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The Thermal Comfort and Hygrothermal Performance of the First Certified Passive House in Estonia

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Abstract: This study presents the thermal comfort and hygrothermal performance of building envelope of the first certified passive single-family detached house in Estonia. Temperature and humidity conditions were measured from different rooms and building envelopes. This article presents analysis of measurement results during the first year after construction. Results showed high room temperature, achieved mainly due to large windows with southern exposure and the small heat loss of the building envelope. High indoor temperature decreased the indoor RH (relative humidity) to quite low levels. Even the RH was low, the moisture excess was high indicating that the design of PH (passive houses) indoor humidity loads cannot be decreased. Humidity in the externally insulated cross-laminated timber panels was observed to be high, caused by drying out of the constructional moisture and the high diffusion resistance of the wood fibre sheathing board. That caused water vapour condensation and risk for mould growth. In conclusion, while planning buildings with high-energy efficiency, more focused attention should be paid to the performance of the building service systems and moisture safety already in the preliminary stages of design.

Key words: PH, nZEB (nearly zero-energy building), hygrothermal performance, moisture safety, indoor climate, overheating.

1. Introduction

In the EU (European Union), buildings account for 40% of total energy consumption. The 2010 EU directive on energy performance of buildings encourages the transition from fossil fuels to renewable energy sources in the building sector and underlines the importance of reducing energy dependency and greenhouse gas emissions in the EU [1]. Europe has adopted an ambitious vision for the energy efficiency of its buildings. By the end of 2018 all new public buildings and by the end of 2020 all new buildings must meet nZEB (nearly zero-energy building) requirements.

The aforementioned directive describes nZEB-s as buildings with very high-energy performance in terms of net energy consumption. The nearly zero or very low amount of energy required should be covered to a very significant extent from renewable sources, preferably produced on-site or nearby. In line with the EU directive, Estonian new energy performance regulations entered into force on 9.1.2013, establishing primary energy requirements for new and renovated buildings [2]. The requirements and corresponding energy certificate classes are shown for three building types out of nine in Table 1.

In addition to national requirements, there are several internationally recognized energy-performance levels. The PH (passive house) standard [3] is one widely known energy performance standard. The PH standard requires thick insulation, minimized thermal bridges, airtightness, insulated glazing and heat recovery ventilation. For PH standard, the quantitative requirements are: annual specific net energy demand for heating at less than or equal to 15 kWh/(m^2·a) and total primary energy for space heating, domestic hot water and household appliances at less than or equal to 120 kWh/(m^2·a).

In Estonia, the renovation of a kindergarten Kaseke with PH components marked the country's first experience with PH concepts [4] during 2008-2009. The monitoring

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Table 1 Energy performance certificate classifications (A-D) and corresponding maximum values of energy performance values (kWh/(m^2·a) for three different types of buildings.

	Maximum energy performance values (Estonian legislation), kWh/(m^2·a)			
	A nZEB	B Low energy building	C Minimum requirements for new building	D Minimum requirements for major renovation
Detached house	50	120	160	210
Apartment building	100	120	150	180
Office building	100	130	160	210

results for kindergarten revealed that the annual heating energy consumption was 13 kWh/(m^2·a) which is a very good result. However, the total energy consumption for the building was as high as 166 kWh/(m^2·a) as a result of constantly working ventilation system [5].

The first complete and certified PH in Estonia is a detached house located at Metsa 5a in the town Põlva (58°03′00.3″ N, 27°03′24.8″ E), designed by Austrian architects and constructed by Estonian designers [6]. Based on calculations, it achieves the annual basis "plus-energy" building classification in the Estonian legislation [7].

This article presents and analyses the thermal comfort and hygrothermal performance of the building envelope of the aforementioned PH during the first year after construction.

2. Methods

2.1 Studied House and Structures

The PH concept has been fully implemented. The building is positioned within the given slope connecting those levels leaving the south and east façade of basement floor exposed to winter sun.

The design and construction of the house has taken into account the characteristics of Estonia's cold northern climate. For example, the main glazed façade is oriented directly to south maximising the use of passive solar gain during the heating season, since the south façade windows have a favourable contribution from the sun and have potential to yield a positive heat balance over the heating season.

The house includes two stories (Figs. 1 and 2) and a basement with total net floor area of 305 m^2. The building envelope surface area is 864 m^2 and has an enclosed volume of 1,586 m^3, corresponding to a compactness factor (A/V) of 0.55 m^{-1} for the building.

The ground level consists of an entrance area, the big living room, the kitchen, the master bedroom and the corresponding auxiliary rooms. The living room is two stories high and is facing the south with a generous glass façade. In the upper floor you find a gallery, which is open to the living room and gives access to three children's bedrooms and a working area. In the basement there is a sauna and a steam bath (both very important in the daily live of the inhabitants) connected with an area for shower and a big room for recreation (fully served with day light). There are also a technical room, a room for the kids and some storage rooms.

The house is built with mixed construction system—the basement is casted concrete construction with thick layer of XPS/EPS insulation depending on the wall/floor type. The aboveground perimeter walls have 300 mm of EPS insulation and belowground perimeter walls have 500 mm of EPS insulation. The floor slab configuration features 300 mm of XPS insulation and 100 mm of EPS insulation.

Ground floor and upper floor have a 94 mm thick cross-laminated timber block elements (Kreuzlagenholz, KLH) as the load bearing layer and 400 mm of cellulose insulation with custom made C-joists made out of timber and OSB sheets. The façade of an original design (Fig. 3, left) was ETICS (external thermal insulation composite system). Customization of the building design was necessary to accommodate the cold climate. Whereas a well-insulated undrained, rendered wooden exterior wall (Fig. 3, left) could be a good solution for a PH built in Austria, this option could result in serious moisture damage [8] and biological growth [9] in a cold climate. Therefore, a new solution was proposed (Fig. 3, right): the exterior wall was constructed with ventilated cavities covered mainly by rendering boards and partly by vertical solar collectors. Also the roof solution was changed: it was insulated with wedge shaped EPS insulation (380-550 mm).

The glazed areas feature krypton filled triple glazing with different low-emissivity coatings depending on the orientation of the windows and glazed doors. The declared thermal transmittance of the glazing units was 0.60 W/(m^2·K) for the southern façade and 0.49 W/(m^2·K) for other orientations, the SHGC (solar heat gain coefficient) for these glazing units is accordingly 0.59-0.62 W/(m^2·K) for southern façade and 0.36-0.37 W/(m^2·K) for other facades depending on the glazing thickness. The wooden window frames (SmartWin) had very low thermal transmittance: 0.75 W/(m^2·K) for openable windows and 0.59 W/(m^2·K) for fixed windows.

The linear thermal transmittance trough connections of building envelope were calculated and too low surface temperatures ($f_{Rsi} > 0.8$ [10]) were avoided with 2D finite element calculation with LBNL Therm software. An overall reduction by 1.9 kWh/(m^2·a) to annual net heat demand was achieved compared to situation with no thermal bridge input using external dimensions.

In total the average thermal conductivity of the whole building envelope (including windows, doors and linear thermal bridges) was 0.146 W/(m^2·K).

The water based wall- and floor-heating system is based on ground source heat pump combined (ground source heat pump) with split solar thermal system.

The building has mechanical supply and exhaust ventilation system with efficient heat recovery. The airflows had been reduced to limit the risk of overly dry air during the winter season. The average airflow rate 0.4 h^{-1} was lower than the requirement [2].

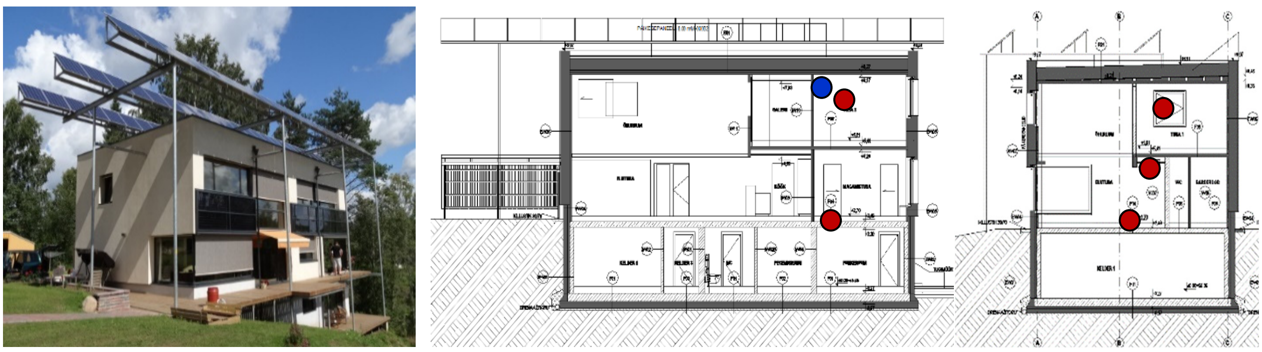


Fig. 1 View from SW (south-west) direction (left) and the sections (middle, right) from the house.

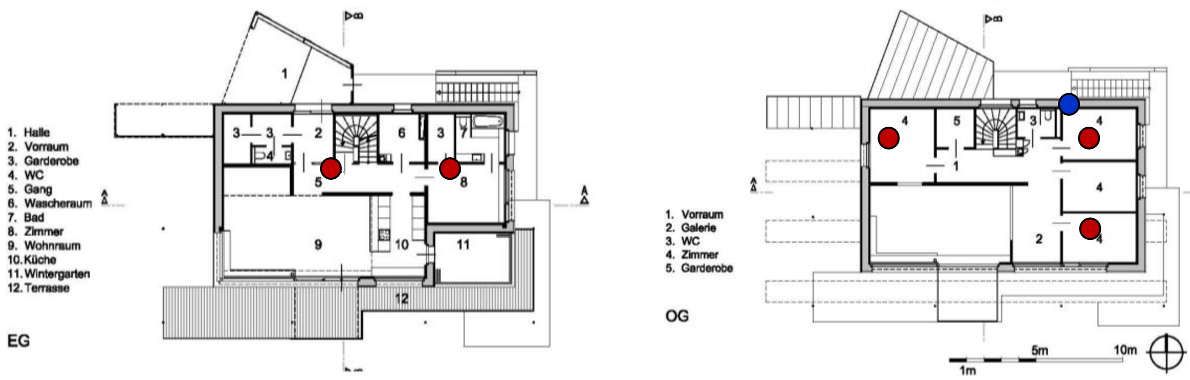


Fig. 2 The plans of the first (left) and the second (right) floors. Red dots show indoor climate measurement points and blue dot show the location of measurement of hygrothermal performance of exterior wall.

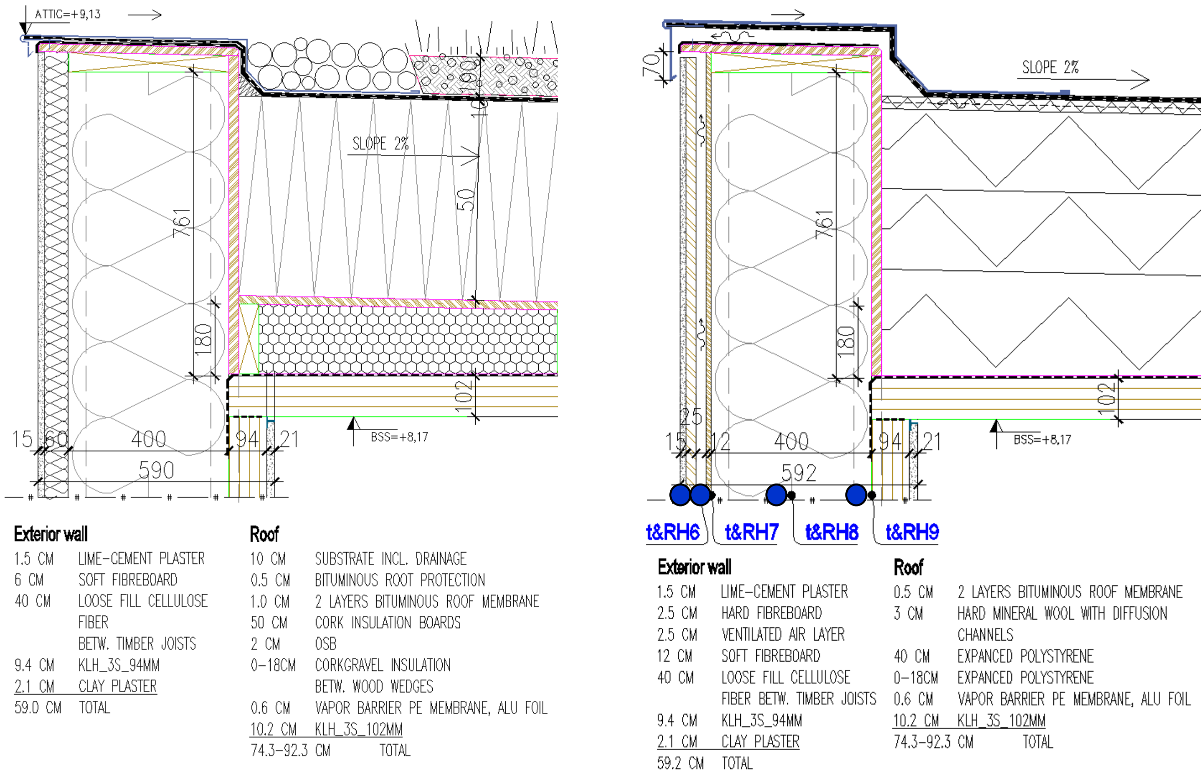


Fig. 3 Exterior wall and roof structures, as originally designed (left), and as constructed (right, blue dots show temperature and RH (relative humidity) measurement points (t&RH6, t&RH7, t&RH8, t&RH9)).

Fig. 4 Northern façade with the location (blue dot) of hygrothermal performance of exterior wall.

2.2 Measurements

Upon completion of house construction in December 2012, an extensive monitoring system was installed to continuously assess the indoor climate (temperature (*t*), RH, and CO_2 (carbon dioxide) levels), performance of building systems and the exterior wall and ventilation system.

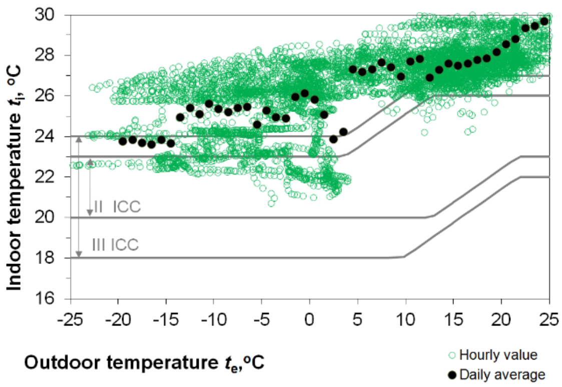
The indoor temperature and humidity conditions were measured with portable sensors (measurement range: (-20)-(+70)°C and 10%-95%, accuracy: ±0.35 °C and ±3%).

The hygrothermal performance of exterior wall was measured on the northern façade with temperature and RH sensors (Φ 5 mm × 51 mm, measurement range: (-40)-(+100) °C, and 00100%, accuracy: ±0.3°C and ±2%) and heat flux plates (Hukseflux HFP-01-05, measurement range ±2,000 W/m^2, accuracy: ±5%). Measurement results were recorded with a computer (Modbus RTU).

3. Results

3.1 Indoor Climate

To provide an overall view of the indoor climate, we analyzed the correlation of the indoor temperature and RH with the outdoor temperature (Fig. 4). Using green dots, the correlation of the hourly indoor temperature with the outdoor temperature outside the northern bedroom with east-facing window is displayed in Fig. 4 (left). Using black dots, the correlation of the average



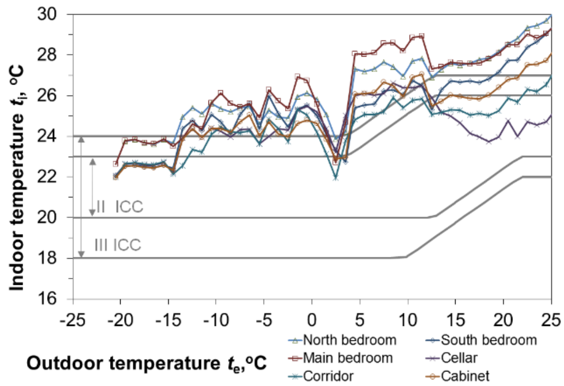
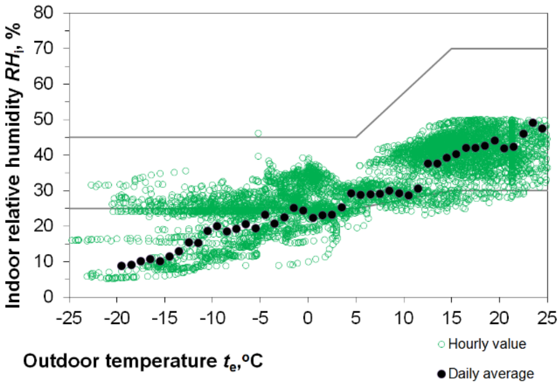


Fig. 4 The dependence of the indoor temperature on the outdoor temperature in the north bedroom on the second floor with east-directed window (left) and the comparison of all rooms (right).



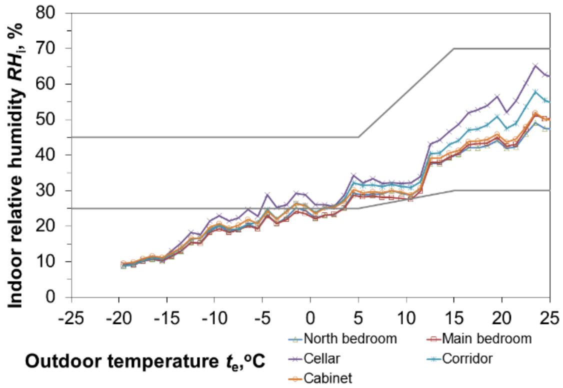


Fig. 5 The dependence of the indoor RH on the outdoor temperature in the north bedroom on the second floor (left) and the comparison of all rooms (right).

daily indoor temperature with the average daily outdoor temperatures outside the aforementioned room is displayed. This represents average thermal conditions in this room. In Fig. 4 (right) temperature conditions from all measured rooms are presented.

Indoor temperature conditions represented 44% from the measured time length to the ICC (indoor climate category) III [11] and 29% from the measured time length to the ICC II. High indoor temperatures were observed through the year. The average indoor temperature during the first heating season was +24.3 °C; 57% from the measured time lengths exceeded winter period's upper limit of the ICC III and 62% exceeded winter period's upper limit of the ICC II. Similarly during summer the upper criteria of ICC exceeded ≈ 60% of the measured time lengths.

The correlation of indoor RH on the outdoor temperature was also analyzed, using a similar method as employed for the room temperature. In Fig. 5 (left), the average indoor RH values from one room are divided by the average outdoor air temperature. Based on each indoor RH sensor and the corresponding outdoor temperature, the daily average value was calculated to form the black dotted line. Each individual curve in Fig. 5 (right) represents, for each room, the average value of the daily indoor RH and the corresponding average daily outdoor temperature. High indoor temperature decreased the indoor RH to quite low levels. Low RH may cause the need for humidifier indoors in ventilation systems that may be hygienically risky and rise indoor humidity loads.

The internal moisture excess was selected to characterize indoor humidity loads. Fig. 6 (left) presents the daily moisture excess in one room during whole measurement period, and the black dotted line represents the weekly average moisture in excess on

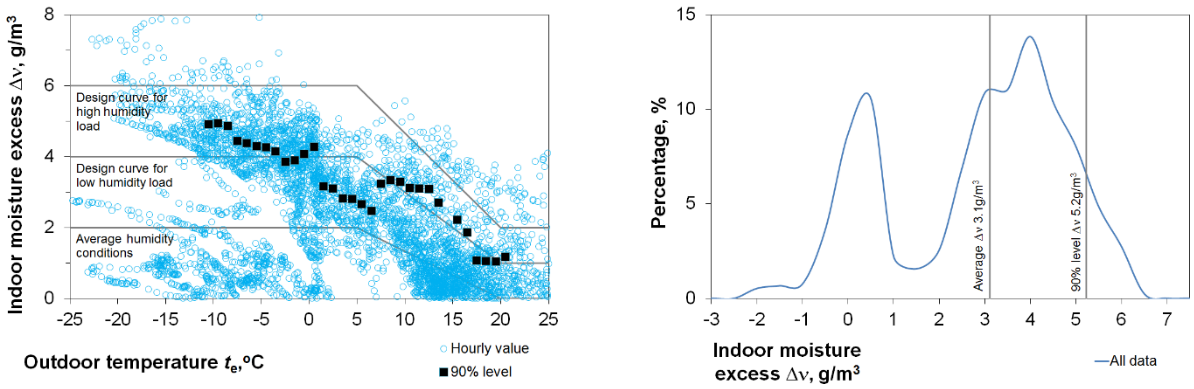


Fig. 6 The distribution of moisture excess.

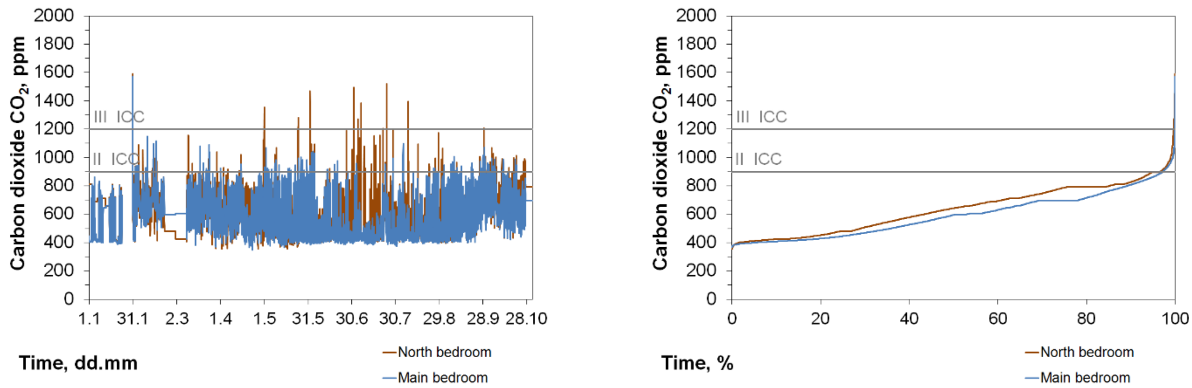


Fig. 7 CO_2 concentration in bedrooms.

90% criticality level (design level). Fig. 6 (right) presents the moisture excess during the winter period. The average value was 3.1 g/m^3, and the design value corresponding to 90% critical moisture level was 5.2 g/m^3. This indoor humidity level represents high humidity conditions [12]. Even the RH was low, the moisture excess was high.

CO_2 concentrations were used to assess the indoor air quality. CO_2 concentrations at 500 ppm and 800 ppm above the outdoor concentration (400 ppm) correspond to the ICC target classifications of average (II) and third (III), as shown in Fig. 7.

3.2 Hygrothermal Performance of Exterior Wall

The hygrothermal performance of the exterior wall was measured at different positions inside the 400 mm thick cellulose insulation (see Fig. 3 right):

- on the internal edge of the insulation: between the insulation and the KLH;
- in the middle of the insulation;
- on the external edge of the insulation: between the insulation and the 12 mm thick wood fiber sheathing board (Kronopol DP50).

Fig. 8 shows the temperature (left) and RH (right) inside the 400 mm thick insulation of the exterior wall. The RH was over 80% until the beginning of the summer (until 1.06.2013). As the exterior walls were insulated in September 2012, high moisture content in the walls lasted for approximately ten months. In the summer, when very high moisture conditions in the exterior wall were determined, two additional temperature and RH sensors (RH 7-2 and RH 7-3) were placed inside the wall. The measurement accuracy of the original sensor was open to discussion. However, similar humidity readings in the new sensors RH 7-2 and RH 7-3 assured the authors of the accuracy of the original sensor: the drying out of constructional moisture (KLH and cellulose insulation) had caused condensation and favorable conditions for mold growth (Fig. 9) inside the exterior wall. Based on a mathematical model of mold growth in wooden material [13], the mold index was near 3, meaning that some growth could also be detected visually and new spores could form.

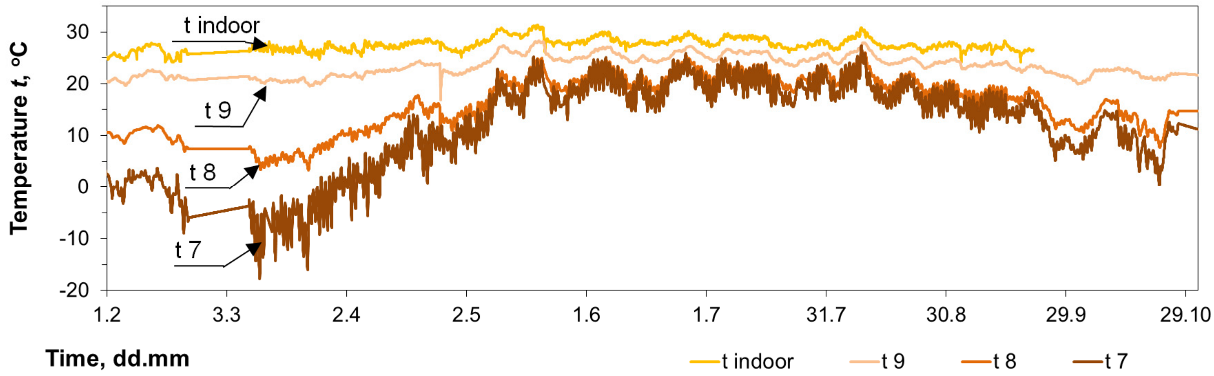


Fig. 8 Temperature (*t*) inside the 400 mm thick insulation of the exterior wall.

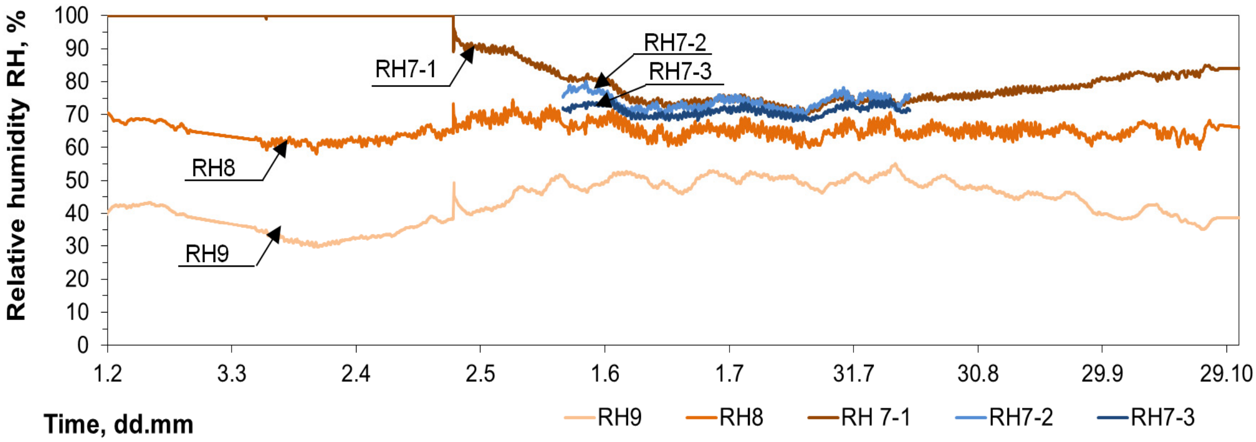


Fig. 9 RH inside the 400 mm thick insulation of the exterior wall.

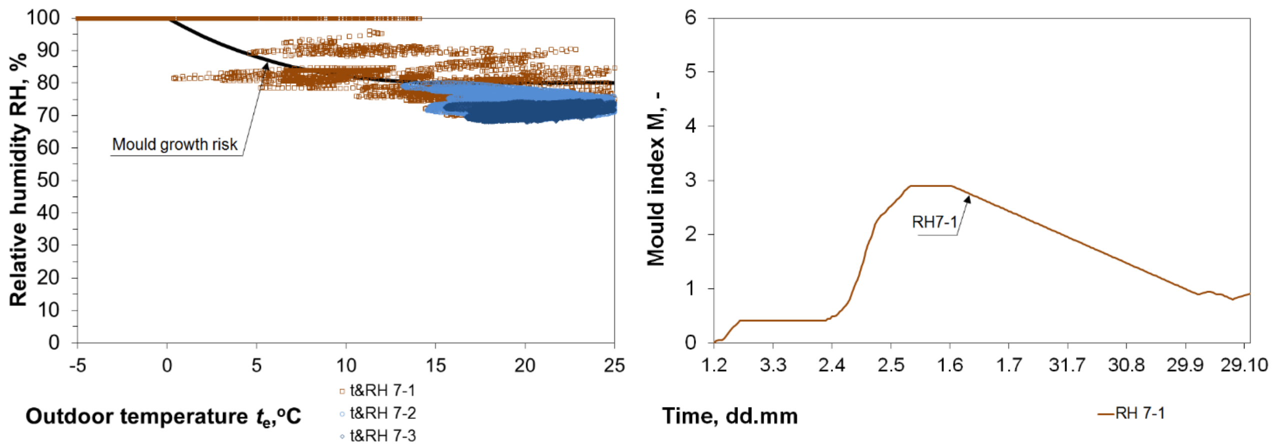


Fig. 10 Temperature and RH between the cellulose insulation and the 12 mm thick wood fiber sheathing board (left) were suitable for mold growth, according to the mold growth index (right, [13]).

4. Discussion

The first certified PH in Estonia was designed by Austrian architects in cooperation with Estonian designers (load bearing structures, service systems), including the involvement of the co-authors of this paper. In preliminary design, the architecture and energy performance had highest priorities. As dynamic simulations on indoor climate hygrothermal performance missed, high indoor temperatures and moisture safety of building envelope were not possible to predict. The indoor climate and hygrothermal performance measures of the exterior wall of this building were monitored and analyzed.

The passive utilization of heat gains is an important factor in the design of a PH. In the cold Estonian climate, literature review suggests that only windows with southern orientation could yield energy-positive results [14]. At the same time, large south-facing windows need flexible solar protection to avoid over-heating indoor climate. South-directed windows could not be the only reason of overheating in the house under consideration, since the north bedroom with east-directed window reached high temperatures as well (Fig. 4, left). During the summer months, only the basement maintained the average indoor temperature within the targets of ICC II (normal level of expectation, for new buildings: PPD (predicted percentage dissatisfied) ≈ <10%).

Due to high temperatures, the indoor RH decreased to quite low levels. During the cold period ($t_e \leq +5$ °C), the indoor RH was below 20% (Fig. 5). The indoor RH was similar in all rooms.

The indoor humidity loads were similar to typical dwellings with high humidity loads: the average value of moisture excess during the winter period was 3.1 g/m^3, and the design value of moisture excess was 5.2 g/m^3 (Fig. 6). This indicates that in design of PH's indoor humidity loads cannot be decreased though the ventilation keeps the indoor air quality within the limits of ICC II recommendations (Fig. 7).

Humidity conditions in externally insulated cross-laminated timber panels (KLH) were high (Fig.9 left), due to the drying out of constructional moisture (KLH and cellulose insulation) and the high diffusion resistance of the wood fiber sheathing board. Careful hygrothermal design and moisture safety considerations should be paramount in the construction of highly insulated building envelopes [15, 16]. Otherwise, water vapor condensation or favorable conditions for mold growth could develop (Fig.9 right).

5. Conclusions

The performance of the first certified PH in Estonia was monitored and assessed during the first year after construction, including detailed analysis of the indoor climate and hygrothermal performance of the exterior walls.

High temperatures in most of the rooms were achieved mainly due to the southern exposure of the large windows and the fact that the adjustable solar protection devices were installed only in the middle of the current monitoring period (May 2013). As the heat loss through the building envelope was small compared to the thermal transmittance of the interior walls and floors, a high average indoor temperature was maintained throughout the house, including the bedroom on the northern side of the building. Due to the high temperatures reached, the indoor RH decreased to quite low levels. The high indoor temperatures indicate that the large windows with southern orientation need adjustable solar protection or heat accumulation devices to avoid over-heating.

Humidity conditions in the externally insulated cross-laminated timber panels (KLH) were elevated for long periods, raising concern for condensation and the risk of mold development. Although the original hygrothermally risky design of the exterior walls, which would have used ETICS with a wooden structure, was upgraded to a less moisture-prone design based on advice of the co-authors and other Estonian experts, excess moisture still became a problem. This was mainly caused by the shortcomings in the constructional technology, such as no rain protection for KLH, no moisture safety protocol during the construction period, and the high diffusion resistance of the wood fiber sheathing board. In parallel with energy performance, also the hygrothermal properties of the building envelope and its impact on the indoor climate should be top priority in the design of PHs.

A key to successful completion of construction projects is clear communication and follow-up between designers and building crew, to ensure that the revised construction guidelines would be fully incorporated in the blueprints. This could reduce problems such as the overheating and moisture build-up encountered in this project. In design of buildings with high-energy performance, focused attention should be paid to the performance of building service systems and moisture safety should be taken into account already in preliminary stage of design.

Acknowledgements

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