Moisture Convection Performance of External Walls and Roofs

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ABSTRACT: Full-scale laboratory measurements were taken and 2D simulations were performed to determine the moisture convection performance of the joint of an external wall and an attic floor. Both the measured and simulated results showed that the building fabric is locally sensitive to exfiltration airflow as moisture convection could cause a remarkable increase in the moisture accumulation rate on the inner surface of the sheathing. The results prove that in modern houses with balanced ventilation, where the positive pressure caused by the stack effect cannot be easily controlled, it is essential to control moisture convection by good airtightness and the use of assembly solutions with improved hygrothermal performance, such as the case with mineral wool sheathing that was tested. The simulated results showed that the use of a constant moisture excess value instead of the profile did not cause any inaccuracy in the moisture content. At the same time, the use of the constant outdoor temperature over a long time period did change the hygrothermal performance, which became significantly more critical when simulated with variable outdoor temperatures. The laboratory measurement and simulation results show that in a cold climate, for the assemblies being studied with mineral wool sheathing, leakage rates of 0.1–0.2 L/(s·m) at a 10 Pa pressure difference may be used as performance criteria for moisture convection in a two-storey house with dimensioning moisture excess 4 g/m³ and a cold outdoor climate. Previous studies on the leakage characteristics show that these leakage rates are easily achievable in practice with careful workmanship.

KEY WORDS: moisture convection, air leakages, hygrothermal performance, exfiltration, building envelope.

INTRODUCTION

THE HUMIDITY GENERATED indoors and the ventilation performance determine the indoor humidity loads for building fabric. In cold

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Figures 1–15 appear in color online: http://jen.sagepub.com
climates, higher indoor water vapor pressure causes diffusion through the building fabric to the outside, which is usually controlled with an appropriate vapor barrier. If there is an air pressure difference resulting from the stack effect or mechanical ventilation, the exfiltration of moist air (moisture convection) can be a critical moisture transport mechanism. Wilson and Garden (1965) examined a number of cases of water and frost damage in masonry and non-load-bearing walls and showed that the quantities of water involved could not have resulted from vapor diffusion or rain penetration, and that condensation resulting from the exfiltration of air was the primary source of moisture. Nevertheless, Bomberg and Onysko (2002) recognized in their review of the heat, air, and moisture control in the walls of Canadian houses that many building practitioners were still preoccupied with considerations of vapor diffusion alone and largely ignored measures to improve airtightness. Burch and TenWolde (1993) showed that in cold winter climate (Madison, WI, USA) a vapor barrier is only effective if air leakage is effectively eliminated, as air exfiltration will increase the moisture content to above fiber saturation during a 3-month winter period. Hagentoft and Harderup (1996) showed that exfiltration leads to unacceptably high moisture content values, even for moderate indoor moisture supplies. The simulation results (Janssens, 1998; Janssens and Hens, 2003) show that even when a roof design complies with condensation control standards, a lightweight system remains sensitive to condensation problems because of exfiltration through the discontinuities, joints, and perforations common to most existing construction methods. Ojanen and Kumaran (1996) showed that the rate of exfiltration directly increased the amount of moisture accumulated in timber-frame external walls. Karagiozis and Salonvaara (1999) showed that in addition to vapor control strategies, air leakage through the building wall system was also found to have a significant parameter dictating the drying performance of the particular barrier Externally Insulated (EIFS) Building Walls. Karagiozis (2001) showed that the effect of airflow has a serious detrimental effect on the hygrothermal performance of the walls, supplying moisture that accumulates in the OSB sheathing layer of a basic brick veneer wall.

Air exfiltration depends on both the pressure differences and the airtightness of the building fabric. Developments in energy performance requirements, as well as in ventilation systems, have led to changes in pressure conditions in well-insulated modern buildings. Passive stack and mechanical exhaust ventilation systems are often replaced by mechanical supply and exhaust ventilation (balanced ventilation) with heat recovery. This means that there is no longer any negative pressure in the building caused by exhaust ventilation. In the case of balanced ventilation, the stack effect will still cause a pressure gradient leading to negative pressure on the
floor level and to positive pressure on the external ceiling level. Kalamees et al. (2007) reported typical negative and positive pressures of 5–10 Pa measured in Finnish houses. Such positive pressures mean that the common assumption of negative pressure indoors is no longer valid, and perhaps the moisture convection performance of external walls and roofs should be improved accordingly.

To assess and predict the long-term hygrothermal performance of building fabric systems, simulation tools and experimental investigations can be used. As air leakages are usually concentrated in the joints of different construction elements, at least 2D measurements or the simulation of these critical joints is needed.

In this study, typical air leakage data from field measurements (Kalamees et al., 2008) are utilized to construct full-scale laboratory measurement cases. The moisture convection performance of the joint between the external wall and the attic floor was measured in the laboratory for two typical external wall constructions. Timber-frame and autoclaved aerated concrete external walls and a timber-frame attic floor with wood fiberboard or mineral wool sheathing were studied. This joint was considered to be the most critical one due to the highest pressure difference caused by the stack effect in houses with balanced ventilation. Laboratory measurements were used for the validation of the simulation model. Long-term performance analyses were carried out with the simulation model for several wall and roof assemblies. The results of these analyses show how the moisture convection performance of assemblies can be improved and that there are limit values for exfiltration airflow rates at typical moisture excess values.

**METHODS**

**Laboratory Measurements**

Two commonly used external wall joints (a timber-frame wall and an autoclaved aerated concrete (AAC) wall (Figure 1)) with a timber-frame attic floor were installed in the laboratory between two climatic chambers. The 2D joint details that were studied consisted of a 1.2-by-0.7-m (width by height) external wall part and a 1.2-by-0.9-m (width by length) attic floor part.

The warm climatic chamber was equipped with heating and humidification units and simulated the indoor climate. The cold climatic chamber was equipped with refrigeration, heating, and humidification units simulating the outdoor climate. The climatic chambers were automatically controlled to
Figure 1. The timber-frame wall connection (left) and the autoclaved aerated concrete wall connection (right) with the attic floor and the structure in the laboratory between the climatic chambers (down). Temperature and RH measurement points are shown by numbered red dots.
maintain constant air temperature, relative humidity (RH), and air pressure difference across the structure being studied. For the temperature and humidity, the calibrated sensors (Vaisala HMP44L) were used. The measurement range was −20 to +60°C and 0−100%RH with accuracy: ±0.4°C, ±2%RH (0–90%RH), ±3%RH (90–100%RH). Pressure differences were measured using calibrated FCO44 differential pressure transducers with accuracy ±2.5% in the measurement range from 0 Pa to ±50–100 Pa. The influence of the wind shield sheathings on the hygrothermal performance was studied by replacing the 12 mm wood fiberboard used in the first test series by a 20 mm mineral wool board covered with spunbonded polyolefin (SBPO) film used in the second test series. The attic floor was insulated with 220 mm thick mineral wool.

There were two test samples in sheathings that were weighed during the test to control the moisture accumulation. When the test samples were removed and inspected regularly, the possible condensation on the inner surface of the sheathings was also detected.

In the timber-frame wall/attic floor joint (Figure 1, left), air leakage was allowed between two air/vapor barrier foils, which were deliberately installed incorrectly, so that the overlap direction was not along the joist, but perpendicular to the joists, and no tightening or tapes were applied. The wall/attic floor joint was tested with three airflow rates. Initially, three test series were carried out with the overlap not tightened (the width of the air leakage path was the total length of the joint). After that, a test series was conducted with a narrower overlap, only 10 cm wide and not tightened (another part was taped). The airflow rate through the leakage was measured with an electronic soap film calibrator (bubble flow meter, the measurement range was 100 cc/min to 30 L/min with accuracy ±0.5% of display reading). Figure 2 shows the airflow rates for both cases with the two sheathing materials. These leakage data (the trendlines of the measured data) were used in the simulations to calculate the exfiltration airflow rates from the measured air pressure differences.

In the AAC wall/attic floor joint, a 1.5±0.5 mm thick air gap was left between the wall plate and the AAC block; see Figure 1, right.

The leakage with a completely tightened overlap was measured for the case with wood fiberboard sheathing. This was still ~15% of the leakage of the case with the overlap not tightened, even though the setup being studied was built to be as airtight as possible.

The laboratory measurements were performed under outdoor temperature conditions of between ±0°C and −11°C. The moisture excess (Δv, the difference between the humidity by the volume of indoor and outdoor air) was 4 g/m³ in the majority of the tests. According to measurements performed in detached houses, this is the design value of moisture excess for
dwellings with low occupancy (Kalamees et al., 2006; Kumaran and Sanders, 2008). The air pressure difference ($\Delta P$ over the test setup was between $+10$ and $+20$ Pa.

**Hygrothermal Simulations**

Using the results from the laboratory measurements, the model of the 2D joint of the external wall and attic floor was validated with the CHAMPS-BES (coupled heat, air, moisture, and pollutant simulation in building envelope systems) simulation tool. This simulation tool is an outcome of a joint effort between the Building Energy and Environmental Systems Laboratory at Syracuse University, U.S.A., and the Institute for Building Climatology at the University of Technology, Dresden, Germany. CHAMPS-BES modeling comprises the description of the fluxes in the calculation domain or in the field (between volume elements including material interfaces) and at the boundary (between volume elements and exterior or interior rooms) by physical models. Also included are models for storage processes such as adsorption, desorption, and release. The numerical solution is performed by semi-discretisation in space (using a finite/control volume method) and subsequent integration.

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**Figure 2.** Measured air leakage through the overlap between two air/vapor barrier foils (timber-frame wall/attic floor).
in time (Grunewald and Nicolai, 2006). Moisture mass balance can be written as:

\[
\frac{\partial}{\partial t} \rho_{REV} = \frac{\partial}{\partial x} \left( j_{\text{conv}}^{m_w} + j_{\text{conv}}^{m_v} + j_{\text{diff}}^{m_v} \right)
\]

\[
= \frac{\partial}{\partial x} \left( -c_{l}^{m_w} K_l \frac{\partial p_l}{\partial x} + \rho_l g \right) - c_{g}^{m_v} K_a \left[ \frac{\partial p_g}{\partial x} + \rho_g g \right] - \frac{D_{v,\text{air}}(T)}{\mu R_v T} f(\theta_g) \frac{\partial p_v}{\partial x}
\]

where:

- \( \rho_{REV} \): moisture (liquid + vapor) density in reference volume, kg/m\(^3\);
- \( j_{\text{conv}}^{m_w} \): convective liquid (capillary) water flux, kg/(m\(^2\)-s);
- \( j_{\text{conv}}^{m_v} \): convective liquid (capillary) water flux, kg/(m\(^2\)-s);
- \( j_{\text{diff}}^{m_v} \): diffusive water vapor flux, kg/(m\(^2\)-s);
- \( c_{l}^{m_w} \): water mass concentration in the liquid phase, kg/kg;
- \( K_l \): liquid water conductivity, s;
- \( p_l \): liquid water pressure, Pa;
- \( \rho_l \): intrinsic density of liquid phase, kg/m\(^3\);
- \( g \): gravity constant, m/s\(^2\);
- \( c_{g}^{m_v} \): water vapor mass concentration in the gas phase, kg/kg;
- \( K_a \): air permeability of the material, s;
- \( g \): gravity constant of water vapor, J/(kg-K);
- \( f(\theta_g) \): function of volume fraction of gas phase, (–);
- \( p_v \): water vapor pressure in gas phase, Pa;
- \( T \): temperature, K;
- \( \mu \): vapor diffusion resistance factor (–);
- \( R_v \): gas constant of water vapor, J/(kg-K);
- \( D_{v,\text{air}}(T) \): vapor diffusivity in free air, m\(^2\)/s;
- \( h_v \): specific enthalpy of water vapor, J/kg.

In the simulations, measured material properties (Vinha et al., 2005) and material properties from the CHAMPS-BES library were used for the density, thermal conductivity, moisture permeability, liquid water diffusivity, and moisture storage functions, see Table 1. The inner surface of the envelope was completely air- and vapor-tight, except one air inflow gap. This inflow gap was modeled as porous building material with the hygrothermal properties of the air.

The materials were determined in such a way that a fiber saturation level of RH 97\% was used as the maximum amount of water captured from the
surrounding humid air that can be stored in the sheathing material under isothermal conditions. For the heat and mass transfer coefficients between the material and surrounding air constant values were used: on the interior surface: $8 \text{ W/(m}^2\cdot\text{K})$ and $2 \cdot 10^{-14} \text{ s/m}$; on the interior surface: $25 \text{ W/(m}^2\cdot\text{K})$ and $5 \cdot 10^{-14} \text{ s/m}$.

The construction grid was 10 mm on average, except the transitions between materials and the air gap, where a smaller grid (down to 0.2 mm) was used, see Figure 3. The total number of the volume elements was about 2500.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density $\rho$, (kg/m$^3$)</th>
<th>Thermal conductivity of the dry material $\lambda$ (W/(m K))</th>
<th>Water vapor diffusion resistance factor $\mu$ –</th>
<th>Air permeability of the dry material (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral wool insulation</td>
<td>22</td>
<td>0.04</td>
<td>1.2</td>
<td>0.0125</td>
</tr>
<tr>
<td>Mineral wool sheathing</td>
<td>92</td>
<td>0.04</td>
<td>1.5</td>
<td>0.00001a</td>
</tr>
<tr>
<td>Wood fiberboard sheathing</td>
<td>280</td>
<td>0.07</td>
<td>4.6</td>
<td>0.00006a</td>
</tr>
<tr>
<td>Air</td>
<td>0.026</td>
<td>1.0</td>
<td></td>
<td>0.1a</td>
</tr>
</tbody>
</table>

*with the relationship of air permeability of air and sheathing materials as well the width of the air gap the air flow rate though the studied joint was changed.

![Figure 3. The grid of the connection of the simulated timber-frame walls with the attic floor.](image-url)
During simulation, the time step varied between 0.0001s and 30 min. depending on the allowed tolerance. The solver reduces time steps due to convergence problems or because the local error exceeds the tolerances.

RESULTS

Laboratory Measurements

Full-scale laboratory measurements were performed to analyze the hygrothermal performance of the joint between an external wall and an attic floor and to obtain reference data for the simulation model. Laboratory tests were carried out in two steps. In the first step, the test was conducted with a closed (taped) air leakage path to achieve equilibrium conditions. This took 1–3 weeks, depending on the case. After that, the leakage was opened and measurement continued with the positive pressure.

The first seven tests were conducted with 12 mm wood fiberboard sheathing under two airflow rates; see Table 2. After the first three test series, the leakage was reduced to lessen the exfiltration, as the test with $-10^\circ$C showed condensation. With reduced leakage the condensation still occurred at an outdoor temperature of $-10^\circ$C (Test 7). The condensation and the formation of frost on the inner surface of the fiberboard sheathing of the attic floor at the end of these tests are shown in Figures 4 and 5. The condensation and frost were not evenly distributed over the surface of the sheathing, but were concentrated on some parts only, indicating that the airflow was multi-dimensional. From Figure 4 (left) it is also possible to see that there was no frost formation near the T&RH sensors, indicating that there was ideal contact between the insulating material and the sheathing.

Table 2. Boundary conditions and determined condensation on the inner surface of the sheathings for the measurement series with 12 mm wood fiberboard sheathing.

<table>
<thead>
<tr>
<th>Test</th>
<th>$T_{\text{out}}$ ($^\circ$C)</th>
<th>$T_{\text{in}}$ ($^\circ$C)</th>
<th>$\Delta v$ (g/m$^3$)</th>
<th>$\Delta P$ (Pa)</th>
<th>$q$ (L/(s·m)) at 10 Pa</th>
<th>Timber-frame wall</th>
<th>AAC wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>+22</td>
<td>+4</td>
<td>+20</td>
<td>0.31</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>$-10$</td>
<td>+22</td>
<td>+4</td>
<td>+20</td>
<td>0.31</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>$-10$</td>
<td>+22</td>
<td>+4</td>
<td>+10</td>
<td>0.31</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>+22</td>
<td>+4</td>
<td>+10</td>
<td>0.18</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>+22</td>
<td>+4</td>
<td>+20</td>
<td>0.18</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>$-5$</td>
<td>+22</td>
<td>+5</td>
<td>+10</td>
<td>0.18</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td>$-10$</td>
<td>+22</td>
<td>+4</td>
<td>+10</td>
<td>0.18</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
material near the cable and the sensor. Another reason for this phenomenon could be the swelling of the fiberboard sheathing. It is possible that the sheathing retreated from the surface of the insulation and the lower surface temperature caused interstitial condensation on the inner surface of the sheathing. A similar phenomenon also happened during the other tests. In addition, the condensation may impair the accuracy of the measured results so that RH sensors show slightly lower values (Vinha, 2007). Therefore, T&RH sensors may not indicate high RH values even though condensation occurred behind the sheathing (Figure 5).

Figure 4. Condensation and frozen mineral wool pieces on the inner surface of the sheathing of the attic floor, timber-frame wall (left), and the AAC wall (right), after Test 7.

Figure 5. Measured RH behind the sheathing of the attic floor in the case of the timber-frame wall during Test 3 (T&RH sensors 4, 5, and 7 in.).
During the 30-day measurement period of Test 1, the increase in the mass-related moisture content of the wood fiberboard sheathing of the attic floor was 10% and the final moisture content was 22%.

To improve the hygrothermal performance of the construction being studied, another sheathing material was tested. The last three tests were conducted with 20-mm mineral wool-board sheathing covered with SBPO film, which is more vapor-permeable and has higher thermal resistance than wood fiberboard sheathing. The improved construction showed better hygrothermal performance and no condensation was determined below the sheathing; see Table 3. However, the exfiltration flow rate was also reduced during the last three test series, because the mineral wool-board sheathing with taped joints improved the airtightness of the assembly.

### SIMULATIONS

#### Comparison of Laboratory Tests and Results of Simulations

To validate the simulation model the measurement data from Case Test 6 were used. The measured and simulated temperature, the RH, and the humidity by volume values of the outer surface of the insulation and the sheathing of the attic floor are shown in Figures 6–8. These results correspond to T&RH sensor locations 4, 5, and 7 in.

The calculated temperatures showed good agreement with the measured ones. The RH and humidity by volume showed greater differences between the measured and calculated results. It was not possible to identify any other specific reason for this discrepancy than a 2D calculation model being used for a 3D problem. It was possible to see some 3D behavior of the exfiltration airflows from the laboratory measurements. On the basis of these results, it was concluded that the model was accurate enough for the analysis of 2D moisture convection phenomena.

### Table 3. Boundary conditions and determined condensation on the inner surface of the sheathings for the measurement series with 20 mm mineral wool-board sheathings.

<table>
<thead>
<tr>
<th>Test</th>
<th>$T_{\text{out}}$ (°C)</th>
<th>$T_{\text{in}}$ (°C)</th>
<th>$\Delta v$ (g/m³)</th>
<th>$\Delta P$ (Pa) at 10 Pa</th>
<th>$q$ L/(s·m)</th>
<th>Determined condensation on the inner surface of the sheathings</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>-5</td>
<td>+22</td>
<td>+4</td>
<td>+10</td>
<td>0.05</td>
<td>No</td>
</tr>
<tr>
<td>9</td>
<td>-10</td>
<td>+22</td>
<td>+5</td>
<td>+10</td>
<td>0.05</td>
<td>No</td>
</tr>
<tr>
<td>10</td>
<td>-5</td>
<td>+22</td>
<td>+2.5</td>
<td>+10</td>
<td>0.05</td>
<td>No</td>
</tr>
<tr>
<td>11</td>
<td>-5</td>
<td>+22</td>
<td>+2.5</td>
<td>+20</td>
<td>0.05</td>
<td>No</td>
</tr>
</tbody>
</table>

During the 30-day measurement period of Test 1, the increase in the mass-related moisture content of the wood fiberboard sheathing of the attic floor was 10% and the final moisture content was 22%.

To improve the hygrothermal performance of the construction being studied, another sheathing material was tested. The last three tests were conducted with 20-mm mineral wool-board sheathing covered with SBPO film, which is more vapor-permeable and has higher thermal resistance than wood fiberboard sheathing. The improved construction showed better hygrothermal performance and no condensation was determined below the sheathing; see Table 3. However, the exfiltration flow rate was also reduced during the last three test series, because the mineral wool-board sheathing with taped joints improved the airtightness of the assembly.
Steady-state Hygrothermal Performance

The simulation model was used to analyze the effects of the indoor humidity load, exfiltration airflow rate, and sheathing material on the
moisture convection performance. First, calculations were carried out for a timber-frame external wall with a constant outdoor temperature and other constant boundary conditions.

A 2-month calculation period was used as the simulations showed that after a 2-month period, steady-state concentrations of humidity or a constant increment in humidity (if condensation occurred) were achieved. The RH after a 2-month simulation period (2 weeks without exfiltration and 1.5 months with exfiltration) with an outdoor temperature of $-10^\circ\text{C}$ is shown in Figure 9 for mineral wool sheathing and in Figure 10 for wood fiberboard sheathing.

The simulation results illustrate the phenomena of exfiltration and moisture convection well. Warm airflow in the porous material may increase or reduce the humidity, depending on the indoor humidity generation. For a given moisture excess value (for example 2 g/m$^3$ in Figure 9), even an ‘optimum’ airflow rate, leading to the lowest possible RH, can be found in some cases. However, with higher moisture excess values, such as the 4 g/m$^3$ used for dimensioning, the airflow quickly increases the RH and causes condensation. The difference between the sheathings is remarkable. Mineral wool sheathing was much more tolerant towards exfiltration, especially at low moisture excess values.
**Figure 9.** Simulated RH behind the mineral wool sheathing of the attic floor in the case of the timber-frame external wall.

**Figure 10.** Simulated RH behind the wood-fiberboard sheathing of the attic floor in the case of the timber-frame external wall.
Variable Moisture Excess

To study the influence of the moisture excess profile, simulations were performed with constant and variable moisture excess:

- constant $\Delta v = + 2 \text{ g/m}^3$ and variable $\Delta v$ of 12 h $\Delta v = \pm 0 \text{ g/m}^3$ and 12 h $\Delta v = + 4 \text{ g/m}^3$;
- constant $\Delta v = + 4 \text{ g/m}^3$ and variable $\Delta v$ of: 12 h $\Delta v = + 2 \text{ g/m}^3$ and 12 h $\Delta v = + 6 \text{ g/m}^3$.

The simulation results in Figure 11 show that the same daily average moisture excess gives the same RH values, and thus the results do not depend on the daily dynamics of moisture excess. This justifies the simulation with a constant moisture excess value, as no error has happened. Another outcome is that the structure does not dry out at periodically low humidity loads if there are also periodically high humidity loads.

Hygrothermal Performance with Real Climatic Data – Dynamic Simulation

Finally, simulations were performed with variable outdoor climate conditions. For the outdoor climate, the moisture reference year (Kalamees and Vinha, 2004) was used. The pressure difference across the assembly was calculated from the indoor and outdoor temperatures at a height from the neutral axis of 2.75 m. A moisture excess of $\Delta v = 4 \text{ g/m}^3$ was used,
corresponding to indoor humidity loads in a dwelling with low occupancy (Kalamees et al., 2006, Kumaran and Sanders, 2008).

First, the exfiltration airflow rate was set to a level at which no condensation occurred in steady-state conditions. This corresponded to 0.14 L/(s·m) at an outdoor temperature of $-10^\circ$C and an air pressure difference of +3.7 Pa (temperature difference 31 K and height from the neutral axis of 2.75 m). This exfiltration rate changed according to the air pressure difference, which depended on the outdoor temperature; see Figure 12.

In a dynamic simulation, this exfiltration rate (0.14 L/(s·m) at +3.7 Pa and no condensation with a constant outdoor air temperature of $-10^\circ$C) caused condensation with a maximum condensate of 2.6 kg/m²; see Figure 13. The length of the significant condensation period was 1.5 months, which is as long as the calculation time used in the steady-state calculation. In the dynamic simulation, the condensate dried out after this 1.5-month period. The average outdoor temperature during this period was about $-10^\circ$C.

Figure 13 shows that the condensation started when the outdoor temperature dropped below $-20^\circ$C. At such low temperatures the condensate started to increase (left-hand zone in the figure) and drying out can be seen after the temperature rises above 0°C (right-hand zone in the figure).

The lower exfiltration rate (0.097 L/(s·m) at +3.7 Pa) that led to RH = 86% behind the mineral wool sheathing of the attic floor with a
constant outdoor temperature of $-10^\circ C$ caused condensation of $0.5 \text{ kg/m}^2$ (exactly the limit according to DIN 4108-3 (2001)) in the dynamic simulation (Figures 13–15). Figure 14 shows the dependence between outdoor temperature and amount of condensate. In the dynamic simulation, condensation started similarly during the cold period and drying out can be seen below $-10^\circ C$.

To avoid the condensation completely in the dynamic simulation, an exfiltration rate corresponding to a steady-state RH $= 81\%$ behind the mineral wool sheathing of the attic floor has to be used. This RH at a $-10^\circ C$ steady state corresponded to an exfiltration rate of $0.05 \text{ L/(s·m)}$ at $3.7\text{ Pa}$; see Figure 15.

**DISCUSSION**

The results stress the importance of airtightness; otherwise, exfiltration will easily cause condensation/the formation of frost on the inner surface of the sheathing of the attic floor, especially with typical dimensioning moisture excess value of $+4 \text{ g/m}^3$ and wood fibreboard sheathings. A higher positive pressure and lower outdoor temperature evidently increased the moisture accumulation rate. And vice versa: a higher outdoor temperature and lower
exfiltration rate caused a remarkable improvement in the hygrothermal performance of the assemblies being tested. Thus, as in the case of balanced ventilation, the positive pressure caused by the stack effect cannot easily be controlled (Kalamees et al., 2007) and it is essential to control moisture

Figure 14. Daily average condensation dependence on outdoor temperature for exfiltration rates of 0.14 L/(s·m) and 0.097 L/(s·m) at +3.7 Pa.

Figure 15. RH behind the mineral wool sheathing of the attic floor in the steady-state simulation vs amount of condensation in the dynamic simulation.
convection by good airtightness and the use of less sensitive assembly solutions, such as the case with mineral wool sheathing that was tested.

The results of the steady-state calculations with constant boundary conditions over some time period showed that there could not be any condensation. Dynamic simulation with variable outdoor weather data showed a large amount of condensate with outdoor temperatures below the value used in the steady-state simulations; however, the structure dried out after 1.5 months in this case. Thus, the constant (average/dimensioning) moisture excess value may be used without loss of accuracy, but dynamic calculation with real weather data is needed for the accurate assessment of condensation. Depending on the criteria, it is necessary to avoid condensation completely or to keep the amount of condensation below a given level (the 75–80% RH criterion that is often used seems not to be relevant in exfiltration analyses as there is no risk of mould growth at minus temperatures, and the drying-out process is also fast because of the airflow).

In the current case the RH of 86% in the steady-state simulation was equal to condensation of 0.5 kg/m² in the dynamic simulation with variable outdoor weather data. To avoid condensation in the dynamic simulation, the limit RH in the steady-state simulation was 81% at an outdoor temperature of $-10^\circ{\text{C}}$.

Depending on the criteria, the safe exfiltration rates were 0.095 L/(s·m) at +3.7 Pa (condensation below 0.5 kg/m², which is the limit according to DIN 4108-3) or 0.05 L/(s·m) at 3.7 Pa (no condensation at all) for the case with the mineral wool sheathing. From these values one can easily calculate the leakage values at a pressure difference of 50 or 10 Pa. According to airtightness measurements in 170 Finnish detached houses (Jokisalo et al., 2009), the average flow exponent was 0.73. With this flow exponent, these exfiltration rates become 0.33 L/(s·m) and 0.63 L/(s·m) at 50 Pa and 0.1 L/(s·m) and 0.2 L/(s·m) at 10 Pa. These exfiltration values apply for sheathing materials with high thermal resistance and water vapor permeability, such as mineral wool. For the wood fiberboard sheathing, the acceptable exfiltration rate is much lower, if any exfiltration at all may be accepted. Leakage characteristics have been widely studied and generally 0.1 L/(s·m) at 10 Pa is not an extremely low value. Sandberg and Sikander (2004, 2007) and Basset (1987) report that a leakage of 0.1 L/(s·m) at 10 Pa can easily be achieved with careful workmanship. Sometimes common tightening solutions might need some improvements. For example, fixing PE foil’ to a wall with a ledge resulted in a leakage of 0.11 L/(s·m), while the same joint with double-sided tape resulted only in 0.0141 L/(s·m) (Sandberg and Sikander, 2004). It should also be noted that the external wall/external ceiling joint, which is considered to be the most critical one in this study, can be tightened in a rather straightforward way in most assembly solutions and
is usually not sensitive to any penetration which is not typical in this ceiling location.

Tests and simulations with mineral wool-board sheathing showed a significantly better hygrothermal performance compared to fiberboard sheathing. Higher vapor permeability and thermal resistance do indeed give the mineral wool-board sheathing better drying potential. At the same time, the tests with the mineral wool-board sheathing were conducted with a lower exfiltration rate (Tables 2 and 3). The leakage path at the air/vapor barrier was the same in all the tests, but in the case of the mineral wool-board sheathing covered with SBPO film, it was possible to tape all the joints and the test structure became more airtight. This shows that the selection of the sheathing material may play an important role in the improving of the airtightness of the building.

In the simulation, it is not possible to take into account the geometrical change (swelling and shrinkage) of the materials. Nevertheless, during the measurements, the fiberboard sheathing swelled as a result of the accumulation of moisture. The joints of the timber-frame and AAC walls with the timber-frame attic floor were simulated as 2D joints. In reality, the convection in the joint was surely 3D (see the condensation areas in Figure 4). These two facts, as well as the fact that the joints under study contain small imperfections that cannot be modeled, may be the main reasons for the differences between the simulated and measured results. There was also a tendency for the accumulation of moisture to continue in the measurements, while, in the simulations, the moisture content remained at a constant level (see measurement point 4, Figure 7).

CONCLUSIONS

The hygrothermal performance of the external wall and attic floor was studied by full-scale measurements in laboratory conditions and by 2D heat, air, and moisture transport simulation with CHAMPS-BES.

The results from the laboratory measurements and simulations showed that the building fabric is locally sensitive to exfiltration airflow, as moisture convection could cause a remarkable increase in the moisture accumulation rate on the inner surface of the sheathing. The results show the effects of air leakage rates, indoor humidity generation, and outdoor temperature. Results prove that in modern houses with balanced ventilation, where the positive pressure caused by the stack effect cannot easily be controlled, the essential way to control moisture convection is good airtightness and the use of assembly solutions with improved hygrothermal performance, such as the tested case with mineral wool sheathing.
The selection of the sheathing material had important effects on both the hygrothermal performance and airtightness of the building fabric. Mineral wool sheathing with SBPO film outperformed wood fiberboard sheathing because of its higher thermal resistance and water vapor permeability, as well as its better airtightness. The laboratory measurement and simulation results show that in a cold climate leakage rates of 0.1 L/(s·m) and 0.2 L/(s·m) at a pressure difference of 10 Pa may be used as performance criteria for moisture convection in a two-storey house with typical dimensioning 4 g/m³ moisture excess, with balanced ventilation. The 0.1 L/(s·m) at 10 Pa refers to no condensation at all and 0.2 L/(s·m) at 10 Pa to a 0.5 kg/m² condensate criterion. Previous studies on the leakage characteristics show that these leakage rates are easily achievable in practice with careful workmanship.

The moisture content of the outer part of the structure did not depend on the daily dynamics of moisture excess. The simulated results showed that the use of a constant moisture excess value did not cause any inaccuracy in the moisture content, and that a periodically low moisture excess did not dry out the structure if there are also periodically high excess values, respectively. At the same time, the use of the average outdoor temperature over a long time period did change the hygrothermal performance, which became significantly more critical when simulated with variable outdoor temperatures. The exfiltration rate, which did not cause condensation at a constant outdoor air temperature, caused a condensate as high as 2.6 kg/m² with a condensation period of 1.5 months with variable outdoor climatic conditions. Thus, the use of a constant moisture excess value with hourly weather data for the analyses can be recommended.

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REFERENCES


Moisture Convection Performance of External Walls and Roofs

(Building Physic Material Properties as a Function of Temperature and Relative Humidity), Tampere University of Technology, Department of Civil Engineering, Structural Engineering Laboratory, Research report 129. Tampere 2005 (in Finnish).
