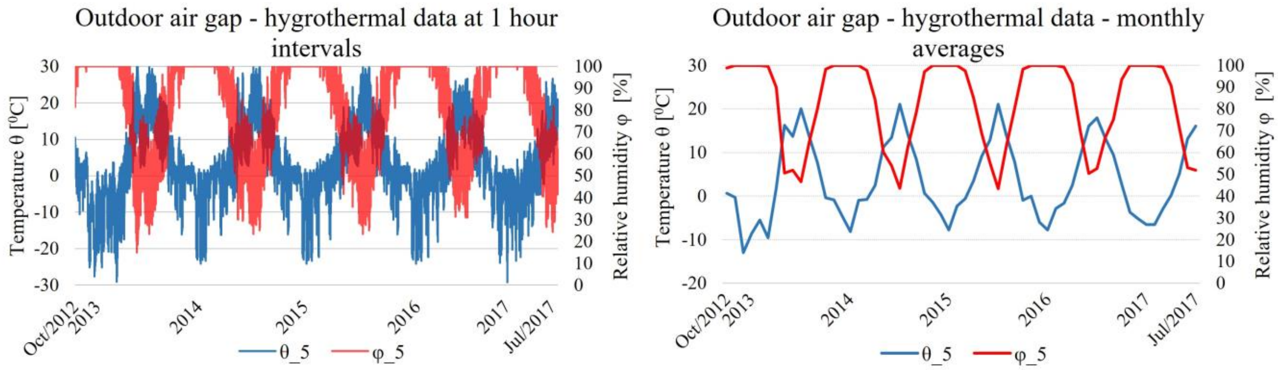

Figure 5. Temperature θ and relative humidity φ inside outdoor air gap (point 5) expressed by real-time data (a) and monthly averages (b).

The indoor conditions are overall stable during a year adapting to seasonal climate. The maximum temperatures are near 30^{0}C and minimum about 20^{0}C, and the relative humidity is between 20 and 50% (Figure 6a). If average monthly values are considered, the temperature achieves maximum 25.0^{0}C and minimum 21.7^{0}C. For average monthly values, the indoor humidity is in the range from 23 to 47% (Figure 6b). The annual indoor temperature follows the trend of outdoor conditions from 2014 to 2016 (Table 2).

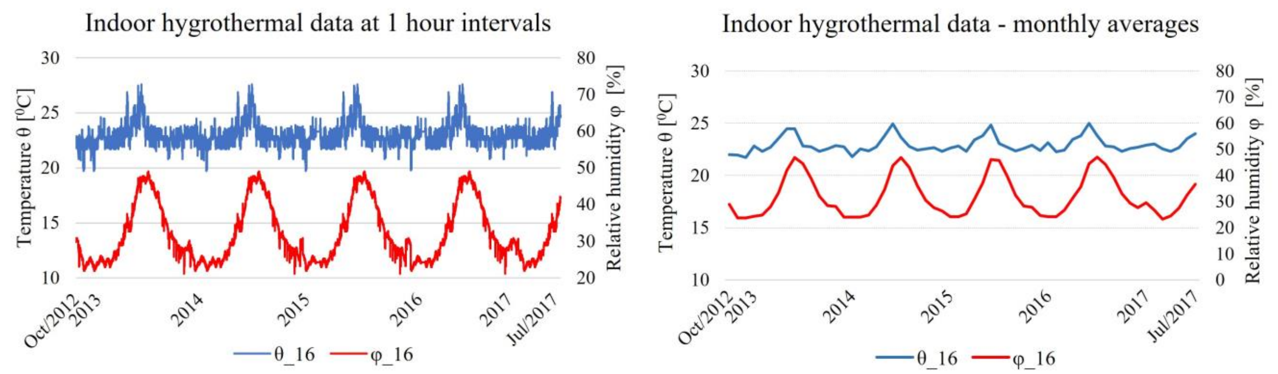

Figure 6. Indoor temperature θ and relative humidity φ (point 16) expressed by real-time data (a) and monthly averages (b).

Table 2. Annual extreme and average temperature and relative humidity indoor and inside outdoor air gap.

	Indoor (point 16)						Outdoor air gap (point 5)					
	θ_{avg} [^{0}C]	θ_{min} [^{0}C]	θ_{max} [^{0}C]	φ_{avg} [%]	φ_{min} [%]	φ_{max} [%]	θ_{avg} [^{0}C]	θ_{min} [^{0}C]	θ_{max} [^{0}C]	φ_{avg} [%]	φ_{min} [%]	φ_{max} [%]
2014	22.93	19.80	29.80	32.95	21.10	49.00	4.64	-24.10	29.90	81.50	23.30	100.00
2015	22.68	19.80	29.80	32.95	21.10	49.00	4.23	-24.10	29.90	82.59	23.30	100.00
2016	22.36	19.90	27.60	32.95	21.10	49.00	4.19	-23.90	26.70	83.20	30.80	100.00

Internal vapour pressure excess (Figure 7a) indicates that majority of the analysed period the moisture flow is directed from indoor out. About 13% of the total hours the moisture flow was directed from outdoor in (negative Δp) (Vinha, 2012). The weekly average moisture excess (Figure 7b) from the measured data indoor and in the outdoor air gap Δv= 1.34g/m^3 for $\theta \leq 5$°C and Δv = 1.18g/m^3 for $\theta > 5$°C. The indoor excess during the analysed agrees with previous studies resulted moisture excess in living rooms of lightweight detached houses 2.1g/m^3 for $\theta \leq 5$°C and 0.5g/m^3 for $\theta > 5$°C (Geving and Holmes, 2011), 1.9g/m^3 for $\theta \leq 5$°C and 0.5g/m^3 for $\theta > 5$°C (Vinha et al., 2018) and 1.7g/m^3 for $\theta \leq 5$°C and 0.4g/m^3 for $\theta > 5$°C (Kalamees et al., 2006).

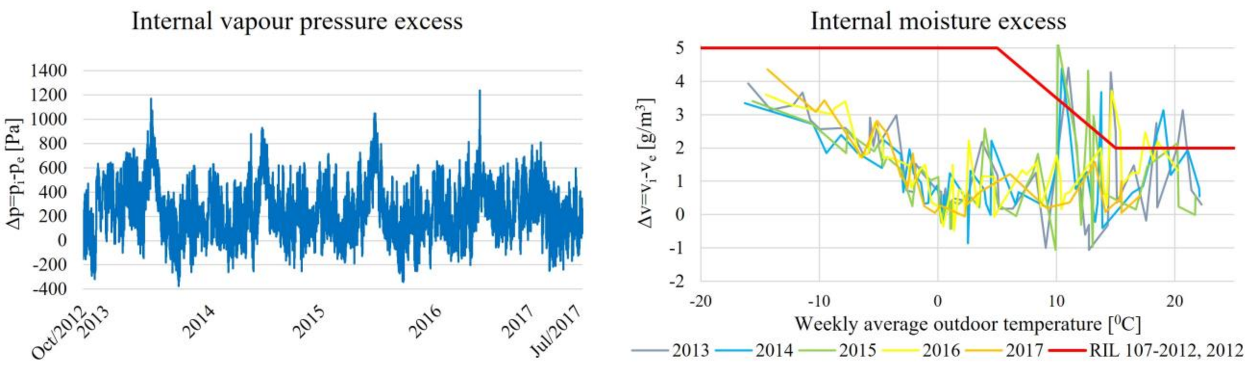

Figure 7. Internal water vapour pressure and moisture excess of measured data.

The thermal comfort of a building depends on combination of temperature and relative humidity. The comfort zones are usually defined for winter and summer separately. For instance, ISO 7730:1994 (2005) defines constant boundaries of comfort zone for winter 20-24^{0}C and 30-70%, and 23-26^{0}C and 30-70% in the summer. The ASHRAE 55-2004 (2004) specifies the indoor comfort conditions by non-constant linear relation between temperature and relative humidity in range of 19.5-24.5^{0}C and 23-86.5% in winter and 22.5-27^{0}C and 19.8-79.5% in summer. The measured indoor conditions mostly fit inside the boundaries of comfort zones defined either of the standards, except a few summer days where temperature exceeds 27°C. The relative humidity is on the lower level of the comfort zones which might possibly results a reduction in dust mite allergens and/or increase in virus survival and may lead to occupants' dry skin, eyes, and nose (Derby et al., 2017). However, no symptoms or discomfort notification has been announced by the occupants.

Mould growth risk

The mould index M evaluation does not show significant mould growth risk at monitored points inside the structure. A subtle mould index was obtained on outdoor top corner of sill plate (point 12). However, the value does not reach a value of mould index 1, and hence the risk of biological growth remains low. High mould index values were obtained inside the air gap separating envelope from outdoor cladding (points 5 and 10). The mould index M strongly depends on material sensitivity and therefore, it is important to treat sensitive building materials to be able to resist outdoor particles' contamination that would lead to mould growth. The hygrothermal conditions inside the outdoor air gap affects two materials: (1) the mineral wool that is considered resistant MSC3 and (2) wooden outdoor cladding. The outdoor cladding is usually untreated wood on the interior surface and thus it is very sensitive MSC1 for mould growth initiation. However, if the interior surface of the outdoor cladding would be planed the sensitive material MSC2 would be considered. Clearly, material sensitivity has significant impact on mould growth, with MSC1 material having a mould index M_{max}=5.99, whereas MSC2 has M_{max}=1.86 and MSC3 M_{max}=0.06 (Figure 8).

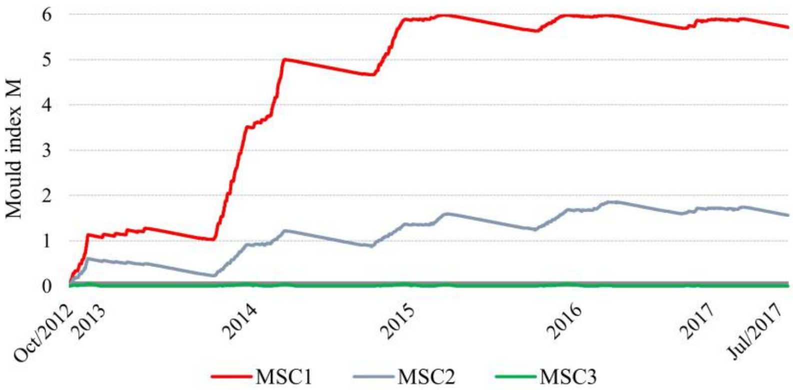

Figure 8. Mould index development inside air gap between envelope and outdoor cladding dependent on different material sensitivity.

Other measured points (1-4, 6-9, 11, 13-16) in the building do not show any sign of mould risk and favourable conditions for mould growth remain 0 (Table 3).

Table 3. Mould index and percentage of total hours in favourable and unfavourable conditions for mould growth.

Measured points	1-2	3-4	5	6-7	8-9	10	11	12	13-16
Material sensitivity	MSC3	MSC2	MSC1	MSC3	MSC2	MSC1	MSC1	MSC1	MSC3
Mould index M	0	0	5.99	0	0	5.99	0	0.50	0
Favourable conditions	0	0	22.13	0	0	23.07	0	8.46	0
Unfavourable conditions	100	100	77.87	100	100	76.93	100	91.54	100

The mould index provides a factor to monitor risk of mould growth, however, the design criteria may vary and significantly influence the obtained results. The presented study does not consider wind-driven rain, because the outdoor cladding is expected to provide barrier between the outdoor climate and outdoor well-ventilated air gap. However, wind-driven rain may significantly influence the mould growth (Gradeci and Berardi, 2019). Improving the accuracy and reliability of mould growth prediction can be achieved by integrating the concepts of target reliabilities (or probabilities of failure) by considering uncertain conditions that may appear and lead to significant impact on the building physics design (Gradeci et al., 2018). The accuracy derived from material sensitivity can be improved by experimental data of different materials, i.e. bamboo fiber (Berger, et al., 2018).

Effect of height on hygrothermal conditions inside building envelope

The data obtained from sensors 6-10 and 1-5 which are located 300 mm and 2000 mm above the floor show increasing difference towards indoor. The sensors' location is the same throughout the envelope. Fault temperature θ data (11^0C during the entire measured period) has been achieved on the interior surface of the main mineral wool insulation (point 1), however, no disruption in relative humidity φ data measurement has been found. A possible reason for misread temperature is disconnection or damage of wire connecting the temperature sensor during the construction, although no visible errors of the structure have been found at this location.

Natural convection provided by openings on the bottom and top of the outdoor cladding causes negligible differences in annual temperature and humidity data inside the outdoor air gap at different height (points 5 and 10). Note, that data in 2012 and 2017 includes only the measured period. The temperature increases upwards by 0.07-0.14^{0}C and relative humidity decreases by 0.06-0.48% (Table 4). However, for instance Vanpachtenbeke et al. (2020) presented importance of considering outdoor brick veneer cladding in the hygrothermal simulations because the height effect may significantly influence difference between simulated and measured hygrothermal conditions.

Table 4. Annual average temperature θ and relative humidity φ at points 6-10 and 1-5 (erroneous θ data at point 1 are illustrated strikethrough).

year	points	θ [^{0}C]	ϕ [%]	points	θ [^{0}C]	ϕ [%]	points	θ [^{0}C]	ϕ [%]	points	θ [^{0}C]	ϕ [%]	points	θ [^{0}C]	ϕ [%]
2012 *(1.10-31.12)*	5	-4.9	99.7	4	2.0	66.5	3	2.7	65.7	2	8.9	37.1	1	11.2	22.5
	10	-4.7	99.5	9	0.1	77.2	8	1.4	74.7	7	6.5	45.4	6	13.9	25.8
2013	5	4.4	79.9	4	9.8	51.6	3	10.3	48.6	2	15.2	30.8	1	11.0	20.0
	10	4.3	80.1	9	8.1	59.8	8	9.1	58.4	7	13.1	37.7	6	18.9	22.8
2014	5	5.5	78.8	4	10.6	50.3	3	11.1	47.7	2	15.8	31.2	1	11.0	20.7
	10	5.3	78.9	9	8.8	59.0	8	9.8	57.7	7	13.4	39.1	6	18.7	24.6
2015	5	3.7	83.0	4	9.2	52.3	3	9.7	49.4	2	14.7	31.2	1	11.0	20.0
	10	3.6	83.5	9	7.3	61.8	8	8.4	59.8	7	12.3	39.4	6	18.2	23.6
2016	5	3.0	86.3	4	8.5	54.9	3	9.0	51.7	2	14.2	32.7	1	11.0	20.7
	10	2.9	86.4	9	6.6	64.5	8	7.7	62.3	7	11.7	41.3	6	17.6	24.7
2017 *(1.1-31.7)*	5	3.2	82.9	4	7.9	56.9	3	8.7	52.5	2	13.7	33.2	1	11.0	20.8
	10	3.1	83.2	9	6.2	66.0	8	7.3	63.2	7	11.0	43.1	6	17.0	25.2

Points 4 and 9 located between rock-wool and gypsum board show increasing temperature and decreasing relative humidity upwards. The difference of the temperature is between 1.7-2^{0}C and relative humidity 8.3-10.5%. The conditions between gypsum board and mineral wool insulation (points 3 and 8) show higher temperature by 1.2-1.4^{0}C and lower humidity by 9-12% at higher positions. In the middle of the mineral wool insulation (points 2 and 7) higher temperature and lower humidity upwards are obtained by 2.1-2.8^{0}C and 6-10% separately. The sill plate is cooled especially by conduction led to and from a ground and effect of thermal bridge in the intersection of base floor, foundation, and envelope. The thermal bridge also impacts the higher humidity obtained in lower position inside the wall. However, except the air gap, the humidity does not exceed 80-85% during the measured period.

Building corner

Sensors 14 and 15 are installed on exterior and interior surface of vapour retarder (Figure 4) and monitor temperature and relative humidity in the corner of the building envelope. The thermal resistance of the vapour retarder is $3*10^{-4}$ (m^2K)/W, and hence the average temperature difference between the points is very small (0.019^0C). Lower humidity is obtained on the exterior of the vapour retarder, especially in cold seasons (Figure 9). The average difference between humidity on the interior and exterior surface of the vapour retarder is 2.44%, excluding the initial period since finalizing the construction in autumn 2012 till April 2013 when the drying process took place; during this time (about 6 months), the initial humidity decreases by 40% on the interior and 20% on the exterior surface of the vapour retarder. The measurement started by heating the house in October 2012, when the humidity was near 70%. The floor heating causes rapid drying of the concrete slab emitting large amount of humidity indoors (Figure 9) compared to common indoor moisture sources.

The progress of the annual relative humidity differences shows a potential to decrease (Table 5). The humidity difference increases with rapid change of the humidity indoor. The vapour retarder does not have significant impact on vapour diffusion through the building corner under monitored conditions. The reason is quite low indoor relative humidity leading to small difference between indoor and outdoor water vapour pressure that slows down vapour diffusion through the building envelope. The relative humidity is between 20 and 50% during the monitored period. Hence, the conditions represent unfavourable conditions for mould growth.

Table 5. Temperature and relative humidity differences between exterior and interior surface of vapour retarder (points 14 and 15) in the building corner.

	2012 *(1.10.-31.12)*	2013	2014	2015	2016	2017 *(1.1.-31.7.)*
θ (14-15)	-0.010	0.010	-0.001	-0.004	-0.048	-0.085
φ (14-15)	17.926	2.484	3.137	3.338	1.557	0.654

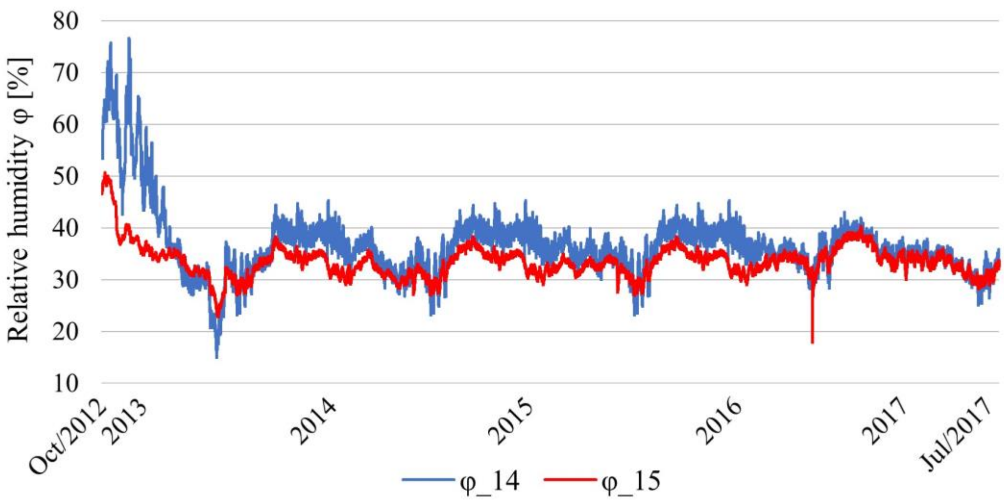

Figure 9. Hourly relative humidity φ on exterior and interior surface of vapour retarder in envelope's corner (points 14 and 15).

Outer surface of main thermal insulation

Exterior surface of the main 200mm thermal insulation layer was measured at three points located above one another: point 3 is at 2,000mm, point 8 is at 300 mm and point 12 is 10mm above floor level. The temperature at points 3 and 8 is positive for the entire measured period, except at the sill plate inside the intersection of mineral wool, sill plate and gypsum board (Figure 10a). The timber allows quicker thermal transfer via higher thermal conductivity than the thermal insulation. Higher heat flux might be also obtained through the material's contact (Figure 11). The intersection also causes significant difference in relative humidity between points 8 and 12 (Figure 10b) although their vertical separation is only 290 mm.

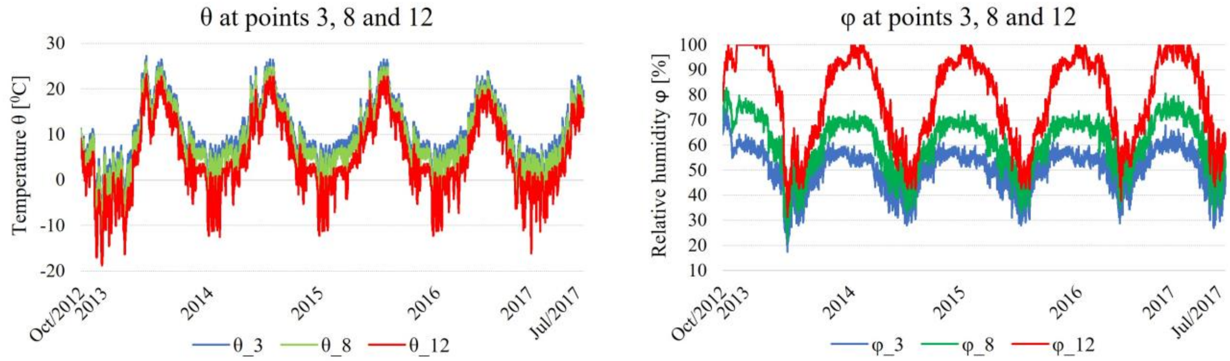

Figure 10. Temperature θ (a) and relative humidity φ (b) on exterior surface of 200 mm thermal insulation layer at different heights.

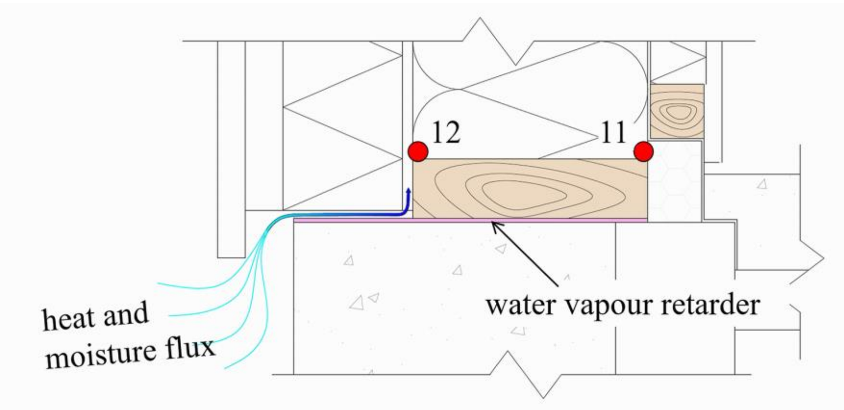

Figure 11. Sill plate with illustration of measured points and expression of heat and moisture flux causing humidity variation depending on exterior climate.

Inner surface of main thermal insulation

The interior surface of the mineral wool layer is monitored at four locations. Points 1 and 6 are in a flat wall (one-dimensional heat and mass transfer), point 15 is inside a corner and point 11 is on top interior corner of sill plate (two-dimensional heat and mass transfer) (Figure 4). Temperature at point 1 is not included. The thermal bridge in the floor-wall junction (point 11) can be seen in the temperature variation over the analysed period (Figure 12a). The ambient of the sill plate is also influenced by higher humidity, which in combination with the varying temperature may lead to higher risk of condensation and/or mould growth. However, the relative humidity does not vary significantly between seasons and it rarely exceeds 50% (Figure 12b). Low inter-season humidity variation was obtained inside the building corner. Because the relative humidity on the interior surface of the 200 mm thermal insulation layer is under 60% during the analysed period, the risk of mould growth is negligible.

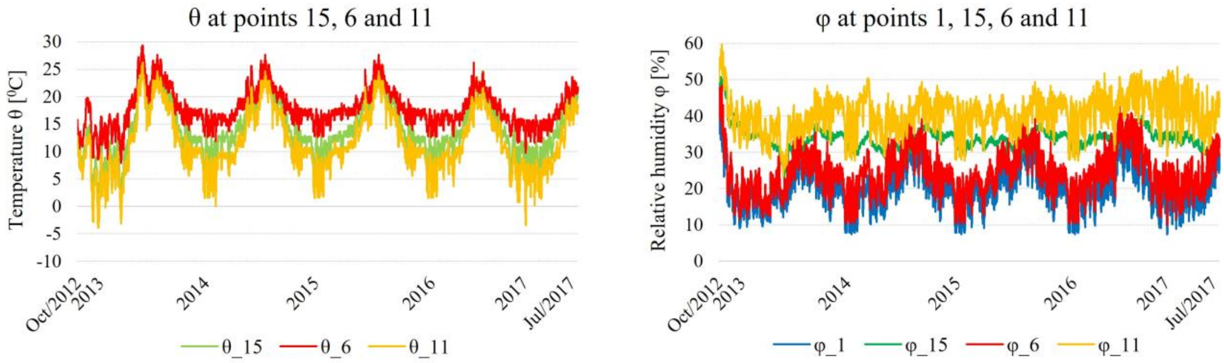

Figure 12. Temperature θ (a) and relative humidity φ (b) on interior surface of 200mm thermal insulation layer at points 1, 15, 6 and 11.

Sill plate

A timber located on top of the foundation is exposed to risk of high humidity and low temperature that may lead to mould growth and further deterioration of the material. The moisture risk mostly consists in capillary from foundation, rainwater trapped in ambient of the sill plate and timber's initial moisture content. Often, the sill plate is exposed to outdoor conditions (water, snow) for a some time during construction before it is covered with upper construction. Then, the timber may achieve full saturation causing a long drying process and vapour diffusion inside the structure after the construction completion. The rising capillary protection is usually provided by installing water vapour retarder on top of the concrete foundation (Figure 11). The temperature and relative humidity were monitored at top corners of the sill plate (points 11 and 12) (Figure 11). The temperature and relative humidity development copy similar trend each monitored year (Figure 13a and Figure 13b). The top of the sill plate is exposed to humidity difference between 10-70%. The initial humidity on the exterior timber surface is near 100% but after starting to heat the indoor environment it decreases into stabilized conditions before next cold season. However, the sill plate is exposed to humidity higher than 80 % near its exterior surface for significant time of a year (about 6 months). The risk of mould growth increases during the autumn where about 8.5% of a year is inside favourable environment for the mould growth (Figure 14b) and starts decreasing during the winter. However, the risk of mould growth remains low (i.e. M<1) (Figure 14a) for the studied building, such that we expect no mould growth during the analysed period. Also, the risk development can be considered in decreasing tendency, because the first two years of the measurement may be influenced by the initial moisture content of the timber.

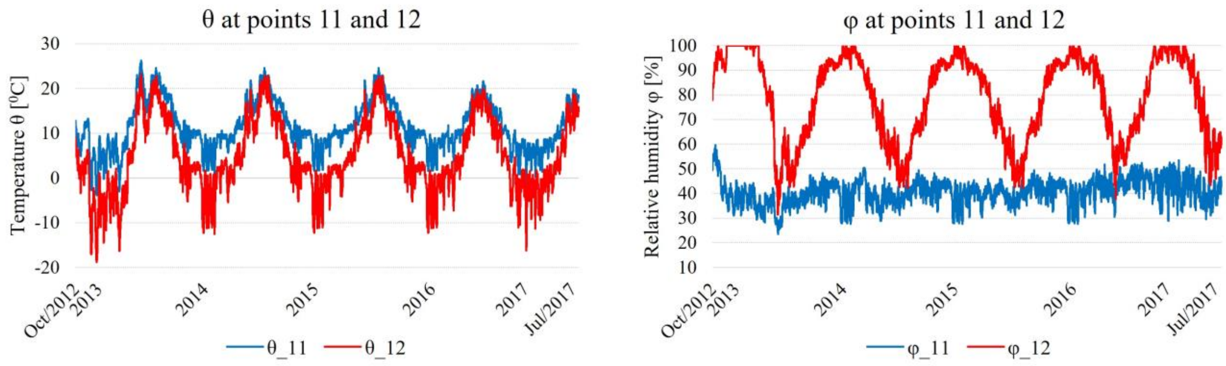

Figure 13. Temperature θ (a) and relative humidity φ (b) on top of sill plate at points 11 and 12.

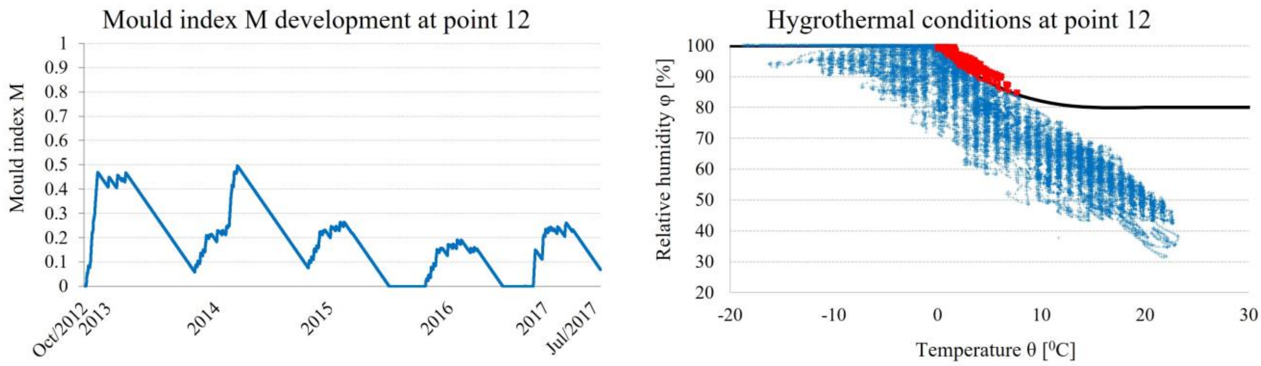

Figure 14. Mould index development (a) and hygrothermal conditions expression (b) (red dots show favourable and blue dots unfavourable conditions for mould growth initiation) on upper outdoor point of sill plate (point 12).

The effect of the high humidity at point 12 was analysed due to two-dimensional hygrothermal analysis and compared with point 8 (Figure 4). The differences of annual temperatures and humidity between analysed and measured data at point 12 and 8 are near 1℃ and 3%. The annual average temperature at the sill plate (point 12) is lower by 3-3.5℃ and average annual relative humidity higher by 15%. The reason is the free access of outdoor conditions via airflow (Figure 11), cooling effect from foundation and bigger moisture storage capacity and water vapour resistance of the sill plate than the ambient mineral wool. The outdoor surface of the sill plate absorbs moisture from outdoor during wet seasons and low temperature caused by the foundation effect and direct contact with outdoor conditions leads to higher humidity compared the point 8. It is expected that the moisture barrier in the interface of the sill plate and concrete foundation slows the moisture diffusion from the foundation and the water content on top of the sill plate remains low. However, it would be beneficial to monitor moisture content on the bottom of the sill plate because the top assessment may overlook moisture problem inside the sill plate (Tariku et al., 2016).

Hygrothermal simulation

Numerical model

The results of hygrothermal simulation via points 9-6 (Figure 4) adequately match the measured data (Figure 15). The measured and calculated data differ somewhat during the study period, with the largest difference achieved on the interior surface of the rockwool (point 9), in which relative humidity varies from -8 to 8% and temperature up to 1.4^{0}C. However, the overall average difference between measured and calculated data is only 0.04% and 0.65^{0}C. The biggest average difference was obtained between mineral wool and vapour retarder (point 6). The calculated temperature and relative humidity are 1.2^{0}C and 4.1% higher. The differences might be caused by definition of material properties, numerical accuracy, measurement accuracy, etc. Nevertheless, because the calculated relative humidity is overall higher than measured, the numerical simulations results may be considered on safe side. Hence, the numerical model can be used for future prediction of hygrothermal performance of the envelope.

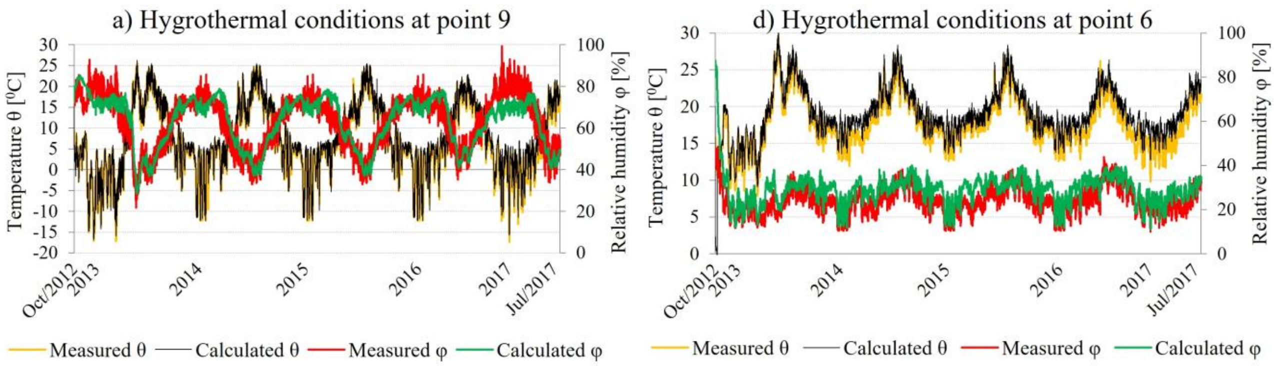

Figure 15. Computed and measured temperature θ and relative humidity φ data at points 9 and 6 (conditions at points 8 and 7 are similar).

Test conditions

The numerical model was subjected to test year data for Finnish design (Jokioinen 2004). Jokioinen is an inland city in Southern Finland and the outdoor environment differs from coastal city of Oulu. Oulu temperature and relative humidity data for individual years recorded from 2000 to 2020 (www.ilmatieteenlaitos.fi) were compared due the Finnish mould growth risk. A very sensitive material subjected the test year data Jokioinen 2004 achieves highest mould growth risk, although Oulu conditions are overall more humid. The reason is especially low temperature that causes unfavourable conditions for mould growth. Therefore, it is assumed that the test year for Finnish design can be used to simulate severe outdoor conditions for hygrothermal analysis of the presented structure. The indoor boundary conditions were derived from the outdoor conditions following a Finnish national guideline (RIL 107-2012, 2012). The guideline recommends more suitable design values of indoor moisture excess in Finnish environment than EN ISO 13788:2012 (Vinha et al, 2018). The hygrothermal conditions at the analysed points were compared via the Finnish mould growth model during one year. Very sensitive material (MSC1) (untreated inner surface of outdoor wooden cladding) subjected to the test year achieves maximum mould index 5.86 and the measured outdoor conditions cause a mould index of 0.94 in 2013, 1.31 in 2014, 1.30 in 2015 and 1.64 in 2016 (Figure 16a). Therefore, the actual microclimate of the house is milder than the test annual Finnish data. The measured monthly average relative humidity achieves nearly full saturation from November to February compared to the test year where humidity is between 90-98%. The test year data represents significantly higher relative humidity from June to September (Figure 16b). The hygrothermal conditions in the air gap between the outdoor cladding and the building envelope are majorly driven by the outdoor climate via well-ventilated air gap. However, the risk of mould growth on the inner side of the outdoor cladding can be minimized by planned surface and/or to applying less mould sensitive material such as anticorrosive pine plate or cork board (Fu et al., 2020). The remaining points (points 6-9) do not show any mould growth risk throughout the envelope. Therefore, in the case, the outdoor and indoor conditions would change towards the design values, they should not have a significant impact on favourable conditions for mould growth risk inside the building envelope. In comparison with presented study, the design conditions drive the moisture flow from indoor out resulting in different approach of hygrothermal analysis of an envelope. Therefore, the conditions may significantly change inside different locations of the envelope depending on pressure differential across the envelope, indoor and outdoor conditions and air leakage (Saber and Maref, 2019).

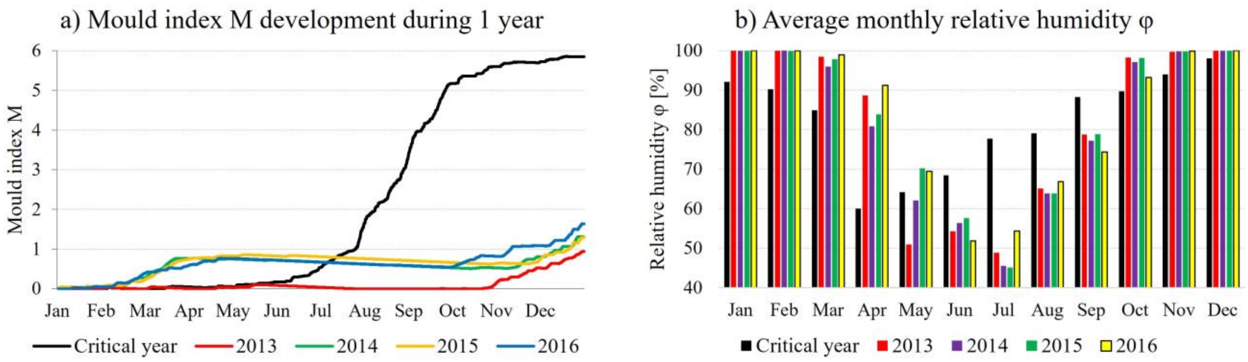

Figure 16. Mould index M development (a) and monthly average view on relative humidity for critical annual data and measured each (whole) year (b).

Conclusion

Monitoring temperature and relative humidity conditions affords detailed insights into a building hygrothermal performance and allow an evaluation of the risks of biological growth inside the structure and validation of computational models. Eventual risks can be avoided before an appearance of excessive mould, that may lead to a major damage of construction material. Despite the great development of hygrothermal numerical techniques, the real-time monitoring allows more accurate data of actual microclimate, that may differ from design values.

The monitored conditions within the studied structure show unsuitable environment for mould growth inside the building envelope. The major impact on the building hygrothermal performance is represented by boundary conditions. The indoor excess agrees with practices of hygrothermal performance of buildings in cold climate. The building envelope subjected to severe outdoor conditions and guided internal excess for residential buildings in Finland does not show any significant risk of favourable mould growth risk conditions inside the building envelope. The severe conditions mainly effect the untreated wooden inner surface of outdoor cladding. The guidelines for house design appeared efficient in the cold and humid climate of North Ostrobothnia/Finland.

The presented monitoring technique provides suitable method to obtain real-life hygrothermal data. The temperature and relative humidity allow actual assessment of the building hygrothermal performance and helps to recognize risks caused by excessive humidity. The measured data concedes to validate computational model which can be applied for simulation of building hygrothermal performance under more severe climatic scenarios to predict risks in the future.

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