Important factors affecting the risk of mold growth in well-insulated wood frame walls in Northern European climates

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Published in:
[Host publication title missing]

2013

Important Factors Affecting the Risk of Mold Growth in Well-Insulated Wood Frame Walls in Northern European Climates

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ABSTRACT

Due to increased awareness of climate change and energy costs, well-insulated buildings have become more common. Furthermore, greater interest has been shown in using wood in building to produce more carbon dioxide-efficient houses. However, thicker thermal insulation in walls increases the risk of high relative humidity (RH) levels and the risk of mold-related damage in wood frame houses.

This paper presents important factors affecting the risk of mold growth in well-insulated wood frame walls in Northern European climates. Recent findings regarding important factors are first briefly summarized. The paper continues with a parametric study in which moisture-critical positions in traditional Swedish wood frame designs are investigated by using hygrothermal modeling. Traditional North European walls with insulation thicknesses of 220 mm are compared to walls with thicker thermal insulation and alternative designs. The influences of the different wall designs in relation to the risk of mold growth are compared using isopleth and a visual mold chart.

It has been found that there is a higher risk of moisture-related damage in thicker insulated walls. However, this risk could be reduced by choosing more suitable designs in which well-ventilated air gaps behind the cladding and exterior vapor-permeable moisture resistant thermal insulation boards are of great importance.

INTRODUCTION

Background

Interest in the use of wood frame constructions has increased as greater attention has been given to building more carbon dioxide-efficient (CO_2-efficient) houses (Dodoo et al. 2012). In Northern European countries there is also a tradition of building wooden houses and timber is readily available (Björk et al. 2009; Björk et al. 2003). Furthermore, increased awareness of climate changes and energy costs has made well-insulated (U-factor < 0.2 $W/m^2{\cdot}K$) walls more common. However, thicker insulation increases the risk of high relative humidity (RH) levels in parts of the construction (Nevander and Elmarsson 1991; Hägerstedt 2012). Since wood and other organic materials has low mold growth resistance compared to other building materials (Nielsen et al. 2004), this property increases the risk of mold damage in well-insulated wood constructions.

State of the Art

Recent findings regarding important factors when building well-insulated houses that are not covered in this parametric study are briefly summarized below.

Besides the variations of mold growth sensitivity in different materials there is also general agreement among researchers around the world that temperature (T), relative humidity, and duration are the main factors affecting mold growth (Viitanen et al. 2010; Sedlbauer 2001; Clarke et al. 1999; Hens 1999). Several mold growth models have also been invented based on these findings. However, these models are limited and have a number of different theories and models regarding the reduction of the amount of mold growth during

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non-favorable mold growth climate conditions. Furthermore, different critical levels with regard to the effects of duration are presented and none of the studied mold growth models include the influence of short time climate variations (Viitanden and Ojanen 2007; Sedlbauer 2001; Isaksson et al. 2010; Pierzyk et al. 2011; Cornick et al. 2003).

It is well-established that rendered undrained wood frame walls, without a drainage and ventilated air gap behind the cladding with outer EPS insulation, so-called ETICS or EIFS walls, are a risk design solution that cannot handle the influence of wind driven rain (WRD) penetrating the facade (Brown et al. 1997; Quirouette and Arch 1997; Künzel 2008). A great number of instances of moisture damage have also been found in Swedish wood frame houses with ETICS walls (Jansson 2011). The influence of a drainage and ventilated air gap behind the cladding (Straube et al. 2004; Piñon et al. 2004; Salonvaara et al. 2007) is further analyzed and discussed in the paper.

Recent Swedish field and laboratory studies showed that the risk of mold growth damage is highly dependent on the prevailing weather conditions during the on-site production phase until the building is weather-proof. Mold growth has been seen in wooden houses that have been exposed only once to rain during the on-site erection of the wooden building elements, even in cases where this has been completed in one day (Olsson et al. 2011; Olsson et al. 2012).

The need for an interior vapor barrier and its location in the building envelope in cold climates has been thoroughly investigated. Possible leakages can be found by blower-door tests. To further improve the moisture safety an exhaust ventilation can be used to prevent interior humid air from penetrating and damaging the wall by a high relative humidity (Vinha 2007; Hagentoft 2001). When an additional interior waterproof membrane is installed for wet rooms, it is important to ensure that the interior waterproof membrane, closest to the interior surface, has a high vapor resistance in relation to the ordinary vapor barrier (Jansson and Samuelson 2005).

Aim

The aim of this study is to give recommendations and show important factors that need to be taken into account during design process and construction in order to build moisture-safe well-insulated wooden houses without risk of sick building syndrome (SBS) and moisture damage. The intention is to present relevant factors by showing examples of different designs, evaluated by using one-dimensional calculations and the Folos 2D visual mold chart (Mundt-Petersen et al. 2012), as elements of the quantitative part of a moisture-safety design process (Hägerstedt and Harderup 2011b).

Limitations

This case study has been carried out as a parametric study and only gives general recommendations based on a southern Swedish standard climate. All calculations were made in one-dimension and the influence of the wooden studs and other thermal bridges as well as possible influence of convection was negligible. The study only considers traditional external wood frame walls and the designs have only been evaluated from a quantitative aspect where professional workmanship was assumed. The definition of RH_{crit} that was used was limited to show the conditions when mold growth on wood based materials is possible.

METHOD

The investigation was carried out as a parametric study with calculations made on differently designed wood frame constructions with the one-dimensional transient heat and moisture calculation tool WUFI 5.0. The materials used were retrieved from the WUFI 5.0 material data base (WUFI 2009a). The one-dimensional calculation tool has been previously blindly verified, using similar walls and material data, with good results (Mundt-Petersen and Harderup 2013).

A reference wood frame wall, designed as a traditional Swedish wall, was modeled. The wall and its boundary conditions are henceforth referred to as the *reference case*.

Initially, the most moisture-critical position (pos) in the wall was established in the reference case. The design and surrounding conditions of the reference case were then varied. The effect of the changes in the most moisture-critical positions were then analyzed and compared to the reference case. Possible measures in order to achieve moisture-safe wooden designs were also studied.

All the different conditions and investigated designs are described separately in connection with the results of each specific case. The variations of conditions and designs that are presented are based on personal experience, previous calculations, and possible changes that could be made in some of the construction systems used by Swedish timber house manufacturing companies (Hägerstedt 2012). Calculation results from the fifth year after construction were used in order to reach quasi stationary conditions and avoid construction moisture and other initial conditions influencing the calculations.

The Folos 2D visual mold chart and isopleth charts were used to evaluate and compare results in different designs, positions within the walls, and surrounding conditions to a moisture-critical limit regarding mold growth (Mundt-Petersen et al. 2012). The chart is briefly described in the analysis of the reference case. The moisture-critical limit used was the LIM I limit (Sedlbauer 2001).

RESULTS AND ANALYSIS

Reference Case and Most Moisture-Critical Position

The reference case intends to simulate a traditional Swedish wood frame wall with mineral wool insulation (λ = 0.037 W/mK). A horizontal cross-section and simplified one-dimensional calculation model are shown in Figure 1. Since a one-dimensional calculation tool was used, layers with mixed materials have been simplified. Wooden studs in the insulation layer and battens in the air gap behind the cladding were disregarded.

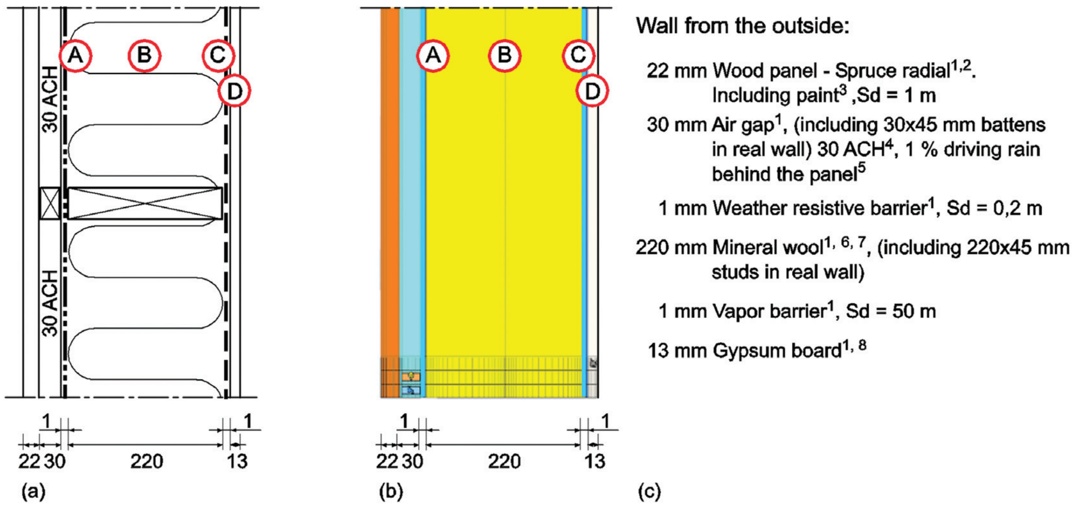

Figure 1 *Reference case: (a) cross-sectional top view of an ordinary Swedish wood frame wall, (b) simplified one-dimensional calculation model, and (c) material specifications, where superscripts indicate the following references: 1. WUFI 2009a; 2. Vik 1996; 3. Nevander and Elmarsson 1994; 4. Hägerstedt and Harderup 2011a; 5. ASHRAE 2009; 6. IEA Annex 24 1996; 7. Paroc 2002; 8. Krus 1996.*

The most moisture-critical Swedish outdoor climate, from the city of Lund, was used during the entire study (Hägerstedt 2012). Lund is located in the far south of Sweden and had an average annual temperature of 9.2°C and average annual relative humidity of 81%. The climate data used showed a significantly higher driving rain load on the south-facing facade (450 mm/a) compared to the north-facing facade (100 mm/a) (WUFI 2009b).

The indoor climate was based on EN 13788 with an initial indoor climate of 20ºC and an RH that varies dependent on exterior vapor content using moisture load level 2, (i.e., 4 g/m^3 is added to the exterior vapor content for temperatures below 0ºC [SS-EN 2001; WUFI 2009b]).

The wall in the reference case was oriented towards the north and the influence of driving rain was taken into account by adding 1% of the driving rain load in the air gap behind the cladding (ASHRAE 2009). Other parameters and boundary conditions were set to simulate as real conditions as possible (Hägerstedt 2012).

Most Moisture-Critical Position. To find the most moisture-critical area in the wall, climate conditions in four different positions, A–D in Figure 1, were calculated and plotted in an isopleth chart with a moisture-critical limit, RH_{crit}, as shown in Figure 2. The RH_{crit} line is defined as the limit above which mold growth is possible and varies depending on the specific material. In this study the LIM I curve referring to biodegradable materials, such as wood, was chosen (Sedlbauer 2001).

The isopleth chart, in Figure 2, shows that the most moisture-critical conditions occur in position A, in the outer part of the wall. Further on, this study focuses on position A and the exterior part of the wall.

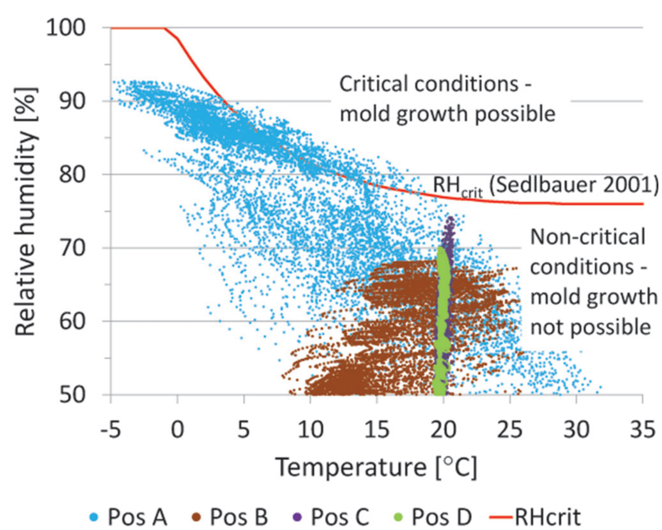

Figure 2 *Calculated climate conditions in position A (turquoise), B (brown), C (purple), and D (green) compared to RH_{crit} (red) (Sedlbauer 2001).*

It should be mentioned that the wooden studs shown in Figure 1 create thermal bridges that increase the temperature in the exterior parts. This reduces the RH and decreases the risk of mold growth in the wood. In this one-dimensional study the influence of the studs has been neglected, as shown in Figure 1, and the results in Figure 2 should be seen as a worst case situation. Two-dimensional studies of thermal bridges show that the temperature approximately increases with 0.5ºC to 1ºC, which reduces the relative humidity with 2.5% to 5% in the outer part of the stud (Forsberg 2011; Olsson 2011). Since the negative effect from thermal bridges on energy use is evident, the thermal bridges normally are eliminated by using lightweight studs or layers with separated studs, which make the one-dimensional worst case calculations appropriate.

Analyzing the Calculated Results Using the Folos 2D Visual Mold Chart. The Folos 2D visual mold chart, in Figure 3, shows the conditions in the most moisture-critical position A, based on information from the isopleth chart in Figure 2. The Folos 2D visual mold chart visualizes temperature (yellow) on the right *y*-axis and RH (turquoise), RH_{crit} (red), and the RH > RH_{crit} difference (light brown) 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}. The hourly RH isopleth dots (turquoise) for one year (8760 h), as shown in Figure 2, resulted in a line when presented over time in the Folos 2D visual mold chart in Figure 3.

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 as shown in Figure 2, (i.e., the chosen RH_{crit} line from Figure 2 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. The RH_{crit} line in this study is based on the LIM I curve invented by Sedlbauer (2001). Based on the findings in the previous State of the Art subsection, it might take months or longer before mold growth occurs if the RH is only slightly above RH_{crit}, especially at low temperatures. Single short periods, even with RH high above RH_{crit}, do not cause damage since mold needs more than a few hours above the RH_{crit} limit to start to germinate.

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

The most moisture-critical conditions occur in the outer part of the wall, close to the air gap, particularly in September, October, and November. The critical conditions also depend on the moisture sensitivity of the material in this position and thermal bridges may decrease the risk of mold growth.

To limit the RH, and the critical conditions, there are generally two types of measures that can be taken: measures to increase the temperature and measures to reduce the amount of vapor content, as shown further on in the study.

Protection Against Mold Growth by Exterior Mold-Resistant Insulation Boards

By attaching exterior vapor permeable insulation boards to the outside of the wooden studs, as shown in Figure 4 and 5, the surrounding temperature on the exterior side of the studs will increase (Maref et al. 2011). The RH and the risk of mold growth on the studs will then decrease (Hägerstedt and Harderup 2011a, 2011b). Exterior insulation boards must be located on the outside of the wood studs, between the studs and the weather resistive barrier, and must be made of moisture-resistant materials so they are not damaged by the high RH that occurs in position A.

The influence of increased total insulation thickness on the conditions in position A was studied. Furthermore, the required minimum thickness of the exterior insulation board

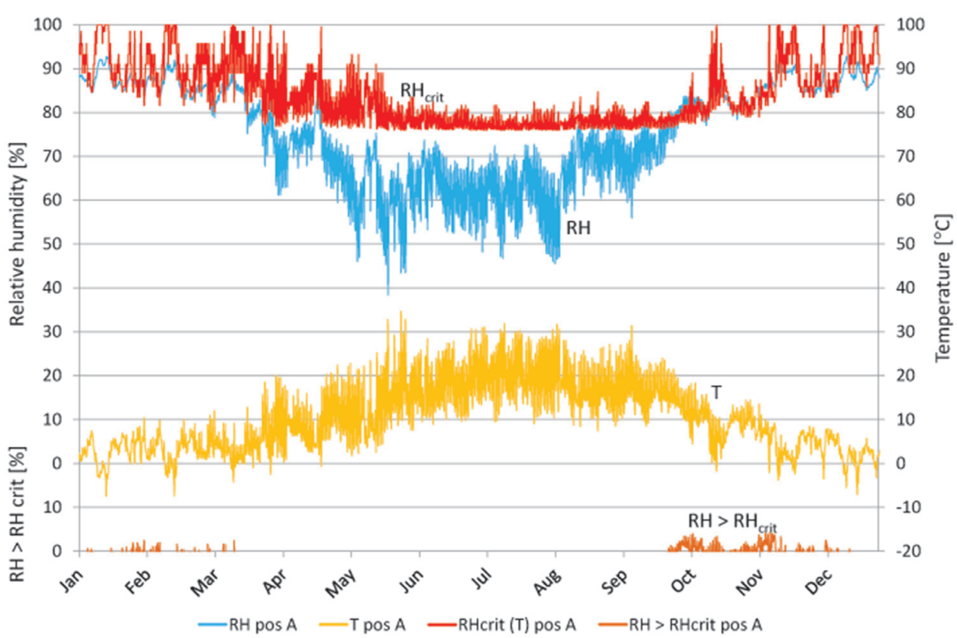

Figure 3 *RH compared to RH_{crit} in position A. RH (turquoise), RH_{crit} (red), temperature (yellow), RH > RH_{crit} (light brown).*

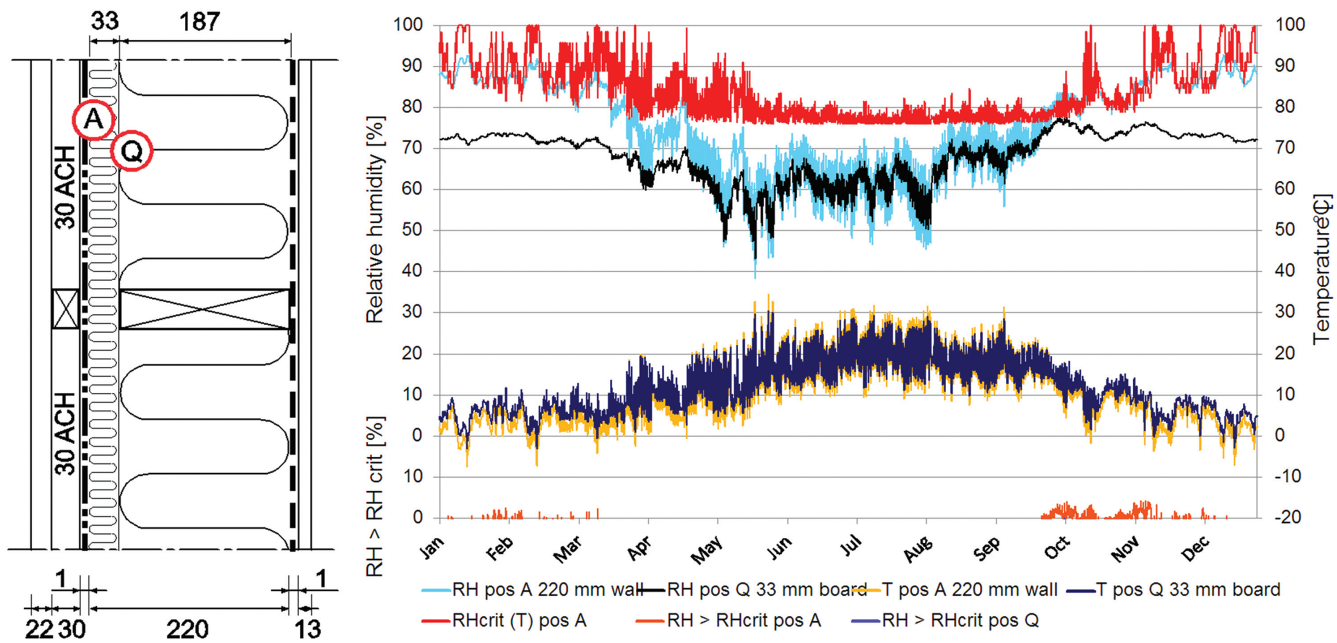

Figure 4 *RH in position A (turquoise) and position Q (black) compared to* RH_{crit} *for a wall with a total insulation thickness of 220 mm, as shown in the cross sectional top view drawing. Temperatures in position A (yellow) and temperatures in position Q (dark blue).* RH_{crit} *is dependent on T in position A (red), RH >* RH_{crit} *in position A (light brown), RH >* RH_{crit} *in position Q (purple) is constant below the critical limit and not shown in the figure.*

on the outside of the wooden studs, in order to avoid mold growth on the studs, was also studied. The minimum thickness of the exterior insulation board was calculated in relation to the total insulation thickness and was determined through iterative calculations. Position Q was located between the exterior insulation board and the mixed layer of studs and insulation. The thermal conductivity (λ = 0.037 W/m·K) was the same in both the exterior insulation board and the layer with mixed insulation and studs.

RH in Positions A and Q with a Total Insulation Thickness of 220 mm and 33 mm Exterior Insulation Board. The required minimum thickness of the exterior insulation board for a wall with a total of 220 mm insulation, as shown in Figure 4, was studied. Calculation results from both position A and position Q are shown together in the same chart.

By iteration it was found that the exterior insulation board needs to be 33 mm thick in order to avoid critical conditions in position Q if the wall has a total insulation thickness of 220 mm. A similar situation to such iteration in a real case study was made by Hägerstedt and Harderup (2011b). Critical conditions in position A are equal to those in the reference case. RH_{crit} in position Q is not shown when the two cases are compared in order to limit the number of plots.

RH in Positions A and Q with a Total Insulation Thickness of 420 mm and 52 mm Exterior Insulation Board. In thicker insulated walls the conditions in position A change and there is a need for a thicker exterior insulation board. The conditions in position A and required minimum thickness of the exterior insulation board for a wall with a total of 420 mm insulation, as shown in Figure 5, were studied. Calculation results from both position A and position Q are shown together in the same chart.

By iteration it was found that the exterior insulation board needs to be at least 52 mm thick in order to avoid critical conditions in position Q if the wall has a total insulation thickness of 420 mm. By comparing position A in Figures 4 and 5 it can be stated that the occurrence of critical conditions increased in the wall with thicker insulation, which also was shown in Table 1.

Summarized results from several calculations show that higher thermal resistance increases the moisture conditions (RH) in position A. Walls with a higher thermal resistance also require a thicker exterior insulation board to avoid critical conditions in position Q, see Table 1.

Calculations when using cellulose fiber insulation and an exterior moisture-resistant mineral insulation board generally show similar results to those presented in Table 1 (Hägerstedt 2012).

Well-Ventilated Air Gap Behind the Cladding

Several of studies discuss the importance of a well-ventilated air gap behind the cladding in wood frame walls. A high airflow in the air gap will vent out moisture that has penetrated the cladding and will contribute to an increased dry out of a wood frame wall (Salonvaara et al. 2007; Straube et al. 2004;

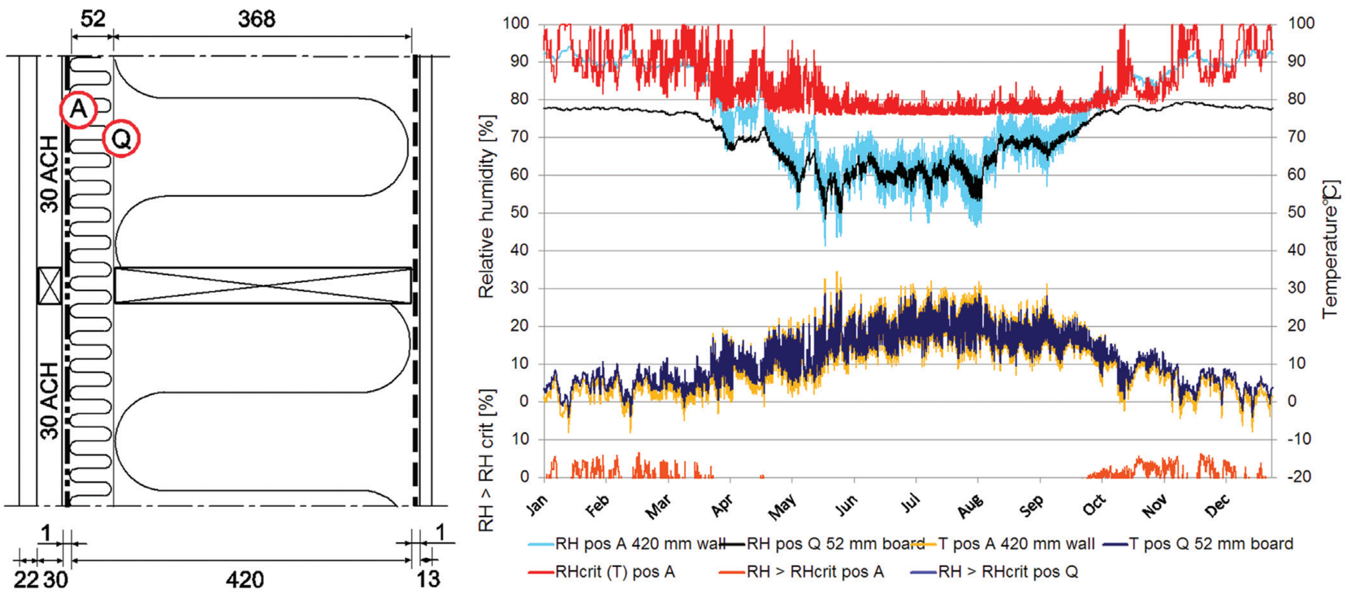

Figure 5 *RH in position A (turquoise) and position Q (black) compared to RH_{crit} for a wall with a total insulation thickness of 420 mm, as shown in the cross sectional top view drawing. Temperatures in position A (yellow) and temperatures in position Q (dark blue). RH_{crit} is dependent on temperature (T) in position A (red); RH > RH_{crit} in position A (light brown); RH > RH_{crit} in position Q (purple) is constant below the critical limit and not shown in the figure.*

Table 1. Minimum Thicknesses of Exterior Insulation Board and the Highest RH above RH_{crit} in Position A Depending on the Total Insulation Thickness of the Wall

Total Insulation Thickness, mm	Thickness of Exterior Insulation Board, mm RH < RH_{crit} Position Q	Highest RH > RH_{crit} (%) in position A Inside the Weather Resistive Barrier
220	33	4.21
270	39	4.61
320	45	5.15
370	49	6.15
420	52	6.71
470	55	7.04
520	59	7.52

Piñon et al. 2004; Hägerstedt and Harderup 2010). The influence on critical conditions in position A was also studied when there was a lower airflow in the air gap behind the cladding than in the reference case. Calculation results from position A with 30 ach compared to 1 ach are shown together in the same chart in Figure 6.

A low airflow in the air gap behind the cladding has a negative influence and the critical conditions occur more frequently and during other periods of the year in position A. In a well-ventilated air gap with vertical battens and wide openings at the bottom and top there is normally a higher air change rate than 30 ach (Falk 2013; Tichy and Murray 2007). Normally, a ventilation rate more than 30 ach does not further improve the conditions in the wall since there is no more moisture available to dry out (Hägerstedt and Harderup 2010).

The Need for Well-Ventilated Air Gaps in Well-Insulated Walls. Differences in the critical conditions in positions A and Q were studied in walls with increased insulation in combination with a low and high air change rate in the air gap. Four cases, as shown in Figure 7, were compared in isopleth charts for positions A and Q: Two cases with 1 or 30 ach in the air gap and a total insulation thickness of 220 mm and two cases with 1 and 30 ach in the air gap and total insulation thickness of 420 mm.

As previously observed, comparing the cases with 1 and 30 ach in the 220 mm insulated wall showed that a low airflow in the air gap behind the cladding had a negative influence on

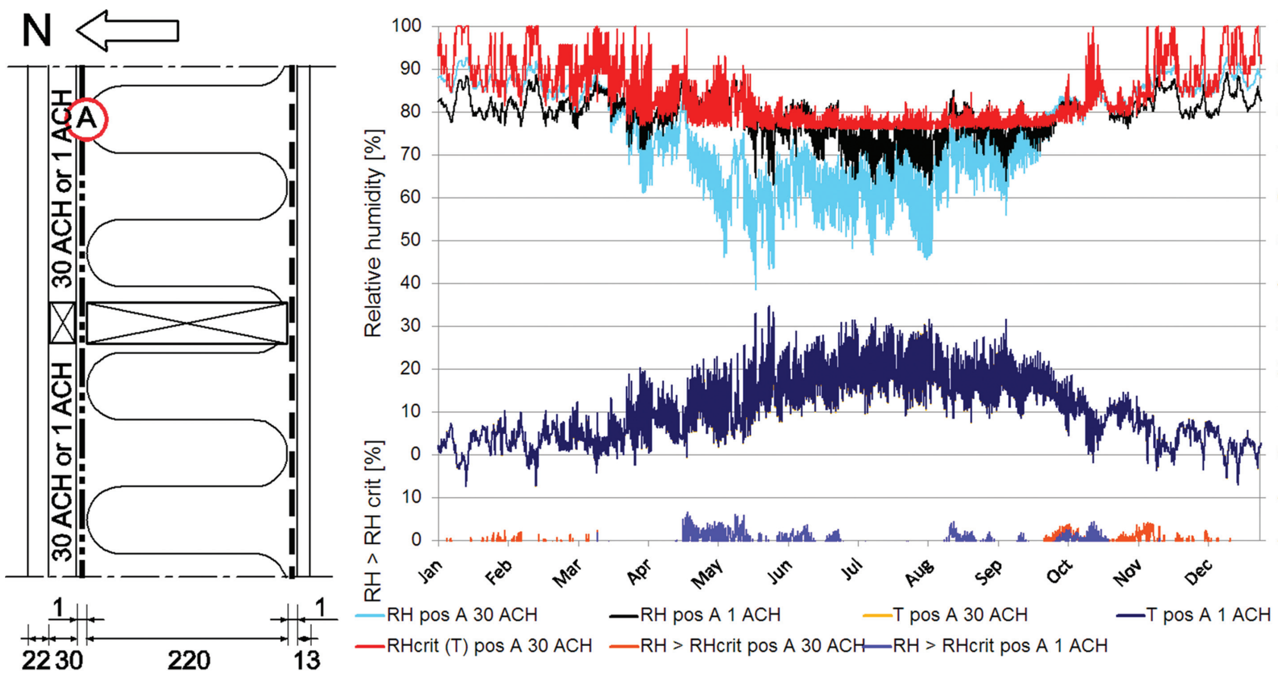

Figure 6 *RH in position A compared to RH_{crit} in a wall with 220 mm insulation, as shown in the cross sectional top view drawing, oriented towards the north with an air change rate of 30 ach (turquoise) and 1 ach (black) in the air gap. The temperature at 30 ach (yellow) is hidden behind the temperature at 1 ach (dark blue). RH_{crit} (red) depends on temperature (T) for 30 ach, RH > RH_{crit} 30 ach (light brown), RH > RH_{crit} 1 ach (purple).*

the critical conditions in position A. The low airflow of 1 ach also has a negative influence in position Q. The isopleth charts show that the critical conditions in position A and Q increased with thicker insulation. However, comparing positions A and Q at 1 and 30 ach in the 220 mm and the 420 mm insulated wall showed that there was a higher negative influence on the critical conditions in the wall with 420 mm insulation. I.e., a low airflow in the air gap had a higher negative influence when the walls were well-insulated. Results in position Q also showed that the critical conditions in the wall could be handled by a high air change rate in the air gap and an exterior moisture resistant insulation board.

Influence of Driving Rain. Driving rain is caused by rain and wind acting at the same time. A driving rain load varies depending on the exterior climate conditions and the facade orientation. As mentioned above, the climate data used showed a significantly higher driving rain load on the south-facing facade (450 mm/a) compared to the north-facing facade (100 mm/a) (WUFI 2009b). The influence of a higher amount of driving rain on a facade oriented towards the south and different airflows of 1 or 30 ach in the air gap, as shown in Figure 8, were studied in position A. The results in Figure 8 can be compared to those for the same wall oriented towards the north, as shown in Figure 6.

If there is a low air change rate, the negative impact of driving rain in position A is significantly higher, as shown in Figure 8, when compared to cases with a lower driving rain load, as shown in Figure 6. A sufficiently high airflow can also handle a high amount of penetrating driving rain. It is therefore very important to establish a sufficient airflow in the air gap behind the cladding if there is a high amount of driving rain. Comparing Figure 6 and 8 also shows that the colder north directed walls have slightly higher moisture critical conditions.

Influence of Different Cladding Materials. The ability to store moisture in different cladding materials also affects the risk of mold damage. Critical conditions in position A in a wood frame wall with an exterior brick facade (solid brick masonry, including mortar joints) (WUFI 2009a; IBP 1994) with a high moisture storage capacity, as shown in Figure 9, were therefore studied. The results in Figure 9 can also be compared to the same type of frame with a wood facade as shown in Figure 6.

The results confirm pervious results by Straube and Finch (2009). The critical conditions in position A are higher, longer, and also occur during other periods when a brick facade, as shown in Figure 9, was compared to the reference case. A low air change rate in the air gap behind the brick facade in Figure 9 created significantly more critical conditions compared to the case with a wood facade, as shown in Figure 6. The increase in occurrence of critical conditions was due to moisture storage capacity in the brick facade. However, a well-ventilated air gap resulted in significantly better conditions in position A when there was a brick facade with a high moisture storage capacity.

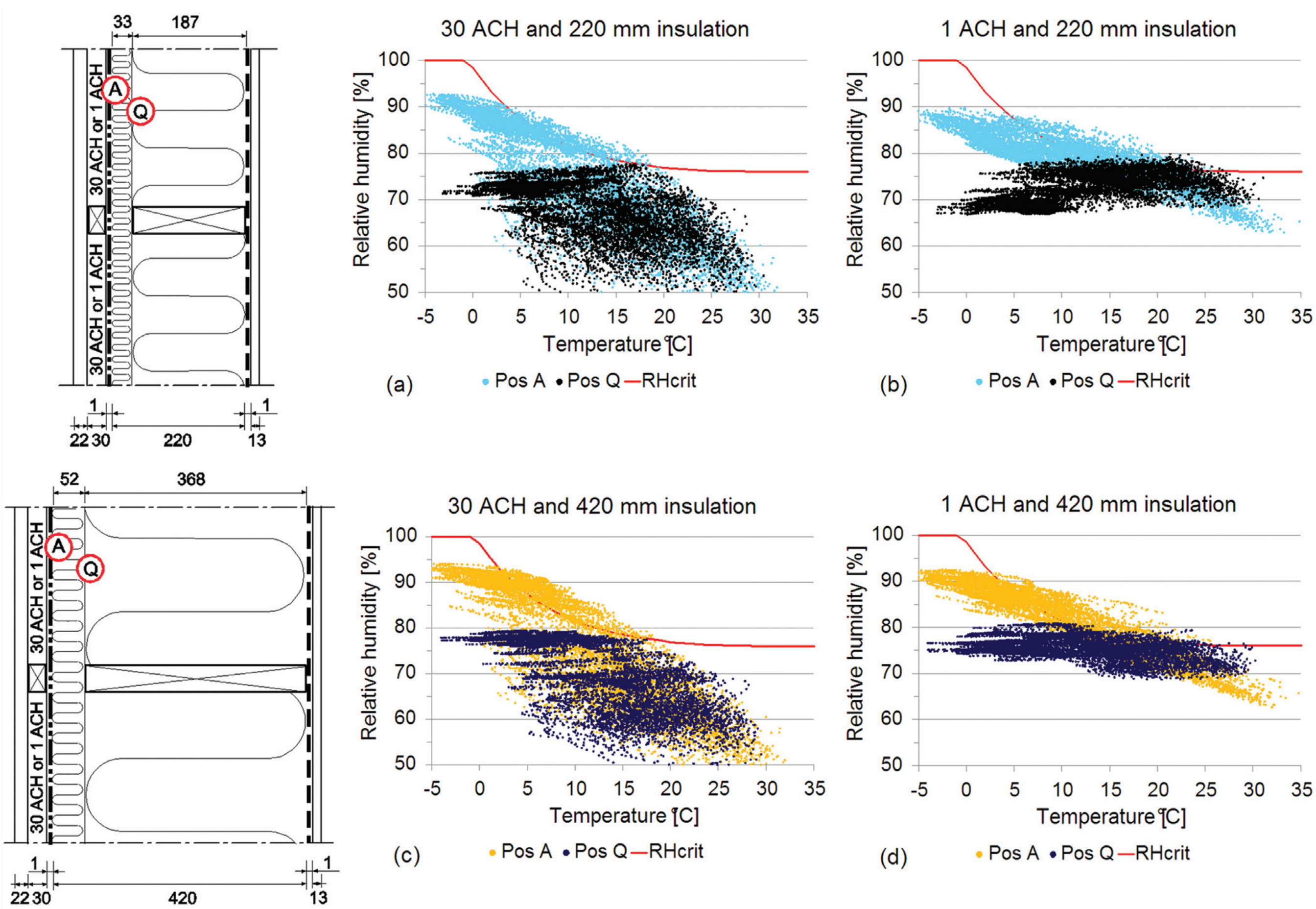

Figure 7 *RH in positions A and Q compared to RH_{crit} (red) for two different insulation thicknesses and two different air change rates in the air gap behind the cladding, as shown in the cross sectional top view drawings. (a) RH 220 mm insulation and 30 ach, position A (turquoise) and position Q (black). (b) RH 220 mm insulation and 1 ach, position A (turquoise) and position Q (black). (c) RH 420 mm insulation and 30 ach, position A (yellow) and position Q (dark blue). (d) RH 420 mm insulation and 1 ach, position A (yellow) and position Q (dark blue).*

Possibilities for Drying out Water Caused by Leakages and Initial Moisture from the Construction Phase

Leakages into walls from rain or driving rain are probably more common than expected. Furthermore, it must also be possible to dry out initial construction moisture. In order to estimate the drying out potential in different constructions, the influence of a leakage of 1% of the driving rain (ASHRAE 2009) located 152 mm from the air gap, close to the middle of the construction, was studied. Four cases in positions A and Q, as shown in Figure 10, were compared in isopleth charts.

Two of the designs had insulation thicknesses of 220 and 420 mm insulation respectively. Two designs had an exterior mold-resistant insulation board of vapor-permeable mineral wool (λ = 0.037 W/mK). The other two designs had exterior mold-resistant insulation of rather vapor-tight expanded polystyrene (EPS) and insulation board with the thermal conductivity 0.037 W/mK and a density of 30 kg/m^3 (WUFI 2009a; Achtziger and Cammerer 1984).

All cases with leakages in Figure 10 showed a higher RH in positions A and Q compared to situations without leakages, as shown in Figure 7 (a) and (c). However, there is a significant difference in high RH in position Q between the cases with vapor-permeable mineral wool and an EPS vapor-tight exterior insulation board. In the case with a total thicker insulation of 420 mm, there is also a significantly higher RH in position Q compared to the case with thinner insulation of 220 mm.

To handle initial construction moisture and possible leakages, the exterior mold-resistant board must be vapor-permeable.

CONCLUSIONS

The study assessed a number of important factors that must be taken into account if moisture-safe well-insulation

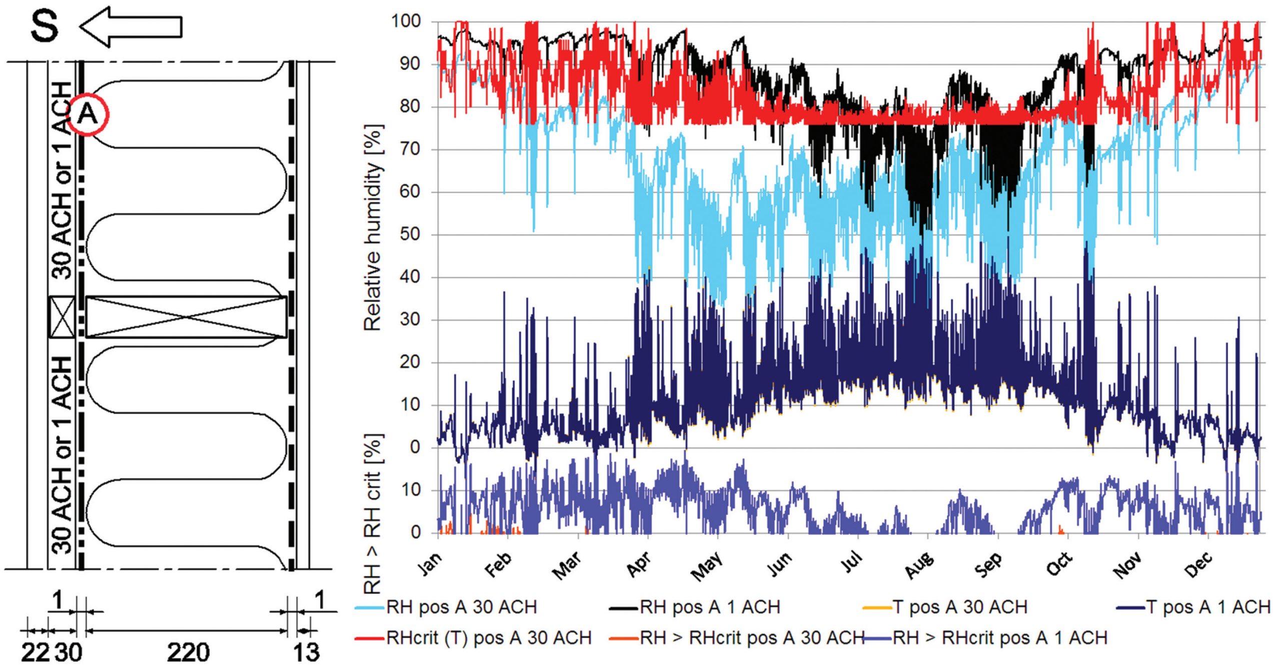

Figure 8 *RH in position A in a wall with 220 mm insulation, as shown in the cross sectional top view drawing, oriented towards the south with an air change rate of 30 ach (turquoise) and 1 ach (black) in the air gap compared to RH_{crit}. The temperature at 30 ach (yellow) is hidden behind the temperature at 1 ach (dark blue). RH_{crit} (red) depends on temperature (T) for 30 ach, RH > RH_{crit} 30 ach (light brown), RH > RH_{crit} 1 ach (purple).*

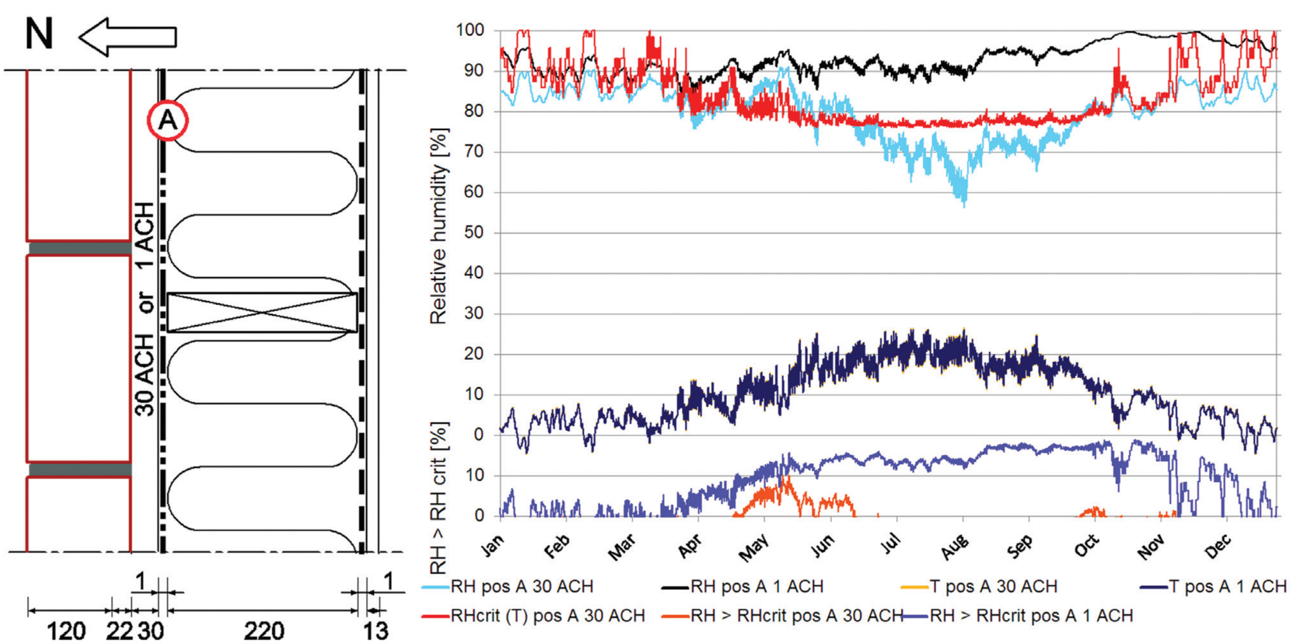

Figure 9 *RH in position A in a wall with 220 mm insulation, as shown in the cross sectional top view drawing, a north oriented brick façade and air change rate of 30 ach (turquoise) and 1 ach (black) in the air gap compared to RH_{crit}. The temperature at 30 ach (yellow) is hidden behind the temperature at 1 ach (dark blue). RH_{crit} (red) depends on temperature (T) for 30 ach, RH > RH_{crit} 30 ach (light brown), RH > RH_{crit} 1 ach (purple).*

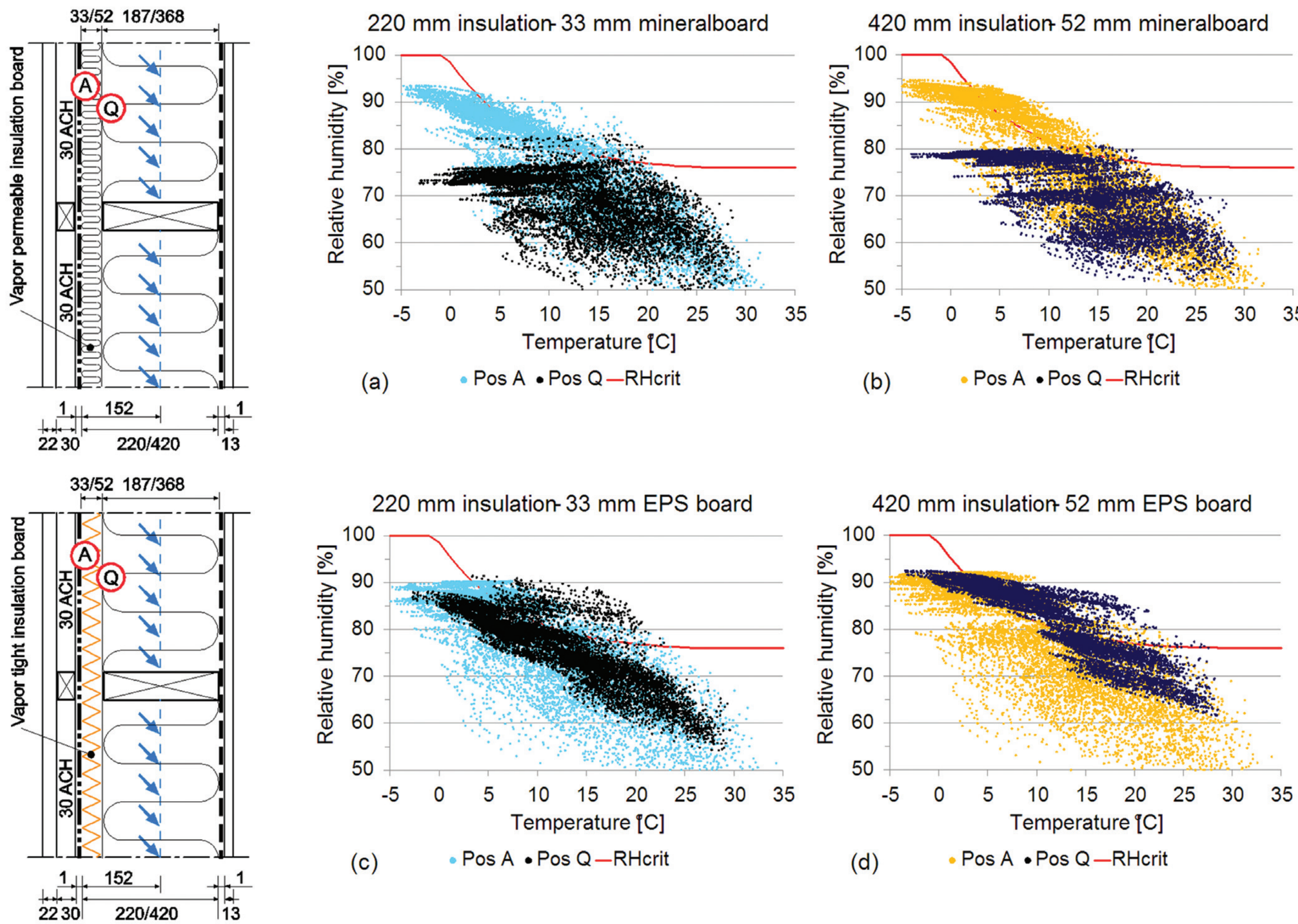

Figure 10 *RH in positions A and Q compared to RH_{crit} (red) for walls subject to a leakage with two different materials used for the exterior insulation board and two different insulation thicknesses, as shown in the cross sectional top view drawings. (a) RH 220 mm–33 mm mineral insulation board, position A (turquoise) and position Q (black). (b) RH 420 mm–52 mm mineral insulation board, position A (yellow), and position Q (dark blue). (c) RH 220 mm–33 mm EPS insulation board, position A (turquoise), and position Q (black). (d) RH 420 mm–52 mm EPS insulation board, position A (yellow), and position Q (dark blue).*

walls are to be built. The results were based on a great number of hygrothermal calculations. The main conclusion was that there is a higher risk of moisture damage in well-insulation wood frame walls. However, this risk can be reduced by implementing suitable designs in which a well-ventilated air gap behind the cladding and the addition of a vapor-permeable exterior moisture-resistant insulation board with high density are of great importance. Further important factors are listed below:

1. Moisture-critical conditions in wood frame walls mainly occur in the exterior part of the wall, based on hygrothermal modeling and Northern European climate used in this study.
2. The occurrences of moisture-critical conditions increase as the thickness of thermal insulation in walls is increased.
3. Studs and other organic materials in the exterior part of a wood frame wall could be protected from moisture-critical conditions by using an exterior moisture-resistant thermal insulation board on the outside of the studs.
   a. The required thickness of the exterior moisture-resistant thermal insulation board varies depending on the total thermal insulation of the entire wall.
4. There is a great need for a well-ventilated air gap behind the cladding in order to build moisture-safe well-insulated walls.
   a. The need increases with higher thermal resistance of the wall.

b. It is especially important when there are high amounts of driving rain
c. It is especially important when the facade material has a high moisture storage capacity, such as a brick facade.

5. Exterior moisture-resistant insulation boards must be vapor permeable to allow initial construction moisture and water from possible leakages to dry out.

ACKNOWLEDGMENTS

This study was supported by Vinnova (the Swedish Government Agency for Innovation Systems) and their partnership, with representatives of the timber industry, which initiated the research projects "Framtidens trähus" (Wood frame buildings of the future) and "ECO2 – Carbon-efficient timber constructions."

NOMENCLATURE

RH_{crit} = limit for possible mold growth in wooden materials

$RH > RH_{crit}$ = critical conditions showing that mold growth is possible

T = Temperature

Pos = Position

REFERENCES

Achtziger, J. and Cammerer, J. 1984. Influence of moisture content on the thermal conductivity of building and insulation materials. Report BI 5-800883-4. Institute for heat protection, München, Germany. In German.

ASHRAE. 2009. BSR/ ASHRAE Standard 160P, *Criteria for Moisture-Control Design Analysis in Buildings*. Atlanta: ASHRAE.

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

Björk, C., Kallstenius, P., and Reppen, L. 2003. Old house design 1880–2000, 5th Ed. Stockholm: Edita Ljunglöfs. In Swedish.

Björk, C., Nordling, L., and Reppen, L. 2009. Single family house design—Swedish single family house architecture 1890–2010. Värnamo: Fälth & Hässler. In Swedish.

Brown, W., Ullett, J., Karagiozis, A., and Tonyan, T. 1997. Barrier EIFS clad walls: Results from a moisture engineering study *Journal of Building Physics* 20(3):206–26.

Clarke, J.A., Johnstone, C.M., Kelly, N.J., Mclean, R.C., Anderson, J.A., and Rowan N.J. 1999. A technique for prediction of the conditions lading to mould growth in buildings, *Building and Environment* 34(4):515–521.

Dodoo, A., Gustavsson, L., and Sathre, R. 2012. Effect of thermal mass on life cycle primary energy balance of a concrete- and wood-frame building. *Applied Energy* 92:462–72.

Falk, J., and Sandin, K. 2013. Ventilated rainscreen cladding: Measurements of cavity air velocities, estimation of air change rates and evaluation of driving forces. *Building and Environment* 59:164–76.

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

Hagentoft, C. E. 2001. *Introduction to Building Physics*. 1st Ed. Göteborg. Studentlitteratur AB.

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

Hägerstedt, S.O., and Harderup, L. E. 2010. Importance of a proper applied airflow in the façade air gap when moisture and temperature are calculated in wood framed walls. Proceedings, 5th International BUILDAIR-Symposium "Building and Ductwork Air-tightness" Copenhagen, Denmark.

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

Hägerstedt, S. O., and Harderup, L. E. 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.

Hens, H.L.S.C. 1999. Fungal defacement in buildings: A performance related approach. *International Journal of Heating, International Journal of HVAC & R Research Ventilation, Air-Conditioning and Refrigerating Research* 5(3):256–280.

IBP. 1994. IBP-Report 35. In German.

IEA Annex 24. 1996. Heat, air and moisture transport in insulated envelope parts, Material properties. International Energy Agency, E*Nergy Conservation in Building Community System*. 3:3.

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

Jansson, A. 2011. External plaster stud walls 2011 - Experience from studies that SP has performed. Report

2011:61. SP Technical Research Institute of Sweden. In Swedish.

Jansson, A., and Samuelson, I. 2005. Double sealing layers in the external walls of wet rooms with internal tile cladding. Report 2005:20. SP Technical Research Institute of Sweden. In Swedish.

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. 2008. Influence of rain water leakage on the hygrothermal performance of exterior insulation system. Proceedings of the 8th Nordic Symposium on Building Physics - NSB 2008, Copenhagen, Denmark, 1:253–60.

Maref, W., Rousseau, M. Z., Armstrong, M. M., Lee, W., Leroux, M., and Nicholls, M. 2011. Evaluating the Effects of Two Energy Retrofit Strategies for Housing on the Wetting and Drying Potential of Wall Assemblies: Summary Report for Year 2007–08 Phase of the Study. RR-315. NRC-CNRC Institute for research in construction. National research council Canada.

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. and Harderup L. E. 2013. Validation of a 1D transient heat and moisture calculation tool under real conditions. Proceedings - Thermal Performance of the Exterior Envelopes of Whole Buildings XII - International Conference, Florida, USA.

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

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

Nevander, L.E., and Elmarsson, B. 2007. *Moisture Handbook—Practice And Theory*, 3rd Ed. Chapter 92.2. Mölnycke: AB Svensk byggtjänst. Elanders Infologistics Väst AB. In Swedish.

Nielsen, K. F., Holm, G., Uttrup, L. P., and Nielsen P. A. 2004. Mould growth on building materials under low water activities - Influence of humidity and temperature on fungal growth and secondary metabolism. *International Biodeterioration & Biodegradation* 54(4):325–36.

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

Olsson, L., Mjörnell, K. 2012. Laboratory investigation of sills and studs exposed to rain. Proceedings of the 5th International Building Physics Conference - IBPC 2012, Kyoto, Japan, 155–61.

Olsson, L., Mjörnell, K., and Johansson, P. 2011. Moisture and mould in prefabricated timber framed constructions during production until enclosure of the house. Proceedings of the 9th Nordic Symposium on Building Physics - NSB 2011, Tampere, Finland, 1:339–46.

Paroc. 2002. Construction paper - Material information. Skövde: Paroc Ltd. www.stenull.paroc.se/produktdat/pdf_down/Pinfo.pdf. In Swedish.

Pietrzyk, K., Samuelson, I., and Johansson, P. 2011. Modelling reliability of structure with respect to incipient mould growth. Proceedings of the 9th Nordic Symposium on Building Physics - NSB 2011, Tampere, Finland, 2:875–82.

Piñon J.P., Burnett, E.F.P., Davidovic, D., and Srebric, J. 2004. The airflow characteristics of ventilated cavities in screen-type enclosure wall systems (RP-1091). Proceedings - Thermal Performance of the Exterior Envelopes of Whole Buildings X - International Conference, Florida, USA.

Quirouette, R., and Arch, B. 1997. Review of the NRCC and USG study of the EIFS barrier walls for wood framed houses in Wilmington, North Carolina. *Journal of Building Physics* 20(4):305–58.

Salonvaara, M., Karagiozis, A. N., Pazera, M., and Miller, W. 2007. Air cavities behind claddings - what have we learned? Proceedings - Thermal Performance of the Exterior Envelopes of Whole Buildings X - International Conference, Florida, USA. XI:A.

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

SS-EN. 2001. SS-EN 13788:2001 - *Hygrothermal performance of building components and elements - Internal surface temperature to avoid critical surface humidity and interstitial condensation - Calculation methods*. Swedish Standards Institute.

Straube, J., and Finch, G. 2009. Ventilated wall claddings: Review, field performance, and hygrothermal modeling. Research report - 0906. Building science press.

Straube, J.F., van Straaten, R., and Burnett E. 2004. Field studies of ventilation drying. Proceedings - Thermal Performance of the Exterior Envelopes of Whole Buildings X - International Conference, Florida, USA.

Tichy, R., and Murray, C. 2006. Developing innovative wall systems that improve hygrothermal performance of residential buildings. Technical report FC26-02NT41498. Washington State University.

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

Viitanen, H., Vinha, J., Salminen, K., Ojanen, T., Peuhkuri R., Paajanen, L., and Lähdesmäki, K. 2010. Moisture and biodeterioration risk of building materials and structures. *Journal of Building Physics* 33(3):201–24.

Vik, T.A. 1996. Determination of suitable wet properties of wood and calculation the moisture balance using determined characteristic values. Diploma thesis. Norwegian University of Science and Technology. In German.

Vinha, J. 2007. Hygrothermal performance of timber-framed external walls in Finnish climatic conditions: A method for determining the sufficient water vapour resistance of the interior lining of a wall assembly. Doctoral thesis publication 658. Tampere University of technology.

WUFI. 2009a. WUFI 5.0 Material data base - Generic materials and Fraunhofer-IBP - Holzkirchen, Germany. Release: 5.0.1.521.DB.24.70. Fraunhofer Institute for Building Physics, Holzkirchen, Germany.

WUFI. 2009b. WUFI 5.0 Climate data base - Lund, Sweden, Europe. Release: 5.0.1.521.DB.24.70. Fraunhofer Institute for Building Physics, Holzkirchen, Germany.