Hygrothermal Performance of Highly Insulated Timber-frame External Wall

Peep Pihelo*, Henri Kikkas*, Targo Kalamees*

* Tallinn University of Technology, Chair of Building Physics and Energy Efficiency, Ehitajate tee 5, Tallinn 19086, Estonia

Abstract

The nearly zero energy buildings (nZEB) ideology foresees first and foremost that heat losses should be reduced remarkably compared to the present levels. The European Union has adopted an ambitious vision for the energy efficiency of its buildings and by the end of 2020 all new buildings must meet nZEB requirements. The efficient way to meet these requirements is to design and build passive, nZEB, highly insulated buildings.

This paper presents the outcomes of analysis of the hygrothermal performance of the highly insulated building envelope of the detached house, built in Estonia. The results indicated that the dry-out period of constructional moisture is directly dependent on initial moisture content of materials in structure and a higher risk was detected if vapor permeability of outer layers in the envelope is low. Also critical aspects of moisture performance change due to the modifications of designed materials in construction process without preliminary analysis are described. Thermal resistance of the wind barrier and water vapor permeability of the vapor barrier, also moisture capacity of insulation layer had the strongest influence on the relative humidity and hence, to mould growth risk in the critical point of highly insulated timber-frame external wall, between the insulation and the wind barrier surface.

In the design of highly insulated timber-frame walls more attention should be paid to the hygrothermal performance and moisture safety analysis. As a result of this study, some of the functional solutions of timber-frame external walls are described in this paper.

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* Corresponding author. Tel.: +372 6202405
E-mail address: peep.pihelo@ttu.ee
1. Introduction

Europe has adopted an ambitious vision for the energy efficiency of its buildings and by the end of 2020 all new buildings in the EU must meet nearly zero-energy building (nZEB) requirements. In line with the EU directive[1], the new Estonian energy performance regulations came into force on July 2015 [2], establishing stricter primary energy use requirements for nZEB, low-energy, new and renovated buildings in Estonia. In addition to national requirements, there are several internationally recognized energy-performance levels implemented. The Passive House (PH) standard[3] is a widely known energy performance standard, which requires minimized energy demand for space heating and therefore thick insulation, absence of thermal bridges, air tightness, efficient windows and heat recovery ventilation.

Already some buildings have been designed and built in past few years in Estonia according to nZEB requirements and PH standards. The Palamuse and Valga municipalities made first steps toward PH already in 2009 in Estonia [4]. The first nZEB and certified PH in Estonia is a detached house located in Põlva that achieved the annual basis “plus-energy” building classification in the Estonian legislation. Estonian factory-built wooden houses have become nZEB and passive houses also are exported to many countries like Finland, Norway, Germany.

Construction Products Regulation [5] sets essential requirements for safety of buildings and other construction works but also to health, durability, energy economy, protection of the environment, economic aspects and other important parts in the public interest. A large number of moisture-related building problems such as mould growth and chemical emissions from decomposed material subjected to high moisture levels, have occurred during the last few years with adverse effects on health, building costs and confidence in the building industry [6]. The first year measurements of the PH in Estonia showed that absence of rain protection of structures, no moisture safety protocol during the construction period as well the high diffusion resistance of the wood fiber sheathing board outside the insulation increased humidity conditions in the externally insulated cross-laminated timber (CLT) panels over the critical level [7]. Hagerstedt and Harderup [8] have brought out the changes in moisture performance because of the modified solution in construction process. Many researchers have shown that increased insulation thicknesses may cause an increase in humidity levels and thereby increased risk of mould growth. Therefore, it is necessary to pay special attention to the hygrothermal performance and moisture safety of highly insulated constructions.

In this study, the hygrothermal performance of timber-frame walls of a detached house, designed to be PH, in Estonia was analyzed. The field measurements during the first two years after construction [9] showed exceeding of mould growth risk level in external walls and relatively high indoor moisture excess. In current study results of measurements and simulations were evaluated for designing highly insulated buildings.

2. Methods

2.1. Description of the constructions

The analyzed detached house, built in 2013, was designed according to PH principles. It has compact design, well insulated airtight structures and efficient service systems which lead to the low energy house classification according to Estonian legislation. External walls are made of composite beams and columns, consisting pinewood and oriented strand board (OSB) with step 625 mm and where cellulose insulation thickness is 500 mm. The interior side of beams was covered with 22 mm finished OSB that gave airtightness and stability of structures. Combinations of 24 mm soft fibreboard and/or 30 mm high density mineral wool slab were used as a wind barrier under finishing rain screen, wooden siding and/or plastered hardboard. The airtightness of the external envelope of the whole building was 0.3 m³/(h·m²). With different combinations of wind barrier and vapor barrier, three types of walls were built for further monitoring (see Fig. 1 below right, wall types 1, 2 and 3), where thermal transmittance was 0.10-0.11 W/(m²·K). Wall type 1 was made to study the influence of PE vapor barrier. Wall type 3, where 24 mm soft fibreboard as wind barrier was intended to use, was initial design solution from architect. That solution was improved by adding 30 mm high density mineral wool slab onto the soft fibreboard in the last stage of design (wall type 2).
2.2. Simulations with dynamic computer software

The dynamic hygrothermal simulation program Delphin, which was developed at the Technical University of Dresden and successfully validated \[10,11\], was used as a calculation tool in this study. Delphin is a simulation program for coupled heat, moisture and matter transport in porous building materials and it is used for different applications, e.g. calculation of mould growth risks with consideration of climate impacts, radiation, wind-driven rain, structure conditions and materials modelling. The calculation model was calibrated with the help of measurement data \[9\] collected throughout 2 years after construction.

In this study, in parallel we used a mathematical model for the calculation of mould growth, decrease and the mould index in changing conditions, designed in Finland \[12,13\]. According to this model, within fluctuating humidity conditions, the total exposure time for response of growth of mould fungi is affected by the time periods of high and low humidity conditions, as well as the humidity and temperature level. In the simulation of mould growth, it is crucial to know the lowest (threshold) conditions where fungal growth is possible on different materials. The boundary curve for the risk of mould growth in the range of temperature between 5 to 40°C on a wooden material can be described by a polynomial function:

\[
RH_{crit} = \begin{cases} 
-0.00267 \times t^3 + 0.16 \times t^2 - 3.13 \times t + 100 & \text{when } t \leq 20 \degree C \\
RH_{min} & \text{when } t > 20 \degree C
\end{cases}
\]  
(1)
where \( t \) is the temperature on the investigated material surface (°C) and \( RH_{\text{min}} \) represents the minimum level of relative humidity, where mould growth is possible (varies according to the sensitivity of the material, for example \( RH_{\text{min}}=80\% \) for wood). The time period that is needed for the onset of mould growth and growth intensity is mainly dependent on water activity, temperature, exposure time and surface quality of the substrate.

In this study, the critical value of the mould index (\( M \)) was set to level \( M=1 \) (no growth, pores are not activated) according to the mould index model to avoid the formation of mould in a structure (Table 1).

<table>
<thead>
<tr>
<th>Mould index (( M ))</th>
<th>Description of mould growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No growth</td>
</tr>
<tr>
<td>1</td>
<td>Small amounts of mould on surface (microscope), initial stages of local growth</td>
</tr>
<tr>
<td>2</td>
<td>Several local mould growth colonies on surface (microscope)</td>
</tr>
<tr>
<td>3</td>
<td>Visual findings of mould on surface, &lt;10% coverage, or &lt;50% coverage of mould (microscope)</td>
</tr>
<tr>
<td>4</td>
<td>Visual findings of mould on surface, 10–50% coverage, or &gt;50% coverage of mould (microscope)</td>
</tr>
<tr>
<td>5</td>
<td>Plenty of growth on surface, &gt;50% coverage (visual)</td>
</tr>
<tr>
<td>6</td>
<td>Heavy and tight growth, coverage about 100%</td>
</tr>
</tbody>
</table>

In order to compare the hygrothermal indicators and to analyze their impact, different indoor boarding (OSB, CLT), thermal insulation materials (mineral wool and cellulose insulation), air and vapor barrier material (polyethylene foil) as well as wind barrier materials (wood fibreboard, dense mineral wool board, oriented strand board) have been used in the calculations of structures, by combining these materials with each other (see Table 2).

Table 2. Properties of materials of studied structures.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity ( \lambda ), W/(m-K)</th>
<th>Moisture storage function ( w ), kg/m³</th>
<th>Water vapor resistance factor ( \mu ), kg/s</th>
<th>Density ( p ), kg/m³</th>
<th>Open porosity ( \phi ), %</th>
<th>Water absorption coefficient ( A_{\text{abs}} ), kg/(m²·s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RH</td>
<td>33%</td>
<td>55%</td>
<td>75%</td>
<td>83%</td>
<td>97%</td>
<td>83%</td>
</tr>
<tr>
<td>Wood fibreboard</td>
<td>0.049</td>
<td>12.5</td>
<td>20.0</td>
<td>28.0</td>
<td>40.0</td>
<td>75.0</td>
</tr>
<tr>
<td>Oriented strand board (OSB)</td>
<td>0.140</td>
<td>31.0</td>
<td>46.0</td>
<td>78.0</td>
<td>110</td>
<td>183</td>
</tr>
<tr>
<td>Cross laminated timber (CLT)</td>
<td>0.130</td>
<td>27.0</td>
<td>38.0</td>
<td>65.0</td>
<td>93.0</td>
<td>180</td>
</tr>
<tr>
<td>Cellulose wool insulation</td>
<td>0.042</td>
<td>3.10</td>
<td>5.00</td>
<td>7.80</td>
<td>11.0</td>
<td>25.0</td>
</tr>
<tr>
<td>Mineral wool wind barrier</td>
<td>0.031</td>
<td>0.21</td>
<td>0.28</td>
<td>0.29</td>
<td>0.96</td>
<td>3.30</td>
</tr>
<tr>
<td>Mineral wool insulation</td>
<td>0.037</td>
<td>0.14</td>
<td>0.18</td>
<td>0.36</td>
<td>0.80</td>
<td>2.40</td>
</tr>
<tr>
<td>PE-foil 0.2 mm</td>
<td>0.400</td>
<td>89000</td>
<td>980</td>
<td>0.001</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The calculations in points AP1, AP2 and AP3 (see Fig. 1) with the simulation model were in good agreement with the measured data (see Fig. 2) and therefore the model is reliable for further research in this study.
The wall types 1, 2 and 3 were analyzed in combinations of different materials and insulation thicknesses. The mould formation risks, moisture dry-out period and impact of initial moisture content of materials of the building envelope’s hygrothermal performance were examined.

2.3. Boundary conditions

In the assessment of hygrothermal risks, the hourly data of the moisture reference year, critical to mould growth in Estonia, was applied for outdoor climate [14]. Indoor climate measurements from Estonian dwellings [15–17] were used for the determination of critical indoor hygrothermal conditions. For simulations, the following conditions were used: average indoor temperature, which was dependent on the outdoor temperature (Fig. 3 left) and 90th percentile of indoor humidity of class 3, representing dwellings with high humidity load (Fig. 3 right) and high occupancy according to national appendix of EVS-EN 15026 [18], which was expressed as indoor moisture excess $\Delta v$ (kg/m$^3$). The initial moisture content of materials was set to $RH=80\%$ and temperature $t=20^\circ C$, which corresponds to the start of construction during the summer-autumn time in Estonia.
3. Results

3.1. Comparison of moisture dry-out and mould risks with different combinations of materials

At the first stage of the study the wall types 1, 2 and 3 (Fig. 1) were examined. Dry-out capability and mould growth were calculated, if the initial moisture content of the building materials, which were used in the calculations, was equal to their equilibrium moisture content at $RH=80\%$ of ambient air (Fig. 4).

At the next stage of the study of the existing walls 1, 2, 3 (Fig. 1), the 24 mm fibreboard wind barrier was changed to 22 mm OSB. This is a recommended solution from structural engineer to increase the stiffness and stability of the building. Dry-out capability and mould growth were calculated, if the initial $RH=80\%$ of ambient air (Fig. 5).
3.2. Evaluation of moisture dry-out and mould risks with different thicknesses of insulation

In Fig. 4 and Fig. 5, the differences of moisture content at points AP1, AP2 and AP3 are clearly shown. At the last stage of the current study the wall type 3 (see Fig. 1 below right) was examined to find maximum initial RH for materials in the structure to keep mould index $M \leq 1$. The 27 mm CLT and insulation thicknesses 400, 500 and 600 mm were compared (Fig. 6).

Fig. 6. Dry-out period (left) and mould index (right) in analyzed point AP3. Materials according to Fig. 1, instead of interior OSB layer = CLT. Limit of initial RH of cellulose wool (above right) or 27 mm CLT (below right) to keep mould index $M \leq 1$, depending on insulation thickness. Initial RH=80% of ambient air.
3.3. Comparison of moisture dry-out and mould risks with different thicknesses of insulation

As a result of calculations, the compendious list of combinations of analyzed highly insulated timber-frame walls was determined (Table 3). The combinations were grouped by the mould index \((M)\) values. In functioning solutions, the mould index is under the critical limit \((M<1)\). Some of the solutions are not recommended as they are defined to be above the critical level of mould growth \((e.g., M>1.5)\). At the same time there are possibilities to consider some of the solutions and their boundary conditions in the cases where mould index is slightly over the critical limit \((1<M<1.5)\) and find the working solution with further analyses.

Table 3. Description of different combinations analyzed *

<table>
<thead>
<tr>
<th>Interior finishing layer</th>
<th>Air&amp;vapor barrier</th>
<th>Insulation 400-600 mm</th>
<th>Wind barrier layer</th>
<th>Additional layer on external side of wind barrier</th>
<th>Mould index ((M))</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSB 22 mm or CLT 27 mm</td>
<td>PE-foil 0.2 mm</td>
<td>Cellulose wool or mineral wool</td>
<td>Wood fibreboard 24 mm or OSB 22 mm</td>
<td>Mineral wool wind barrier &gt;30 mm</td>
<td>(M&lt;1)</td>
<td>No mould growth</td>
</tr>
<tr>
<td>OSB 22 mm or CLT 27 mm</td>
<td>-</td>
<td>Cellulose wool</td>
<td>Wood fibreboard 24 mm or OSB 22 mm</td>
<td>Mineral wool wind barrier &gt;30 mm</td>
<td>(M&lt;1)</td>
<td>Mould risk is very low</td>
</tr>
<tr>
<td>OSB 22 mm or CLT 27 mm</td>
<td>-</td>
<td>Cellulose wool or mineral wool</td>
<td>Mineral wool wind barrier &gt;30 mm</td>
<td>-</td>
<td>(M&lt;1)</td>
<td>Mould risk is very low</td>
</tr>
<tr>
<td>OSB 22 mm or CLT 27 mm</td>
<td>-</td>
<td>Mineral wool</td>
<td>Wood fibreboard 24 mm or OSB 22 mm</td>
<td>Mineral wool wind barrier &gt;30 mm</td>
<td>(1&lt;M&lt;1.5)</td>
<td>Vapor retarder and additional calculation are recommended</td>
</tr>
<tr>
<td>OSB 22 mm or CLT 27 mm</td>
<td>-</td>
<td>Cellulose wool</td>
<td>Wood fibreboard 24 mm</td>
<td>-</td>
<td>(1&lt;M&lt;1.5)</td>
<td>Vapor retarder and additional calculation are recommended</td>
</tr>
<tr>
<td>OSB 22 mm or CLT 27 mm</td>
<td>-</td>
<td>Mineral wool</td>
<td>Wood fibreboard 24 mm</td>
<td>-</td>
<td>(M&gt;1.5)</td>
<td>Not recommended, mould risk is too high</td>
</tr>
<tr>
<td>OSB 22 mm or CLT 27 mm</td>
<td>-</td>
<td>Cellulose wool or mineral wool</td>
<td>OSB 22 mm or CLT 27 mm</td>
<td>-</td>
<td>(M&gt;1.5)</td>
<td>Not recommended, mould risk is too high</td>
</tr>
</tbody>
</table>

* The calculations were made with initial \(RH=80\%\) and temperature \(t=20^\circ C\) with Estonian moisture reference year (MRY) climatic data.

4. Discussion

The conducted hygrothermal simulations showed that a careful selection of materials makes it possible to design timber-frame external walls that are moisture safe and provide low thermal transmittance. The hygrothermal performance of the timber-frame external wall was found to be dependent most of all on the thermal resistance of the wind barrier and vapor permeability of the wind barrier and vapor barrier layer. The importance of air&vapor barrier layer can be seen, if to compare points AP1 (wall with PE-foil air&vapor barrier layer) with AP3 (without air&vapor barrier layer) – the absence of a vapor resistant layer contributes to higher moisture load from the indoor side, because of vapor pressure differences during the majority of a year, and therefore to higher mould growth risk in the structure. In the case of constructions that have been insulated with non-capillary mineral wool, a vapor barrier has to be included to keep moisture load below critical.
The importance of the thermal resistance of a wind barrier can be seen in Fig. 4 where at points AP1 and AP2 (wood fibreboard wind barrier with additional layer of dense mineral wool slab) the level of mould index is under the critical level and significantly lower, compared to point AP3 (wood fibreboard wind barrier only). The higher thermal resistance of wind barrier layer decreases the RH level at the critical zone, where insulation and wind barrier layers are joined. The increase of mould growth risk in the course of the lowering of the thermal transmittance was lower for some wind barriers – these materials can be described by higher thermal resistance and water vapor permeability (e.g. wood fibreboard vs OSB, see Fig. 4 and Fig. 5).

When the initial moisture content of the materials has increased (e.g. absence of rain protection for structures, no moisture safety protocol during the construction period), the timber-frame external wall’s risk of mould growth increased. Fig. 6 shows that increase of initial moisture content RH>85% of the insulation layer (which may count up to 90% of whole volume of highly insulated construction) or use of highly wet wooden details (in Fig. 6 below) will lead to mould growth as the mould index increases M>1. According to Swedish building regulations [19] and if there is no any other restrictions from producer, longterm RH level of materials above 75% is considered to be critical for mould growth. It was found in current study and confirmed by preceding research [20] as well that constructional moisture dry-out takes at least 1 year in Estonian climate if all the quality norms are fulfilled and demands that have been placed by hygrothermal design, are properly followed. In Fig. 4 and Fig. 5 the risks that arise, if vapor barrier is missing or a wind barrier with low vapor permeability or low thermal resistance is used, are clearly shown.

In the comparison of insulation materials – mineral wool and cellulose insulation – the cellulose insulation showed lower mould growth risk than mineral wool in conditions of cold climate. This was mainly due to the differences of moisture capacity and capillary moisture transfer properties of insulation materials. Cellulose insulation has higher moisture storage capacity than mineral wool and therefore moisture increase is slower. Therefore, the wall remains in the dry condition longer and RH stays lower. If the originally designed by engineer wind barrier (for example, wall type 3 of the studied house) would be combined with mineral wool insulation, it would lead to serious mould growth (mould index M=4). Therefore, it is needed always to perform the hygrothermal analysis before changing any materials.

Andersen et al. [21] showed the tendency that the moisture content behind wind barrier, measured in the north-facing facade element with mineral wool, was higher than in the facade element insulated with cellulose insulation. Pihelo and Kalamäes [20] compared mineral wool and cellulose wool behavior in timber-frame structures and pointed out that mould formation risks are considerably lower with cellulose insulation and when a proper air&vapor barrier layer is installed. Therefore, capillary transport properties and moisture capacity of wood and paper based materials should be exactly known and considered.

In the current design standard [22] the importance of hygrothermal and moisture safety design is minimized. Designers (engineers and architects) should include the hygrothermal modelling into design practice to assure the moisture safety of structures and sustainability of nZEB in the long term.

5. Conclusions

The timber-frame external wall of a detached house, designed to be PH, in Estonia with different material combinations was analyzed by hygrothermal simulations to find out the moisture influence on the hygrothermal performance of the highly insulated building envelope. The risk of mould growth was used as the performance criterion to predict the acceptability of the hygrothermal performance.

Hygrothermal simulations indicated that thermal resistance and water vapor permeability of the wind barrier layer had the strongest influence on the RH in the critical point of timber-frame external wall, between the insulation and the wind barrier surface. It is possible to keep mould index M<1 with studied insulation materials and wind barriers, in properly designed combinations, and thus help to ensure moisture safety of highly insulated building envelopes.

With wind barriers that have a higher thermal resistance and water vapor permeability (thermal resistance R≥0.8 m²·K/W; equivalent air layer thickness Sd≤0.05 m), the increase of mould growth risk was lower. When the wind barrier has low thermal resistance and vapor permeability (R<0.8 m²·K/W; Sd>0.05 m), it may need an additional thermal insulation to minimize mould formation risks in the contact surface of wind barrier and insulation layer. The drying out time of constructional moisture was longer for walls with outer layers of lower vapor permeability and/or
missing vapor barrier, which also causes a higher risk for mould growth. The results of insulation material comparison revealed that the structure has lower mould growth risk with hygroscopic cellulose insulation than with mineral wool. In conclusion, the building envelope of the nZEB needs more careful hygrothermal design and thorough consideration of different material properties. The prerequisites there for hygrothermal performance and designing are carefully considered vapor control layer, the vapor permeability of which is controlled by hygrothermal calculations, and insulation and wind barrier layers with high thermal resistance and vapor permeability.

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