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Validation of a One-Dimensional Transient Heat and Moisture Calculation Tool under Real Conditions

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ABSTRACT

Stricter Swedish building regulations require a moisture-safety design process to be carried out before houses are built. In order to predict moisture-critical conditions, a properly verified, user-friendly and reliable calculation tool that could be used in this design phase, is required.

This paper initially presents a blind method that could be used in order to verify heat and moisture calculation tools in a reliable manner. Furthermore, general results and findings from blind validations using a transient heat and moisture calculation tool are summarized and presented. The comparisons include measurements and calculations of temperature and relative humidity and were carried out in northern European climates.

In general, the results show a good correlation between measured and blindly-calculated values. Comparisons show that the studied tool can be used during the design phase to predict moisture risks. However, factors such as the influence of impaired-temperature measurements on relative humidity have to be taken into account. There is also a need for outdoor climate-boundary conditions that take into account critical periods. Measurements and calculations also established that the most moisture-critical conditions in general occurred in the exterior part of the frame, behind the air gap.

INTRODUCTION

Background

Several studies show that mold and moisture-related damage is linked to high costs. As much as 30% of single-family houses and 15% of other buildings in Sweden have moisture-related damage (Boverket 2009). Individuals, as well as insurance companies and the national economy, are affected by these costs.

At the same time, the risk of moisture-related damage generally increases in new houses. The awareness of climate changes, increased energy costs, and new energy demands have resulted in new houses being more well-insulated (BBR 2011). Besides the positive effect of reduced energy needs, thicker insulation also results in a building envelope in which critical parts more often become exposed to higher levels of relative humidity (RH). Higher relative humidity leads to the increased probability of occurrences of mold growth (Nevander and Elmarsson 1991; Hägerstedt and Arfvidsson 2010; Hägerstedt 2012).

As a consequence, recent Swedish building regulations have stipulated stricter requirements when predicting the risk of mold and moisture damage in order to reduce this kind of problem. Moisture conditions that create odors, unhealthy indoor climates, and mold growth that affect the health of a building's occupants are forbidden. Furthermore, it is strictly recommended that these factors should be taken into account and verified before a house is built (BBR 2011).

To minimize the risk of moisture damage, a reliable and validated user-friendly moisture calculation tool is needed to predict the hygrothermal performance. A tool that could be used to make it possible to check and compare different designs before a house is built (Boverket 2009; Mjörnell et al. 2012). From experience, it is known that the construction

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industry today only uses one-dimensional and fast calculation tools, if any tool is used at all, in the moisture-safety design process.

Today, there are several tools available that could be used to predict the hygrothermal performance and mold risks in constructions. Unfortunately there are only two calculation tools, WUFI and DELPHIN, that are commercially available and could be seen as user-friendly. Neither of these calculation tools seems to have been properly verified by independent researchers using blind methods, i.e., verified without knowing the measurement results before making comparisons with unadjusted calculated results (Mundt-Petersen 2012). Experiences from the northern European building trade also show that only one-dimensional methods are used. Furthermore, the only studies found with explicit blind comparisons focus on moisture control by allowing a high airflow in the air gap between the cladding and exterior mold-resistant insulation boards (Hägerstedt and Arfvidsson 2010; Hägerstedt and Harderup 2011a; 2011b). Only a few studies in northern European climates are found in which it is possible to compare measured and calculated values, such as Nore (2009); Geving and Holme (2010); Geving et al. (2011); Hägerstedt and Arfvidsson (2010); Hägerstedt and Harderup (2011a; 2011b). Most of the other verifications that were found could not be seen as independent as they were needed during the software development process or carried out by the developers, such as Künzel (1995); Krus (1996); Künzel et al. (2002); Künzel et al. (2004); Zirkelbach et al. (2011). There is also a lack of real-life field studies in houses where people are actually living (Nore 2009; Salonvaara et al. 2010; Geving and Holme 2010; Zirkelbach et al. 2011). It can therefore be established that there is no independent and blind verified user-friendly moisture calculation tool. There is also a lack of verified calculation tools in which real field conditions and northern European climate conditions have been studied (Mundt-Petersen 2012).

In order to determinate an independent blindly verified moisture calculation tool, measurements were carried out in a Swedish research project with starting points at the end of 2008 and in early 2009. The project comprised 148 measuring positions, of which 85 positions were in walls and 63 positions in roofs and attics, and measured temperature (T), relative humidity (RH) and moisture content (MC) in five different houses located in four different parts of Sweden over a period of approximately three years (Framtidens trähus 2012).

Aim

The aim of the entire project was to validate a hygrothermal tool to be used in the design phase to avoid mold and moisture damage and evaluate the risk of damage in studied building envelopes. However, the aim of this paper was to summarize the results of comparisons between measurements and blind calculations of temperature and relative humidity carried out in wood-frame walls during the period 2008 to 2011 in northern European climates.

The study aimed to show whether it might be possible to use the one-dimensional transient heat and moisture calculation tool WUFI 5.0 as a tool during the design phase in order to predict and evaluate the risk of mold growth and moisture damage. It was also intended to analyze under what conditions the calculation tool can be used and to show important factors that highly affect the correlation between measured and calculated values.

Furthermore, this paper aims to present a method that describes how calculation tools could be reliably verified under real conditions by using blind calculations.

Since the Folos 2-D visual mold chart was used in the comparison between calculated and measured values, the risk of mold growth was simultaneously evaluated in the studied positions in the walls (Mundt-Petersen et al. 2012).

Limitations

This paper presents a limited number of examples with general results from the entire investigation of 85 different positions. Only comparisons between measured and calculated temperature and relative humidity are shown. Complete comparisons between measured and calculated values in all the studied positions are presented in five separate reports (Mundt-Petersen 2013a; 2013b; 2013c; 2013d; 2013e).

The study is limited to an investigation of wood-frame walls with well-ventilated air gaps behind the cladding and an interior, well functioning vapor barrier. A detailed description of studied designs, calculation models and used material data are not given, but could be found in Mundt-Petersen (2013a; 2013b; 2013c; 2013d; 2013e; 2013f). Measurements and; calculations were carried out in northern European climates.

The study does not in detail analyze analytical solutions and physical and numerical models in the investigated calculation tool. Influence of possible measurement errors is discussed by Sandberg et al. (2011) and Mundt-Petersen (2013f). No detailed analysis of material data in the calculations models was made.

All calculations were made in one-dimension since this is the only tools that is widely used in the construction industry. The influence of wood studs and other thermal bridges were therefore deemed as neglectable in the calculations. Furthermore, possible influence of convection was neglected. The walls were also assumed to have been the results of perfect workmanship when compared to the drawings and calculation models used.

The definition of RH_{crit} that was used was limited to showing the conditions when mold growth on wood based materials are possible.

METHOD

All calculations were made blind, i.e., made without knowing the results of any measurements. Blind comparisons could also be called single-blind. All calculations and comparisons in this study were made single-blind and were carried out by independent organizations and testers, although this is not specifically highlighted in each specific case. Blind calculations are equivalent to situations when the designers carry out the heat and moisture calculations before a house is built. Comparisons with calculated values, made after the measured values had been received, were evaluated using the Folos 2-D visual mold chart.

Blind Comparisons Between Measured and Calculated Values. Initially, measuring sensors for temperature, relative humidity and MC were mounted at different depths and locations in the walls during the construction phase. The position of each sensor was well documented in drawings and photos. All the construction phases were monitored to establish any possible deviations between the drawings and the real conditions in the built wall. Measurements were started as soon as possible, sometimes before the houses were occupied, and were carried out using a wireless Protimeter Hygro Trac system (Sandberg 2011; Mundt-Petersen 2013f; GE Sensing 1996). Hourly measurements of temperature, relative humidity, and MC for each specific position were then separately stored by a measurement collector, inaccessible to the persons involved in evaluating the calculation tool.

Over a period of three years, when the measurements were carried out, calculation models of each studied position were made. The calculation models were based on drawings and photos from the construction phase with the intention of reflecting as real conditions as possible. However, since the calculation tool being evaluated was one-dimensional, the possible influence of beams, sills and studs was not included in the calculations.

In 2012 calculations were carried out for each studied position for the period 2008 to 2011, without knowing the measured results. The calculations were made using the indoor and outdoor climate-boundary conditions collected from indoor measurements and closely located outdoor climate stations (SMHI 2012).

After the blind calculations had been completed and sent to the measurement collector, the previously inaccessible measurements were retrieved. Comparisons between the measurements and the calculated temperature and relative humidity were then made over time using the Folos 2-D visual mold chart.

Note that it was possible to make adjustments to the calculation models to achieve better correlation, or even a perfect match, between the measured and blindly-calculated values in almost all the studied positions. However, this was not a part of the blind verification presented in this paper.

The Need for Blind Comparison. Software used as a tool to predict mold and moisture-related damage before a house is built to be blindly verified and without being influenced by the program developer. In this case, this was fulfilled by carrying out the calculations before the results of the measurement were known, i.e., they were blind calculations, and they were then compared to the measurements. Blind validations are reliable since intentional or unintentional adjustments of calculated results, to obtain better correlations to the measured values, are impossible. There are also other positive effects since the blind calculations are similar to the situation the designer has to deal with before a house is built. This provides important information about how the user perceives the tool. Many poor calculation results are due to inaccurate models or incorrect boundary conditions—such as unrealistic climate data, false material data, or inaccurate surface resistance—created by the user. Errors like these could be avoided by providing better default values, clearer instruction manuals, or stricter parameter limit values in the software.

Notice that the method used is not double-blind since it is possible to guess the measured results before the calculations are made. This is also possible during the design phase. It should also be mentioned that nonblind comparisons might be needed in the early development phase of equations and calculation tools.

Folos 2-D Visual Mold Chart. The Folos 2-D visual mold chart was used to evaluate and compare results between measured and calculated values in different designs, positions within the walls, and surrounding climates. Besides showing the measured and calculated values and the correlation between measured and calculated values, the Folos 2-D visual mold chart also indicates the risk of mold growth. By using the Folos 2-D visual mold chart, it is also possible to establish measures to be taken and to compare different designs in order to reduce the risk of mold growth (Mundt-Petersen et al. 2012).

The chart is briefly described together with the general results to make it easier to understand when it is used in context. The moisture-critical limit used was the LIM I limit (Sedlbauer 2001).

MATERIALS

The Studied Houses. Measurements and calculations were carried out in five different wood-frame houses. The measurement and calculation positions were located at different depths and locations in the walls, which had five different designs and faced different directions. The studied designs are shown together with examples of comparisons in the results section. The houses were located in four different towns in Sweden (as shown in Figure 1) each with different climate conditions.

Choice of Evaluated Calculation Tool. The criteria for choosing the evaluated tool were that it had to be user-friendly and available to the Swedish timber industry, i.e., a commercial tool (Boverket 2009). The most user-friendly and commercial software seems to be WUFI, and that is why it was chosen for the blind evaluation. The chosen tool was also specifically mentioned as a possible tool in previous investigations (Boverket 2009).

The materials and material data used in the calculation models were chosen from the WUFI 5.0 material data base (WUFI 2009). All calculation models, including the used materials and material data, are presented together with the description of the studied positions in separate reports. In these, the positions and the results from comparisons between

Figure 1 *Locations of the studied houses in Sweden.*

measurements and calculations over the investigated period are presented (Mundt-Petersen 2013a; 2013b; 2013c; 2013d; 2013e; 2013f). Detailed boundary conditions and material data are given by Mundt-Petersen (2013f).

The Climate-Boundary Conditions and Periods with Impaired Climate-Boundary Data. To achieve better agreement between measured and calculated values, use of the standard outdoor climate in the calculation tool was avoided. Real measured climate data from climate stations closely located to the studied houses was collected during the measuring period and then used in the calculations (SMHI 2012).

Periods with flawed climate data or a lack of climate data have been replaced and are shown in the Folos 2-D visual mold chart together with the other results.

RESULTS, ANALYSIS, AND DISCUSSION

This section presents examples of general results and findings that could be established from 85 positions at different depths in walls with different designs, locations and orientations in five different houses (Mundt-Petersen 2013a; 2013b; 2013c; 2013d; 2013e). The investigated design is shown together with the results in each figure, in which the studied positions are marked with a red cross.

General Results and Description of the Folos 2-D Visual Mold Chart

In general, there was a good correlation between the measured and blindly-calculated values in most of the studied positions, as shown in the examples in Figures 2, 3, and 6, i.e., the calculated values can be used in further analysis to predict the risk of mold growth in a reliable manner. However, there are also differences between measured and calculated values in many positions. These are presented and analyzed below. Possible factors influencing differences are also discussed.

Description of the Folos 2-D Visual Mold Chart. The Folos 2-D visual mold chart (in Figures 2 to 10) shows calculated temperature (yellow) and measured temperature (dark blue) on the right *y*-axis. The calculated relative humidity (turquoise), measured relative humidity (black), RH_{crit} dependent on the calculated temperature (red), and the $RH > RH_{crit}$ difference for calculated values (light brown) and measured values (purple) are shown on the left *y*-axis. The time presented on the *x*-axis indicates the conditions at any specific time, and of particular interest are the periods when $RH > RH_{crit}$.

Critical conditions occur, and mold growth is possible, when the RH is above the RH_{crit} line. The RH_{crit} line is defined by the temperature that, at any specific time, exceeds the RH_{crit} limit LIM I invented by Sedlbauer (2001), i.e., the chosen RH_{crit} line is converted over time by using the actual temperature at each point in time. This means that critical conditions depend on the prevailing RH and temperature, where a high temperature gives a lower RH_{crit} line and vice versa.

However, depending on the moisture resistance of different materials and legislation in different countries, other mold growth limits could be used by choosing another appropriate RH_{crit} curve. A further description of the Folos 2-D visual mold chart and how it can be used can be found in a separate paper (Mundt-Petersen et al. 2012).

General Results. Examples of general results are shown in Figures 2, 3, and 6.

Impaired Climate-Boundary Data. Periods with impaired or lack of climate-boundary data have been replaced. Those periods are shown as dots or a line (green) at the top of the Folos 2-D visual mold chart. Vertical lines indicate a short period with lack of climate-boundary data and dots creating a horizontal line indicate longer periods that lack climate-boundary data. Lower values of dots or longer vertical lines indicate the lack of outdoor temperature or relative humidity data, which has a higher influence on the calculation results than the higher values or shorter lines that indicate lack of other less important climate-boundary conditions.

Influence of Temperature on the Relative Humidity

Differences between measured and blindly-calculated relative humidity depend in many cases on differences between measured and calculated temperatures, i.e., the vapor content is the same but different measured and calculated temperatures give different vapor contents at saturation. Furthermore, this creates differences between the measured

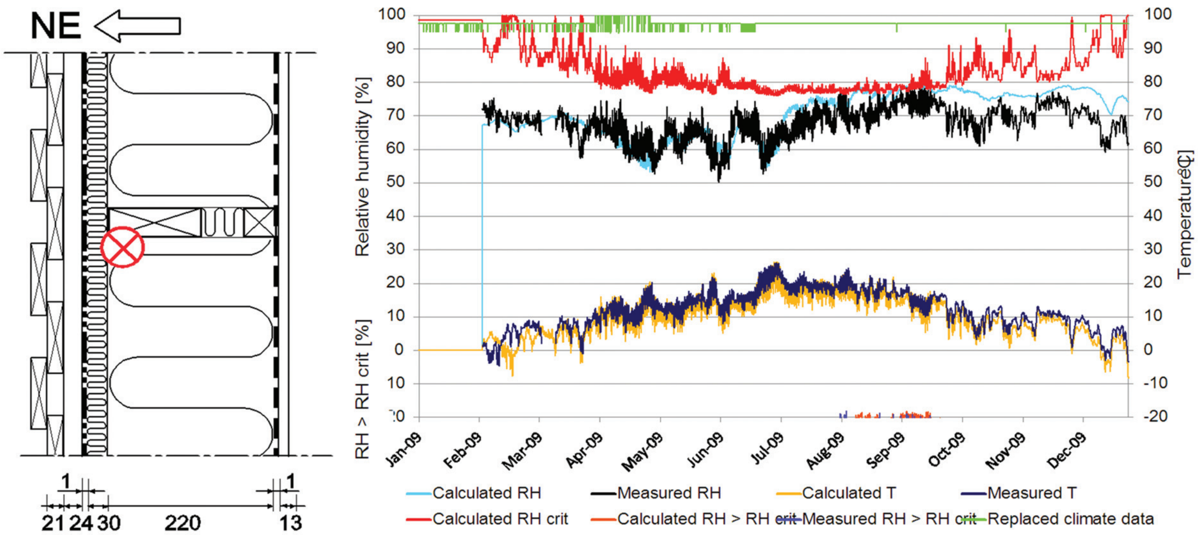

Figure 2 *Example of comparisons between measured and calculated RH and temperature behind a mold-resistant facade insulation board in the exterior part of a wall. Calculated RH (turquoise) and measured RH (black). Calculated temperature (yellow) and measured temperature (dark blue).The RH_{crit} derived from the calculated temperature (red). Calculated RH > RH_{crit} (light brown) and measured RH > RH_{crit} (purple). Periods with replaced climate-boundary data (green).*

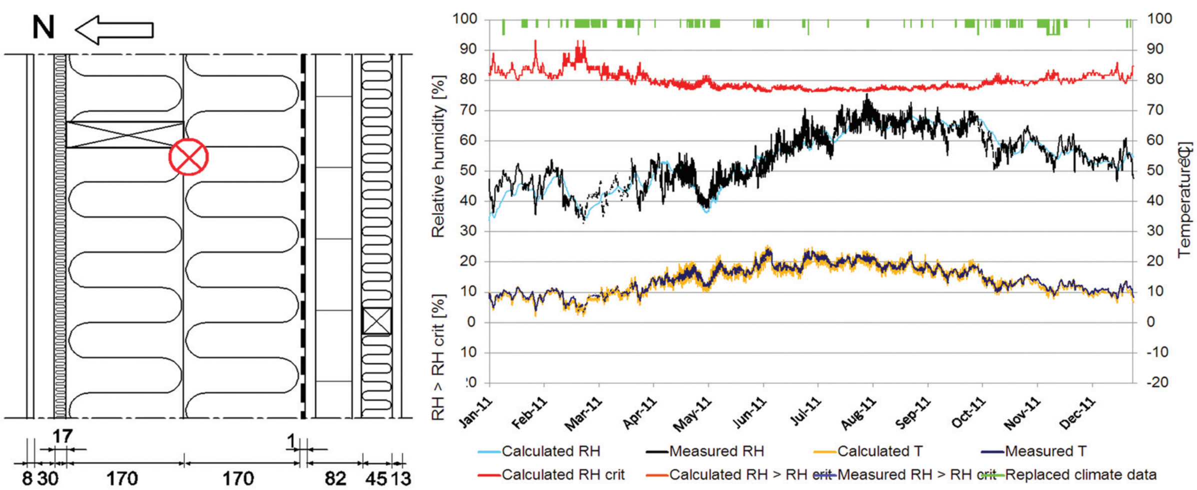

Figure 3 *Example of comparisons between measured and calculated RH and temperature in the middle of a wall. Calculated RH (turquoise) and measured RH (black). Calculated temperature (yellow) and measured temperature (dark blue). RH_{crit} derived from the calculated temperature (red). Calculated RH > RH_{crit} (light brown) and measured RH > RH_{crit} (purple). Periods with replaced climate-boundary data (green).*

and calculated relative humidity. This particular effect of temperature on relative humidity can be found in all the studied designs and houses. In most studied positions, a higher measured temperature creating a lower relative humidity, as shown in Figures 4 and 5, were found.

Differences Between Measured and Calculated Values During Cold Periods. Differences, depending on temperature, between measured and blindly-calculated relative humidity mainly occur during the colder periods in the outer part of the studied walls. As expected, differences tend to be greater in a colder climate, as shown in the example in Figure 4.

There may be several reasons for differences between measured and blindly-calculated temperature in the exterior part of studied walls during colder periods.

One factor was the thermal bridges due to studs and beams that are disregarded in the one-dimensional calculations. Studs and beams located close to the measuring sensor in the exterior part of the wall cause higher temperatures. This also explains why this effect becomes more obvious in colder climates. Two-dimensional studies of thermal bridges in a central Sweden climate show that the temperature increases by approximately

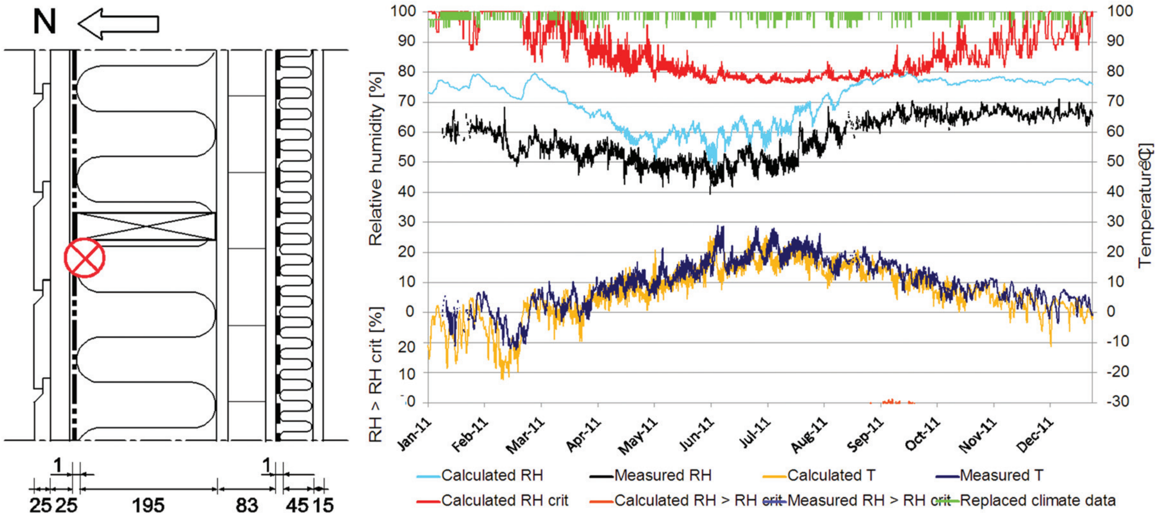

Figure 4 *Example of comparisons between measured and calculated RH and temperature in the exterior part of a wall located in the northern part of Sweden. Calculated RH (turquoise) and measured RH (black). Calculated temperature (yellow) and measured temperature (dark blue). The* RH_{crit} *derived from the calculated temperature (red). Calculated RH >* RH_{crit} *(light brown) and measured RH >* RH_{crit} *(purple). Periods with replaced climate-boundary data (green).*

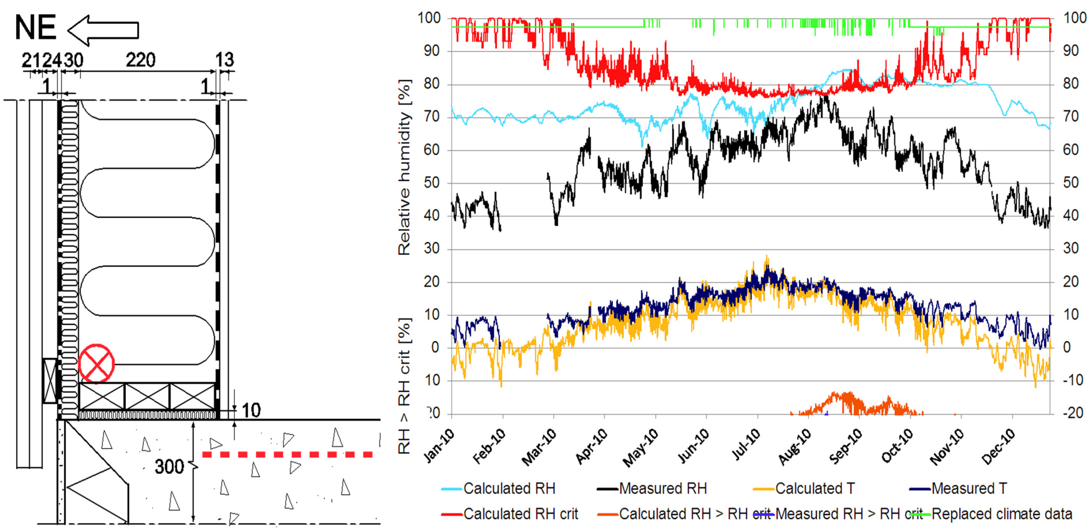

Figure 5 *Example of comparisons between measured and calculated RH and temperature, where measurements were carried out on the topside of the sill behind a mold-resistant facade insulation board in the exterior part of a wall. Calculated RH (turquoise) and measured RH (black). Calculated temperature (yellow) and measured temperature (dark blue).* RH_{crit} *derived from the calculated temperature (red). Calculated RH >* RH_{crit} *(light brown) and measured RH >* RH_{crit} *(purple). Periods with replaced climate-boundary data (green).*

0.5°C to 1°C. This reduces the relative humidity by 2.5% to 5% in the outer part of the stud (Forsberg 2011; Olsson 2011).

The sensor thickness of approximately 50 mm may also affect the temperature. Its size reduces the thickness of the surrounding thermal insulation which creates a higher temperature in the studied position, especially when the outdoor temperature is low. The temperature may also depend on the specific location of the temperature sensor within the larger measuring sensor. Furthermore, the sensor might create heat during measurement processing.

Another factor might be that differences between measured and calculated temperatures have a greater influence on the relative humidity of the lower vapor content that occurs in a cold climate.

Differences between the measured and calculated values may also depend on incorrect or delayed measured relative

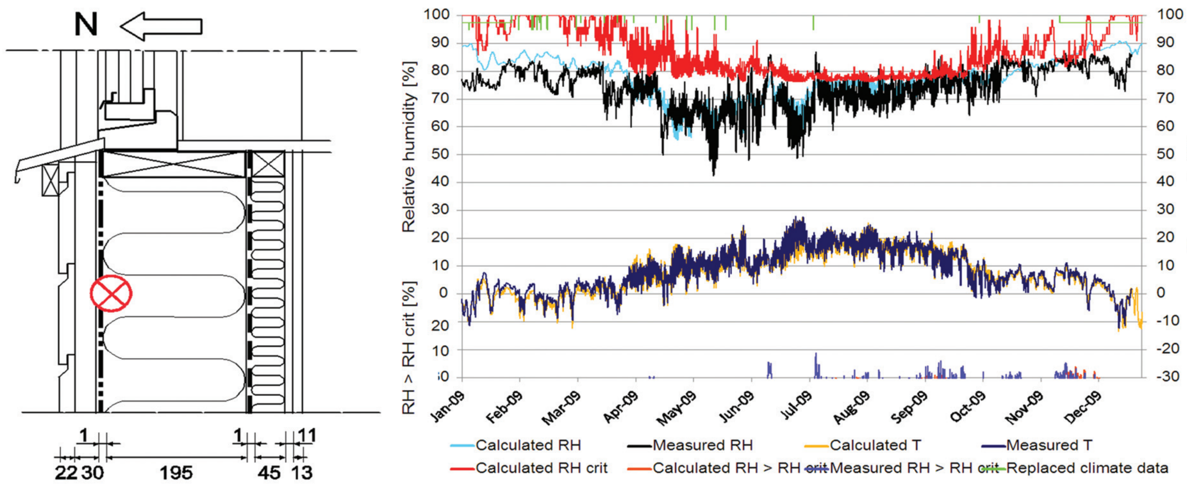

Figure 6 *Example of comparisons between measured and calculated RH and temperature in the exterior part of a wall. Calculated RH (turquoise) and measured RH (black). Calculated temperature (yellow) and measured temperature (dark blue). RH_{crit} derived from the calculated temperature (red). Calculated RH > RH_{crit}(light brown) and measured RH > RH_{crit} (purple). Periods with replaced climate-boundary data (green).*

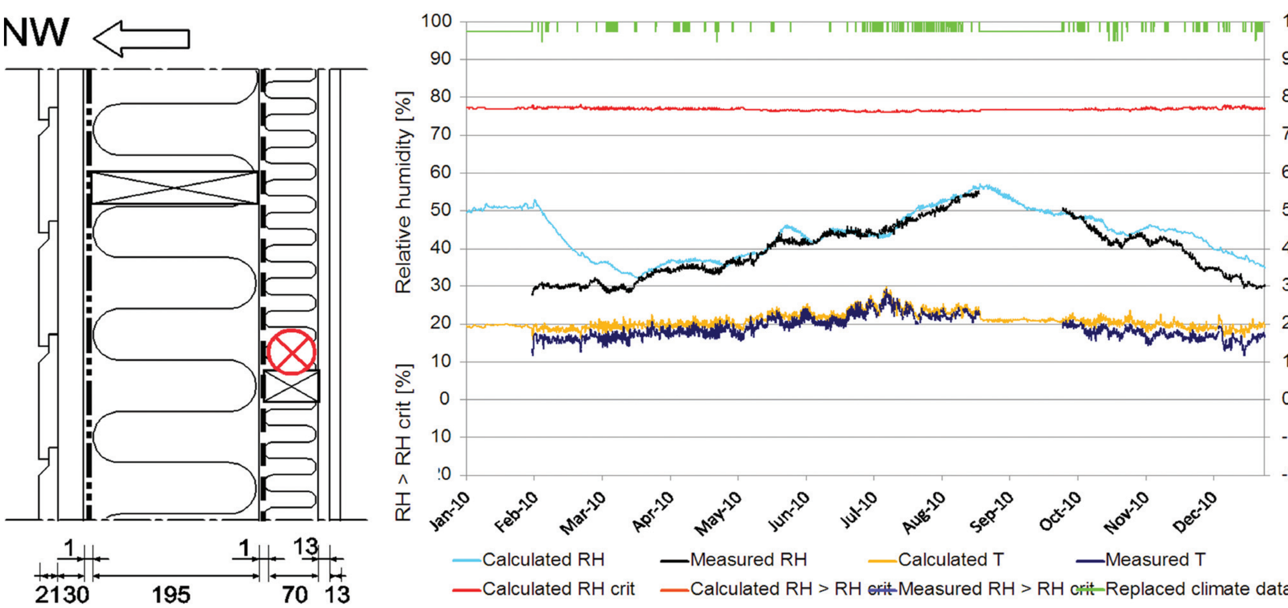

Figure 7 *Example of comparisons between measured and calculated RH and temperature in the installation layer on the inside of the vapor barrier in the interior part of a wall. Calculated RH (turquoise) and measured RH (black). Calculated temperature (yellow) and measured temperature (dark blue). RH_{crit} derived from the calculated temperature derived from the calculated temperature (red). Calculated RH > RH_{crit} (light brown) and measured RH > RH_{crit} (purple). Periods with replaced climate-boundary data (green).*

humidity. This becomes more evident in the winter when the outdoor relative humidity is high.

Influence of Under-Floor Heating Close to the Sill. A number of sensors were mounted at different depths in the wall on top of the sill, as shown in Figure 5.

In houses with under-floor heating, as shown in the slab in Figure 5, a positive effect was generated as a higher temperature reduced the relative humidity in this area. Higher temperatures also improve the drying-out process and make the sill warmer. It is important to observe that this positive effect requires vapor-permeable insulation that allows the drying-out process to take place.

However, the differences between measured and calculated values clearly show that it is not possible to use one-dimensional

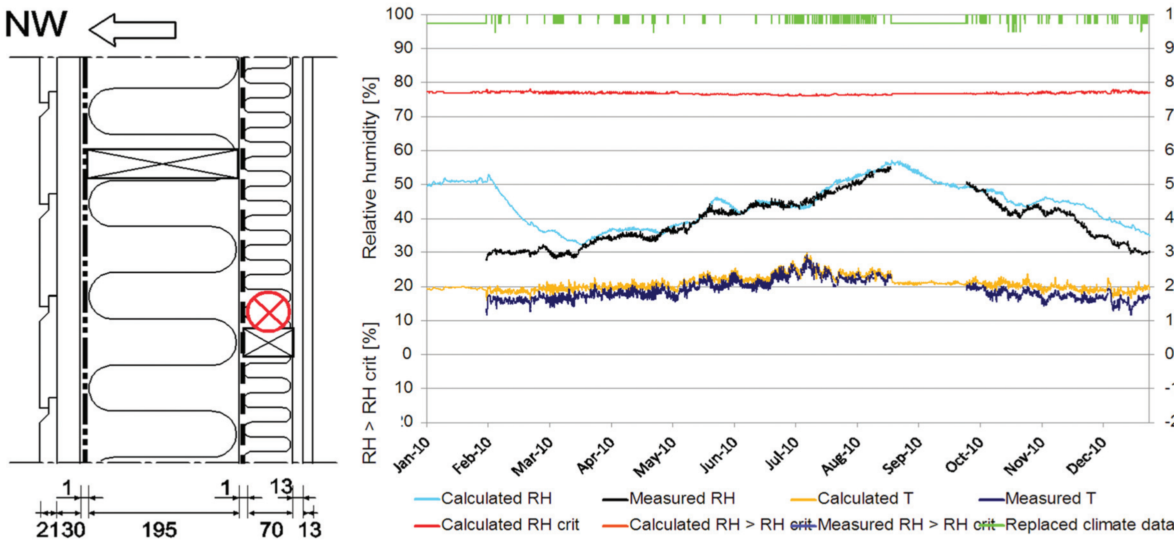

Figure 8 *Example of comparisons between measured and calculated RH and temperature in the installation layer between the vapor barrier and the interior waterproof membrane in the interior part of a bathroom wall over a period of three years. Calculated RH (turquoise) and measured RH (black). Calculated temperature (yellow) and measured temperature (dark blue).* RH_{crit} *derived from the calculated temperature (red). Calculated RH >* RH_{crit} *(light brown) and measured RH >* RH_{crit} *(purple). Periods with replaced climate-boundary data (green).*

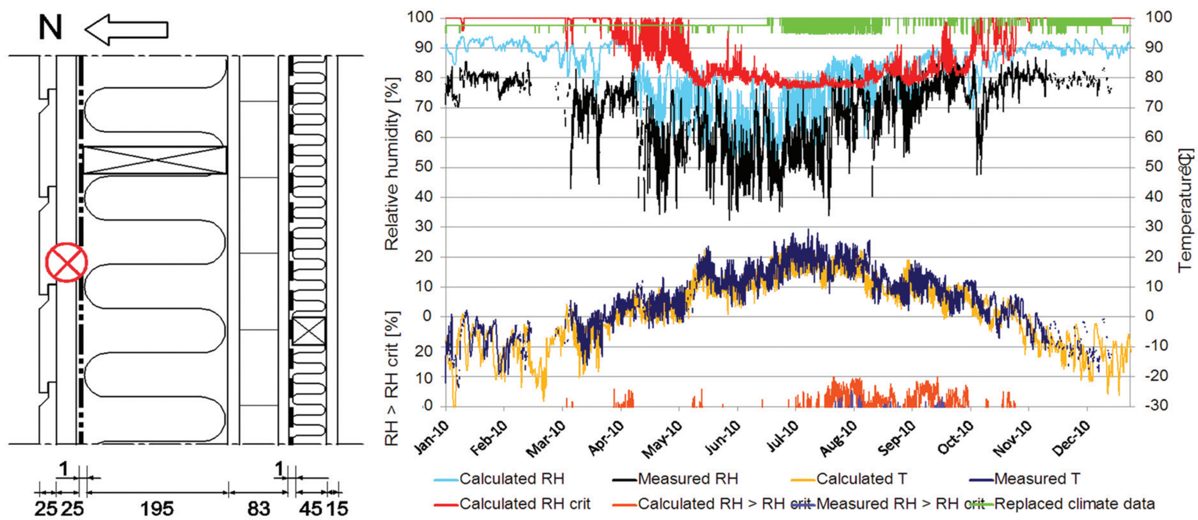

Figure 9 *Example of comparisons between measured and calculated RH and temperature in the air gap behind the cladding. Calculated RH (turquoise) and measured RH (black). Calculated temperature (yellow) and measured temperature (dark blue).* RH_{crit} *derived from the calculated temperature (red). Calculated RH >* RH_{crit} *(light brown) and measured RH >* RH_{crit} *(purple). Periods with replaced climate-boundary data (green).*

calculation tools in all situations and that heating sources need to be included in the evaluation of a design.

Most Moisture-Critical Positions. By using the Folos 2-D visual mold chart for the studied positions at different depths it could be established by both measurements and calculations that the most moisture-critical conditions occurred in the outer part of the wall. The critical conditions mainly occurred during longer periods at the end of the summer or in early autumn when there was high vapor content and low temperature that created a high relative humidity, as shown in Figure 6. Higher temperatures deeper within the wall reduced the relative humidity and furthermore the risk of mold growth. An exterior mold-resistant facade insulation board on the outside of the studs behind the air gap, as shown in Figure 2, which increases the temperature where there are organic mold-sensitive wood beams, can therefore be used as moisture protection. However, when the relative humidity is high at low outdoor temperatures below 0°C, there are no

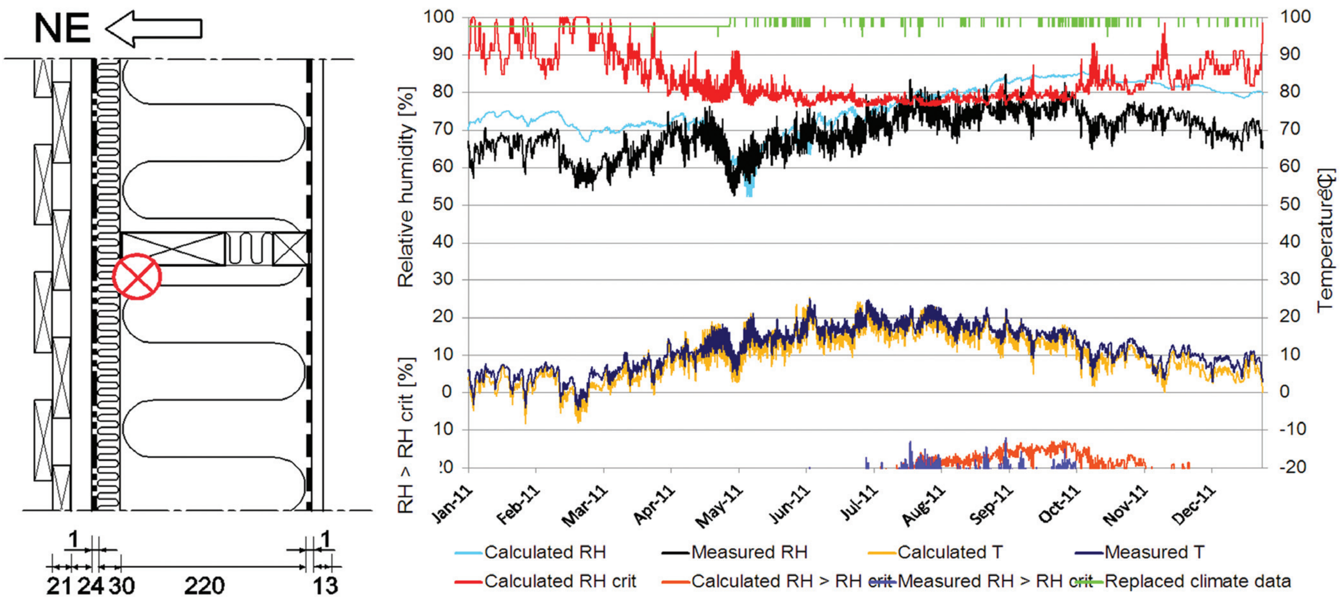

Figure 10 *Example of comparisons between measured and calculated RH and temperature behind a mold-resistant facade insulation board in the exterior part of a wall. Calculated RH (turquoise) and measured RH (black). Calculated temperature (yellow) and measured temperature (dark blue). RH_{crit} derived from the calculated temperature (red). Calculated RH > RH_{crit} (light brown) and measured RH > RH_{crit} (purple). Periods with replaced climate-boundary data (green).*

moisture-critical conditions. Such nonmoisture-critical conditions occur during the winter period in the studied house in northern Sweden, as shown in Figure 4. Thinner walls also have higher temperatures on the exterior parts, which reduce the relative humidity and the risk of mold growth.

Influence of Vapor Content on the Relative Humidity

In some cases the differences between the measured and blindly-calculated values is difficult to explain. They occurred during the winter, when the relative humidity was low, in the inner part of some of the studied walls, mainly in the installation layer (in which cables and sockets are located) behind the vapor barrier, as shown in Figure 7. It should not have been possible to record that both the measured temperature and relative humidity were below the calculated values at the same time. The reason may have been the influence of the moisture capacity of the stud in the installation layer or flaws in the measurements or calculation models. The location of the measured indoor climate-boundary conditions, remote from the studied wall, might also have created the anomalous result.

However, this is not as common, nor does it have as big an influence as the differences in temperatures have on the relative humidity.

Drying-Out in Installation Layers in Bathrooms between Two Vapor-Tight Membranes

In four positions in two of the studied designs, sensors were mounted in the installation layer in bathrooms, between the vapor barrier and the interior waterproof membrane (blue dashed line) as shown in Figure 8. Measurements in these positions indicated that the speed of the drying-out process was faster here than predicted by the calculations, as shown in Figure 8. A faster rate of drying out could also be observed in the not presented MC measurements.

The faster drying-out process may depend on several factors. The vapor barrier, outside of the installation layer, probably have bad joints and overlaps. Vertical or horizontal vapor transport, which cannot be taken into account in the one-dimensional calculations, may also speed up the drying-out process. The vapor barrier might also have been damaged or have a lower vapor resistance in reality than the vapor barrier used in the calculation model.

Correlation between Measured and Calculated Values in Air Gaps behind the Cladding and on the Exterior Facade

Several positions in the air gap behind the cladding were studied in all five houses. In the house located in the north of Sweden, comparisons between measured and calculated values were also carried out on the outside of the façade surface.

In general, all comparisons between measured and calculated values in the air gap showed a significantly lower measured relative humidity of approximately 10% to 15% compared to calculated values. The lower measured relative humidity is a result of a higher temperature and occurs during the entire studied period (as shown in Figure 9).

Differences between measurements and calculations on the cladding surface in the house located in the north of Sweden were similar to the corresponding differences in the air gap. However, the comparisons in the wall oriented towards the south had bigger differences than the other studied directions. Those differences were probably created by the influence of solar radiation that could be better simulated in the calculation.

Amplitude Variations in Temperature and Relative Humidity

Where moisture-critical conditions are concerned, the amplitude might be of interest as mold growth is dependent on the duration of the critical conditions (Viitanden and Ojanen 2007; Isaksson et al. 2010). The amplitudes in different positions, in Figures 2 to 8, show that there were greater amplitudes in the measured temperature and relative humidity than in the blindly-calculated values in the construction. Close to the inside of the wall there were low amplitudes in both the measured and calculated values (as shown in Figures 7 and 8). In the middle of the wall, the amplitudes are slightly larger, mainly in the measured values (as shown in Figure 3). Closer to the air gap, the amplitudes, mainly of the measured values, become significantly greater, (as shown in Figures 2, 4, 5, and 6). In the air gap and on the outside of the facade, the amplitudes are mainly the same when the measured and calculated values are compared, as shown in Figure 9. The amplitudes of both the measured and calculated values were also lower during the cold periods of the year (as shown in Figures 2, 4, 5 and 6). Comparisons (not presented here) also show that there were larger amplitudes in the calculated and measured values in positions orientated towards the south (Mundt-Petersen 2013b; 2013d).

Variations in amplitudes during different periods of the year and for different orientations of the studied positions depend on differences in temperature. There were greater variations in temperature during the summer and these created larger amplitudes during those periods. Furthermore, the positions orientated towards the south were affected more by the heat variations created by solar radiation.

The studied positions in the exterior part of the wall were more affected by the variations in the outdoor climate than the positions closer to the interior side of the wall, which were thermally influenced by the more stable indoor climate.

The reason for different amplitudes between measured and blindly-calculated values in the exterior part of the studied walls may have depended on the difference in heat and moisture capacity in the actual materials compared to the materials in the calculation model. The specific measurement sensors were also protected by a plastic shell and not directly exposed to the surrounding material. This material may include a volume of air that is more quickly affected by temperature changes than the surrounding materials.

Influence of Variations in Climate-Boundary Conditions between Different Years

The outdoor surrounding climate affects the conditions in the exterior part of a wall. Significant variations between different years were found by comparing the same positions over longer periods. By comparing the relative humidity in Figures 2 and 10, for the same position during two different years (2009 and 2011), it was found that there were significantly different behaviors.

The conclusions are that the different outdoor climates during different years created major variations in the studied positions. The variations affected temperature, relative humidity and duration, all of which affect the risk of mold growth (Viitanden and Ojanen 2007; Isaksson et al. 2010). Outdoor climate variations between different years especially affected the most moisture-critical positions in the exterior part of the wall.

It may therefore be questionable whether mean or standard climate-boundary conditions should be allowed in the moisture-safety design process for external walls as they may reduce or disregard the influence of moisture-critical periods. Climates that do not include critical outdoor periods may result in negative consequences when the risk of mold growth is investigated before a house is built. There is therefore a need for reliable outdoor climate-boundary conditions including the effect of periods with moisture-critical climate or other safety factors that could be used during the moisture-safety design phase.

The variations between different years also show that correct climate-boundary conditions must be used during validation of transient mold growth models and of transient heat and moisture calculation tools.

The influence of periods with impaired climate-boundary conditions (as shown in green in Figures 2 to 10) that affect the correlation between measured and calculated values could also be found in some positions. However, as long as the period with impaired climate data not is too long, it does not seem to have any major influence on the comparison between measured and calculated values.

CONCLUSIONS

Although there are a number of differences between the measured and blindly-calculated values shown above, it must be stated that most of the 85 blind comparisons show such a good correlation, as shown in Figures 2, 3 and 6, that they could be used to predict the risk of mold growth in further analysis. It may therefore be established that WUFI 5.0 can be used as a tool to predict moisture risks in wood-frame walls with a well-ventilated air gap and an interior vapor barrier. However, there are factors and observations that affect the results and these need to be taken into account if the tool is to be used for moisture safety purposes. These include:

1. Differences in temperature can have a great effect on the relative humidity.

    a. In the studied positions the measured temperature was in general higher than calculated values, which make the measured relative humidity lower than the calculated values.
2. A correct calculation model must be created in the calculation tool. It is essential that reliable outdoor climate-boundary conditions are used.
    a. This is necessary because outdoor climates have a great influence on the exterior moisture-critical part of wood-frame walls.
    b. Mean or standard outdoor climate-boundary conditions without extremes must not be used.
    c. It should be investigated whether it is possible to use other safety limits combined with mean or standard climates.
    d. Solar radiation has a higher influence on the hygrothermal conditions in the outer part of a wall in reality compared to calculated results.
3. One-dimensional models cannot be used in all situations and influence of heating sources need to be considered in the hygrothermal calculations.
4. The amplitudes of the measured values were higher than the calculated values, especially in moisture-critical positions in the exterior part of the wall.
5. Note that previous studies also show that a correct airflow in the air gap was required in the calculation model in order to obtain correct results (Hägerstedt and Arfvidsson 2010). It must therefore be possible to obtain these flows in the finished house.

Furthermore, it was found that the most moisture-critical positions generally occurred in the exterior part of the wall, in organic material on the inside of the air gap. Under-floor heating had a positive influence on the studied walls with vapor permeable materials on the outside.

Comparisons between measured and calculated values over time must also be made using real climate-boundary conditions as there are significant variations in annual climate that affect the results between different years.

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NOMENCLATURE

RH	=	relative humidity
RH_{crit}	=	limit for possible mold growth in wooden materials
$RH > RH_{crit}$	=	critical conditions showing that mold growth is possible
T	=	temperature

REFERENCES

BBR. 2011. *Swedish Building Regulations 2012* (In Swedish). Karlskrona: The Swedish National Board of Housing, Building and Planning.

Boverket. 2009. The standard of our houses—Report on the Swedish governments commissions regarding the technical standard of Swedish buildings (In Swedish). Karlskrona: The Swedish National Board of Housing, Building and Planning.

Forsberg, T. 2011. Moisture rearrangements in exterior walls, Report 2011:14 (Report 2011:14). Bachelor thesis. KTH Royal Institute of Technology.

Trähus, F. 2012. Project information (In Swedish). www.framtidenstrahus.se.

Sensing, G.E. 2006. Protimeter HygroTrac – Wireless environmental monitoring. www.veronics.com/products/Relative_humidity-transmitter/Hygrotrac.pdf.

Geving, S. and J. Holme. 2010. The drying potential and risk for mold growth in compact wood frame roofs with built-in-moisture. *Journal of Building Physics* 33(3):249–69.

Geving, S., Kvalvik, M., and Martinsen, E. 2011. Rehabilitation of basement walls with moisture problems by the use of vapour open exterior thermal insulation. *Proceedings of the 9th Nordic Symposium on Building Physics—NSB 2011, Tampere, Finland,* 1:323–30.

Hägerstedt, S.O. 2012. Moisture safe wood constructions—guidelines for wall design, Report TVBH-3052 (In Swedish). Lund University.

Hägerstedt, S.O. and J. Arfvidsson. 2010. Comparison of field measurements and calculations of relative humidity and temperature in wood framed walls. *Thermophysics 2010 – Conference proceedings, 15th International Meeting of Thermophysical Society, Valtice, Czech Republic,* 93–101.

Hägerstedt, S.O. and L.-E. Harderup. 2011a. Comparison of measured and calculated temperature and relative humidity with varied and constant air flow in the facade air gap. *Proceedings of the 9th Nordic Symposium on Building Physics – NSB 2011, Tampere, Finland,* 1:147–54.

Hägerstedt, S.O. and L.-E. Harderup. 2011b. Control of moisture safety design by comparison between calculations and measurements in passive house walls made of wood. *Proceedings of the 12th International Conference on Durability of Building Materials and Components – XII DBMC, Porto, Portugal,* 1:25–32.

Isaksson, T., S. Thelandersson, A. Ekstrand-Tobin, and Johansson, P. 2010. Critical conditions for onset of mold growth under varying climate conditions. *Building and Environment* 45(7):1712–21.

Krus, M. 1996. Moisture transport and storage coefficients of porous mineral building materials – Theoretical principles and new test methods. Doctoral thesis, Fraunhofer Institute for Building Physics. University of Stuttgart.

Künzel, H.M. 1995. Simultaneous heat and moisture transport in building components, One- and two-dimensional calculation using simple parameters. Doctoral thesis, Fraunhofer Institute of Building Physics. University of Stuttgart.

Künzel, H.M., H. Künzel, and A. Holm. 2004. Rain protection of stucco facades. *Proceedings of the Thermal Performance of the Exterior Envelopes of Whole Buildings IX – International Conference, Florida, USA*.

Künzel, H.M., T. Schmidt, and A. Holm. 2002. Exterior surface temperature of different wall constructions – comparison of numerical simulation and experiment. *Proceedings of the 11th Symposium for Building Physics, Dresden, Germany,* 1:441–49.

Mjörnell, K., J. Arfvidsson, and E. Sikander, 2012. A method for including moisture safety in the building process. *Indoor and Built Environment* 21(4):583–94.

Mundt-Petersen, S.O. 2012. Literature study/State-of-the-art —Mould and moisture safety in constructions, Report TVBH-3053. Lund University, Sweden.

Mundt-Petersen, S.O. 2013a. Comparison of hygrothermal measurements and calculations in a single-family wooden house on the west coast of Sweden, Report TVBH-3054. Lund University. In press.

Mundt-Petersen, S.O. 2013b. Comparison of hygrothermal measurements and calculations in a multi-family wooden house on the north-eastern coast of Sweden, Report TVBH-3055. Lund University. In press.

Mundt-Petersen, S.O. 2013c. Comparison of hygrothermal measurements and calculations in a single-family wooden house in the Swedish town of Växjö, Report TVBH-3056. Lund University. In press.

Mundt-Petersen, S.O. 2013d. Comparison of hygrothermal measurements and calculations in a multi-family wooden house in the Swedish town of Växjö, Report TVBH-3057. Lund University. In press.

Mundt-Petersen, S.O. 2013e. Comparison of hygrothermal measurements and calculations in a single-family wooden house in the Swedish municipality of Upplands-Bro, Report TVBH-3058. Lund University. In press.

Mundt-Petersen, S.O. 2013f. Moisture safety in wood frame walls – Blind evaluation of the hygrothermal calculation tool WUFI 5.0 using field measurements and determination of factors affecting the moisture safety. Licentiate thesis, Report TVBH-3059. Lund University.

Mundt-Petersen, S. O., P. Wallentén, T. Toratti, and J. Heikkinen, 2012. Moisture risk evaluation and determination of required measures to avoid mold damage using the Folos 2D visual mold chart. *Thermophysics 2012—Conference proceedings, 17th International Meeting of Thermophysical Society, Podkylava, Slovakia* 134–41.

Nevander, L.E. and B. Elmarsson. 1991. Moisture safety design of timber constructions, Report R38:1991 (In Swedish), Lund University.

Nore, K. 2009. Hygrothermal performance of ventilated wooden cladding. Doctoral theses, Report NTNU 2009:31. Norwegian University of Science and Technology.

Olsson, L. 2011. Laboratory investigation of timber frame walls with various weather barriers, Report 2011:56 (In Swedish). SP Technical Research Institute of Sweden.

Salonvaara, M., M. Pazera, and A. Karagiozis. 2010. Impact of weather on predicting drying characteristics of spray-applied cellulose insulation. *Proceedings of the Thermal Performance of the Exterior Envelopes of Whole Buildings XI—International Conference, Florida, USA*, I:B.

Sandberg, K., Pousette, A., and Dahlquist, S. 2011. Wireless in-situ measurements of moisture content and temperature in timber constructions. *Proceedings of the 12th International Conference on Durability of Building Materials and Components – XII DBMC, Porto, Portugal,* 1:191-98.

Sedlbauer, K. 2001. Prediction of mold fungus formation on the surface of and inside building components. Doctoral thesis, Fraunhofer Institute for Building Physics, University of Stuttgart.

SMHI. 2012. Climate data statistics (In Swedish). Swedish Meteorological and Hydrological Institute. www.smhi.se/Professionella-tjanster/Professionella-tjanster/statistik-och-data/bestall-vaderstatistik-1.1629.

Viitanen, H., and T. Ojanen. 2007. Improved model to predict mold growth in building materials. *Proceedings of the Thermal Performance of the Exterior Envelopes of Whole Buildings X – International Conference, Florida, USA*, V:A.

WUFI. 2009. WUFI 5.0, Material data base. Release: 5.0.1.521.DB.24.70. Holzkirchen, Germany: Fraunhofer Institute for Building Physics.

Zirkelbach, D., B. Schafaczek, and H.M. Künzel. 2011. Thermal performance degradation of foam insulation in inverted roofs due to moisture accumulation. *Proceedings of the 12th International Conference on Durability of Building Materials and Components – XII DBMC, Porto, Portugal,* 1:529–36.