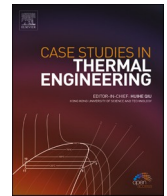


Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

Case Studies in Thermal Engineering

journal homepage: www.elsevier.com/locate/csite

Hygrothermal performance of well-insulated wood-frame walls in Baltic climatic conditions

Anatolijs Borodinecs^{a,*}, Vladislavs Jacnevs^a, Lakatos Ákos^b, Staņislavs Gendelis^c

^a Riga Technical University, Latvia

^b University of Debrecen, Hungary

^c University of Latvia, Latvia

ARTICLE INFO

Keywords:

Hygrothermal performance
Wood-frame walls
Bio-based insulation
Wind-vapour barrier ratio
Moisture management

ABSTRACT

This study investigates the hygrothermal performance of wood-frame walls in the Baltic region under varying moisture loads, comparing bio-based and conventional insulation materials. The research combines experimental climate chamber testing with DELPHIN simulations to assess moisture risk mitigation, energy efficiency and mould growth resistance. The results highlight that bio-based insulations, such as wood fibre, outperform conventional materials due to higher vapour diffusion resistance ($\mu = 5$) and superior moisture-buffering capacity. For instance, wood fibre insulation reduced the RHT-index by 30.6 % compared to mineral wool while maintaining mould indices below 0.71. Furthermore, the study identifies optimal wind-to-vapour barrier ratios, such as 1:2 for cellulose insulation, that mitigate mould risks in high-moisture conditions. The findings advocate for adopting vapour-open wall assemblies and bio-based materials to enhance building durability, energy efficiency and moisture resilience in cold climates.

1. Introduction

Throughout a building's lifespan, its external structure is subject to various influences. From an energy perspective, changes in external temperature are the most decisive, as they determine the building's heat load or heat demand. Moisture is another external factor that can have a considerable impact. Moisture in building structures affects the building materials and, consequently, the building itself [1]. From the perspective of thermal performance stability, wetting properties are crucial features of thermal insulation materials [2]. Unexpected changes in a sample's physical properties and thermal characteristics can occur due to sorbed water in its gaseous, vapour, liquid or solid state. The state of moisture within thermal insulation materials affects their physical properties in different ways: vapour state provides a smaller thermal conductivity and density change; liquid state increases thermal conductivity, has a chemical effect on some materials, can cause corrosion damage and is also aesthetically disadvantageous; ice state represents the final phase of a previously committed error; the resulting volume change can cause structural damage [3].

Despite a strong understanding of moisture management, transport mechanisms and mould growth in buildings, moisture issues persist, causing significant financial implications and poor indoor conditions. Constructing moisture-proof walls is crucial, regardless of materials or design, as moisture damage leads to additional expenses, health issues and poor indoor air quality, potentially causing Sick Building Syndrome [4]. Despite improvements in construction quality, it is likely that due to higher energy efficiency standards, some moisture-related problems have been fully eliminated. For example, increased insulation and airtightness can lower

* Corresponding author.

E-mail address: anatolijs.borodinecs@rtu.lv (A. Borodinecs).

<https://doi.org/10.1016/j.csite.2025.105772>

Received 30 November 2024; Received in revised form 6 January 2025; Accepted 7 January 2025

Available online 20 January 2025

2214-157X/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC license (<http://creativecommons.org/licenses/by-nc/4.0/>).

temperatures in exterior layers and raise indoor humidity, heightening the risk of interstitial condensation while maintaining or reducing drying potential [5].

In a broader sense, water - of which moisture-related issues are just one aspect - is responsible for approximately 75 % of building failures. Effective water management is crucial for building longevity [6]. As one of four main moisture transport mechanisms, a vapour diffusion, which is driven by water vapour pressure gradient, is primarily considered in building enclosure moisture safety calculations and is described in relevant building codes. However, in general, it rarely causes significant damage [7].

Earlier moisture control relied on simplified vapour diffusion calculations, known as Glaser method, which can be misleading because it does not consider various weather conditions and material parameters. For instance, this method unfairly disadvantages hygroscopic materials, like bio-based insulation, by predicting condensation instead of slightly increasing moisture content. However, different numerical hygrothermal simulation tools have been developed [8] to adapt corresponding models, which, in turn, are also recognized internationally [9].

Kumaran developed another calculation method [10].

The Fick diffusion equations for material flow can be described as follows.

$$\frac{\partial m_m}{\partial t} = -\rho_0 D_w \times \text{grad}(u) = -\rho_0 D_w \frac{\partial u}{\partial x} \quad (1)$$

where the left side of the equation is the density of moisture flow rate, while at the right side of the equation, the dry density of the material is (ρ_0), and the D_w diffusion coefficient with u is the moisture content (in kg/kg). The authors determined diffusion coefficients from the moisture absorption factor in the above work. Diffusion material flow is a gaseous flow in which the equalization of different concentrations causes the movement.

The moisture absorption factor A_w (reached from a water immersion experiment) divided by the maximum volumetric moisture content w_c and square the quotient, gives a diffusion coefficient as follows:

$$D_w \approx \left(\frac{A_w}{w_c} \right)^2 \quad (2)$$

Wooden structures and wood-frame walls are becoming increasingly popular in construction and are being applied to both new building projects and the renovation of existing ones. European regulations require buildings and industries to transition their energy systems toward greater efficiency, decarbonization and reliance on renewable sources. Moreover, the design process for wooden frame construction can be automated, reducing construction time and simplifying the design phase. This speeds up construction and makes the design process more efficient [11].

As mentioned before, water vapour diffusion occurs in building structures due to pressure differences between the two sides of the structure, passing through the small pores of the materials. In a heating climate, where vapour predominantly moves from the interior to the exterior, a vapour barrier is usually placed on the "warm" interior side to prevent and minimize this process [12]. That is why a general rule suggests using a highly vapour-absorbent material on the cold external side of the structure and a material with low air and vapour permeability on the warm side. To ensure a moisture-safe wood-frame wall, it is crucial to provide a sufficiently vapour-open wind barrier that allows moisture to dry out. Generally, a ratio of wind and vapour barrier water vapour diffusion resistance is recommended to be at least 1:10 [13] noted in his work that under Finnish climatic conditions, the optimal vapour diffusion resistance ratio of wall linings varies from 0 to 1:80. However, when sheathings are highly permeable to water vapour, this range could be narrowed to 0 to 1:40. In Belgium, the corresponding ratio is recommended to be from 1:6 to 1:15 [15].

Nevertheless, the introduction of bio-based insulation has called previous recommendations into question due to its favourable hygroscopic properties in comparison with conventional insulation, such as higher moisture capacity and capillary moisture transfer, which enable it to endure short-term periods of high moisture loads and effectively redistribute moisture [16]; [17], and higher diffusion resistance that allows insulation to act as a vapour barrier on its own [18]. The inclusion of ecological and recycled materials in new wood-frame projects is also explained by their compliance with the sustainability goals set by the EU policy; this approach reduces carbon emissions and promotes energy sustainability in the construction industry [19].

Comparing mineral wool and cellulose insulation application possibilities in wood-frame walls, Morelli et al. generally recommend following the 1:10 wind-vapour barrier ratio. However, for cellulose insulation, this ratio can be reduced to 1:5, or even to 1:3 or 1:1,5, if the moisture load is low and predictable. Yet, these variations only highlight the need for careful design assessments that consider geographic and used material specificity when assessing moisture safety in wall structures [20]. Another theoretical research concluded that the vapour barrier could be removed entirely from the wood-frame wall structure if insulation with sufficiently high vapour diffusion resistance, such as wood fibre insulation, is used [21]. In a milder climate of the UK, Latif et al. investigated the efficiency of hemp insulation, a more moisture-safe solution in a wood-frame wall without a vapour barrier, compared to stone wool. Additionally, wood-frame walls insulated with wood-hemp insulation, both with and without installed vapour barriers, were also considered. Although no evidence of mould growth was detected, both walls were prone to hygrothermal risk, with the wall without a vapour barrier being more vulnerable [21], [22]. A comparison of mineral wool and wood shavings insulation shows that the average relative humidity values were significantly lower for walls insulated with hygroscopic wood shavings than those insulated with non-hygroscopic mineral wool. In one of the stages of the research, the average annual relative humidity levels for wood chip thermal insulation were even lower by 5–10 %; however, in this case, the most influencing factor could have been the different U-values of the walls [23]. Similar results involving cellulose and mineral wool insulation comparison were obtained in terms of mould growth risk. The wall with the same configuration, except for the insulation type, showed a mould growth risk with mineral wool, but no such risk

was found in the wall insulated with cellulose [24]; [17].

Still, some of the research done in the past has not recorded the obvious hygrothermal advantage of installing hygroscopic bio-based insulation in wood-frame walls. Geving et al. have not found a significant difference between wood fibre and mineral wool insulation results; all tested wood-frame cells performed well, but the higher moisture capacity of the bio-based insulation slowed down the wetting and drying processes of that insulation [25]. Some similar results were obtained under moist indoor air leakage conditions, where wood fibre insulation showed a mould growth risk identical to that of walls with mineral wool. However, they can prevent undesired wetting by redistributing moisture over its volume [26]. The importance of vapour diffusion resistance and moisture capacity of insulation is emphasised by Vanderschelden et al. although the mould growth risk for mineral wool has not significantly exceeded that of cellulose [27].

Furthermore, the claim that well-insulated structures are subject to a greater hygrothermal risk remains uncertain. Some authors obtained worrying results that showed a noticeable increase in relative humidity and mould growth index values when changing only the thickness of the insulation layer of the examined wood-frame wall [17]. Others suggest that even highly insulated wood-frame walls (insulation thickness of 650 mm) show no significant moisture risk, assuming that inappropriately vapour-tight wind barriers are the main point of concern [28]. Though the moisture-related risk in highly insulated wood-frame walls could be somewhat greater, primarily due to the extended drying time of built-in moisture, it is usually sufficient to follow the general air tightness and wind-vapour barrier ratio installation requirements of the built structure, while choosing suitable building materials [29].

2. Methods

2.1. Creation of hygrothermal model

This study evaluates the feasibility of employing a traditional timber-frame wall structure in the Latvian climate with bio-based and conventional insulation without installing a vapour barrier, by utilizing dynamic hygrothermal modelling. Further simulations were carried out to achieve the determined goal using DELPHIN 6.1 software. DELPHIN is a simulation tool created at the Dresden University of Technology for the combined transfer of heat, air, moisture and various substances (e.g. salt) in porous building materials; it is used for different purposes, including the evaluation of condensation potential and the calculation of the risks of mould formation. DELPHIN was validated according to EN ISO 15026 and EN ISO 10211 standards [30], and is widely used in the scientific community. According to available statistics, DELPHIN is the second most used simulation tool for hygrothermal research [31].

2.2. Description of the experiment

Before performing the corresponding simulations, some materials were validated by the experiment. The experiment was carried out using the climate chamber. The experimental (refer to Fig. 1) wall consists of 12,5 mm plasterboard finishing boards on both sides and a 300 mm layer of wood fibre insulation, one of the ecological thermal insulation types, between wooden studs. The U-value of the wall is equal to $0,14 \text{ W}/(\text{m}^2 \cdot \text{K})$. In addition, three relative humidity and temperature sensors, using HOBO UX100-023 data loggers, were embedded in the wall at different thicknesses (marked by points A, B and C), and two more sensors were located next to the wall inside and outside the climate chamber to record the appropriate climate. These sensors record the mentioned physical parameters with 10 min interval. These data were further processed, and the identical design was simulated using DELPHIN.

As for the climatic parameters inside and outside the climate chamber, it should be mentioned that the chamber is located inside the Riga Technical University rooms, so its air parameters were not regulated (Fig. 2), constantly fluctuating around $20 \text{ }^\circ\text{C}$. On the other

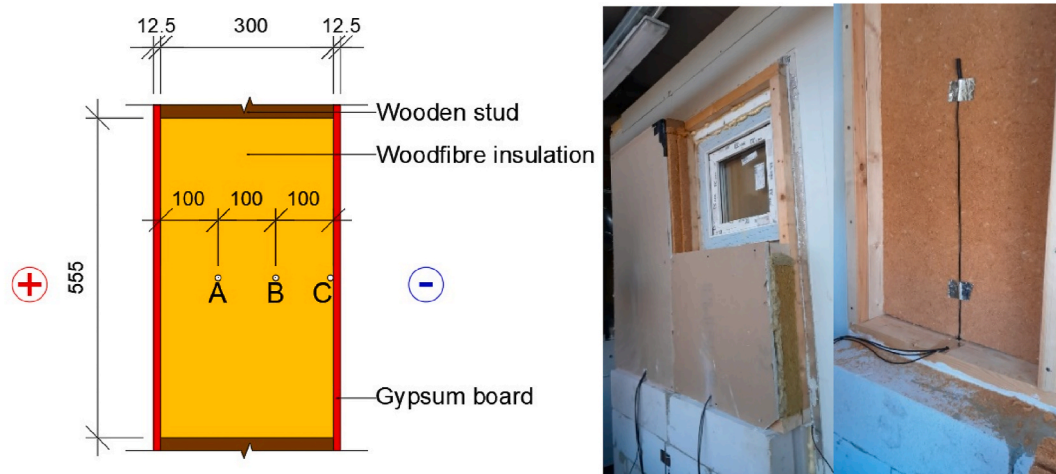


Fig. 1. Experimental wood-frame wall.

hand, the temperature of the outdoor spaces was controlled using an air conditioner which simulates the cold season temperatures characteristic of the Latvian climate. The duration of the experiment was 648 h or 27 days.

A summary of the experiment boundary conditions is shown in Table 1.

However, the second part of the study includes several DELPHIN simulations, where external wooden frame walls were analysed at different moisture loads with different thermal insulations and the vapour barrier S_d -values. As options for insulation materials that can be used in wood-frame walls in Latvia, mineral wool, cellulose and wood fibre insulation were chosen as these types of insulation are readily available on the local market and are often examined in scientific literature.

2.3. General assumption and boundary conditions

As it was already mentioned, a wall selected for a hygrothermal analysis is taken from several actual building projects and, in its base form, is quite common for the European climate zone similar to Latvia; however, in this article, this wall is presented in its modified version, characterised by atypical installation depth of the vapour barrier, which exceeds optimal 1/3 or 1/4 depth of installation of vapour barrier inside the insulation layer [14]. The observed wall (Fig. 3) consists of 25-mm gypsum board layer, a first main layer of 120-mm of insulation and wood-frame, a vapour barrier (if present), a second main layer of 195-mm of insulation and wood-frame, 9.5-mm of modified gypsum board that plays a wind barrier role, 25-mm of ventilated air gap and 8-mm cement board cladding is shown in Table 2. Some used material properties can be found in Table 2; the vapour barrier is excluded from the simulation as a material layer and appears only as an additional equivalent air layer thickness (S_d -value). Generally, material properties remained unchanged and were selected from the DELPHIN database, though the asterisk shows specific properties that were modified according to the manufacturer's information for the particular materials mentioned in the analysed building projects.

In general, considering that the U-values of the selected wall variants are affected only by the type of thermal insulation used, these values range from 0.12 W/(m²·K) for walls with mineral wool insulation to 0.14 W/(m²·K) for walls with cellulose insulation.

The inclination of the simulated wall is 90°, and the orientation is 0° (north-facing wall). The initial temperature was set to 20 °C, but with relative humidity of 80 % (50 % for simulation of the experimental wall), an air exchange rate in the ventilated cavity equals 50 1/h.

Besides, the simulations were performed in two different indoor climates. The indoor environment was chosen to be calculated based on input weather data, according to EN ISO 15026 for increased moisture load. The temperature range during a year is constant: 20–25 °C, and the range of relative humidity levels is 35–65 % for increased moisture load. Then, the real measured values (temperature and relative humidity specifically, which have higher values than the prior climate data set) from the bathrooms of the apartments in Riga were set as indoor boundary conditions. This specific case was selected because “wet” rooms, such as bathrooms, are more than usual and are highly exposed to a moisture damage risk [4]. Data collecting was fulfilled using HOBO U12-013 data loggers from the 29th of August to the 17th of October, with 10-min intervals (Fig. 4). The total duration of the simulation was 50 days.

Obtaining all required climate data for Latvian cities has presented challenges. Consequently, outdoor climate data from the Meteororm 8.2.0 database was utilized to simulate the wall in Riga, considering the following parameters at hourly intervals: ambient temperature, relative humidity, wind-driven rain, short wave solar radiation and sky radiation (Fig. 5).

However, freely available (also at hourly intervals) air temperature and relative humidity data from the local Riga meteorological station were collected and processed to verify these data. As seen in Fig. 6, the monthly mean values from 2006 to 2023 from the weather station and similar data from the Meteororm database from 2000 to 2019 correlate reasonably well. Data from Meteororm shows the lowest temperature in each month, the most considerable difference is 1.7 °C in February and March, but the relative humidity values do not have such a clear trend, the most significant difference is observed in January, when it reaches 1.7 %. Thus, it was found that the climatic data from Meteororm is reliable and can be used for simulation purposes.

As gypsum board contains wood-based elements (such as paper coating), which are susceptible to mould and moisture damage, a 1-mm thick layer near the contact with the insulation layer of this wind barrier was monitored in the simulations mentioned above, (point 1). Additionally, a 1-mm thick layer of insulation before the vapour barrier was also examined in the case of an experimental indoor bathroom climate, as moisture can accumulate in this area under high moisture loads from the interior (point 2).

Since condensation threatens wood-frame walls and mould formation, there is a need for assessment tools and models that could

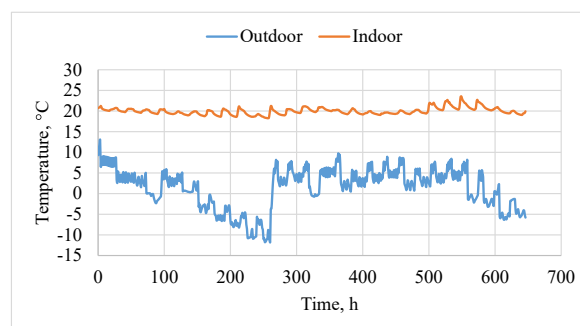


Fig. 2. Temperature variation of outdoor and indoor environments during the experiment.

Table 1

A summary of the experiment boundary conditions.

Experiment	Climate data		Comments
	Outdoor	indoor	
1 theoretical	Meteonorm 8.2.0	EN ISO 15026 for increased moisture load	In combination with the experiment nr3 used for the validation of theoretical model
2 theoretical	Meteonorm 8.2.0	Measured temperature and relative humidity in the bathroom	
3 practical	Average $(-2,62)^{\circ}\text{C}$ fluctuation from 6,5 to $(-15,5)$	Average $19,98^{\circ}\text{C} \pm 0,84^{\circ}\text{C}$	Measurements in the climatic chamber (Fig. 2)

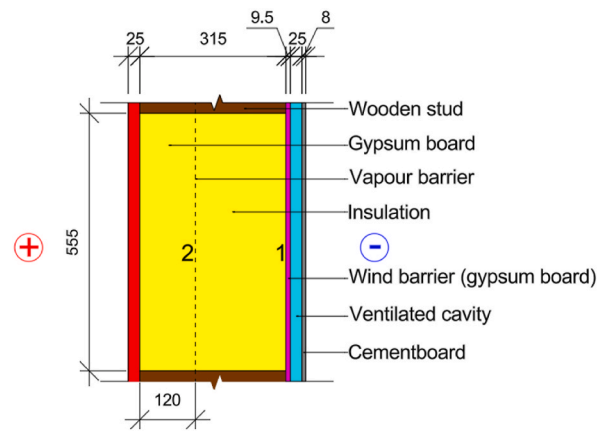


Fig. 3. DELPHIN studied wood-frame wall.

Table 2

Properties of the simulated materials.

DELPHIN ID	Material	Bulk density, kg/m ³	Specific heat capacity, J/(kg·K)	Thermal conductivity, W/(m·K)	Water vapour diffusion resistance factor -	Water uptake coefficient, kg/(m ² ·s ^{0.5})	Effective saturation, kg/m ³	Hygroscopic sorption value at RH = 80 %, kg/m ³
599	Gypsum board	680*	1826	0.21*	10*	0.18	574.9	8.8
646	Mineral wool	112*	840	0.035*	1	0	900	0.2
580	Cellulose	55.2	2544	0.04*	2.3*	0.56	780	6.3
693	Wood fibre insulation	50*	2100*	0.038*	5*	0.0029	530	17.9
599	Wind barrier (gypsum board)	726*	1826	0.25*	15*	0.18	574.9	8.8
16	Air gap	1.3	1050	0.138	0,4	1*10 ⁻⁷	1000	0
654	Cement board	1158.8	1188	0.313	26.4	0.01	283.6	70.9

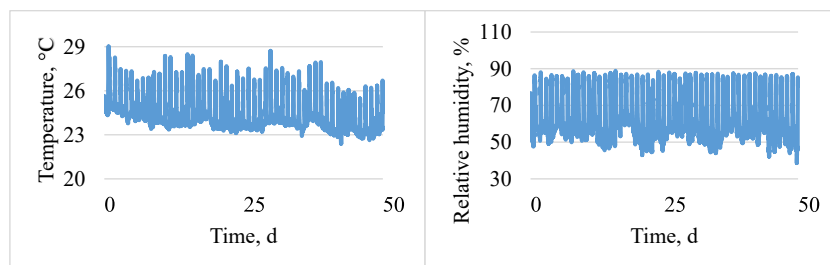


Fig. 4. Measured boundary condition data for the bathroom simulation.

help prevent such failures already at the design stage. When introducing the used mould model, it should be noted that the relative humidity level at which mould growth begins is often set as high as 80 %, which is a relevant value for biogenic and timber-containing materials. In addition, the corresponding temperature is set to 0 °C because the growth of mould practically cannot take place at negative temperatures [32].

Assessing mould growth risk in the selected wall structure can be effectively done using the VTT model, which is incorporated into DELPHIN. This model, created by Hukka and Vittanen in Finland [33], has received wide recognition over the years and uses Equation (3). Firstly introduced as an empirical model for mould growth prediction for timber, today it can also be used for other typical building materials; hence, factors only related to timber materials, W (timber species) and SQ (surface quality), are applicable in this specific case, otherwise they are equal to zero ([32]; H [34]).

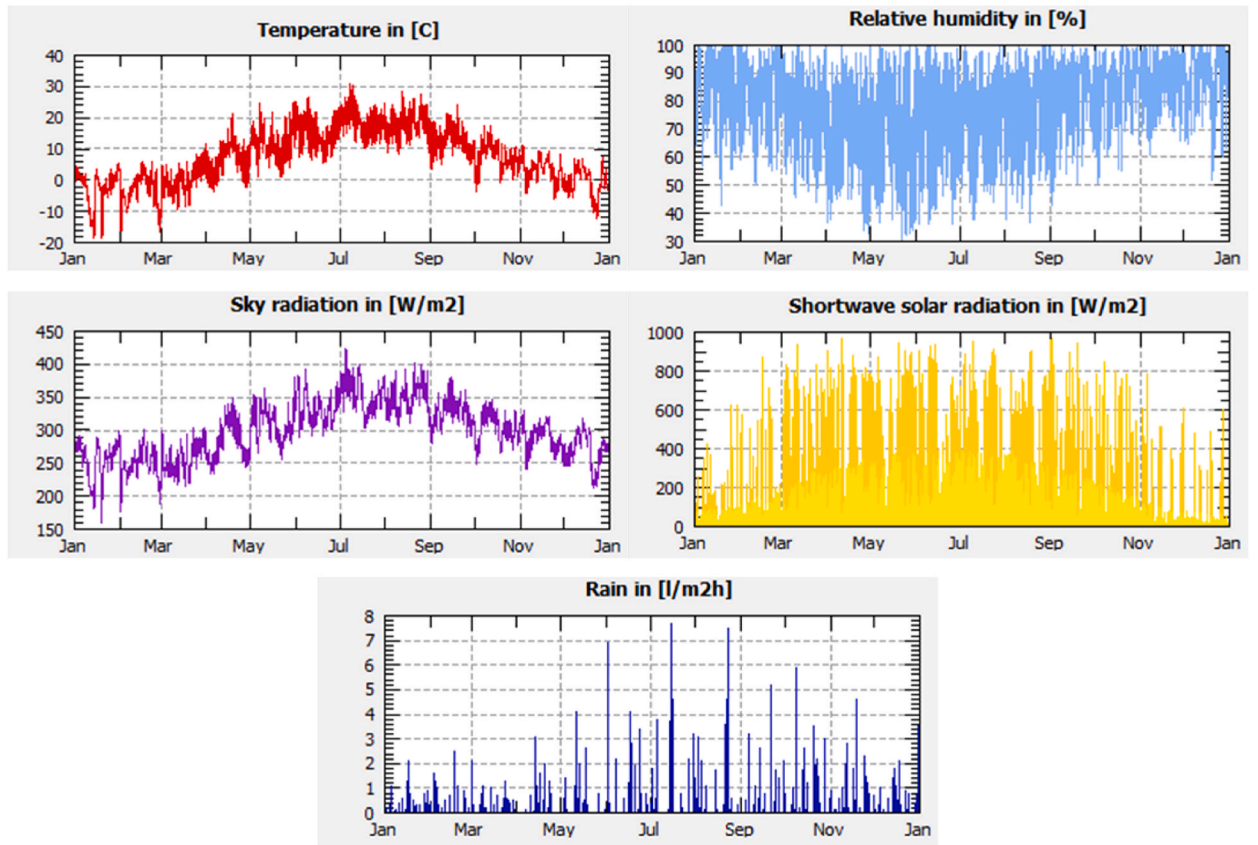


Fig. 5. Outdoor climate data.

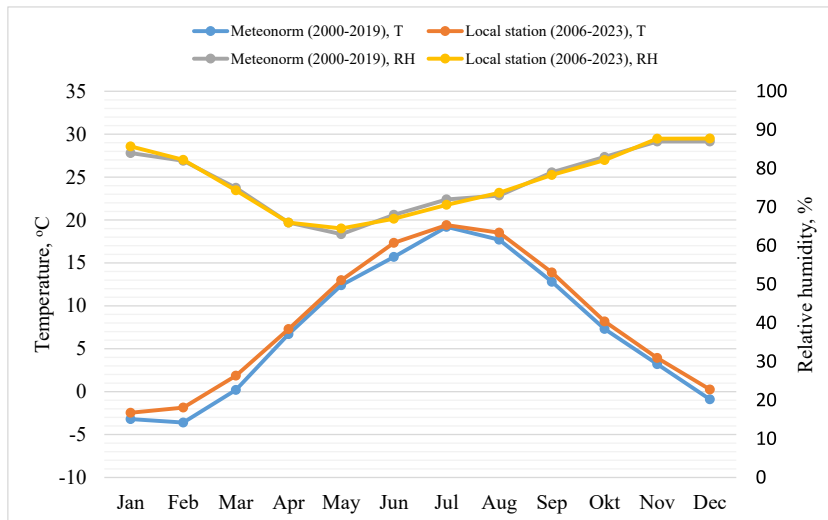


Fig. 6. Comparison of average month temperature and relative humidity values for Riga.

$$\frac{dM}{dt} = \frac{1}{7 \cdot \exp(-0,68 \cdot \ln T - 13,9 \cdot \ln RH + 0,14 \cdot W - 0,33 \cdot SQ + 66,02)} \cdot k_1 \cdot k_2, \quad (3)$$

where M – mould index;

- t – time;
- T – temperature;
- RH – relative humidity;
- W – timber specie;
- SQ – surface quality;
- k_1 – mould growth intensity coefficient;
- k_2 – mould growth intensity moderation coefficient.

The evaluation involves setting parameters such as relative humidity, temperature and material-specific characteristics. The model produces a mould index (M-index), which ranges from 0 to 6, indicating the extent of mould damage on materials [35]. Risk interpretation is based on a traffic light classification system, and in this study, as only surfaces not in direct contact with indoor air are inspected, an M-index <2 is chosen to be a threshold, which also signifies no risk and is marked as green, ensuring a conservative assessment approach (H. [34]).

Knowing that it is also obligatory to set material-specific parameters to utilize the VTT model, the selection of the appropriate values is complex and not straightforward, as various sources demonstrate inconsistency. To predict mould growth accurately when this growth has been observed, it is recommended to use the material sensitivity class either “sensitive” or “susceptible”, even though some materials may belong to other classes [36]. Consequently, the relevant choices were made as follows: for gypsum board material, the sensitivity class was designated as “sensitive”, while the surface sensitivity class was set to “very sensitive”, indicating a soiled surface, complete with organic dust or aged material. The mould growth decline rate was set to “almost no decline”. For insulation materials at Point 2, the parameters remained the same, except for the mineral wool sensitivity class which was set to “medium resistant” [37].

Another parameter for evaluating the possibility of mould growth is the so-called cumulative RHT-index, which reflects the total effect of moisture and temperature on the structure under consideration [18]:

$$RHT = \sum (\varphi - \varphi_{\min}) \cdot (T - T_{\min}), \text{ ja } \varphi > \varphi_{\min} \text{ un } T > T_{\min}, \quad (4)$$

kur RHT – hygrothermal response index;

- RH – relative humidity, %;
- RH_{\min} – the minimum relative humidity at which there is a risk of mould growth, %;
- T – temperature, °C;
- T_{\min} – the minimum temperature at which there is a risk of mould growth, °C;

Equation 4 sums all values for each simulation or measurement interval. This equation is convenient for comparing similar structures when choosing alternative building materials for specific building elements [18].

DELPHIN simulations usually lasted three full years. If the mould growth index did not reach a stable value, additional simulations with extended durations were conducted.

3. Results and discussions

Before proceeding to the experimental results from the climatic chamber and their comparison with DELPHIN simulated models,

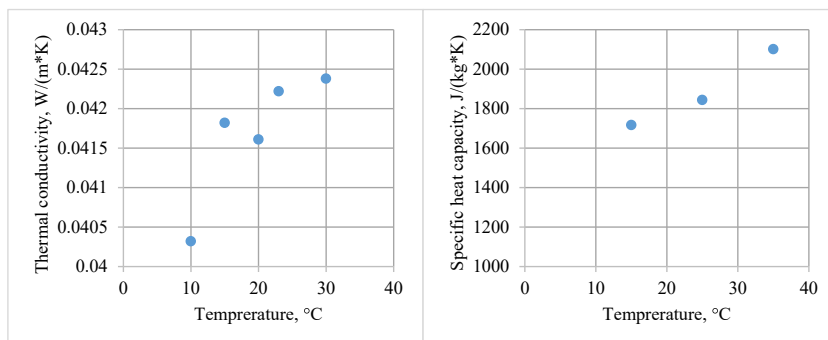


Fig. 7. Thermal conductivity and specific heat capacity measurements of wood fibre board.

measurements of some basic hygrothermal parameters of wood fibre insulation, conducted in the accredited laboratory of the University of Latvia, are presented.

Measurements of thermal conductivity and specific heat capacity were made in a Netzsch 446 Lambda heat flow meter (HFM), which is appropriate for insulation materials with thermal conductivities up to 1 W/(m·K). The meter operates in compliance with ASTM C 518, ISO 8301, DIN EN 12667, DIN EN 13163 and JIS A 1412 test methods. Based on them, $\lambda_{10} = 0.40$ W/(m·K), but C_p is in the range of 1717 and 2101 J/(kg·K) (Fig. 7). Its accuracy is about 2 %. Moreover, a water vapour permeability test in GINTRONIC GraviTest 9400-50 according to EN ISO 12572 (method A) was held, where under constant conditions of 23 °C and 50 % of relative humidity, the average insulation water vapour diffusion resistance (μ -value) was 2.56 (see Fig. 8).

Although the obtained wood fibre insulation data are not as optimistic as values provided by the manufacturer and two out of three examined parameters are closer to those of cellulose insulation used in the DELPHIN tool, it was decided to remain committed to the predefined values. This decision was made due to the difficulty in predicting how this material will perform in actual construction situation, given potential variations in storage conditions. Besides that, the mentioned measurements were made individually for one board and not confirmed by the more detailed investigation. In addition, another water vapour permeability test was conducted using a similar material. Researchers at Aalborg University obtained a μ -value of 5,88, which is closer to the given value [38].

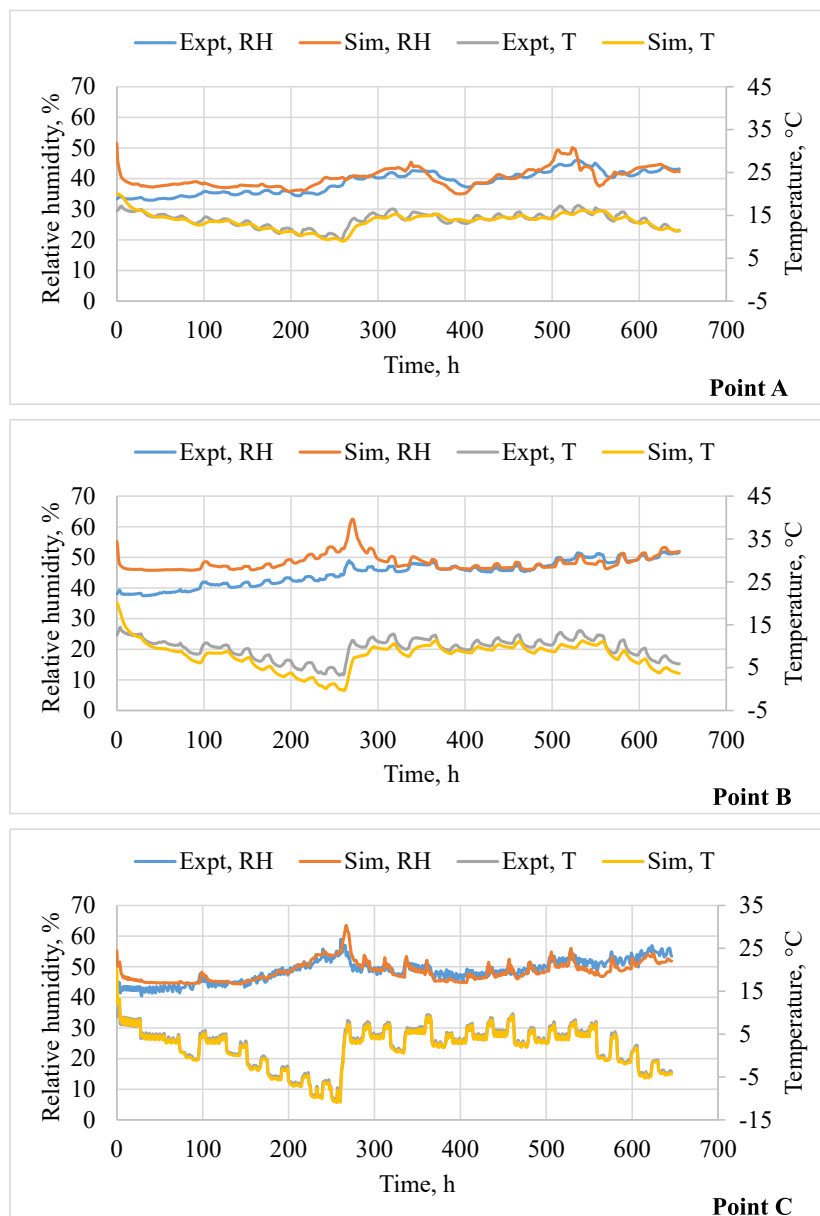


Fig. 8. Comparison of experimental wall relative humidity and temperature values with DELPHIN simulations.

Advancing to an examination of the experimental findings, it can be concluded that the majority of the curves closely align with those created from the measurement data. However, the most significant discrepancy remains evident at all points of the relative humidity curves during the initial stage. This could be explained by the fact that the humidity change has greater inertia than the temperature change. In addition, as demonstrated later, the simulated curves at point C align most closely with the experimental curves. This is because point C is closer to the changing outdoor air and responds more quickly and accurately to evolving conditions.

During the mathematical analysis, it was determined that the average absolute difference between the simulation and measurement points is, respectively, from point A to point C: 2.3 %; 3,8 %; 1.7 % for relative humidity values and 0.6 °C; 1.9 °C; 0.4 °C for temperature values.

The standard deviation, or root mean square deviation, often used to compare hygrothermal measurement and simulation data, is also calculated for each point. 10 % and 5 °C are accepted as reference values that should not be exceeded [39]. Obtained values from point A to point C: 2.8 %; 5 %; 2.2 % for relative humidity values and 0.9 °C; 2.1 °C; 0.6 °C for temperature values. Thus, it can be argued that at each point, both parameters are lower than the reference values.

The last comparison criterion is the Pearson correlation coefficient, which shows the linear correlation between two sets of data. In respective values from point A to point C: 0.75; 0.43; 0.8 for relative humidity values and 0.91; 0.94; 0.99 for temperature values. As it can be seen, the temperature curves have a very high correlation (above 0,9 at all points), and the relative humidity curves have a sufficiently high correlation at points A and C. In contrast, a weak correlation at point B can be explained by the already mentioned large discrepancy at the beginning of the experiment. If the same calculation is made only for the curve after 300 h, it will reach 0.76.

To frame the information mentioned above, it can be concluded that DELPHIN software is suitable for further analysis of external timber frame walls. All subsequent graphs were obtained using DELPHIN software.

Starting the overview of simulation results with general relative humidity levels under increased moisture load, it should be noted that condensation in DELPHIN occurs when relative humidity reaches 95 %. It is clear from Fig. 9 that only walls insulated with wood fibre are free of condensation, although more vapour tight barriers also tend to reduce moisture related risks at point 1 insufficiently. Furthermore, average relative humidity values during the heating season in Latvia, which lasts from the beginning of October till the beginning of May, exceed the 80 % limit in every simulated wall, indicating a specific risk of mould growth.

Another comparison of all structures is made through the RHT-index, which was calculated for each of them only for the last third year of the simulation. This was done to avoid the unstable values at the beginning of the first year (Fig. 10).

Assuming a wall with rock wool insulation and a vapour barrier with an S_d -value equal to 64 m as the base scenario, the poorest results (i.e., the highest RHT-indexes) were obtained with mineral wool thermal insulation which has a lower vapour barrier S_d -value, and cellulose thermal insulation without a vapour barrier. This is consistent with the analysis of relative humidity values. In the case of wood fibre insulation without a vapour barrier, the RHT-index is 30,6 % lower compared to the base scenario (in general, wood fibre insulation produces the best results). This suggests the possibility of abandoning the installation of a vapour barrier when using ecological thermal insulation. Although cellulose thermal insulation, despite the relative RHT-index reduction at the same installed vapour barrier S_d -value compared to mineral wool thermal insulation, it still performs worse in a direct comparison with the base scenario when no vapour barrier is used (by 8.3 %).

As mould growth index is calculated considering relative humidity and temperature parameters in a given area of interest, which remain consistent year after year due to fixed indoor and outdoor climates, it is apparent that the mould index will also reach a quasi-steady state. Consequently, the maximum values of the mould growth index, which return to their peak each year, are considered reasonable and representative for evaluating observed building structures.

Thus, Fig. 11 clearly shows that, although exterior walls with cellulose thermal insulation without a vapour barrier showed the

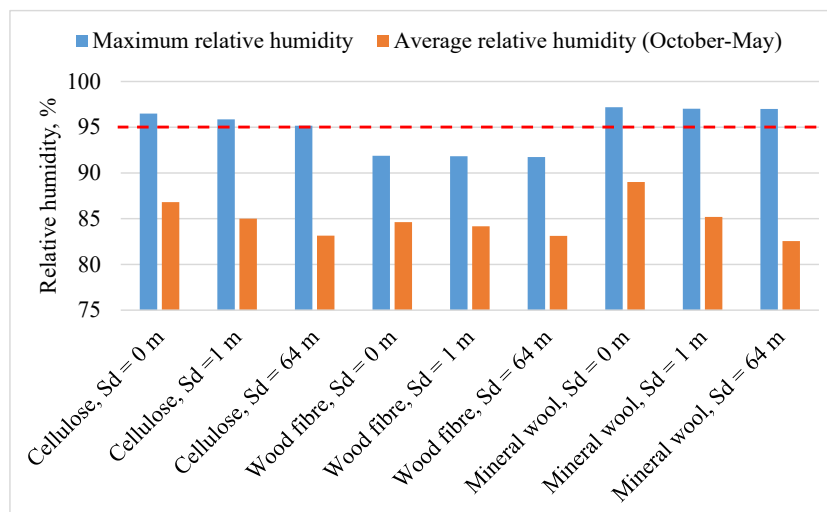


Fig. 9. Relative humidity level at point 1.

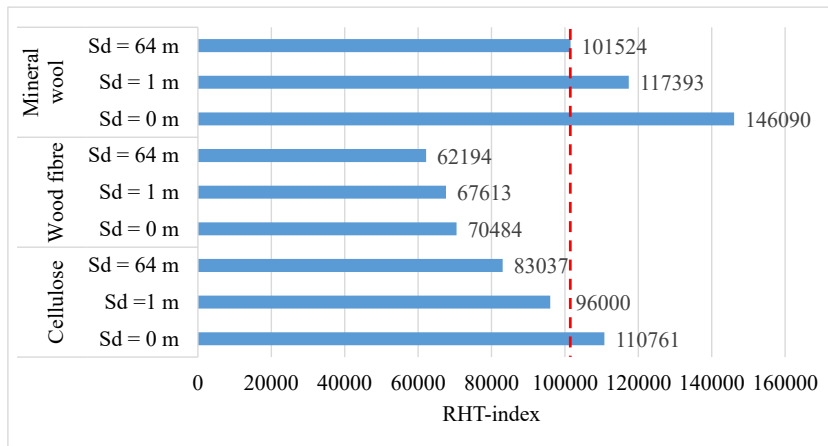


Fig. 10. RHT-index at point 1.

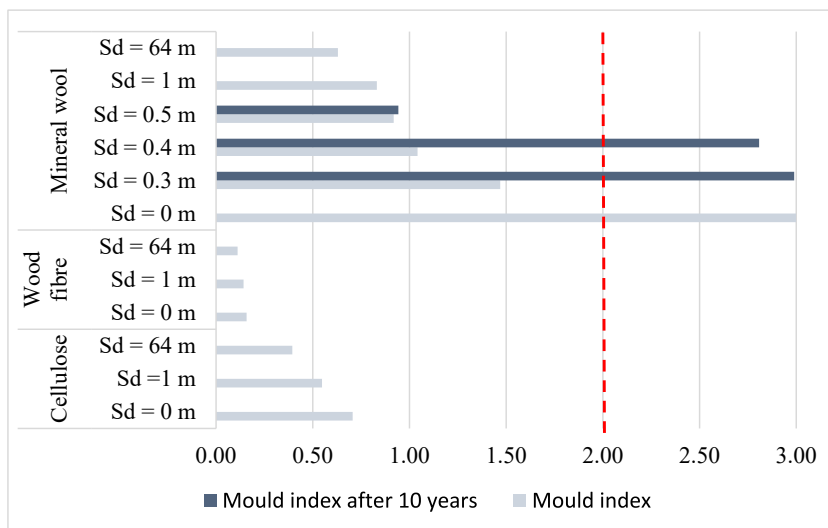


Fig. 11. Maximum mould index at point 1.

worse result than the base scenario according to the RHT-index, this design does not contribute to significant activation of mould on the inner surface of the wind barrier. None of the walls exceed the relevant factor of 2, with the maximum being 0.71. Looking at the results of wood fibre, they again predict the lowest maximum M-index (0,16) among the selected insulation materials. This can be explained by the higher μ -value (5 vs 2.3) and the higher possible moisture storage below the condensation limit. The only wall that is not safe according to the chosen assessment methodology is the one with mineral wool insulation and with no vapour barrier or at Sd-value equal to 0 m. In this case the given M-index value has not stabilized, which means that the situation will only worsen in the coming years, predicting an even more unfavourable outcome.

Since the results from the original stimulations indicate that walls with mineral wool insulation cannot be protected from the risk of mould growth, additional simulations were performed to determine the minimum yet optimal wind-vapour barrier ratio. For this, without changing the constructive walls solution, vapour barrier Sd-values between the previously examined 0 m and 1 m were chosen, starting with an Sd-value of 0.3 m and using a step of 0.1 m. A 10 years simulation was conducted. Still, Fig. 11 reveals that the Sd-value of 0,5 m is sufficient to ensure a slight increase in the M-index. Other values allow mould index to approach an unacceptable maximum value only after 10 years of simulation, a trend that would not be noticeable if the simulation lasted only 3 years.

All in all, knowing S_d -value of the wind barrier, along with its' thickness and water vapour resistance values (0.1425 m), makes it easy to calculate the optimal minimal wind-vapour barrier ratio for the observed structure, which is 1:3.5.

Fig. 12 compares modelling results where the bathroom moisture load - introduced 's by the authors of this article to test the performance of timber frame exterior walls under non-standard conditions not described in the current EN ISO 15026 – applies to both areas behind the vapour barrier and the wind barrier.

With the help of the first additional simulation, a positive result for cellulose insulation is obtained with the Sd-value of the vapour

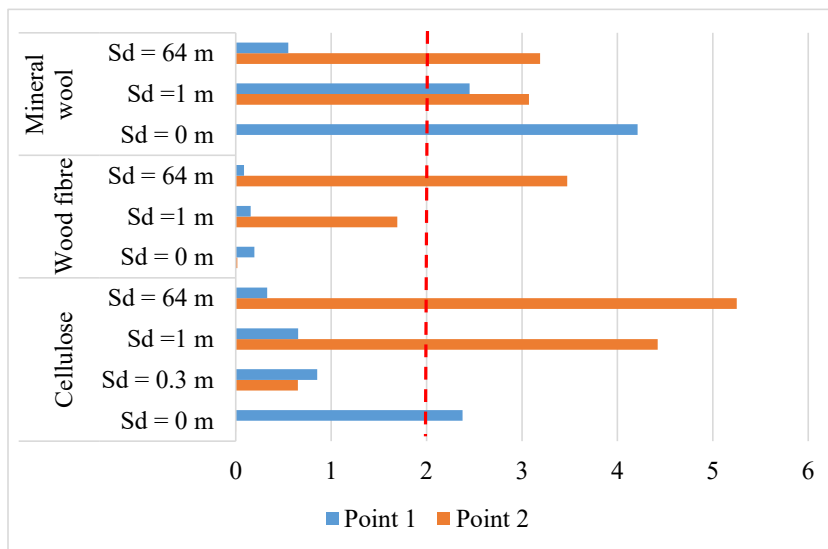


Fig. 12. Maximum mould index at point 1 and point 2 under the experimental bathroom climate.

barrier equal to 0.3 m. At point 1 the M-index is stable, reaching a maximum of 0.85, while at point 2 the M-index becomes more than 3 times lower in comparison with the option where no vapour barrier is used. Thus, the optimal wind-vapour barrier ratio for a wood frame exterior wall with cellulose thermal insulation under this moisture load is 1:2.

In contrast to cellulose thermal insulation, wood fibre insulation again demonstrates the possibility of omitting the vapour barrier. However, it is important to note that under such extreme moisture loads, excessively high Sd-values of vapour barriers can be dangerous, as they may provoke mould growth inside the insulation layer.

Nevertheless, bars related to mineral wool insulation in Fig. 12 point out that for all variations of vapour barriers, the mould index at one of the points exceeds the factor equal to 2. In addition, it was impossible to reach acceptable values even for vapour barrier Sd-values between the used ones. This means that this construction is unsafe with any vapour barrier, requiring a review of the overall wall design, for example, reducing the depth of the vapour barrier installation or inserting an additional thermal insulation layer after the wind barrier.

Final simulations were run to control condensation accumulation under highly humid and warm indoor climates. It is clear from Fig. 13 that the amount of condensate throughout the observed walls does not accumulate in both cases, without and with the most impermeable vapour barrier, which was chosen because they previously showed the biggest M-index at one of the examined areas. In both cases, a certain amount of condensate can be observed in the cold season (approximately from the end of October to the end of March), where the maximum amount is 0.53 kg, which, however, dries up during the year. Thus, it can be stated that all the constructions under review are safe from this point of view.

4. Conclusions

This study analyses wood-frame wall structures insulated with several bio-based and conventional materials under Baltic climate

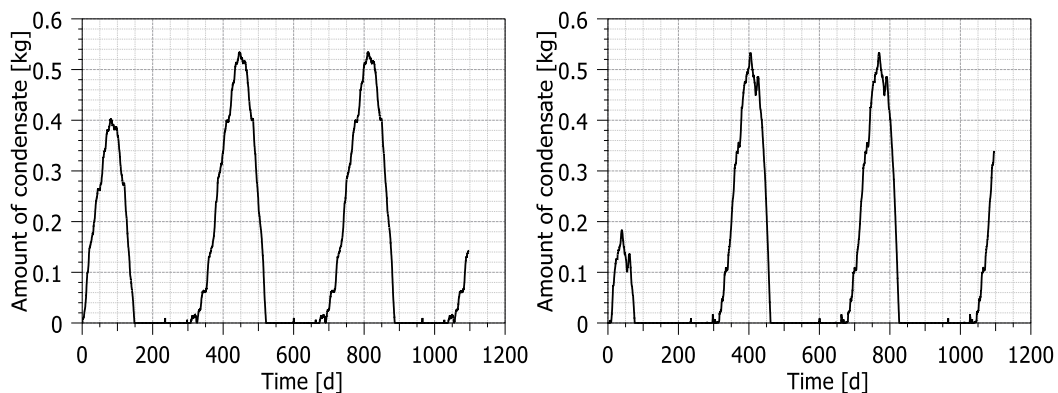


Fig. 13. Amount of condensate in a whole structure behind a ventilated cavity with mineral wool insulation, Sd = 64 m (left) and Sd = 0 m (right).

- [10] M.K. Kumaran, Moisture diffusivity of building materials from water absorption measurements, *J. Therm. Envelope Build. Sci.* 22 (4Apr 1999)Pages268–367 (1999).
- [11] A. Borodinec, A. Geikins, E. Barone, V. Jacnevs, A. Prozumens, Solution of bullet proof wooden frame construction panel with a built-in air duct, *Buildings* 12 (2022), <https://doi.org/10.3390/buildings12010030>.
- [12] V. Cammalleri, E.G. Lyon, Condensation in the building envelope: expectations and realities, in: *SSPC 2003: the Industrial Protective Coatings Conference and Exhibit, New Orleans, 2003*, pp. 210–219.
- [13] L. Gullbrekken, B. Time, Towards upgrading strategies for nZEB-dwellings in Norway, *J. Sustain. Architect. Civ. Eng.* 25 (2019) 35–42, <https://doi.org/10.5755/j01.sace.25.2.22067>.
- [14] J. Vinha, *Hygrothermal Performance of Timber-Framed External Walls in Finnish Climatic Conditions: A Method for Determining the Sufficient Water Vapour Resistance of the Interior Lining of a Wall Assembly* (Ph.D. Thesis), Tampere University of Technology, Tampere, 2007.
- [15] M. Vanpachtenbeke, J. Van den Bulcke, J. Van Acker, S. Roels, Hygrothermal performance of timber frame walls with brick veneer cladding: a parameter analysis, in: *E3S Web of Conferences*, 2020, <https://doi.org/10.1051/e3sconf/20201720>.
- [16] P. Pihelo, H. Kikkas, T. Kalamees, Hygrothermal performance of highly insulated timber-frame external wall, in: *Energy Procedia*, Elsevier Ltd, 2016, pp. 685–695, <https://doi.org/10.1016/j.egypro.2016.09.128>.
- [17] P. Pihelo, T. Kalamees, The effect of thermal transmittance of building envelope and material selection of wind barrier on moisture safety of timber frame exterior wall, *J. Build. Eng.* 6 (2016) 29–38, <https://doi.org/10.1016/j.job.2016.02.002>.
- [18] A.E. Leszmann, M. Morelli, T.V. Rasmussen, Moisture performance requirements for insulation in exterior wood-frame walls without a vapour barrier, *J Phys Conf Ser* 2654 (2023) 12115, <https://doi.org/10.1088/1742-6596/2654/1/012115>.
- [19] S.-V. Georgescu, D. Şova, M. Campeanu, C. Coşoreanu, A sustainable approach to build insulated external timber frame walls for passive houses using natural and waste materials, *Forests* 13 (2022), <https://doi.org/10.3390/f13040522>.
- [20] M. Morelli, T.V. Rasmussen, M. Therkelsen, Exterior wood-frame walls—wind–vapour barrier ratio in Denmark, *Buildings* 11 (2021), <https://doi.org/10.3390/buildings11100428>.
- [21] E. Latif, M.A. Ciupala, S. Tucker, D.C. Wijeyesekera, D.J. Newport, Hygrothermal performance of wood-hemp insulation in timber frame wall panels with and without a vapor barrier, *Build. Environ.* 92 (2015) 122–134, <https://doi.org/10.1016/j.buildenv.2015.04.025>.
- [22] E. Latif, M.A. Ciupala, D.C. Wijeyesekera, The comparative in situ hygrothermal performance of Hemp and Stone Wool insulations in vapour open timber frame wall panels, *Construct. Build. Mater.* 73 (2014) 205–213, <https://doi.org/10.1016/j.conbuildmat.2014.09.060>.
- [23] J. Hietikko, E. Tuominen, I. Valovirta, J. Vinha, Timber-framed exterior walls insulated with wood shavings: a field study in a nordic climate, *Build. Environ.* 254 (2024), <https://doi.org/10.1016/j.buildenv.2024.111371>.
- [24] J. Langmans, S. Roels, What are the hygrothermal consequences of applying exterior air barriers in timber frame construction in Europe? *J Build Perform Simul* 8 (2015) 191–204, <https://doi.org/10.1080/19401493.2014.899733>.
- [25] S. Geving, E. Lunde, J. Holme, Laboratory investigations of moisture conditions in wood frame walls with wood fiber insulation, in: *Energy Procedia*, Elsevier Ltd, 2015, pp. 1455–1460, <https://doi.org/10.1016/j.egypro.2015.11.170>.
- [26] N.S. Bunkholt, P. Røither, L. Gullbrekken, S. Geving, Effect of forced convection on the hygrothermal performance of a wood frame wall with wood fibre insulation, *Build. Environ.* 195 (2021), <https://doi.org/10.1016/j.buildenv.2021.107748>.
- [27] B. Vanderschelden, N. Van Den Bossche, M. Steeman, Hygrothermal performance of bio-based insulation material in wood-frame walls exposed to unintended moisture sources, in: *1st International Conference on Moisture in Buildings*. London, 2021, <https://doi.org/10.14293/icmb210063>.
- [28] K. Viljanen, X. Lu, An experimental study on the drying-out ability of highly insulated wall structures with built-in moisture and rain leakage, *Appl. Sci.* 9 (2019), <https://doi.org/10.3390/app9061222>.
- [29] L. Gullbrekken, S. Geving, B. Time, I. Andresen, J. Holme, Moisture conditions in well-insulated wood-frame walls. Simulations, laboratory measurements and field measurements, *Wood Mater. Sci. Eng.* 10 (2015) 232–244, <https://doi.org/10.1080/17480272.2015.1064473>.
- [30] L. Sontag, A. Nicolai, S. Vogelsang, Validierung der Solverimplementierung des hygrothermischen Simulationsprogramms Delphin, Dresden, 2013.
- [31] Y. Yıldız, An overview of hygrothermal simulation tools, *Dicle Üniversitesi Fen Bilimleri Enstitüsü Dergisi* 10 (2021) 273–286.
- [32] T. Ojanen, H. Viitanen, R. Peuhkuri, K. Lähdesmäki, J. Vinha, K. Salminen, Mold growth modeling of building structures using sensitivity classes of materials, in: *Thermal Performance of the Exterior Envelopes of Whole Buildings XI*, 2010.
- [33] A. Hukka, H.A. Viitanen, A mathematical model of mould growth on wooden material, *Wood Sci. Technol.* 33 (1999) 475–485, <https://doi.org/10.1007/s002260050131>.
- [34] H. Viitanen, M. Krus, T. Ojanen, V. Eitner, D. Zirkelbach, Mold risk classification based on comparative evaluation of two established growth models, in: *Energy Procedia*, Elsevier Ltd, 2015, pp. 1425–1430, <https://doi.org/10.1016/j.egypro.2015.11.165>.
- [35] S. Fantucci, F. Isaia, V. Serra, M. Dutto, Insulating coat to prevent mold growth in thermal bridges, in: *Energy Procedia*, Elsevier Ltd, 2017, pp. 414–422, <https://doi.org/10.1016/j.egypro.2017.09.591>.
- [36] P. Johansson, L. Lång, C.M. Capener, How well do mould models predict mould growth in buildings, considering the end-user perspective? *J. Build. Eng.* 40 (2021) <https://doi.org/10.1016/j.job.2021.102301>.
- [37] A. Nicolai, H. Fechner, PostProc 2 manual [WWW Document]. URL, https://bauklimatik-dresden.de/postproc/help/en/index.html#_vtt_mould_model, 2020. (Accessed 22 March 2024).
- [38] Ljevakovic, R., Moric, I., Szefer, G., n.d. Experimental Investigation of the Hygric Properties of Bio-Based Building Insulation Materials with Novel Apparatus and Procedure.
- [39] N.K. Friis, E.B. Møller, T. Lading, Hygrothermal assessment of external walls in Arctic climates: field measurements and simulations of a test facility, *Build. Environ.* 238 (2023), <https://doi.org/10.1016/j.buildenv.2023.110347>.