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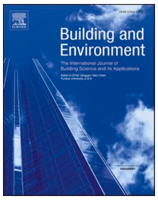

Effect of forced convection on the hygrothermal performance of a wood frame wall with wood fibre insulation

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ABSTRACT

Wood-based thermal insulation materials have interesting hygroscopic characteristics because of their high moisture capacity. The present paper investigates the moisture conditions in wood-frame walls with wood fibre thermal insulation. The effect of forced convection of moist air into the construction is studied in particular. Laboratory measurements were carried out on a full-scale wall model divided in five sections with various configurations. The wall sections had different combinations of exterior air barrier, thermal insulation and interior vapour retarder. Each section was prepared with an air leakage to simulate supply of moist air to the wall construction through forced convection. The measurement results provided insight in the moisture conditions in the wall and internal distribution of moisture in the wall sections. The results show that walls with wood fibre insulation may have the same risk of high moisture levels as walls with mineral wool insulation. However, the results indicate that wood fibre insulation absorbs condensation and melting water, while the mineral wool does not. Hence, the results imply that the wood fibre insulation has the benefit of distributing the moisture over a larger volume than the mineral wool insulation. Furthermore, the investigations indicate that using an exterior air barrier with high thermal resistance results in a generally lower moisture level in the wall construction, which can be considered favourable regarding risk of mould growth.

1. Introduction

1.1. Wood-fibre based insulation

Growing awareness of environmental sustainability have given increased attention to energy efficiency and emission reduction in the building sector. In addition to energy use, focus on embedded energy and CO_2-emissions coupled to building materials has become essential in the development towards concepts as Zero Emission Buildings [1]. In order to meet the demands of improved energy efficiency and environmental sustainability, the choice of building materials plays an important role [2–4]. Thermal insulation for building applications is commonly produced based on materials from petrochemicals (often polystyrene) or minerals (glass or rock) [5]. The general awareness of sustainability has, however, encouraged an increased focus on thermal insulation based on natural or recycled materials. In the given context, the favourable carbon footprint of wood makes wood-fibre based insulation an interesting choice. Wood-fibre based insulation could be beneficial as it may demand less energy during production and may contribute to lower emissions compared to mineral or petrochemical based insulation materials [6–9], at the same time as inheriting good insulating properties [10–12].

At the same time as assessing the environmental impact of materials, their suitability for use in buildings must be evaluated. In addition to the favourable carbon footprint, wood-based insulation products have interesting hygroscopic characteristics, as their moisture capacity is higher than for conventional materials like mineral wool insulation [12–15]. Due to this characteristic, using natural and highly hygroscopic insulation may have a positive effect on the moisture conditions in wood-frame constructions [16–19]. Understanding the performance of constructions with wood-fibre insulation is highly dependent on understanding the hygrothermal performance of the material. Therefore, the performance in regard of moisture exposure due to for example air leakages must be taken into account. In a wood-frame construction, local air leakages from the interior may lead to increased moisture content in the insulation layer [20]. Given an airtight continuous layer

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on the inside of the insulation layer, air leakages will not be a problem. However, deficiencies in the airtight layer may allow for forced convection induced by pressure differences across the building envelope. Forced convection in air permeable insulation will affect the moisture distribution in the construction [21], as redistribution of moisture occurs when water vapour is transported with the circulation of air through the insulated cavities of a timber frame construction.

1.2. Previous research

The influence of air leakages and air exfiltration on wood-frame walls have been investigated through experimental studies [21–26], simulations [27–29] and hygrothermal simulations combined with experiments [30–32]. The literature includes different analyses of the behaviour and hygrothermal properties of natural and hygroscopic insulation materials. Both experimental research in laboratory and field studies, as well as numerical studies, have been performed.

Geving et al. [33] performed a laboratory investigation on the moisture conditions in 15 test cells (600 × 600 mm) with 300 mm wood fibre or mineral wool insulation. Different combinations of interior vapour barriers and exterior air barriers in a Nordic climate during summer and winter conditions were studied. Wood fibre and mineral wool showed similar performance in regard to RH at the external side of the insulation layer. Depending on the type of exterior air barrier, the wood fibre insulation performed similar or slightly worse than mineral wool during winter conditions and similar or slightly better than mineral wool during summer conditions. The mineral wool showed fast wetting and drying. The use of thick wood fibre boards as exterior air barrier or smart vapour barrier had a positive influence on the moisture conditions.

Different organic (among others wood fibre) and mineral based insulation products were tested under normal use in dwellings in a field study by Rasmussen et al. [34]. The wall structures were constructed without internal vapour barrier, while a PE vapour barrier was used in the roof structures. Measurements of moisture content over a period of two years showed no risk of moisture problems for any of the materials.

Latif et al. [35] performed a study on a full-scale wood-frame test building in Wales, comparing the hygrothermal performance of hemp insulation and stone wool insulation. The outdoor climate was comparable to Nordic climate. The walls of the building were vapour open, with no vapour barrier. The study showed that both walls with hemp and stone wool had a risk of mould growth. The likelihood of condensation in the insulation layer seemed to be higher when using stone wool insulation. A follow-up study by Latif et al. [36] on the same wood-frame test building investigated the hygrothermal performance of the timber frame walls with and without a vapour barrier. In this study a wood-hemp composite insulation was investigated. The study showed that the risk of condensation was higher when no vapour barrier was used. Furthermore, a delay was observed in the external part of the insulation in response changes of the internal relative humidity.

Simonson et al. [18] carried out a field study on a wood-frame building with cellulose insulation in the walls and roof. The study found low risk of mould growth after the initial period of drying of built-in moisture. The authors also performed hygrothermal simulations which showed that the indoor vapour resistance should be larger than the outdoor vapour resistance by a factor of more than 3:1 to minimize mould growth. This was valid both for mineral wool and cellulose insulation. The study indicated that cellulose performed slightly better than mineral wool insulation in regard to risk for mould growth as the moisture capacity of the cellulose insulation reduced the duration of time that mould growth was possible.

Levin et al. [37] also carried out a field study combined with hygrothermal simulations calibrated to the field measurements. Measurements were conducted in wood-frame houses with cellulose insulation in the walls and roof. The houses had vapour open interior and exterior layers. The measurement results showed no immediate danger of moisture damages. However, the hygrothermal simulations showed that there was a risk of condensation given moisture supplies larger than 2–4 g/m^3.

Hygrothermal simulations on wood frame walls with hygroscopic insulation or mineral wool reported by Vinha [16], showed that a more vapour open interior lining was acceptable given the use of a highly hygroscopic thermal insulation material. This was only applicable in combination with an insulating vapour open exterior air barrier, e.g. a wood fibre board. Given a less permeable exterior air barrier, the opposite was concluded.

The effect of forced convection on the hygrothermal performance of highly insulated building structures was studied by Økland [21]. Wood-frame walls insulated with mineral wool subject to forced convection through air slits in the bottom and top of interior and exterior linings were investigated. Laboratory measurements were performed on walls with air layers in different positions to simulate bad workmanship, compared to a wall insulated as perfectly as possible. The results suggested that forced convection through the air gaps could strongly influence the moisture content in the studs in the walls. However, wood-fibre insulation was not included in the study.

An experimental and numerical investigation of a cellulose insulated ceiling subjected to air leakage was investigated by Belleudy et al. [31]. The study showed that even a small airflow though the construction had a large impact on the moisture and temperature fields in the building envelope.

Derome [22] performed a laboratory study on the hygrothermal performance of large-scale flat roofs with cellulose insulation. The main aim was to investigate changes in moisture content in the insulation layer due to deposition of moisture through different air leakage paths. The study showed that condensation could be postponed by using hygroscopic insulation. It was observed that short exfiltration paths gave less condensation than long paths. In some cases, high moisture was observed at the exit of air leakage paths due to melting of ice after transition from cold wetting periods to drying periods. Furthermore, it was observed that adding an interior vapour retarder slightly reduced the moisture accumulation in the cellulose insulation but did not affect the dry-out of the insulation.

Ge et al. [26] and Wang et al. [30] investigated the effect of air leakage on the hygrothermal performance of highly insulated wood-frame walls. In Ref. [26], different insulation materials, including cellulose insulation, was studied under field conditions in Ontario, Canada. The test walls were subjected to a simulated air leakage from the interior. The study found that the moisture content of an OSB sheathing was lower if a thermally insulating layer was added on the exterior side of the OSB. Also, the moisture content of the OSB was lower for walls with cellulose insulation compared to walls with fibre glass insulation due to the hygroscopic properties of the cellulose. Through investigation of two air infiltration models and an experimental study on thirteen test walls [30], found that walls with cellulose insulation have lower mould growth risk.

1.3. Knowledge gap

Several studies on the topic of hygroscopic insulation materials have been performed. However, a review of the literature reveals knowledge gaps on the subject of wood fibre insulation. To the authors' knowledge, no studies have treated the effect of air leakages and forced convection of moist air into wood-frame constructions with wood fibre insulation.

1.4. Objectives and scope

The purpose of the present study was to experimentally investigate the moisture conditions in wood-frame walls with wood fibre thermal insulation. Little of the cited research has investigated the hygrothermal performance of wood fibre insulation, and no studies have investigated the robustness of such insulation in the case of leakages of moist air into the construction. Therefore, one important goal of this study was to investigate the difference in hygroscopic capacity of wood fibre insulation compared to mineral wool insulation given leakages of moist air from the inside. It was desired to investigate whether the use of wood fibre insulation results in a more resilient construction in regards of the extra strain that air leakages from the inside may constitute. A Nordic climate was chosen to examine the performance of the insulation. A central objective is that experimental investigations in this study could contribute to the development of numerical models for parametric studies on constructions with wood fibre insulation in different climates.

2. Method

To investigate the hygrothermal performance of wood frame walls with wood fibre insulation, a test template (wall element model) and two climatic chambers were used. An experimental approach in laboratory gave the possibility to control the outdoor and indoor climate as well as the air pressure conditions, which was important in order to understand the performance of different wall configurations.

The present study is part of a larger investigation of wood frame walls with wood fibre insulation. This includes a laboratory study [33] with 15 test cells given a one-dimensional configuration, omitting the effect of the wooden frame and internal convection, and one laboratory study on five full height wall sections including the effect of the wooden frame and internal convection. The latter study is not yet reported. The present study investigates five full height wall sections including the effect of the wooden frame as well as internal and forced convection. The results from all the tests are planned to form a basis for future numerical modelling, to carry out parametric studies on walls with wood fibre insulation in a variety of different climates.

2.1. *Experimental model*

The experimental study was carried out on a laboratory model of a full-height wood-frame wall element constructed by 48 mm × 300 mm wooden studs. The outer dimensions (width × height) of the element are 3820 mm × 4120 mm. The wall element is divided into five sections (WS1 – WS5) with centre-to-centre distance 600 mm and height 2500 mm, see Fig. 1. The five wall sections constitute the test area. As shown in Fig. 1, the wall extends on all sides around the test area. This boundary zone is filled with EPS insulation and is not included in the investigations. In addition, a plastic foil is mounted on top of the top sill and between the two bottom sills in order to prevent moisture transport into the boundary zone above and beyond the test area.

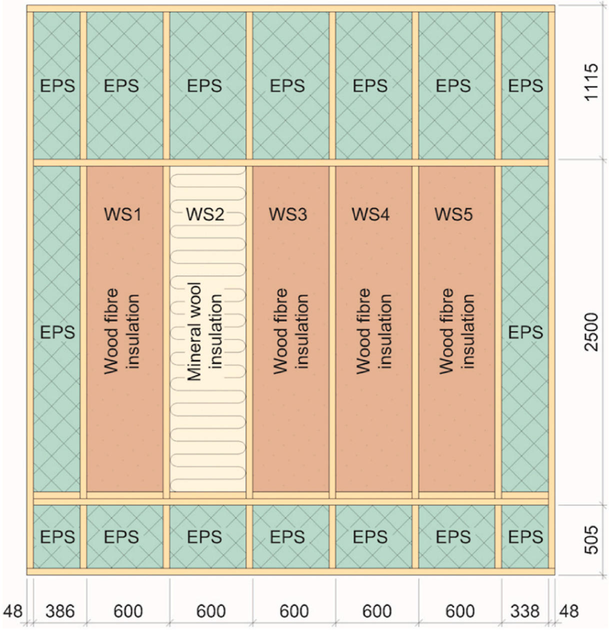


Fig. 1. The tested wood-frame wall element with the five wall sections. Dimensions are given in millimetres. A plastic foil is mounted on top of the top sill over the test area and between the two bottom sills under the test area. This is not shown in the figure.

The five wall sections have different combinations of material layers (exterior air barrier, thermal insulation, vapour retarder and interior lining), described in section 2.2. The aim is to compare the moisture conditions in the five sections. The general configuration of the wood frame wall element is:

- Exterior air barrier
- 300 mm thermal insulation
- Vapour retarder
- Interior lining

The wall element was installed between two climatic chambers for simulation of outdoor and indoor climate on each side of the element.

2.2. *Wall configurations and material properties*

The five wall sections were given different configurations. Material properties for the materials used in the wall element are shown in Table 1. In addition, the sorption curve (adsorption and desorption) for the wood fibre insulation is shown in Fig. 2. Table 2 gives an overview of the composition of the five wall sections. Wall section 1 (WS1) is considered the standard construction, while the other wall sections (WS2 – WS5) have adjustments compared to WS1. Table 2 also describes the position of the air leakage in the different wall sections.

2.3. *Simulation of air leakage*

One of the main goals of the study was to investigate the hygrothermal performance of wood-frame walls with wood fibre insulation given forced convection of moist air from the interior through the wall construction and to the exterior. To simulate an air leakage through the wall, the board materials on the interior and exterior side of each wall section were prepared with a horizontal row of 26 holes with 6 mm diameter (corresponding to a 1.4 mm wide continuous slit in the boards). A wider slit was cut in the vapour retarder foil material on the rear side of the interior lining to allow for air to pass into the insulation layer from the interior. The wall element was constructed as airtight as possible before adding the holes and slits to be able to control the leakage of air into the construction.

On the warm face of the wall model, i.e. in the interior board and vapour retarder, the air leakage location was 100 mm above the top edge of the bottom sill. See Fig. 3. In wall section 5, the leakage location on the interior side was in the upper part of the wall, 100 mm from the lower edge of the top sill. On the cold face of the construction, i.e. in the exterior air barrier layer, the air leakage location was 100 mm from the lower edge of the top sill in all the five wall sections.

2.4. *Instrumentation*

The wall sections were instrumented with sensors for measurement of relative humidity (RH) at the interface between the exterior air barrier and the insulation layer, as well as sensors for measurement of moisture content (MC) in the wooden top and bottom sills of the wooden frame. The sensors were positioned as given in Fig. 4 and Table 3.

RH was measured at the exterior side of the insulation (between the exterior air barrier and the thermal insulation), as this is typically a critical area in regards of high moisture level and risk of mould growth. The sensors were installed in slots in the exterior surface of the insulation to avoid any air gaps between the insulation and the exterior air

Table 1
Material properties.

Layer	Material	Density, ρ [kg/m^3]	Vapour resistance, s_d [m]	Thermal conductivity, λ [W/mK]
Exterior air barrier	Wood fibre board[a], 12 mm	235	0.2[b]	0.048
	Wood fibre board[a], 50 mm (2 × 25 mm)	280	0.4[b]	0.048
Thermal insulation	Wood fibre batt	50	–	0.038
	Glass wool batt	16	–	0.035
Vapour retarder	Vapour retarder foil	–	2	–
	OSB, 12 mm	640	4.6 (50% RF) – 0.94 (75% RF)	0,13
Interior lining	Gypsum fibre board	1150	0.16	0.32

[a] Bitumen impregnated porous wood fibre board.
[b] Measured at average RH = 72%.

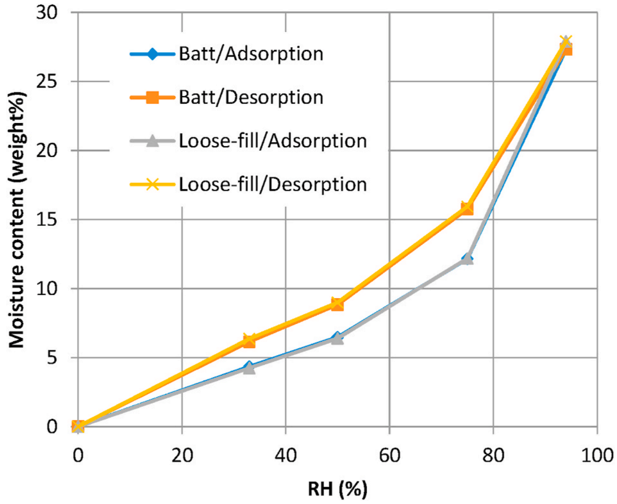


Fig. 2. Sorption curve (adsorption and desorption) for the wood fibre insulation (the wood fibre batt is used in the present study).

barrier. RH sensors of the type EE06 (E + E Elektronik) were installed in four different heights in each wall section. See Fig. 4 and Table 3. The sensors have a range of 0–100% and a given accuracy of ±3%. The sensors were calibrated at 50% and 75% RH and found to be within ±1–2%.

The MC of the top and bottom sills was measured manually by traditional resistance measurements (Greisinger GMH 3830). Two screws installed with a distance of 25 mm were used as one electrode pair. Eight electrode pairs were installed in each wall section. Four pairs were installed in the top sill (T1 – T4) and four in the bottom sill (B1 – B4). Measurements were carried out both on the lower side and exterior side of the top sill and the upper side and exterior side of the bottom sill. The position of the electrode pairs is described in Table 3 and Fig. 4. The electrode pairs were duplicated, with two sensors in each of the four positions. It is the average of measurements from each location that is considered in the analyses. The MC measurements are corrected for temperature.

2.5. Boundary conditions

The wall sections were tested under three different sets of boundary conditions, as given in Table 4. The external and internal boundary conditions were selected to represent three following periods, starting with a winter period with low indoor air humidity (day 1–26), followed by a winter period with a moderate indoor air humidity (day 26 – day 48). The winter periods were chosen to give possibility for moisture accumulation in the construction. Finally, the third period simulated a spring period with dry-out potential, with higher outdoor temperature and indoor air humidity (day 48–62). Table 4 shows the planned boundary conditions. The actual values during the experiments may differ slightly. Climatic loads and measurements were carried out for the given amount of days before the climate was changed. The wall element was constructed in a period with low RH in the laboratory air, meaning the materials in the different wall sections had a low and approximately equal level of moisture at the beginning of the first test period.

3. Experimental research

The experimental results show the development in relative humidity (RH) and wooden moisture content (MC) during the three periods with different boundary conditions. A system shutdown between period 1 and period 2 resulted in 5 days (day 21–26) with laboratory climate in the

Table 2
Overview of the composition of the different wall sections. Wall section 1 (WS1) is considered the standard construction, while the other sections have adjustments compared to WS1. The deviations in each section compared to WS1 are highlighted.

Layer		Wall section				
		WS1	WS2	WS3	WS4	WS5
Exterior air barrier	Wood fibre board, 12 mm	×	×		×	×
	Wood fibre boards, 2×25 mm			×		
Thermal insulation	Wood fibre batt, 300 mm	×		×	×	×
	Glass wool batt, 300 mm		×			
Vapour retarder	Vapour retarder foil	×	×	×		×
	OSB, 12 mm				×	
Interior surface	Gypsum fibre board, 13 mm	×	×	×		×
	None (OSB, 12 mm)				×	
Air leakage	Bottom of vapour retarder, top of exterior air barrier	×	×	×	×	
	Top of vapour retarder, top of exterior air barrier					×

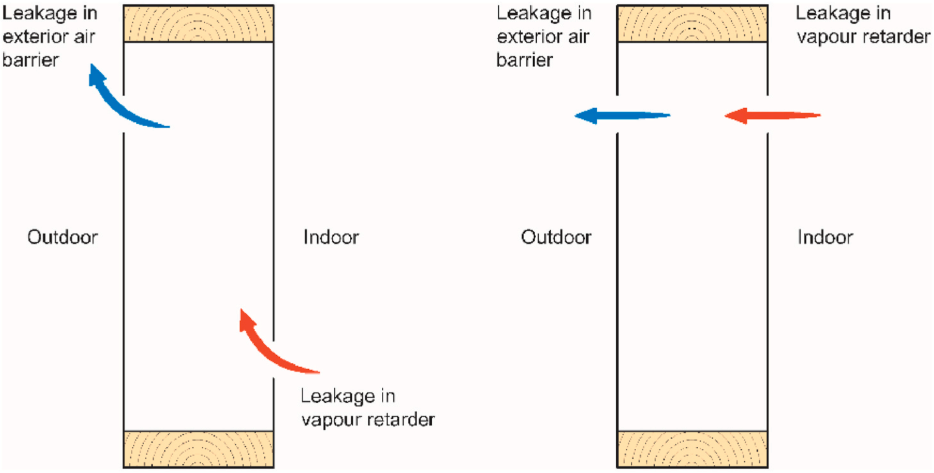


Fig. 3. Cross section showing the intended leakage path for moist indoor air in wall sections 1–4 (left) and wall section 5 (right).

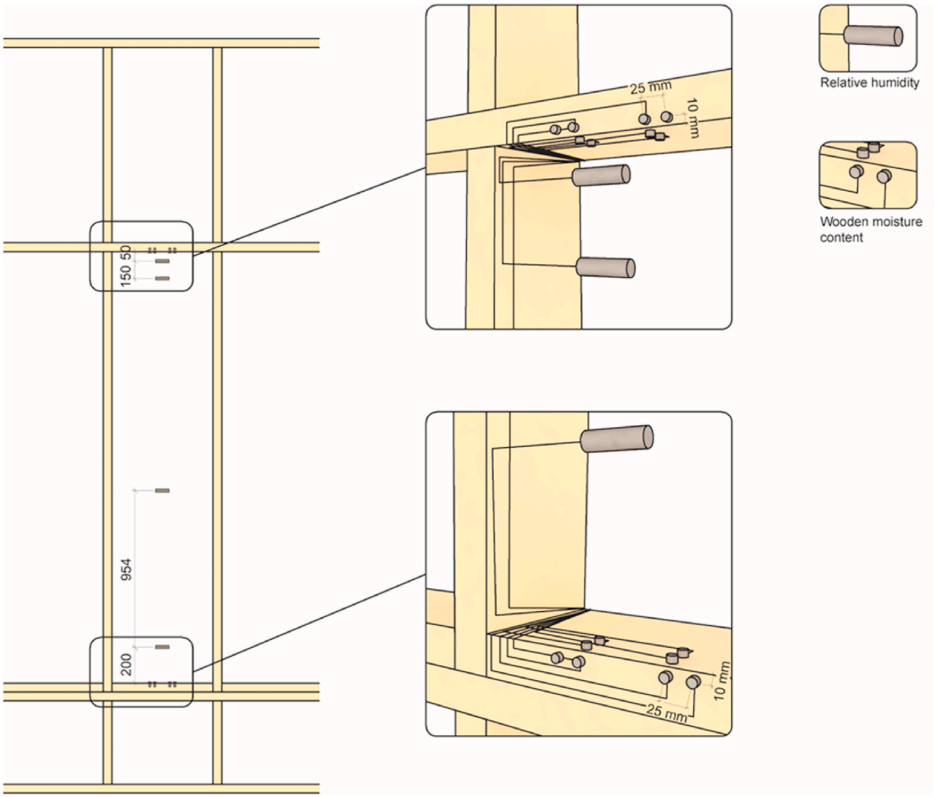


Fig. 4. Localization of RH sensors and MC sensors in one wall section. Dimensions are given in millimetres.

Table 3
Position of RH sensors and MC sensors.

RH sensor	Position
RH1	50 mm from lower side of top sill
RH2	200 mm from lower side of top sill
RH3	In the middle of the wall section
RH4	200 mm above upper side of bottom sill
MC sensors	**Position**
T1 and T2	Exterior front of top sill
T3 and T4	Lower side of top sill
B1 and B2	Exterior front of bottom sill
B3 and B4	Upper side of bottom sill

climatic chambers. Therefore, the main focus of the discussions will deal with period 1 and the transition between period 2 and period 3 (the transition from winter climate to spring climate).

3.1. *Relative humidity*

The development in RH at the interface between the exterior air barrier and the insulation layer in the five different wall sections is shown in Fig. 5. The RH is measured 50 mm below the top sill (Figs. 5a), 200 mm below the top sill (Fig. 5b), in the middle of the wall height (Figs. 5c) and 200 mm above the bottom sill (Fig. 5d). Table 5 summarizes the RH levels in the wall sections at the end of period 2 and the beginning of period 3.

As seen from the results, the RH in the wall section with mineral wool

Table 4
Planned boundary conditions.

Period	Climate	Outdoor temperature	Outdoor RH	Indoor temperature	Indoor RH	Moisture supply[a]	Pressure difference[b]	Duration of period
		[°C]	[%]	[°C]	[%]	[g/m^3]	[Pa]	[days]
1	Winter I	−15	≈55	23	20	2.5	10	26
2	Winter II	−15	≈55	23	25	4.0	10	22
3	Spring	10	≈70	23	32	1.5	–	15

[a] Difference in moisture concentration in indoor and outdoor air.
[b] Pressure difference between indoor and outdoor air (overpressure at the warm side of the construction).

(WS2) reached stability quickly after the beginning of the first winter period. The wall sections with wood fibre insulation took longer time to stabilize. In many of the sensor positions the RH in these sections was not stable at the end of period 1. For instance, the RH reached a level higher than 80% within a few days in the top position (Fig. 5a) in the section with mineral wool (WS2), while the standard construction with wood fibre insulation (WS1) used the whole first period to reach an RH of 80%. After the system shutdown between day 21 and 26, the RH decreased in all sections. When experiments were started again in period 2, the RH in all sections reached stability faster than in period 1.

The results from the bottom of the wall are shown in Fig. 5d. Comparing the standard construction (WS1) with the section with mineral wool (WS2), it is apparent that the RH in the bottom of the wall was higher in WS1 during period 1 and most of period 2. After the first few days of period 1 the RH level in WS1 was approximately 16–31 %RH higher than in WS2. The difference decreased in period 2, as the RH in WS1 was 10–23 %RH higher than in WS2. At the transition to spring climate (period 3), the RH in WS2 increased and reached approximately the same level as WS1. See Fig. 5d and Table 5. From Fig. 5d and Table 5 we can also observe that WS1 dried out faster in the bottom of the wall than WS2. Furthermore, the results show that the RH in the top and middle of the sections with wood fibre insulation (except WS5) was lower than the RH in the top and middle of WS2. For instance, the RH 200 mm from the top sill in WS1 was 21–35 %RH lower than the RH 200 mm from the top sill in WS2 during period 1. As for the bottom of the wall, the difference between the wall sections decreased in period 2.

From the results in Fig. 5 it is apparent that the wall section with a 50 mm exterior air barrier (WS3) had lower RH levels than the standard construction with 12 mm exterior air barrier (WS1). The RH at the rear side of the exterior air barrier in WS3 never reached the same level as WS1. The difference is most distinct in the bottom and middle of the wall. The average RH during the first period was 77% and 63% in the bottom and middle of WS1, respectively, while it was 62% and 50% in the bottom and middle of WS3, respectively. Hence, the average RH was 13–15 %RH lower in WS3 than in WS1 in the first period. In the spring period (period 3) this difference was approximately 10 %RH.

Comparing the wall section with OSB as vapour retarder (WS4) with the standard construction (WS1), the results show that the RH levels in these sections were very similar in the uppermost sensor position (Fig. 5a) and in the bottom of the wall (Fig. 5d). In the middle of the wall (Fig. 5c), WS1 had higher moisture level than WS4, while the opposite occurred 200 mm from the top sill (Fig. 5b). For instance, the average RH in period 1 in the sensor position in the middle of the wall was 9 % RH lower in WS4 than in WS1, while it was 9 %RH higher in WS4 than in WS1 in the sensor position 200 mm from the top sill.

Furthermore, the results show that the moisture distribution in the section with air leakage in the top of the vapour retarder (WS5) was distinctly different than in the other wall sections, with high RH in the top of the wall (Fig. 5a and b) and low RH in the bottom and middle of the wall (Fig. 5c and d). For instance, the average RH during period 1 in the position 200 mm below the top sill was 27 %RH higher than in the standard construction (WS1), while the average RH during period 1 in the position 200 mm above the bottom sill was 30 %RH lower than in the standard construction. The differences in average RH between WS1 and WS5 were approximately the same in period 3 as in period 1, but as seen in Fig. 5 the dry out processes in the two sections during period 3 were different. While the RH level in WS5 increased in the top of the wall and decreased in the middle and bottom of the wall at the transition to spring climate, the opposite happened in WS1 (except in the sensor position 50 mm from the top sill where the RH increased also in WS1).

3.2. *Wooden moisture content*

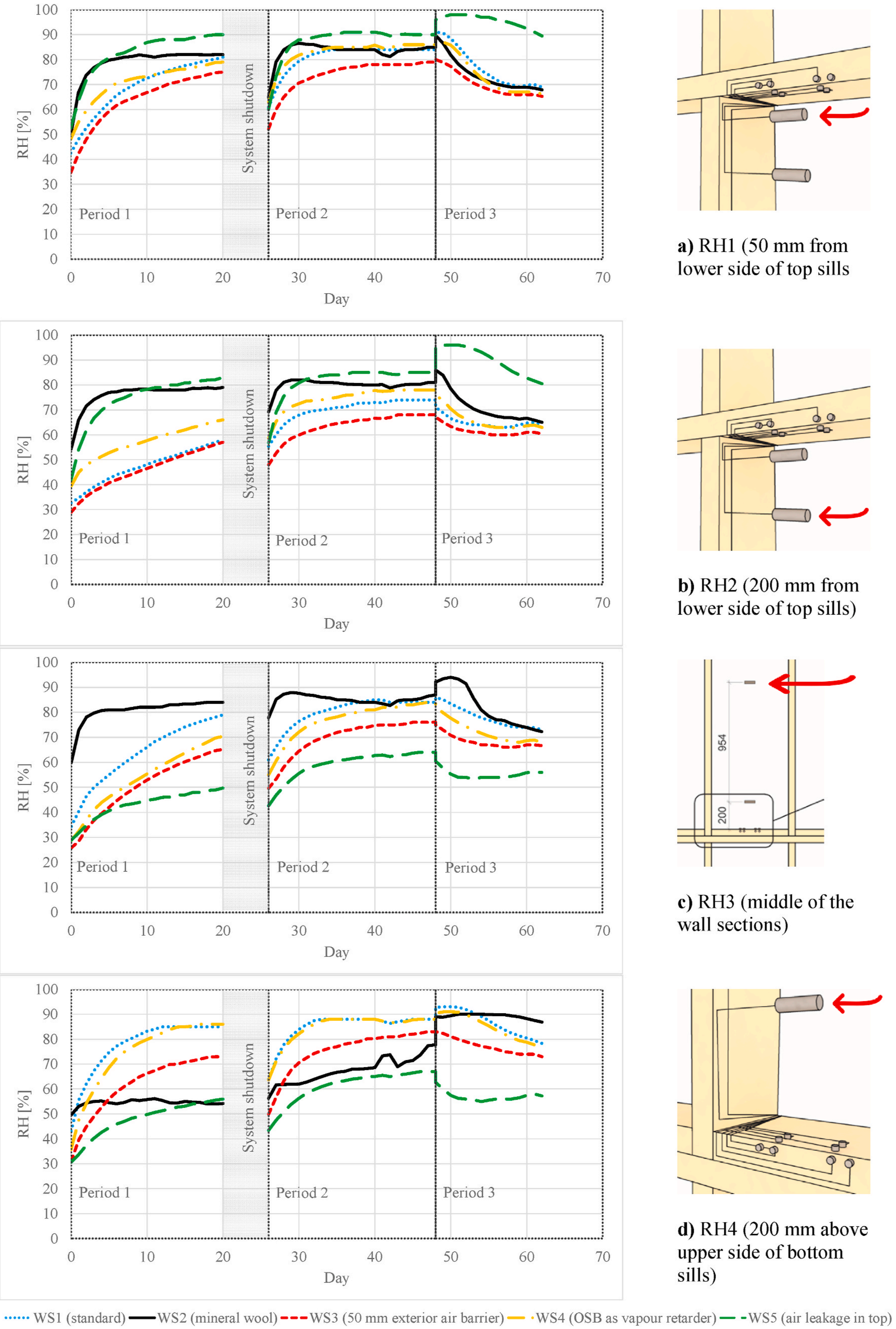
The development in wooden moisture content (MC) in the top and bottom sills of the five wall sections is shown in Fig. 6. The MC is measured on the exterior front of the top sill (Fig. 6a), on the lower face of the top sill (Fig. 6b), on the exterior front of the bottom sill (Fig. 6c) and on the upper face of the bottom sill (Fig. 6d). See Fig. 4 for further explanation of the measurement positions. The vertical axes in Fig. 6 have the same maximum axis bound to simplify the comparison of the measurements. Note that some measurements are found outside this bound.

The results in Fig. 6a and b shows that the top sill in the section with mineral wool (WS2) had MC lower than or equal to the sections with wood fibre insulation. On the upper face of the bottom sill, the MC in WS2 was also in general lower than the other sections during period 1 and 2, as shown in Fig. 6c. After the transition to spring climate, however, a large increase in the MC in this measurement position occurred. High moisture level was also measured in the exterior front of the bottom sill in WS2 compared to the sections with wood fibre insulation. See Fig. 6d.

Comparing the MC in the section with 50 mm exterior air barrier (WS3) to the standard construction (WS1), the development in MC for the two sections was quite similar. The difference in MC was less than ±2 weight-% in 67% of the measurements. However, the largest difference between the two sections was measured to be 19 weight-%. The MC in the sills of the wall section with OSB as vapour retarder (WS4) was similar to the standard wall construction (WS1). In 70% of the measurements the difference in MC between the two sections was less than ±2 weight-%. The largest difference between these two sections was 13 weight-%. Comparing the MC in the sills of the standard construction (WS1) and in the section with air leakage in the top of the vapour retarder (WS5), Fig. 6a and b shows that the MC was higher in the top sill of WS5 than of WS1, while Fig. 6c and d shows that the MC was lower in the bottom sill of WS5 than of WS1. This is the same trend as observed in the RH measurements.

4. Discussion

The main aim of the present research was to investigate the moisture conditions in wood frame walls with wood fibre insulation. For comparison, the moisture conditions when using mineral wool insulation was also studied. Wall sections WS1 (standard construction), WS3 (50 mm exterior air barrier), WS4 (OSB as vapour retarder) and WS5 (air leakage in the top of vapour retarder) were built with wood fibre insulation, while wall section WS2 was constructed with mineral wool insulation.



a) RH1 (50 mm from lower side of top sills

b) RH2 (200 mm from lower side of top sills)

c) RH3 (middle of the wall sections)

d) RH4 (200 mm above upper side of bottom sills)

Fig. 5. Relative humidity (RH) measured at the interface between the exterior air barrier and the insulation layer in the five wall sections.

Table 5

Change in RH in the different wall sections at transition from period 2 (P2) to period 3 (P3). Red shaded cells indicate that an increase in RH occurred after transition from winter climate to spring climate.

		WS1	**WS2**	**WS3**	**WS4**	**WS5**
RH1	End of P2	84 %	85 %	79 %	86 %	90 %
	Start of P3	91 %	90 %	80 %	87 %	96 % → 98 %
	Dry-out starts	Immediately	Immediately	Immediately	Immediately	After 6 days
RH2	End of P2	74 %	81 %	68 %	78 %	85 %
	Start of P3	71 %	86 %	67 %	76 %	95 % → 96 %
	Dry-out starts	Immediately	Immediately	Immediately	Immediately (rapid)	After 4 days
RH3	End of P2	84 %	87 %	76 %	84 %	64 %
	Start of P3	86 %	92 %	75 %	83 %	61 %
	Dry-out starts	Immediately	Immediately	Immediately	Immediately (rapid)	Immediately
RH4	End of P2	88 %	78 %	83 %	88 %	67 %
	Start of P3	93 %	89 % → 90 %	82 %	90 %	63 %
	Dry-out starts	After 4 days	After 10 days	Immediately	After 3 days	Immediately

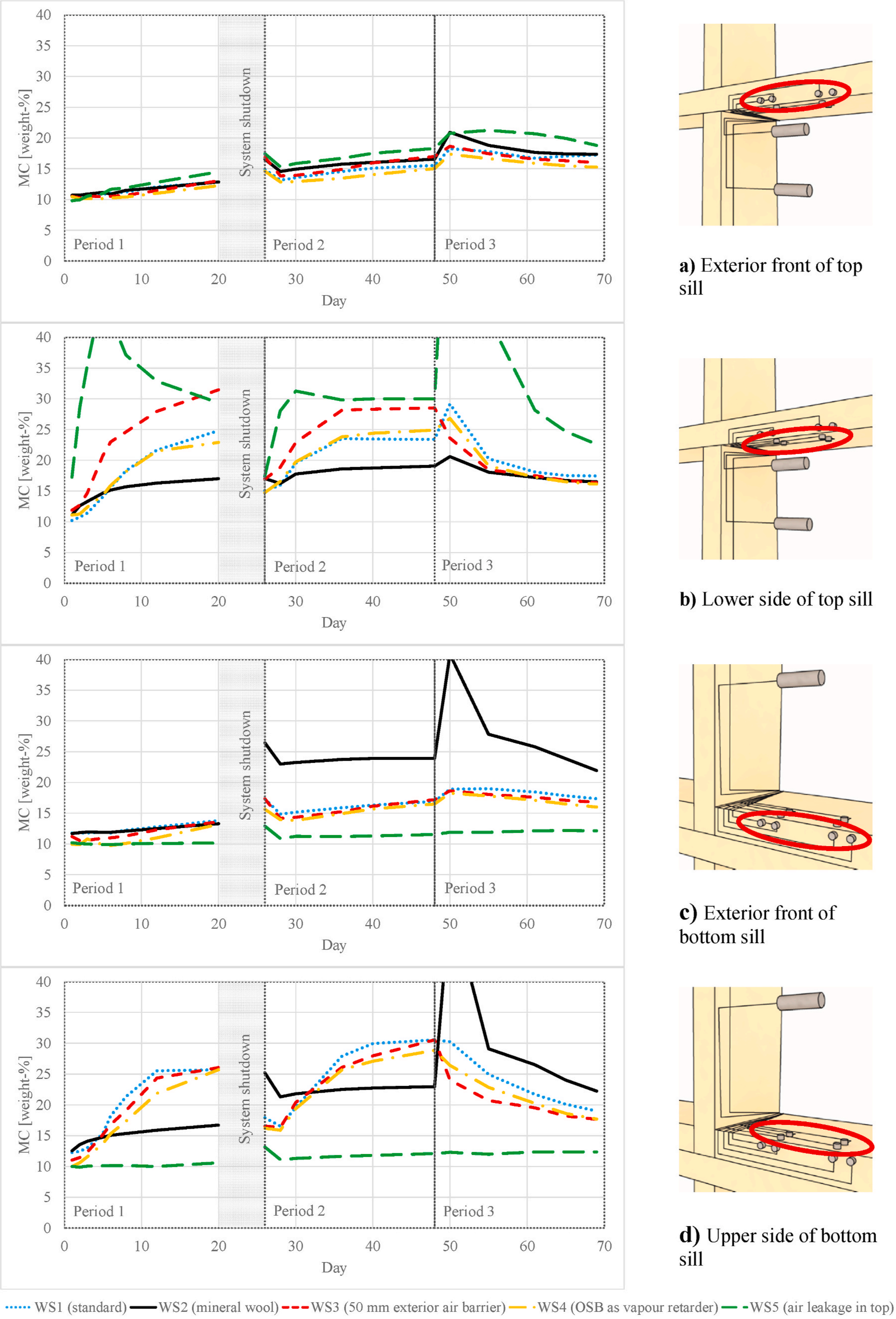
4.1. Comparison of wood fibre insulation and mineral wool insulation

In general, all the wall sections are influenced by the combination of outward directed vapour diffusion, natural convection and forced convection (air leakage from interior) making both the RH (Fig. 5) and the MC (Fig. 6) at the cold face of the insulation layer increasing during the winter periods. The moisture levels never reached 100% RH, which indicates that no condensation occurred at the measuring points. The wooden moisture content, however, showed values up to 25–30 weight-% (and in some cases peaks up to 80 weight-%), which indicates presence of free water. In addition, ice formation was observed in the top of all the wall sections at the end of period 2. This shows that condensation of water occurred during the experiments.

The development in RH at the interface between the insulation layer and the exterior air barrier was different in the five wall sections. As presented in chapter 3, the RH in the wall section with mineral wool (WS2) reached stability faster than the sections with wood fibre insulation. This difference in RH development between WS2 and the sections with wood fibre insulation is probably mostly due to the moisture capacity of the wood fibre insulation, as absorption of moisture in the insulation may delay the rise in RH. Hence, the RH in the sections with wood fibre insulation used longer time to stabilize.

Studying the distribution of moisture from bottom to top of the wall sections, differences between the section with mineral wool (WS2) and the sections with wood fibre insulation is also observed. The results from the present study show that the moisture levels in general were high at the opposite side of the deficiency (air leakage) in the vapour retarder in all the sections with wood fibre insulation. Desmarais et al. [23] made a similar observation. This was not the case in the section with mineral wool (WS2). As seen in Fig. 5d, the RH in the bottom of WS2 was very low during the winter periods compared to most of the other wall sections. In the middle of the wall, however, the RH was higher in WS2 than in the sections with wood fibre insulation. It may seem like the air leakage travelled on the interior side of the insulation layer in the lower half of WS2 before continuing to the exterior side of the insulation layer in the middle of WS2. This is also indicated by the RH at the interior face of the exterior air barrier in the bottom of WS2 in period 1, which was approximately equal to the RH in the exterior climatic chamber (≈55%). In addition to the possible moisture uptake in the wood fibre insulation, this differences in moisture distribution between WS2 and the sections with wood fibre insulation may be explained by different air leakage paths in the wall sections. As the humid air flows from the interior side of the construction and through the wall, it will gradually be cooled down. Accordingly, the RH of the air flowing through the wall will increase. In the present experiment with forced convection, the air will flow inside the insulated cavity along the path with lowest resistance. Depending on the air leakage path, the RH may increase at different places in the wall sections. Each wall section was insulated by two batts of 1200 mm height to achieve the necessary total insulation height. Consequently, the insulation layer was discontinuous in the middle of each section. This may explain the higher RH in the middle of WS2 compared to the bottom of WS2. One reason why this was not observed in the wood fibre sections is that wood fibre insulation is stiffer than mineral wool insulation, which contributes to avoiding any air gaps in-between the two insulation batts. Hence, the distribution of moist air in WS2 may be more affected by e.g. joints in the insulation layer and possible air voids towards the interfaces between the insulation and the other materials. This was also observed by Økland [21] in a study of wood-frame walls insulated with mineral wool subject to forced convection through air slits in the bottom and top of interior and exterior linings. Laboratory measurements were performed on walls with air layers in different positions to simulate bad workmanship, compared to a wall insulated as perfectly as possible. The results suggested that forced convection through the air gaps could strongly influence the moisture content in the studs in the walls.

Furthermore, the differences in moisture distribution in the sections with mineral wool or wood fibre insulation can be explained by different air permeabilities of the materials. Gullbrekken et al. [38] measured the air permeability of mineral wool to be 1.1 × 10^{-9} m^2 and 2.6 × 10^{-9} m^2 parallel and perpendicular to the main fibre direction, respectively. The air permeability of wood fibre insulation parallel and perpendicular to the main fibre direction was 2.6 × 10^{-9} m^2 and 3.5 × 10^{-9} m^2, respectively. Hence, a larger air leakage and increased moisture transport is expected in the bottom of the wood fibre insulated walls (except WS5 where the air leakage is in the top of the wall) compared to the wall insulated with mineral wool (WS2). In addition, there is a difference between the practical air permeability of an insulated cavity and the air permeability of the insulating material itself. Compared to the air permeability of the material, which is tested in a standardized and perfectly insulated test rig, the practical air permeability includes small imperfections caused by e.g. air voids in the interfaces between the insulation and other materials. Hence, this characteristic may indicate to



a) Exterior front of top sill

b) Lower side of top sill

c) Exterior front of bottom sill

d) Upper side of bottom sill

Fig. 6. Comparison of development in wooden moisture content (MC) in the five wall sections.

what degree the insulation is able to fill the cavity between the wooden studs. The practical air permeability of mineral wool was investigated by Gullbrekken et al. [39]. They found that it was 10 times larger than the material value. Because the wood fibre insulation is stiffer, a smaller difference between the practical air permeability and the air permeability is expected. Hence, the moisture distribution in a wood fibre insulated wall compared to a mineral wool insulated wall is expected to be less affected by e.g. small air voids between the insulation and the other materials.

In period 3 (spring period), there was no forced pressure difference across the wall construction. Consequently, in this period there was no expected moistening of the wall sections due to humid air from the interior. However, as presented in Table 5 and observed in the measurements of MC in Fig. 6, increases in RH and MC occurred in some sensor positions in all the wall sections after the transition to spring climate. This indicates melting of ice formed during the winter periods. For instance, as presented in Table 5, an increase in RH after the transition to spring climate was observed in all sensor positions in the wall section with mineral wool (WS2). The increase was largest in the bottom of the wall, where the RH increased by 11 %RH. In addition, the RH in the bottom of the wall stayed high for 10 days before dry-out started. The same trend was observed in the bottom of the standard construction with wood fibre insulation (WS1), but with a shorter time before dry-out begun. The increase in RH in the bottom of the wall sections after transition to spring climate indicates that melting water has run down the rear face of the exterior air barrier to the bottom of the wall. However, as seen in Fig. 6c and d, it was only the bottom sill in WS2 that showed a distinct increase in MC at the transition to spring climate. This implies that the wood fibre insulation in WS1 absorbs melting water, while the mineral wool in WS2 does not. Instead, more free water runs down to the bottom of WS2 and moistens the bottom sill. This is also indicated by the larger increase in RH in the bottom of WS2 in period 3 compared to the sections with wood fibre insulation. The results imply that the wood fibre insulation may have the benefit of temporarily absorbing free water (e.g. from melting ice formation) to avoid unwanted wetting of the bottom of the wall. On the other hand, the moisture uptake in the wood fibre insulation may prolong the presence of high moisture levels in other parts of the construction. When comparing WS1 and WS2 we see that these two sections have approximately the same RH at the end of period 3 in all positions except in the bottom of the wall. Also, even though the RH in the upper half of the wall seems to take longer time to reach a level of 80–90% in the sections with wood fibre insulation, the drying of the upper half of the wall in period 3 seems to take the same amount of time as in the section with mineral wool insulation. This means that even though the maximum RH may be lower in the sections with wood fibre insulation, the total risk of mould growth does not necessarily need to be lower than for the mineral wool.

4.2. *The effect of an exterior air barrier with larger thermal resistance*

The measurement results indicate that using an exterior air barrier with higher thermal resistance, in this case an exterior air barrier with a thickness of 50 mm instead of a 12 mm barrier, seems to have a positive effect on the RH at the interface between the exterior air barrier and the insulation layer. The RH at the rear side of WS3 (50 mm barrier) never reached the same level as in WS1 (12 mm barrier). The 50 mm thick wood fibre barrier has higher vapour resistance than the 12 mm wood fibre barrier, which could possibly slow down drying towards the exterior. However, the thicker exterior air barrier also increases the temperature at the intersection between the exterior air barrier and the insulation, hence decreasing the RH. This effect has also been observed in other studies [33,41]. Using an exterior air barrier with high thermal resistance may provide a more robust construction which could be able to handle a lower vapour resistance at the warm face of the insulation layer or, as in this case, air leakages through the interior barrier layer, without moisture damage. Even though WS3 showed lower RH than WS1, the MC was not particularly low compared to WS1, as shown in Fig. 6. In Fig. 6b, it is observed that the MC on the lower face of the top sill in WS3 was high during period 1 and 2 compared to WS1. This may be explained by ice formation in the holes (air leakage) in the exterior air barrier. Because of the thicker barrier in WS3, the air leakage path is longer. Ice formation may have reduced the air leakage rate out through the exterior air barrier more in WS3 than in WS1, hence increasing the risk of condensation on the lower face of the top sill.

4.3. *The effect of type of vapour retarder*

The wall section with OSB as vapour retarder (WS4) showed approximately the same development in MC as the standard construction (WS1), as seen in Fig. 6. The development in RH was also similar for the two sections in the bottom of the wall and in the uppermost sensor position (50 mm from the top sill). It is not unexpected that the moisture conditions in WS1 and WS4 are similar, as it is forced convection that dominates the moisture distribution during period 1 and 2. Hence, the interior barrier layer is of less importance. In the middle of the wall and 200 mm from the top sill (Fig. 5b and c), the differences in RH between WS1 and WS4 were larger, especially during the first period. This result is difficult to explain. One possible reason for the differences in the first period may be that the wood fibre insulation had different moisture levels from the beginning of the experiment.

4.4. *The effect of the air leakage path*

The moisture distribution between the wall section with air leakage in the top of the vapour retarder (WS5) was distinctly different than in the other wall sections. The results showed high RH and MC in the top of the wall and low RH and MC in the middle and bottom of the wall. The difference is obviously due to the different position of the air leakage on the interior side of the wall in WS5. The results indicate larger formation of ice and water in the top of this section, shown by the increase in RH and MC after transition to spring climate and the longer dry-out process at the end of period 3. At inspection of the wall element at the end of period 2 it was observed that all the holes in the exterior air barrier were filled with ice in WS5.

As seen in Fig. 6d, little water moistened the bottom sill in WS5. As the air leakage was entirely in the top of the wall, little condensation occurred in the bottom of the wall during the winter periods. In addition, the wood fibre insulation in the middle and lower part of the wall was subject to little moisture during the winter periods. Consequently, the wood fibre insulation in this section may have been able to absorb more melting water than in the other sections with wood fibre insulation (WS1, WS3 and WS4), hence contributing to reduce the moisture load on the bottom sill. Therefore, the MC in the bottom sill of WS5 was lower than in WS1, WS3 and WS4.

As seen in Fig. 6b, the MC at the lower face of the top sill in WS5 increased during the first days of period 1 before it decreased during the rest of period 1. This development may be explained by the method used for measurement of MC. The electrodes (screws) are not insulated and may therefore measure MC also at the surface of the wood. As the air leakage was localized entirely in the top of WS5, condensation may have been formed at the lower face of the top sill at the beginning of the experiment. Absorption of the moisture by the wood fibre insulation may explain the decrease in MC in the second half of period 1. The high MC level at the given sensor position (>40 weight-%) also indicates that the electrodes measured the presence of free water.

5. Conclusions

The present study has investigated the moisture conditions in wood frame walls with wood-fibre insulation. The development of moisture levels in the construction due to air leakages of moist air from the interior was studied and compared to a structure with mineral wool insulation. The results show that walls with wood fibre insulation have the same risk of high moisture levels as walls with mineral wool insulation. However, the measurements imply that the wood fibre insulation may have the benefit of temporarily absorbing free water (e.g. from melting ice formation) to decrease unwanted wetting of the bottom of the wall. The wood fibre insulation is able to distribute the moisture over a larger volume than the mineral wool insulation. Furthermore, the investigations indicate that using an exterior air barrier with high thermal resistance results in a generally lower moisture level in the wall construction, which can be considered favourable regarding risk of mould growth. The use of OSB as a vapour retarder (low vapour resistance) does not seem to have a distinct effect on the moisture conditions when the construction is subjected to forced convection.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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