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

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Licentiate thesis

To Vesslan

Preface

This licentiate thesis summarizes the first part of my research studies which began in June 2008. The work was carried out both as theoretical and applied research in the on-site constructions and wood frame house industry factories. I found the variations in my work and the applied research attractive and valuable even if the differences between "pure" and applied research have been confusing during some periods.

Rådmansö-Västernäs May 2013

S. Olof Mundt-Petersen

Abstract

Due to increased awareness of climate change and higher energy costs, well-insulated buildings have become more common. Furthermore, the interests of using wood in building to produce more carbon dioxide-efficient houses have increased. However, thicker thermal insulation in walls increases the risk of high relative humidity levels and the risk of mould-related damage in wood frame houses. In order to predict moisture damage it is important to have a properly verified, user-friendly and reliable calculation tool that can be used in the design phase.

The first part of the thesis presents a blind method that can be used in order to verify heat and moisture calculation tools in a reliable manner. General results and findings from blind validations using a one-dimensional 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.

The thesis also presents important factors affecting the risk of mould growth in well-insulated wood frame walls. A parametric study is presented in which moisture-critical positions in traditional Swedish wood frame designs in Northern European climates are investigated by using hygrothermal modeling. Traditional Swedish walls with insulation thicknesses of 220 mm are then compared to walls with thicker thermal insulation and alternative designs.

In general the comparisons of measured and blindly calculated values show a good correlation. The results 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 affecting the calculated RH have to be taken into account.

There is also a need for developing outdoor climate boundary conditions that take into account critical periods and variations between different years.

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

Sammanfattning

Hårdrare krav på lägre energianvändning i byggnader samt ökade energipriser har gjort att välisolerade hus har blivit allt vanligare. Ökad medvetenhet om koldioxidens påverkan på klimatförändringarna har också ökat intresset för trähus. Tjockare isolering i trähus ökar dock risken för höga fukttillstånd och med detta också risken för fuktskador. För att kunna förutse och undvika risken för fuktskador finns ett behov av ett pålitligt och användarvänligt beräkningsverktyg som kan användas i projekteringsfasen.

Denna studie visar en metod som kan användas för att blint verifiera värme- och fuktberäkningsprogram på ett trovärdigt sätt med de förutsättningar som normalt råder i projekteringsfasen. Generella resultat från en omfattande studie med jämförelser mellan fältmätningar och blinda beräkningar av temperatur och relativ fuktighet redovisas. I jämförelsen visas även om, när och varför förhållanden som gör mögelpåväxt möjlig uppstår på olika platser i fem studerade hus på olika orter i Sverige.

I studien redovisas också faktorer och parameterar som har stor inverkan på risken för mögelpåväxt på organiskt material i träregelväggar. Fuktkritiska positioner i en traditionell svensk träregelvägg med 220 mm mineraullsisolering studeras i en parameterstudie med hjälp av kopplade fukt- och värmeberäkningar. Utformningen och de omgivande förutsättningarna för den traditionella träregelväggen modifieras därefter och resultatet från beräkningar med de nya förutsättningarna jämförs med varandra och även med beräkningar från den ursprungliga väggen.

Generellt visar resultaten från jämförelsen på en god överensstämmelse mellan fältmätningar och blinda beräkningar. Resultaten visar också att utvärderat verktyg kan användas i projekteringsfasen för att bedöma risken för kritiska fukttillstånd. Dock finns flera parametrar och faktorer som påverkar förutsättningarna för att göra en korrekt bedömning. Felaktigt beräknad temperatur som i sin tur påverkar den relativa fuktigheten är en parameter som kan ha stor betydelse. Vidare påverkar variationerna i utomhusklimatet risken för mögelpåväxt i de mest kritiska positionerna i så pass stor utsträckning att det finns ett behov av ett pålitligt dimensionerande utomhusklimat. Det dimensionerande utomhusklimatet bör innehålla extremt klimat samt även beakta variationer mellan olika år.

Resultaten visar vidare att det är en högre risk för påväxt av mögel i väggar med tjock isolering. Genom att ha en väl ventilerad luftspalt bakom fasaden skapas en robustare vägg med lägre risk för fuktskador. En diffusionsöppen mögelresistent, yttre isolering som monteras på utsidan av träreglarna, behövs för att minska risken för mögelpåväxt på utsidan av reglarna.

Contents

1 Introduction

1.1 Background

Interest in the use of wood constructions has increased as greater attention has been given to building more carbon dioxide-efficient (CO_2-efficient) houses (Dodoo, Gustavsson and Sathre 2012). In Northern European countries there is also a tradition of building wooden houses since timber is readily available (Björk, Kallstenius and Reppen 2003; Björk, Nordling and Reppen, L. 2009).

The awareness of climate changes, increased energy costs and new energy demands has also made well-insulated (U-value < 0.2 W/m^{2}K) walls more common (BBR 2011). Besides the positive effects of reduced energy needs, thicker insulation also results in a building envelope in which critical parts more often become exposed to high levels of relative humidity (RH). Higher relative humidity leads to increased probability of occurrences of mould growth (Nevander and Elmarsson 1991; Paper II; Technichal background report I). Since wood has low mould growth resistance compared to other building materials (Nielsen et al. 2004; Johansson et al. 2005), this property increases the risk of mould damage in well-insulted wood constructions.

At the same time investigations show that as much as 30 percent of the single-family houses and 15 percent of other buildings in Sweden have moisture-related damage (Boverket 2009). Several studies also show that mould and moisture-related damages are linked to high costs. A huge amount of money is spent each year by individuals, as well as companies and insurance companies, to rectify damage (Boverket 2009; Josephson and Hammarlund 1999).

As a consequence recent Swedish building regulations have stipulated stricter requirements when predicting the risk of mould and moisture damage in order to reduce the risk of those problems. Moisture conditions that create odors, unhealthy indoor climates and mould growth that affect the health of a building's occupants are forbidden. It is strictly recommended that these factors should be taken into account and verified before a house is built by a moisture-safety design process (BBR 2011).

To predict and minimize the risk of moisture damage there is a need of a reliable and user-friendly moisture calculation tool, that could be used to make it possible to check and compare different designs before a house is built (Boverket 2009; Mjörnell, Arfvidsson and Sikander 2012). There are two commercial and user friendly tools, WUFI and DELPHIN, that could be used to predict mould and moisture risks in constructions, as found in the technical background report B. Neither of these tools seems to have been verified by blind methods, as shown in appended paper V, i.e. verified without knowing the measurement results before making comparisons with unadjusted calculated results. The awareness in the entire construction industry, as well clients and consultants as construction companies and other contractors, need to be increased of which factors that highly affect the risk of mould growth and moisture-related damages.

1.2 Aim

The aim of this thesis was to find important factors that need to be taken into account and give recommendations in order to design and build moisture-safe houses without risk of moisture damage and secondary problems, such as SBS (Sick Building Syndrome).

The study aims to show whether it might be possible to use the transient heat- and moisture calculation tool WUFI 5.0 as a tool in the moisture safety design process in order to predict and evaluate the risk of mould growth and moisture damages. The purpose was also to analyze under what conditions the tool can be used and to show important factors that highly affect correlation between calculated and measured values from field measurements.

The study also evaluated the moisture-safety in five different real houses. This was made in parallel with the evaluation of the calculation tool WUFI 5.0 by comparing measurements from five new wood frame houses both to the risk of mould growth and blindly calculated values at the same time.

1.3 Limitations

The thesis considers wood frame walls located in northern European climates with an air gap behind the cladding and an interior vapour barrier. Studied designs were limited to a number of common Swedish designs and houses where also measurements have been carried out. Studied walls were also assumed to be the results of a perfect workmanship when compared to the drawings and used in the calculation models.

All calculations were one-dimensional, the influence of the wooden studs and other thermal bridges as well as possible influence of convection were deemed negligible. In general, studied designs were evaluated in a quantitative aspect where possible influences of qualitative issues such as detailing in joints, wall-corners, windows were excluded. Using one-dimensional calculations evaluating two- and three-dimensional wood frame walls also limit the possibilities to consider possible influence of initial moisture from the construction phase. However, since those two- and three- dimensional limitations in the calculations were included in the measurement results their influence will be considered in the discussion.

The thesis does not deal with detailed physical models in evaluated calculation tools. Functions and parameters used in the calculation tools were not specifically analyzed. No detailed analysis of materials and material data in the calculations models was made, possible bad correlation between material in the calculations and real materials was not directly studied.

A major part of the study was a case study where measurements were carried out in five real houses with occupants. This part of the study was therefore limited to the specific designs of those houses where measurements were carried out. The measurements were also governed by the specific conditions and properties in each specific studied building, i.e. each specific project schedule, production plan, building location, building direction, measuring period, instrumentation of measuring sensors and construction type. Local factors that might affect the measurements were not possible to control.

The definition of moisture critical limit, RH_{crit}, that was used was limited to showing the conditions when mould growth on wood based materials are possible. The background of chosen RH_{crit} is further described in section 2.4.

Possible sources of error are mentioned and discussed. Some known parameters that might create errors are also analyzed in order to find factors highly affecting the calculation results. However, a complete analysis of all possible sources of error and their effect on the results are not made since it would require extensive work.

1.4 Intended readers

The thesis primarily intends to be read and used by consultants and the timber house industry. It is also meant to be used by researchers in the area of house construction, wood based materials and wooden- and wood frame houses. Major parts of the thesis could also be used in teaching and education at different levels. Conclusions and recommendations that are presented can be used by local authorities in their duty to prevent houses with poor moisture safe design from obtaining building permission. The technical background report I that gives recommendations for moisture safe wood frame wall designs are especially written in Swedish to reach more easily the Swedish timber house industry, consultants dealing with wood frame houses and Swedish authorities.

1.5 Structure of the thesis, reading guide and appended conference papers and technical background reports

Conference papers that are included in the thesis and technical background reports supporting the results are linked and coupled into major findings and conclusions. Included documents, together or separately, support findings or show differences and also areas with lack of knowledge.

The initial and second sections of this report give an introduction to the thesis and a description of methodology and methods. In the third section current knowledge from a literature review is summarized. Section 4 is concerned with the blind verification of the calculation tool that has been used and it presents new results based on the five technical background reports C – G. Section 5 considers factors affecting the risk of mould growth based on new findings from the technical background report A. Section 6 presents a general analysis and discussion where findings from the entire thesis are analyzed and discussed. At the same time cross references to conference papers and previous presented findings from other researchers are given. Finally general conclusions and recommendations are given in the section 7. Section 8 includes references and section 9 presents all included conference papers. Section 10 describes used boundary and initial conditions that were used in the calculations. Used materials and material data in the calculation models are also presented and linked to references.

Included conference papers and reports in this thesis are listed in the section 1.6. All included conference papers are attached in appendix II in section 10 at the end of the thesis.

Seven individual technical background reports document the detailed data that was used in the thesis and will be referred to in the thesis for further reading. The technical background report B with a detailed literature study/ state-of-the-art includes a short description of each studied document. This technical background report was also summarized in the paper VI. The five technical background reports C – G present results from blind comparisons between measured and calculated values and evaluation of moisture safety in 150 positions located in the five different wood frame houses that are a part of this study. Those results were based on hourly measurement and calculations of temperature, relative humidity and moisture content over a period in between three to four years and are each of between 200 and 400 pages. Each of the 150 studied positions where measurements and calculations were carried out were also described. At the end of these five technical background reports, the general results from each specific report were summarized. The technical background report A, in Swedish, deals with moisture safe wood constructions and gives guidelines for wall design.

1.6 List of publications

1.6.1 Appended conference papers

The thesis consists of the following conference papers:

    I.   S. Olof Hägerstedt, Lars-Erik Harderup, Importance of a proper applied airflow in the facade air gap when moisture and temperature are calculated in wood framed walls, 5th International Symposium on Building and Ductwork Air-tightness October $21^{th} - 22^{th}$ 2010, Copenhagen/Lyngby, Denmark, 2010.

    II.   S. Olof Hägerstedt, Jesper Arfvidsson, 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, Brno University of Technology, Faculty of Chemistry, November $3^{th} - 5^{th}$ 2010, 978-80-214-4166-8.

    III.   S. Olof Hägerstedt, Lars-Erik Harderup, Control of moisture safety design by comparison between calculations and measurements in passive house walls made of wood, XII DBMC, International Conference on Durability of Building Materials and Components April $12^{th} - 15^{th}$ 2011 – Conference proceedings, Porto, Portugal, 2011, 978-972-752-132-6.

    IV.   S. Olof Hägerstedt, Lars-Erik Harderup, Comparison of measured and calculated temperature and relative humidity with varied and constant air flow in the facade air gap, 9th Nordic Symposium on building Physics NSB, May $29^{th} -$ June 2th 2011, Tampere, Finland 2011, 978-952-15-2574-2.

    V.   S. Olof Mundt-Petersen, Petter Wallentén, Tomi Toratti, Jorma Heikkinen, 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, Brno University of Technology, Faculty of Chemistry, October $31^{th} -$ November 2nd 2012, ISBN 978-80-214-4599-4.

    VI.   S. Olof Mundt-Petersen, Lars-Erik Harderup, Moisture safety in wood frame constructions – What do we know today? – A literature overview, Sustainable Building Conference 2013, SB13, May $22^{th} - 24^{th}$ 2013, Oulu, Finland 2013.

1.6.2 Technical background reports

The thesis was based on the following technical background reports:

    A.   S. Olof Hägerstedt, Moisture safe wood constructions – guidelines for wall design, Fuktsäkra Träkonstruktioner – Vägledning för utformning av träbaserade ytterväggar, Report TVBH-3052. Lund University 2012, ISBN 978-91-88722-43-0, In Swedish.

    B.   S. Olof Mundt-Petersen, Literature study / State-of-the-art – Mould and moisture safety in constructions, Report TVBH-3053, Lund University 2012, ISBN 978-91-88722-44-7.

    C.   S. Olof Mundt-Petersen (2013a), Comparison of hygrothermal measurements and calculations in a single-family wooden house on the west coast of Sweden, Report TVBH-3054, Lund University 2013, ISBN 978-91-88722-45-4.

    D.   S. Olof Mundt-Petersen, (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 2013, ISBN 978-91-88722-46-1.

E. S. Olof Mundt-Petersen, (2013c), Comparison of hygrothermal measurements and calculations in a single-family wooden house in the Swedish town of Växjö, Report TVBH-3056, Lund University 2013, ISBN 978-91-88722-47-8.

F. S. Olof Mundt-Petersen, (2013d), Comparison of hygrothermal measurements and calculations in a multi-family wooden house in the Swedish town of Växjö. Report TVBH-3057, Lund University 2013, ISBN 978-91-88722-48-5.

G. S. Olof Mundt-Petersen, (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 2013, ISBN 978-91-88722-49-2.

1.6.3 Other publications

In addition to the previously listed conference papers and reports the author has also written or contributed the following publications which have had an influence on the direction in which the research has preceded.

1. Tomi Toratti, Jorma Heikkinen, S. Olof Mundt-Petersen, Jesper Arfvidsson, Calculations and measurements of moisture and temperature in highly insulated house walls made of wood for a moisture safe design, World Conference on Timber Engineering, WCTE, 16th – 19th July 2012, Auckland, New Zealand 2012.

2. Wood in carbon efficient construction, Book summarizing the results from the ECO2 project – wood in carbon efficient constructions, in press.

3. Tomi Toratti, Jesper Arfvidsson, S. Olof Mundt-Petersen, Service life and moisture safety, International Holzbau-Forum Nordic, IHN 13, 23th – 24th May 2013, Kouvola, Finland, 2013.

2 Methodology and methods

This chapter presents the overall method, detailed methods for each specific part of the thesis and definitions and the analysis tools that have been developed.

The method is divided into three main parts. The initial part is a literature review that offered an overview and summarized knowledge in the area. The literature review also intended to show possible gaps and flaws in the area of moisture safety. The second part was carried out as a case study that aims to verify that the calculation tool works in real conditions and to find factors that affect the calculation results in conjunction to measurements. The third part was made as a parametric study and aims to find factors and parameters that affect the moisture safety in wood frame walls and show differences in importance between those factors. The verification of the calculation tool in the second part is important to make the results in the parametric study reliable. To find factors that affect the calculations, both sources of error and factors affecting differences between measurements and blindly calculated values were summarized and analyzed.

Comparisons between the case study and the parametric study and the papers were possible since the same principles in the comparisons, as shown in paper V, and the same moisture-critical limit was used in the entire thesis. The analysis tool was also invented in a manner that several of factors were evaluated at the same time.

2.1 Literature review search strategy

Since moisture safety consist of both qualitative and quantitative issues both of those sub-areas was included in the literature study. The effect of, and connection between those factors also made it necessary to include documents on different levels. For example doctoral theses and international reviewed journal articles were included as well as national institute reports, conference papers and master- and bachelor theses as described in paper VI.

Initially, searches in open access data bases in the area were carried out, but mostly with poor results. The only open database that showed relevant and reasonable hits was Google Scholar. Conference proceedings from the latest conferences in the area have been used and scanned. This has given both an overview of the present knowledge level and a good picture of the most recent research results that have been published. The fact that some research in the area is connected to national experience or local conditions and traditions have made it necessary to include national institute reports and master's and bachelor's theses in the study. In addition, the database at SP Technical Research Institute of Sweden was used. Articles related to the evaluated tool WUFI, given by both the institute that developed the calculation tool and other independent institutes, was also found on the WUFI homepage.

A more detailed description of the literature review search strategy could be found in the paper VI and in the supporting technical background report B, that also give a short description of each studied document.

2.2 Case study for blind validation of WUFI 5.0 in real conditions

All calculations were made blind, i.e. made without knowing the results of any measurements, in the part of the study that intend to verify if WUFI 5.0 is a reliable tool to predict moisture critical conditions. Blind comparisons could also be called single-blind. Blind calculations are equivalent to

situations when the designers carry out the heat and moisture calculations before a house is built. However, in order to receive results possible to compare to measurements available real in- and outdoor climate boundary conditions were used. Comparisons with calculated values, made after the measured values had been received, were evaluated using the Folos 2D visual mould chart as described in section 2.5 and paper V.

2.2.1 Blind comparison between measured and calculated values

Initially, measuring sensors for temperature, relative humidity and moisture content 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. The construction phases in each studied house were followed in order to document 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, Pousette and Dahlquist 2011; GE Sensing 1996). Hourly measurements of temperature, relative humidity and moisture content 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. Used material data and initial boundary conditions are presented in Appendix I. Used material data was also described together with each specific wall design and studied position in the technical background reports C – G supporting the thesis. However, since the calculation tool being evaluated was one-dimensional, the possible influence of beams and studs was not included in the calculations.

In 2012 blind calculations were carried out for each studied position for the periods 2008/2009 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 to 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 2D visual mould chart, described in section 2.5.

2.2.2 Control and supplementing lack of outdoor climate boundary conditions

Hourly outdoor climate boundary values were measured by SMHI (2012) and used in the calculation models. Unfortunately there were periods when there was a lack of hourly outdoor climate data to be used as climate boundary conditions in the blind calculations. There were single hours, shorter and longer periods with missing data. A simple method, as described below, in order to supplement these periods was therefore devised.

Lack of hourly temperature, relative humidity and radiation climate boundary data were supplemented in the steps as described below.

1. Lack of hourly temperature, relative humidity and radiation climate boundary data was supplemented by available three hourly data that also were received from SMHI. Those

periods were not marked as lack of climate data since the replaced data consist of high quality climate data (SMHI 2012).

2. If no three hourly data were available, shorter periods less than seven days with lack of temperature, relative humidity or radiation climate data were replaced with previous day hourly data value. I.e. the last daily temperature and relative humidity data could be repeated for seven days.

3. Longer periods than seven days with lack of climate data were primary supplemented with available three hourly data during all three missing hours.

4. If no three hourly climate data was available, hourly climate data from the same day and same time but in the previous year was used.

Lack of hourly wind speed, wind direction, air pressure and rain climate boundary data were supplemented in the steps as described below.

1. Lack of wind speed etc. climate boundary data was supplemented by available three hourly data that also were received from SMHI. Those periods were not marked as lack of climate data since the replaced data consist of high quality climate data (SMHI 2012).

2. If no three hourly data were available, shorter periods less than seven days of other climate data such as wind speed, wind direction, rain and air pressure was supplemented with previous hourly value.

3. Longer periods than seven days with lack of climate data were supplemented with available three hourly data during all three missing hours.

4. If no three hourly climate data was available, hourly climate data from the same day and same time but previous year were used as supplementation.

Long wave radiation was created by WUFI 5.0 explicit radiation balance.

Used hourly climate boundary data that was used in the blind calculations are presented in each of the specific supporting technical background reports C – G that present measurement results and comparisons between measured values and calculations.

The hourly climate data was also controlled and compared with other available climate data, mainly the three hourly climate data. Rainfall was compared using the mean value for the last six or twelve hours compared to hourly rain load and deviation between used and controlled rain load to the total amounts of rain the last six or twelve hours since the controlled rain load was measured in periods of six or twelve hours. Hourly temperatures and relative humidity climate boundary conditions were also controlled and compared with available measured micro climate carried out using a wireless Protimeter Hygro Trac system (Sandberg, Pousette and Dahlquist 2011; GE Sensing 1996).

All periods when the outdoor climate boundary conditions were supplemented, besides the long wave radiation and the diffuse radiation that always was supplemented, was shown together with the calculation and measurement results as described in section 2.5.4.

2.2.3 Supplementing lack of diffuse solar radiation and diffuse solar radiation model
Unfortunately there is a complete lack of diffuse solar radiation climate data in the areas where the studied houses were located. A simple model to create diffuse radiation dependent on used global radiation data was therefore developed. The model was based on experience from measured global

and diffuse radiation in Växjö during 1996. Since the global radiation is equal to the sum of diffuse and direct solar radiation the direct solar radiation could also be calculated using this method.

The model estimated the diffuse solar radiation as a function of the amount of global radiation. In case of a high amount of global radiation (Wh/m^2) the model estimated that a low percentage of the global radiation consists of diffuse radiation. As lower amount of global radiation (Wh/m^2) the model estimates the higher percentage of the global radiation consists of diffuse radiation. During nights with no global radiation at all, or in case of a global radiation below 2 Wh/m^2, the diffuse radiation is assumed to be zero. The percentage of global radiation that assumes to consist of diffuse radiation was changed stepwise between different amounts of global radiation as shown in table 1.

Table 1. Calculated diffuse radiation created from different percentage of current global radiation dependent on different amount of global radiation.

Global radiation	Percent diffuse of global radiation		Diffuse radiation
Wh/m^2	%		Wh/m^2
0 – 1.9	0	→	0
2 – 99.9	100	→	2 – 99.9
100 – 119.9	99	→	99 – 118.7
120 – 159.9	88	→	105.6 – 140.7
160 – 199.9	77	→	123 – 154.9
200 – 299.9	66	→	132 – 198.9
300 – 399.9	55	→	165 – 220.9
400 – 499.9	44	→	176 – 220.9
500 – 699.9	33	→	165 – 231.9
700 –	22	→	154

2.2.4 Supplementing lack of indoor climate boundary conditions

Indoor climate boundary conditions consist of temperature and relative humidity. In one house the indoor temperature and relative humidity were measured using Vaisala INTERCAP transmitters HMD/W40/50 (Sandberg, Pousette and Dahlquist 2011; Vaisala 2008; Technical background report G). In four houses the temperature and relative humidity were measured using the same wireless Protimeter Hygro Trac system (Sandberg, Pousette and Dahlquist 2011; GE Sensing 1996; Technical background report C – F) as mounted into the walls.

Shorter periods with lack of indoor climate boundary data were primary supplemented with previous hourly value. Longer periods than seven days were supplemented with climate data from the same hour in the previous year. If no climate data from the previous year were available the temperature was set to a constant value of 22 degrees and the relative humidity to 45 percent in four houses during the entire year, as shown in the technical background report C, E, F, G. In the fifth studied house, presented in the technical background report D the following year climate data were used. In case of lack of data during the 29th of February data from the 28th of February was repeated.

In one building the indoor climate measurements of temperature and relative humidity were carried out in three different apartments, as described in the technical background report F. When there was inadequate climate data in one apartment, available measured climate boundary conditions from the other apartments were primary used for supplementation, before supplementation by previous

hourly value as described above. If blind calculations were carried out in the climate frame in other apartments where no specific indoor climate conditions were available a mean value of all available indoor climate boundary data from that house was used as the indoor boundary climate conditions, as shown in the technical background report F.

For calculations carried out in exterior walls in bathrooms an interior relative humidity of 99 percent was used since the plaster behind the tiles always is assumed to be wet (Jansson 2005).

Since the indoor climate boundary conditions were carried out using the same system as used in measurements in the walls, periods with lack of indoor climate boundary conditions mainly occurs during the same periods where there was a lack of measurement results in the walls.

2.3 Method finding important factors affecting the risk of mould growth

The investigation to find and evaluate factors which affect the risk of mould growth, was carried out as a parametric study with calculations made on differently designed wood frame constructions. The calculations were carried out with the one-dimensional transient heat and moisture calculation tool, WUFI 5.0. Materials and climate boundary condtions were retrieved from the WUFI 5.0 material data base (WUFI 2009a) and climate data base (WUFI 2009b).

A reference wood frame wall that was designed as an ordinary Swedish wall, and also intended to imitate some of the previously studied walls where measurements were carried out, was modeled. The wall and its initial boundary conditions, as shown in Figure 29, are referred as the "reference case".

Initially, the most moisture-critical position in the wall was established for 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 found in some of the construction systems used by Swedish timber house manufacturing companies. Results from the fifth year after construction were used in order to avoid the initial conditions influencing the calculations.

The Folos 2D visual mould 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 mould growth. This is presented in paper V.

2.4 Definition of used moisture critical limit

Due to Swedish regulation the moisture critical limit was defined as the moisture conditions where a material loses its features or properties (BBR 2011). This could be bacterial contamination, mould growth or rot decay as well as static deformations, moisture related movements or other damage dependent on different situations and materials. In determination of the highest moisture conditions that could be allowed, the moisture critical limit should be used. Factors affecting when mould growth occurs such as temperature, relative humidity and duration could be included. Uncertainties

in calculation models, initial parameters, material data or measurement method should be taken into account (BBR 2011).

The moisture critical limit on wood in houses could basically be linked to when mould growth occurs on the material. Organic materials, such as wood, seem to be the most moisture sensitive to damages compared to other building materials and the primary risk is mould growth (Johansson et. al 2012; Johansson et. al 2005). Since this study considers the moisture risk in wood frame walls, i.e. building materials in wood frame walls, where wood is the most moisture sensitive building material, the critical limit focuses on the risk of mould growth on wood.

There is broad agreement that temperature, relative humidity and duration are the main factors, besides the exposed materials, affecting the risk of mould growth (Viitanen et. al 2010). The relationship between temperature and relative humidity and its influence on the risk of mould growth is quite similar in many the of known mould growth models. However, there are a number of different theories and models for reducing the amount of mould growth during non-favourable mould growth climate conditions. This is discussed in paper V and VI and in the supporting technical background report B based on results from Viitanen and Ojanen (2007); Sedlbauer (2001); Isaksson et. al (2010); and Pietrzyk, Samuelson and Johansson (2011).

Based on the facts presented above the critical limit, further on called RH_{crit}, was defined as "moisture critical conditions when mould growth is possible on wooden material". The influence of temperature and relative humidity were considered in RH_{crit} limit but without taking into account the influence of duration. This was also the major reason that the critical limit indicates when mould growth "is possible" and not when mould growth "occurs". However, the duration is shown and its influence could also be added in the analysis tool when reliable mould growth models considering duration become verified, as presented in paper V.

Other materials have other RH_{crit} sensitivity levels comparable to the limit that is used for wood in this study. As mentioned above, different materials have various moisture critical limits and the materials may lose their function and features in other ways, such as decay, strength and chemical reactions, before mould growth occur.

Since possible uncertainties should be taken into account, according to the Swedish building regulations (BBR 2011), the most moisture sensitive mould growth model created by Sedlbauer (2001) was used in the RH_{crit} limit in this study. However, other sensitivity levels to mould growth regarding other materials and other mould growth models can be added in the analysis tool.

2.5   Analysis tools

There are different ways of evaluating the results from measurements and calculations. Used and developed analysis tools, as presented in paper V, were based on the findings in the literature review in paper VI and are also described in the technical background report B.

Two tools have been used to analyze the results. The isopleth chart, as shown in figure 1, where RH_{crit} occurs when the relative humidity, at a specific temperature and time was above the RH_{crit} line (red). I.e. the RH_{crit} line should not be exceeded by the isopleth dots (turquoise) where each dot indicates an hourly temperature and relative humidity at each specific time. As mentioned above, RH_{crit} varies dependent on temperature (Sedlbauer 2001; Viitanen et. al 2010). Different materials have different

RH$_{crit}$ lines (Johansson et. al 2012; Johansson et. al 2005) and there are also different RH$_{crit}$ lines between different mould models (Viitanen et. al 2010).
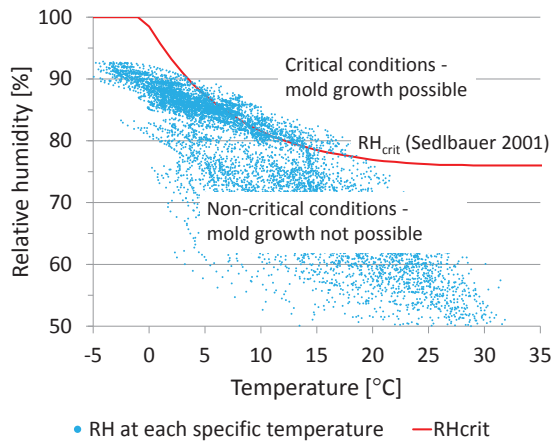

Figure 1. Example of isopleth chart including RH$_{crit}$ line (red) (Sedlbauer 2001) and hourly isopleth dots for one year below and above the RH$_{crit}$ limit.

However, the isopleth chart does not show when the RH$_{crit}$ conditions occur in time and if there could be a risk of mould growth considering the influence of duration. The isopleth chart does not show underlying factors, such as possibilities to reduce the vapour content or increase the temperature, that make it possible to limit or avoid the risk of mould growth.

Besides the isopleth chart another tool, the Folos 2D visual mould chart, was developed in order to compare and analyze the results in a way that satisfies the aims and intention in the study. The chart was used in both the case study and the parametric study and allows different analysis and comparisons. At the same time the main underlying factors affecting the risk of mould growth such as temperature, relative humidity and duration were considered.

The Folos 2D visual mould chart is briefly described below. A more detailed description of the tool and how it can be used could be found in paper V. The Folos 2D visual mould chart was also supplemented with two other charts evaluating the results that are presented below.

2.5.1   Parameters in the Folos 2D visual mould chart

The Folos 2D visual mould chart, as shown in Figure 2, visualizes the factors temperature (yellow) on the right y-axis and relative humidity (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 each specific time and particularly the periods when RH > RH$_{crit}$.

Input consists of hourly temperature and relative humidity and definition of RH$_{crit}$ limit that could be captured from an isoplet chart as shown in Viitanen et. al (2010). Hourly temperature (yellow) and relative humidity (turquoise) were plotted for each specific point in time creating a line in the Folos 2D visual mould chart. I.e. the same turquoise isopleth dots as shown in Figure 1 create a line in the Folos 2D visual mould chart.
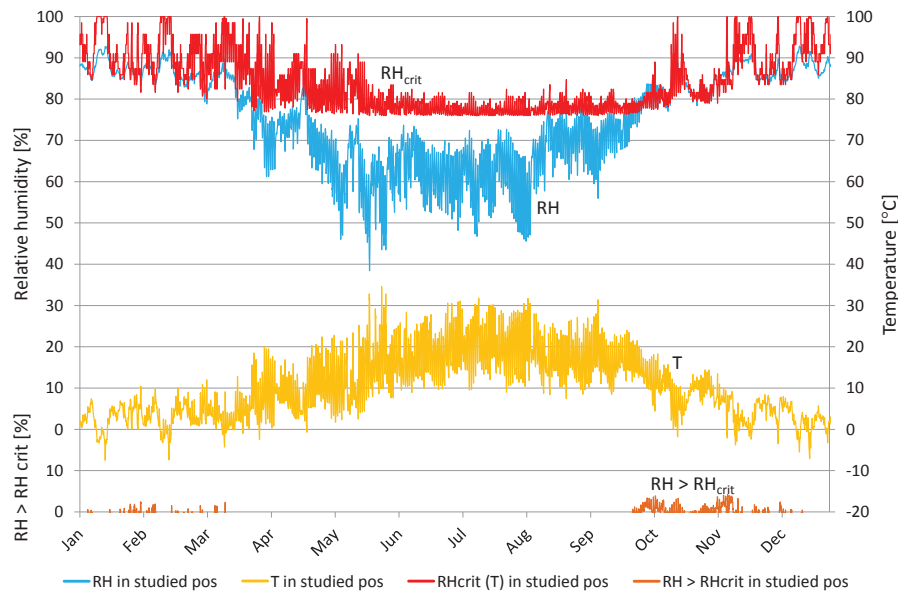
Figure 2. Example of the Folos 2D visual mould chart including the parameters temperature (yellow), RH (turquoise), RH$_{crit}$ (red) and RH > RH$_{crit}$ (light brown).

RH$_{crit}$ conditions occur, and mould growth is possible, when the RH is above the RH$_{crit}$ line. The RH$_{crit}$ line (red) is defined by the temperature that, at any specific time, exceeds the RH$_{crit}$ limit as shown in Figure 1, i.e. the chosen RH$_{crit}$ line from Figure 1 is converted over time by using the actual temperature at each point in time. This means that RH$_{crit}$ conditions depend on the prevailing relative humidity and temperature, where a high temperature gives a low RH$_{crit}$ line and vice versa. The RH$_{crit}$ line in Figure 2 is based on the Sedlbauer (2001) LIM I curve, as shown in Figure 1. However, it is easy to use another mould growth model by choosing another appropriate curve.

The parameter RH > RH$_{crit}$ shows how much, when and for how long time the relative humidity exceeds the RH$_{crit}$ conditions.

2.5.2 Evaluating the risk of mould growth and required measures to limit the risk of damage

Periods, when mould growth is possible, are shown as periods when RH > RH$_{crit}$ in the Folos 2D visual mould chart. The greater the RH > RH$_{crit}$ differences and the longer the periods when RH > RH$_{crit}$, the higher the risk of mould growth. The level of relative humidity and the risk of mould growth on a specific material can mainly be affected by changing the vapour content or the temperature, which affects the vapour content at saturation.

Since a lower level of vapour content or a higher temperature gives a lower relative humidty it is easy to define what measures are needed. Periods with RH > RH$_{crit}$ and hight temperatures have to be dealt with using measures that reduce the vapour content. Periods with RH > RH$_{crit}$ and low temperatures and low vapour content could be dealt with applying measures that results in higher temperatures in the studied position. Shorter periods with RH > RH$_{crit}$ would probably not need to be dealt with as the duration of RF > RH$_{crit}$ is not long enough to create mould growth. In some cases measures might be required that can create both lower vapour content and higher temperature in the studied position.

If it not is possible to create non-critical conditions, or the risk of mould growth is not predicted to be eliminated by a model that includes the influence of duration, then the design has to be changed.

It is also possible to add a parameter in the chart that considers the influence of duration, as shown in paper V. However, this is not made in this thesis since the differences between the models that consider the influence of duration are too big at present.

2.5.3   Comparing and analyzing results using the Folos 2D visual mould chart

The Folos 2D visual mould chart was used to compare and analyse the results that were obtained from measurements and blind calculations. This was made by adding three additional lines with relative humidity (black), temperature (dark blue) and RH > RH$_{crit}$ (purple) in the same chart, as shown in Figure 3 and 4.

The additional lines might come from a different design, different position or the same position but with other climate conditions, as shown in Figure 3. By comparing the RH > RH$_{crit}$ (brown and purple) for two different cases at the same time it is possible to determinate which case has the highest risk of mould growth at the same time as a level of the risks are presented. It is also possible to establish measures to be taken and to compare different designs in order to reduce the risk of mould growth as described in paper V. These comparisons were mainly carried out between different designs, different directions of studied wall and different positions in the parametric study in section 5 and paper II – IV.
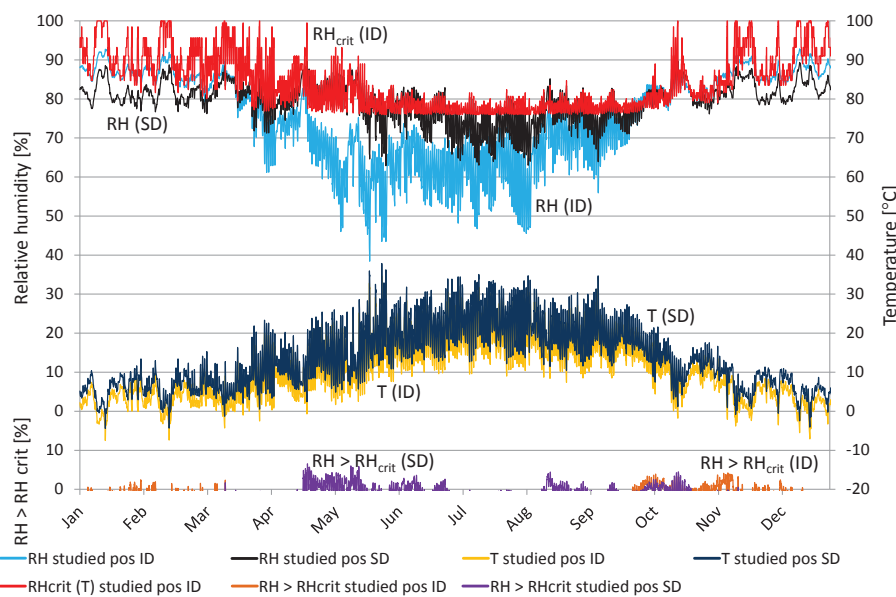
Figure 3. Example of comparison betweeen calculated results for two different designs. Initial design (ID) temperature (yellow), RH (turquoise), RH$_{crit}$ (red) and RH > RH$_{crit}$ (light brown). Second design (SD) temperature (dark blue), RH (black) and RH > RH$_{crit}$ (purple).

The additional lines could also be measured values, in order to be compared to blindly calculated values. By comparing measured and blindly calculated temperature (yellow and dark blue) and relative humidity (turquise and black) it becomes possible to establish deviations between measured and blindly calculated values, as shown in Figure 4.
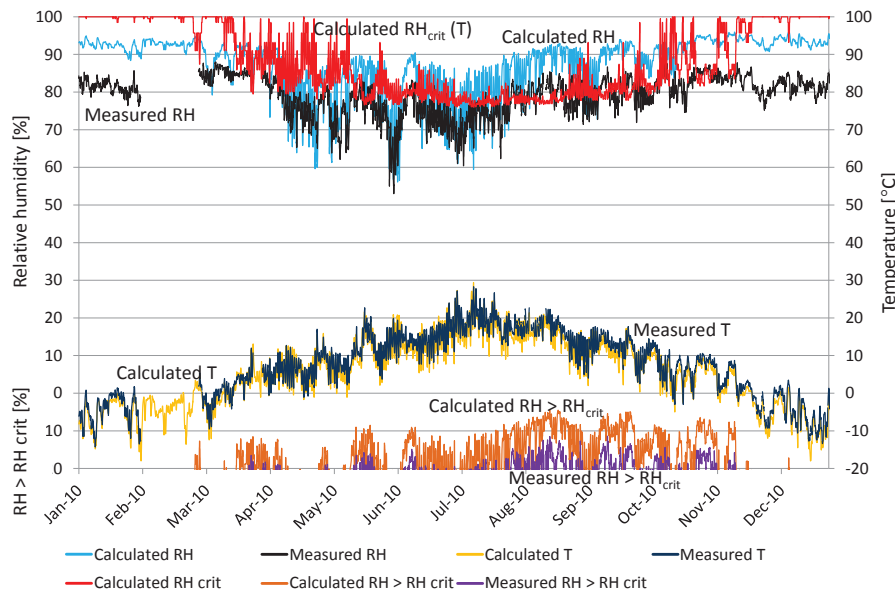
Figure 4. Example of comparison between measured and blindly calculated temperature and RH in a construction. Measured temperature (dark blue), calculated temperature (yellow), measured RH (black) calculated RH (turquise), RH$_{crit}$ dependent on calculated temperature (red), measured RH > RH$_{crit}$ (light brown). Second design temperature (dark blue), RH (black), measured RH > RH$_{crit}$ (purple) and calculated RH > RH$_{crit}$ (light brown).

Besides showing the measured and blindly calculated values and the correlation between measured and calculated values the risk of mould growth and possible measures to reduce the risk of mould growth are also visualized. The comparisons of the specific positions in walls are used in the case study in section 4 and paper I – IV. Some of the papers only include a pure comparison without showing the risk of mould growth.

Charts in this thesis always show the calculated relative humidity and temperature as the turquoise and yellow plotted lines. Notice that the RH$_{crit}$ line (red) is always calculated from the temperature (yellow) in the initial case. In order to limit the number of plots there is only one line showing the RH$_{crit}$ (red).

Paper I – IV have different color combinations than described above. The intervals on the axis are also different in different studied positions.

2.5.4 Additional parameters and charts analysing the case study results

In order to clarify differences between measured and blindly calculated temperature and relative humidity, additional measurement of moisture content and defects in climate boundary conditions are presented in two supplementing charts. The supplementing charts were added to the case study and also included in the five technical background reports C – G that supports the thesis.

The first additional chart, as shown in Figure 5, presents recalculated measured and blindly calculated vapour content (yellow and black), periods with lack of climate data (brown), measured moisture content (green) and where it was possible, blindly calculated moisture content (red).
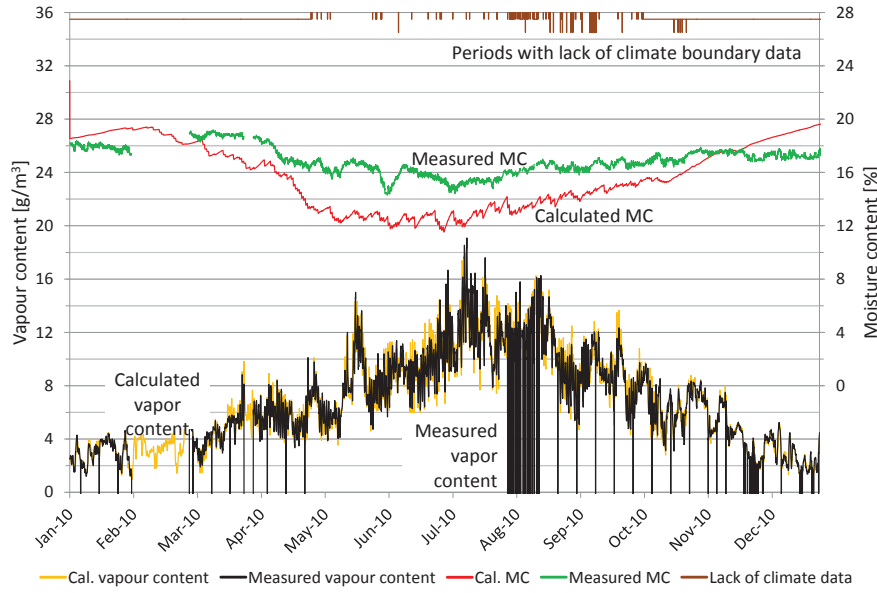
Figure 5. Example chart showing comparison between recalculated vapour content for measured (black) and blindly calculated (yellow) values, periods with lack of climate data (brown), and measured (green) and blind recalculated (red) moisture content.

Both measured and blindly calculated temperature and relative humidity were recalculated to vapour content (black and yellow) using the basic relationship as shown in Equation 1.

$$RH = \frac{v}{v_s} \cdot 100 \qquad\qquad (1)$$

Where RH is the relative humidity, v the vapour content and v_s the vapour content at saturation depending on the temperature (Nevander and Elmarsson 1991). Relative humidity and temperature are known from the measured or the blindly calculated values. Recalculated measured vapour content (black) showing 0 g/m^3 indicates periods with lack of measured temperature and relative humidity. Single periods were marked as a black vertical line down to zero and longer periods consist of no values at all.

As mentioned in the section 2.2.2 and 2.2.4 were periods with impaired or lack of climate boundary data replaced. Those periods are shown as dots or a line (brown) at the top together with the calculation and measurement results as shown in Figure 5 and in the five technical background reports C – G supporting the thesis. Vertical brown lines indicate a short period with lack of climate boundary data. Dots creating a horizontal line indicate longer periods which lack of climate boundary data. Dots creating a horizontal line on the second row from the top or longer vertical lines indicate lack of outdoor temperature or relative humidity data which has a higher influence on the calculation results than parameters on the first row from the top. Dots creating a line on the first row from the top or shorter vertical lines indicate lack of other less-important climate boundary conditions, such as wind direction, wind speed, air pressure, solar radiation, rainfall and indoor temperature or relative humidity.

All periods with impaired or lack of climate boundary data for each specific climate parameter is also marked with black lines, in the same manner as descried in the paragraph above, when the specific

climate is presented, as shown in figure 27 and 30 and the supporting technical background reports C – G.

Measured moisture content was captured from studs, facade panels and cross-laminated timber (CLT) where the sensors were mounted. On facade panels and CLT where it was possible due to the one-dimensional calculation model, the moisture content was also blindly calculated (red) and compared to measured values (green). Since the measured moisture content was given in the unit mass by mass [%] and the calculated moisture content was given mass by volume [kg/m^3] the calculated values was recalculated to mass by mass by estimating a wood density of 455 kg/m^3.

The second additional chart, as shown in figure 6, presents the percentage difference between measured and blindly calculated temperature (yellow) and relative humidity (light blue) based on the amount of comparisons. The amounts of comparisons between measured and calculated values, temperature (yellow) and relative humidity (light blue), over each studied year are presented.
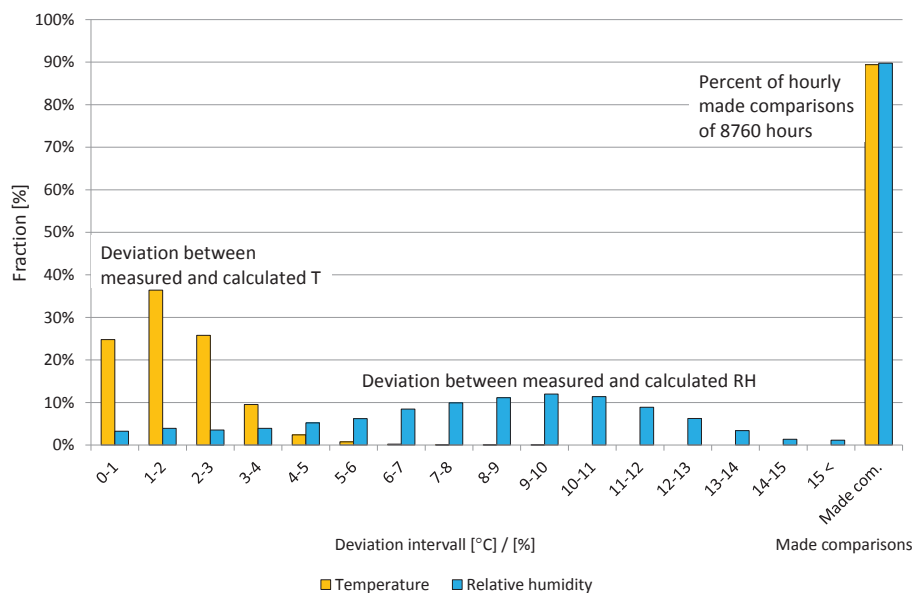
Figure 6. Example chart showing the amount and size of deviations between measured and calculated temperature (yellow) and relative humidity (light blue) and the percent of made comparison during a year for temperature (yellow) and relative humdity (light blue).

The percentage of possible comparisons is presented in the two right hand bars, temperature (yellow) and relative humidity (light blue). The bars indicate how many hourly comparisons for temperature (yellow) and relative humidity (light blue) were carried out in percent of the maximum 8760 hours per year. Incomplete comparisons during the entire year are due to periods where a lack of measurement data makes comparisons impossible.

Regarding the amount of possible comparisons the deviations between measured and blindly calculated temperature and relative humidity are shown in steps of one degree C for temperature or one percent for relative humidity up to the deviations above 15 degrees C and 15 percent RH. I.e. the percentage of the total amount of made comparisons that have a deviation between 0 and 1 for degrees C temperature (yellow) and percent relative humidity (light blue) are given in the left hand bars. The percentage of the total amount of comparisons that have a deviation between 1 and 2 for

degrees C temperature (yellow) and percent relative humidity (light blue) are given in the second left hand bars etc.

2.6 Possible sources of errors and factors affecting the calculations and measurements

There were several factors affecting the calculations and measurements and possible sources of errors that could cause deviations in the results. Some of these factors and sources of errors were neither possible to affect nor to control. The full range of possible sources of error and the possible influence these factors might have on the results were not seen as possible to analyze completely together.

However, a part of the intention in this study is to find such factors and possible sources of errors affecting the calculations and measurements. These errors and factors will be further discussed and analyzed in section 6.

2.6.1 Measurement sensors

Measurements were carried out using a wireless Protimeter Hygro Trac system. Each sensor was calibrated and adjusted before the sensor was mounted in each studied position (Sandberg, Pousette and Dahlquist 2011; GE Sensing 1996; Hoogenboom 2009). Since most of the 149 sensor were built in into a wall, slab or roof it was not possible to make any further calibrations. However, in one of the buildings measurements were carried out in a roof construction with a cold attic that was available during the entire measuring period, as shown in the technical background report F. Fourteen available sensors from this attic and two sensor located in exterior climate were remounted after 26 months and calibrated by Lars Olsson at SP Borås.

The calibrations were carried out in 20 °C at 54.4 % and 85.1 % relative humidity. The relative humidity was held by saturated salt solutions in closed buckets. The buckets including sensors and saturated salt solutions were placed in a climate chamber with stable temperature conditions. Uncertainties in measurements are expected to 2 %. The climate conditions were controlled with measurement uncertainties of 2 % with K = 2 (Nordtest method, 1988; SP Eti-QD). After calibration the sensors were remounted in the cold attic and exterior climate.

Calibration of relative humidity shows a mean deviation of -0.6 % at 54.4 % relative humidity and 3.3 % at 85.1 % relative humidity. I.e. the measured relative humidity was on average 0.6 % lower in reality compared to presented results at a relative humidity of 54.4 %. The measured relative humidity was in average 3.3 % higher in reality compared to presented results at a relative humidity of 85.1 %.

The mean value of all calibrated sensors shows a deviation of -0.3 °C at 20 °C. I.e. the measured temperature was in average 0.3 °C lower in reality compared to presented results at a temperature of 20 °C. In relation to free air this approximately creates 1 % higher relative humidity at 55 % relative humidity and 1.5 % higher relative humidity at 85 % relative humidity, if the relative humidity would have been calculated using Equation 1.

Since a second calibration, after the sensors been running, only was possible on 16 of the 149 sensors no results in the entire study were correlated to the second calibration results. This was not made since calibrated sensors were not located in the studied walls considered in this thesis and to

not create individual differences. The influences of deviations caused by errors in the measurements are discussed in section 6.

2.6.2   Measurements

The sensor thickness of approximately fifty millimeters may affect the measurements in studied position. Since its size reduces the thickness of the surrounding thermal insulation it might primarily affect the temperature in the studied position, and furthermore the relative humidity that is affected by the temperature.

The influences of the sensor thickness are bigger in thinner insulated walls since the thickness takes a higher amount of the total insulation thickness. The effect of possible deviations dependent on the sensor thickness might also be bigger in case of higher differences between the in- and out-door temperatures.

Another effect could be that the sensor might create heat during measurement processing that affect the temperature and the relative humidity.

Sensors measuring temperature and relative humidity are mounted approximately four centimeters from a wood stud or a wood beam and surrounded by mineral wool. The studs or beams, which have the highest risk of mould growth, might have a higher temperature, and as a consequence a lower relative humidity compared to the measurements. This needs to be considered when evaluating the risk of mould growth using measured values.

The measurements might also be affected by local and project specific factors that were not possible to control such as the influence of changes in the surrounding topography or vegetation.

2.6.3   WUFI 5.0 calculation tool

Possible deficiencies in the calculation tool WUFI 5.0 numerical and physical model that might create systematic errors are not considered and are also a part of the total error.

2.6.4   WUFI 5.0 calculation models

Thermal bridges due to studs and beams are disregarded in the one-dimensional calculations. The influence of two- and three-dimensional factors surrounding studs and beams, especially in the exterior part of the wall, cause higher temperatures and lower relative humidity in reality. In the case study the close location of the studs and beams to the measuring sensor might affect the measuring results with a higher temperature and a lower relative humidity compared to blind calculated one-dimensional values. Two-dimensional laboratory and parameter studies of thermal bridges in a central Swedish climate show that the temperature increases by approximately $0.5\,^{\circ}$C to $1\,^{\circ}$C. This reduces the relative humidity by 2.5% to 5% in the outer part of the stud (Forsberg 2011; Olsson 2011).

The one-dimensional calculation limits the possibilities to consider the influence of initial construction moisture affected by the excluded wood studs and wood beams. This might create artificially good results compared to reality, mainly in the initial period of the calculations until the initial moisture becomes dried out and the construction is in balance with the surrounding climate conditions. The influence of moisture-, heating- and ventilation sources dependent on two- and three dimensional factors, such as the influence of under-floor heating and possible moisture storage in beams excluded from the calculations, was not considered in the one-dimensional calculations.

The air flow in the air gap behind the cladding was normally set to be constant during the calculations. In reality the air flow was mainly affected by the wind, temperature differences, the size of in- and out gaps, the air gap size and possible barriers in the air gap (Falk and Sandin 2013). However, paper IV considers the influence of a varied air flow in the air gap behind the cladding.

The amount of wind driven rain and the location of the wind driven rain in the calculation models might be different compared with reality. High amount of wind driven rain, and a bad location, might affect the calculation results in studied positions.

Defects in the calculation models might also be caused by the user, unconsciously or dependent on lack of knowledge of functions in evaluated calculation tool. The user knowledge and the user capacity to handle the tool and make reliable calculation models including important factors is always of importance to get an accurate result.

2.6.5 Material parameters used in the WUFI 5.0 calculations

Material parameters were captured from the WUFI 5.0 material data base. The intention was that materials data and material parameters that were developed by the same team as developed the calculation tool should be used as far as possible since those material properties were probably adjusted to the WUFI 5.0 numerical and physical model. Possible poor coincidence between material properties used in the calculations and real material used in the investigated buildings is as a part of the limitations.

In some positions it became possible to compare measured moisture content to calculated moisture content mass by mass in percent. In those comparisons the calculated moisture content was received in mass by volume kg/m^3. The calculated moisture content mass by volume, kg/m^3, was therefore recalculated to mass by mass, kg/kg, using the wood density 455 kg/m^3. Since the wood density varies between different wood studs, the differences in density were not considered in each specific position.

There are limitations in the way WUFI 5.0 handles different material properties during the calculations. For instance is it only possible to include one sorption curve for each material which means that the differences between the absorption and desorption curves for the different materials used could not be considered. Further limitations considering materials, and material properties could be found in WUFI 5.0 user manuals and the technical background report B that support the thesis. Materials that were used in the calculations are specified in the section 9.1.

2.6.6 Climate, initial and boundary conditions used in the WUFI 5.0 calculations

Wrong initial conditions used in the calculation models may create deviations between the measured and calculated results. During the parametric study defects in the initial conditions were treated by using results from the fifth year without influence from factors such as initial construction moisture.

During the case study there were different times and ways of starting the calculations. In one case the calculation was forced to start before the house was built due to numerical limitations. In one case the calculation start from the time when exterior climate boundary conditions were available, i.e. two month after the house was built. In other cases the calculations starts the same day as the house was built. None of the calculations in the studied houses considered the influence of initial moisture content. All calculations include the date when the studied houses were occupied. Further

details considering calculations periods and calculation starts could be found in the technical background reports C – G supporting the thesis.

Boundary conditions that were not possible to establish or consider in the calculations may also have created deviations in the calculation results in comparison to real conditions.

Initial and boundary conditions that were used in the calculations are specified in the section 10.2.

The deviations in used climate boundary conditions in the calculations could depend on several factors which are discussed in the analysis in section 6.

2.6.7 Leakage from inside and outside

Leakages from the outside caused by wind driven rain penetrating the cladding are expected. This is taken into account by adding 1 % of the rain load in the air gap behind the cladding in the calculation models (ASHRAE 2009). The air gap behind the cladding is expected to drain out leaking water and have a capillary braking effect that prevents the water from reaching the frame.

Leakages from the inside is not expected and not considered in the calculation models. All studied designs have an interior vapour barrier. Four of five studied houses have exhaust air ventilation and the fifth house was tested for air leakages by blowed door test with good results. All interior waterproof membranes in bathrooms are expected to be both vapour and water tight.

2.6.8 Difference between drawing and built walls

Differences between drawing and real built walls was not expected. As mentioned the construction phases were thoroughly followed and deviations between the drawings and the real conditions was documented and taken into account in the calculation models. A perfect workmanship was assumed if no deviations were found. Possible deviations caused in the late phase of the on-site construction or after the houses were inhabited were not taken into account.

3   Results – Major findings from literature review

The main findings and conclusions that could be established in the literature review are presented below. Based on the studied journal articles, conference papers, dissertations, theses, standards, books and other documents, knowledge could be summarized and several conclusions could be established based on the contents of approximately 140 studied documents. The references below are examples of those studied documents. These major findings can also be found in paper VI.

Research shows that basic knowledge exists in the area of heat, moisture, moisture transport and mould models (Nevander and Elmarsson 1994; Viitanen 1996; Vinha 2007; Krus 1996; Künzel 1995). However, there are several documents that determine the need of further research in the area since moisture related damage is common and has a great effect on both financial and health issues (Boverket 2009). Furthermore, the construction industry needs to carry out further work with regard to moisture protection in existing construction systems. Investigations also show that attitude, unclear responsibilities and deficiencies handling moisture safety issues in the industry are a part of the problem (SOU 2002:115; Stadskontoret 2009; Arfvidsson and Sikander 2002).

There is broad agreement about the main factors affecting the risk of mould growth (Viitanen et. al 2010). However, possible ways of reducing mould growth and its influence on health need to be further investigated as well as critical levels with regard to the effects and duration. The effects of short-time variations between critical and non-critical conditions also have to be further studied. There seems to be no consensus concerning the best model how to analysis mould and mould growth. Therefore this area need to be further developed to direct or indirect show possible actions how to substantially reduce or avoid the risk of mould growth in critical constructions (Viitanen and Ojanen 2007; Sedlbauer 2001; Isaksson et. al 2010; Pietrzyk, Samuelson and Johansson 2011; Togerö, Svensson Tengberg and Bengtsson 2011).

Moisture safety design process is needed to reduce the risk of mould and moisture related damages. It is established that both qualitative and quantitative issues need to be considered in the moisture safety design process and it needs to be in focus and dealt with from the planning phase, throughout the entire building process (BBR 2011; Mjörnell, Arfvidsson and Sikander 2012; Harderup 1998).

New waterproofing membranes and systems with high quality joints in bathrooms need to be developed. There is also a need to ensure the vapour tightness when the membranes are in contact with high relative humidity. The difference in vapour resistance between different membranes in exterior bathroom walls also needs to be handled in the design and construction phase (Jansson 2005; Jansson 2006; Jansson and Samuelson 2011, Jansson 2010).

Generally there are good materials, tools and detail-solutions to build airtight constructions. It also seems to be a positive ongoing developing process with new materials and new tools in the material industry. However, it is always best to try to find design solutions with good opportunities for air tight joints and connections to be readily made (Sikander 2010; Sandberg and Sikander 2004; Adalberth 1998; Wahlgren 2010).

Experience and studies from rendered non-drained and unventilated facades with wood frame walls, so-called ETICS or EIFS walls, are a risk design solution and should be avoided in order to build moisture safe wood frame constructions. The importance of a ventilated air gap behind the facade in

order to reach a long service life is also established. Regardless of the design the influence of wind driven rain has to be considered (Falk and Sandin 2013; Falk 2010; Samuelson and Jansson 2009; Jansson 2011; Samuelson, Mjörnell and Jansson 2007).

It is possible to build wood frame constructions with high thermal resistance, but there is an increased risk of mould and moisture damage. According to the following sections, paper I – V and several studied documents a number of specific factors affecting the moisture safety of well-insulated wood frame houses have been identified and must be considered (Nevander and Elmarsson 1991; Samuelson 2008; Nore 2009; Sandin 1993; Sandin 1991).

Wood frame houses cannot become exposed to rain during the construction phase in order to safely avoid the risk of mould growth. By being built under a tent or concentrating the on-site construction to a single day without rain using building elements, this risk could be avoided. This is especially important in well-insulated houses which are more sensitive to moisture (Mjörnell, Arfvidsson and Sikander 2012; Olsson, Mjörnell and Johansson 2011; Olsson 2011; Brander, Esping and Salin 2005)

In order to predict and avoid moisture damage it is also shown that there is a need for user-friendly and reliable moisture calculation tools and methods (Boverket 2009). According to the supporting technical background report B do user-friendly tools exist but do not seem to be widely spread in the construction industry today. However, none of the studied moisture calculation tools, no matter if they are commercial or used for research, seems to be verified to real conditions by blind comparisons (Krus 1996; Künzel 1995; Sandberg 1973; Sasic Kalagasidis 2004; Häupl et. al 1997; Maref et. al 2003; Rode and Burch 1995; Laujjarinen and Vinha 2011; Maref et. al 2002).

4 Results – Blind validation and evaluation of WUFI 5.0 in wood frame walls

This chapter summarizes the general results from the comparisons between measurements and blind calculations of studied positions in several different wood frame walls. All calculations and comparisons in this section were made blind although this is not specifically highlighted in each specific case. The results are based on the five technical background reports C – G. Examples of general findings that occur in several of studied positions are presented below. Similar blind comparisons between measured and blindly calculated values could also be found in paper I – IV.

4.1 Choice of evaluated calculation tool

According to paper VI and the supporting technical background report B there are several tools available that could be used to predict mould and moisture risks in constructions. Unfortunately there are only two calculation tools, WUFI and DELPHIN, that are commercially available and could be seen as user-friendly. As mentioned before, neither of these calculation tools seems to have been verified by blind methods, i.e. verified without knowing the measurement results before making comparisons with unadjusted calculated results. Paper VI also establishes 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.

The WUFI 5.0 one-dimensional version was chosen for evaluation since it seems to be the most widely used calculation tool of the two commercial alternatives and that the one-dimensional version seems to be the one that is broadly used in the construction industry, as described in paper VI and the supporting technical background report B.

4.2 Materials

4.2.1 Studied houses

Measurements and blind 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 presented comparisons. The houses were located in four different towns in Sweden, as shown in Figure 7, each with different climate conditions.
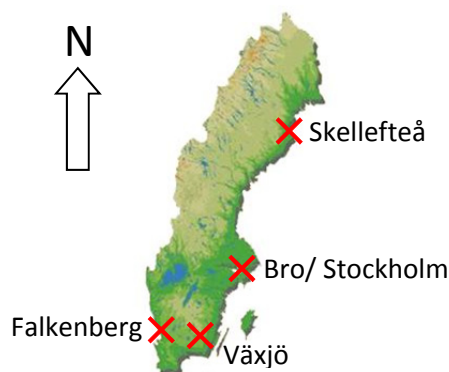

Figure 7. Location of the studied houses in Sweden.

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4.2.2 Studied positions

The locations of the studied positions were mainly chosen for two reasons. One was to study the positions where previous knowledge and experience had shown a high frequency of damage. The second was to have a couple of positions in a row at different depths in different directed walls in order to obtain purer measurements and more reliable conditions in order to verify the WUFI 5.0 calculation tool.

The choice of the studied house and its location was governed by the properties for new-build houses from the housing company participating in the study.

The locations of the studied positions and a more detailed specification and drawing of the position is given in the five technical background reports C – G that supports the thesis. In some cases photos, showing the sensor, are provided in the results chapter in connection with the part in which each studied position is presented in detail.

4.3 General results

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 8 – 10 below. However, there are also differences between measured and calculated values in many positions. These are presented in sections 4.4 – 4.13. Differences and possible factors influencing differences are also discussed in conjunction with other factors found in paper I – V and the results from section 5 in the general analysis and discussion in section 6.
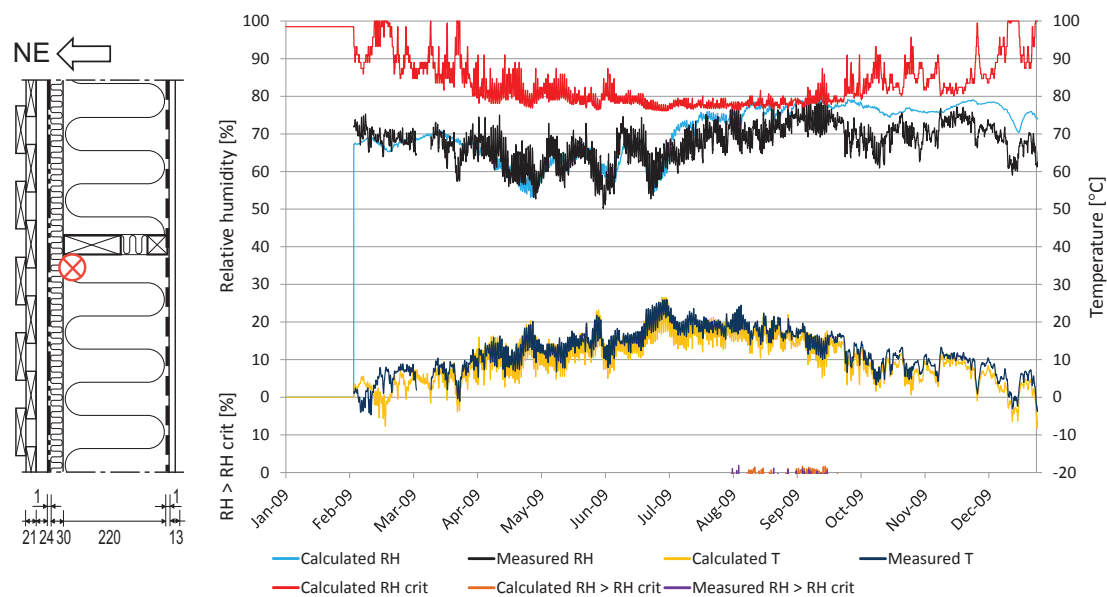
Figure 8. Example of comparisons between measured and blindly calculated RH and temperature behind a mould-resistant facade insulation board in the exterior part of a wall. Blindly calculated RH (turquoise) and measured RH (black). Blindly calculated temperature (yellow) and measured temperature (dark blue). RH$_{crit}$ derived from the calculated temperature (red). Calculated RH > RH$_{crit}$ (light brown) and measured RH > RH$_{crit}$ (purple).
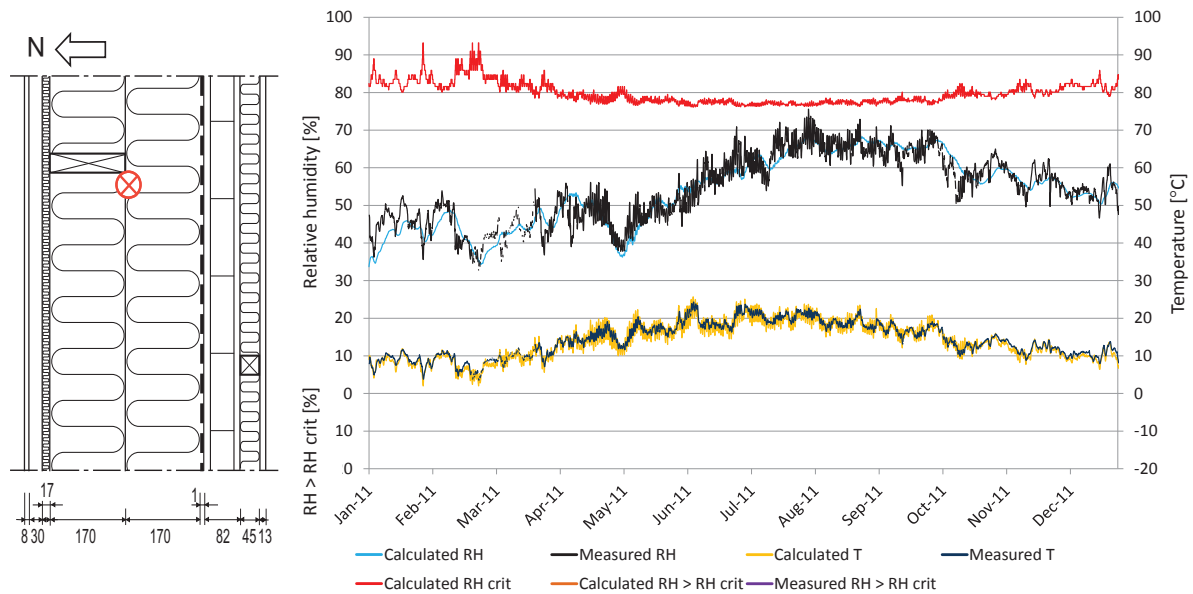
Figure 9. Example of comparisons between measured and blindly calculated RH and temperature in the middle of a wall. Blindly calculated RH (turquoise) and measured RH (black). Blindly calculated temperature (yellow) and measured temperature (dark blue). RH$_{crit}$ derived from the calculated temperature (red). Calculated RH > RH$_{crit}$ (light brown) and measured RH > RH$_{crit}$ (purple).
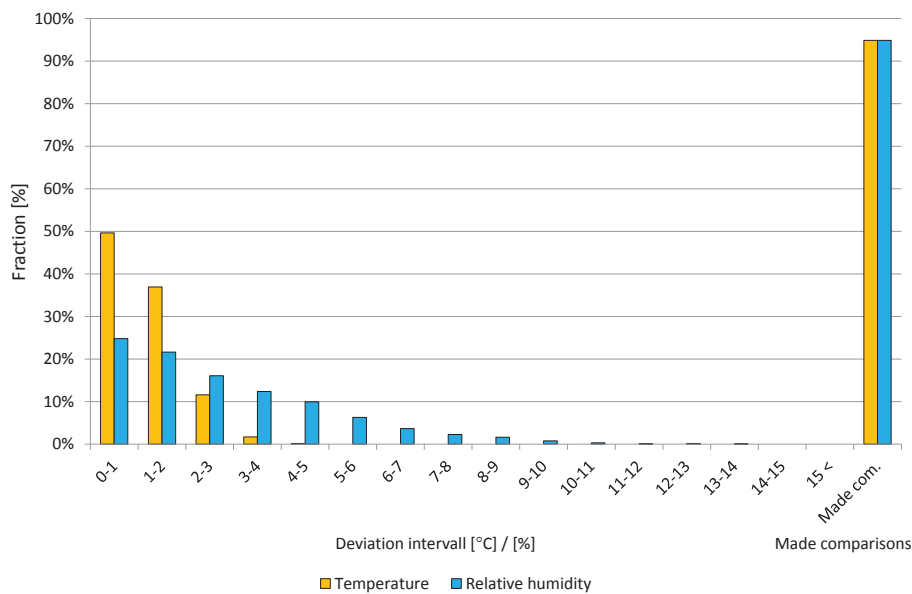
Figure 10. Agreement and the size of deviations, based on the results as shown in Figure 9, between measured and blindly calculated temperature (yellow) and relative humidity (light blue). The percentage of made comparisons of the total amount of hours during one year for temperature (yellow) and relative humidity (light blue) are shown on the right hand bars.

4.4 Influence of temperature on the relative humidity

Differences between measured and blindly calculated relative humidity might be caused by differences between measured and calculated temperatures, as shown in Figure 11.
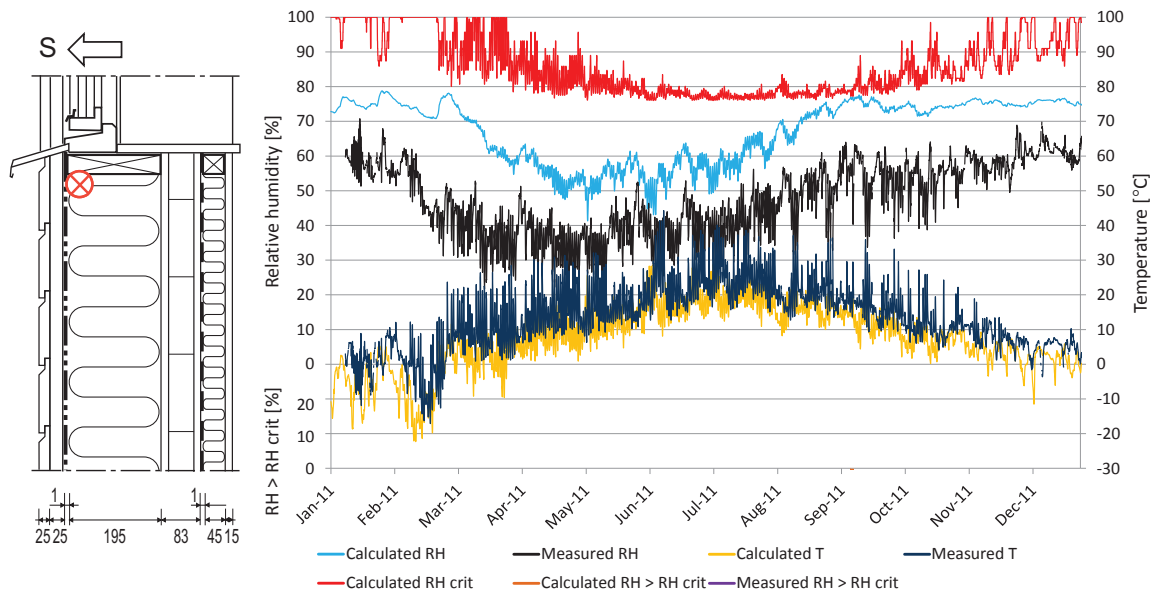
Figure 11. Example of comparisons between measured and blindly calculated RH and temperature where the differences in blindly calculated temperature seems to cause a constant deviation between measured and blindly calculated relative humidity. Blindly calculated RH (turquoise) and measured RH (black). Blindly 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).

I.e. the vapour content is the same, as shown in Figure 12, but different measured and blindly calculated temperatures give different vapour contents at saturation. This creates differences between the measured and calculated relative humidity, as shown in Figure 11. The particular effect of temperature on the relative humidity can be found in all the studied designs and houses. In most of the cases where the temperature seems to affect the relative humidity there were higher measured temperatures creating a lower relative humidity.
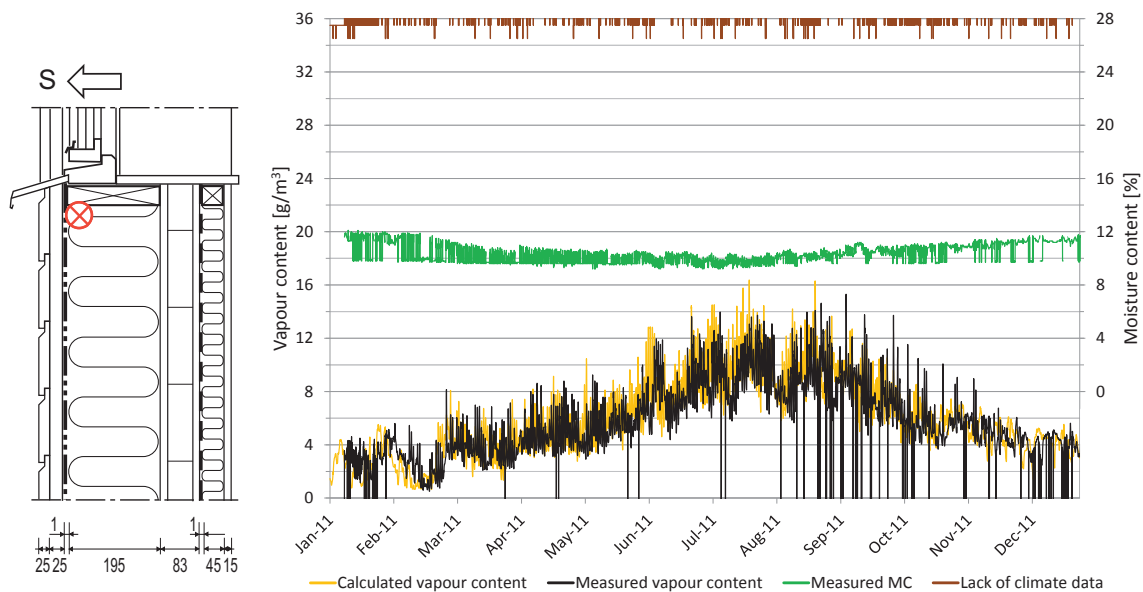
Figure 12. Example of comparisons between recalculated vapour content for measured (black) and blindly calculated (yellow) values, periods with lack of climate data (brown), and measured (green) moisture content.

4.4.1 Differences between measured and calculated values during cold periods

There were periods when there was a more or less constant differences between measured and blindly calculated temperature that caused differences between measured and calculated relative humidity, as shown in Figure 11 and 12. However, differences depending on temperature between measured and calculated relative humidity mainly seems to occur during the colder periods in the outer part of the studied walls. The differences tend to be greater during the winter and in a colder climate, i.e. the studied walls in the northern part of Sweden, with a colder climate, show greater differences, as shown in the example in Figure 13.

Figure 13. Example of comparisons between measured and blindly calculated RH and temperature in the exterior part of a wall located in the Northern part of Sweden. Blindly calculated RH (turquoise) and measured RH (black). Blindly 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).

4.4.2 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. In those positions close to the under-floor heating a positive effect was generated as a higher temperature reduced the relative humidity in this area, as shown in Figure 14.
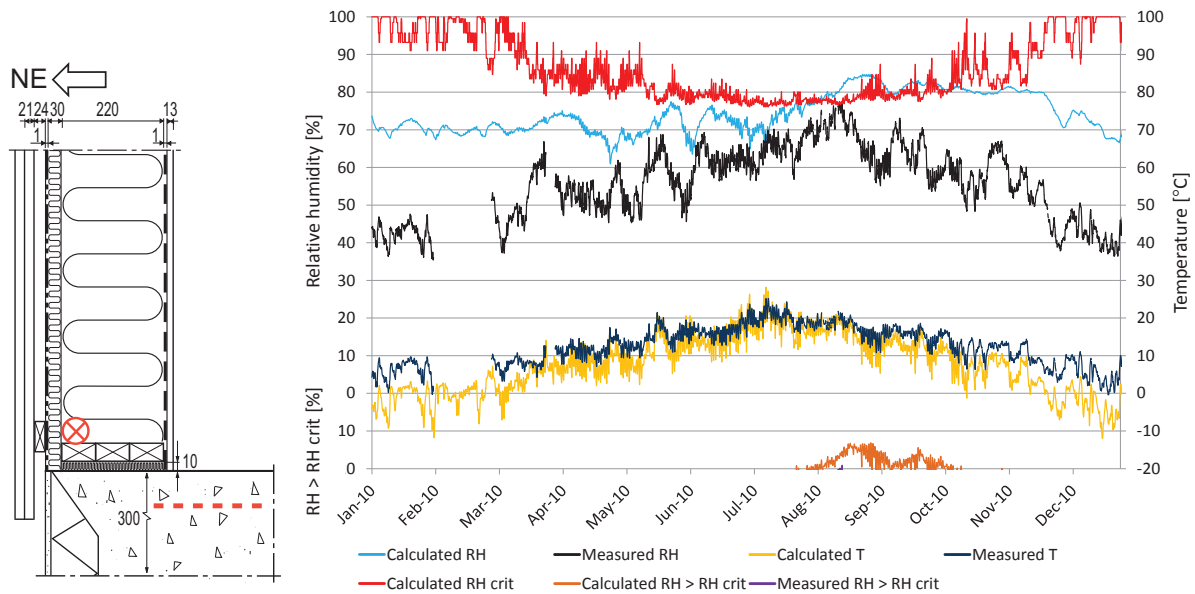
Figure 14. Example of comparisons between measured and blindly calculated RH and temperature, where measurements were carried out on the topside of the sill behind a mould-resistant vapour permeable facade insulation board in the exterior part of a wall. Blindly calculated RH (turquoise) and measured RH (black). Blindly 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).

The higher measured temperature and lower measured relative humidity mainly occurs during the winter when the under-floor heating probably was switched on.

4.5   The most moisture-critical position

By comparing the results in the Folos 2D visual mould 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 vapour content and low temperature that created a high relative humidity, as shown in Figure 15.
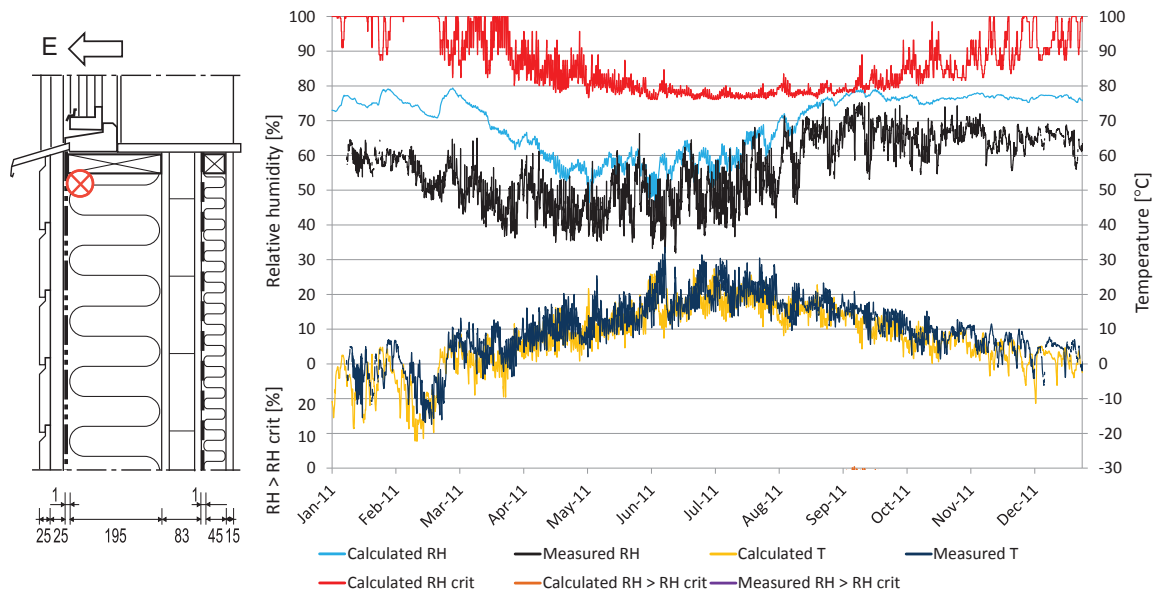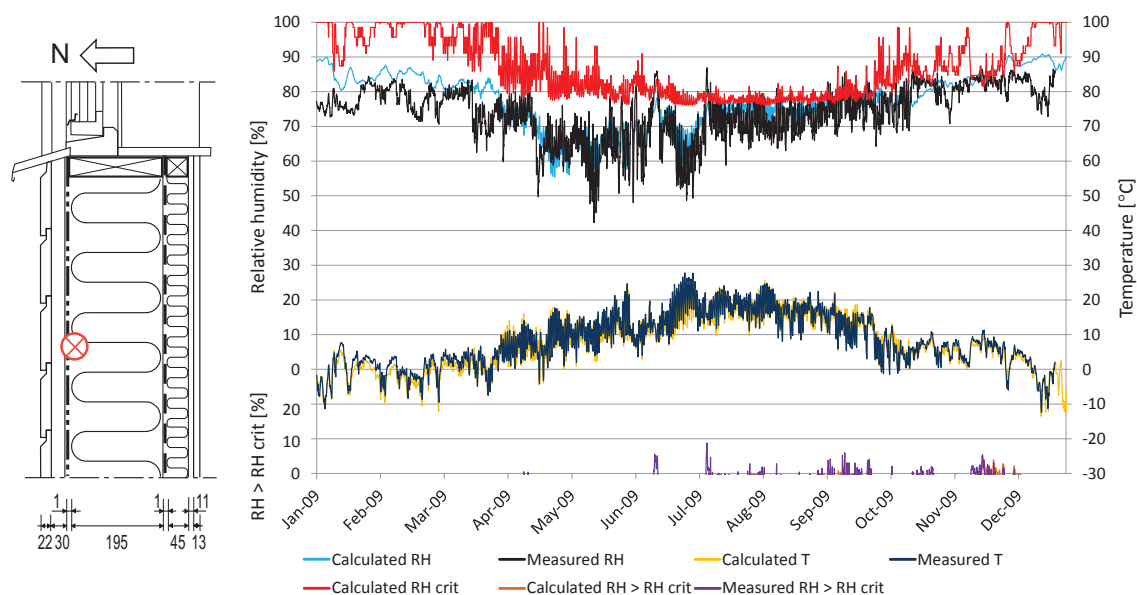
Figure 15. Example of comparisons between measured and blindly calculated RH and temperature in the exterior part of a wall inside the wind barrier. Blindly calculated RH (turquoise) and measured RH (black). Blindly calculated temperature (yellow) and measured temperature (dark blue). RH$_{crit}$ derived from the calculated temperature (red). Calculated RH > RH$_{crit}$ (light brown) and measured RH > RH$_{crit}$ (purple).

Higher temperatures deeper into the wall reduced the relative humidity and the risk of mould growth. An exterior mould-resistant facade insulation board on the outside of the studs behind the air gap, as shown in Figure 8 and 9, increases the temperature where there are organic mould-sensitive wood beams and can therefore be used as moisture protection. However, when the relative humidity is high at low outdoor temperatures below 0°C, there are no moisture-critical conditions. Such non-moisture-critical conditions occur during the winter period in the studied house in northern Sweden, as shown in Figure 11 and 13. Thinner walls also have higher temperatures in the exterior parts, which reduce the relative humidity and the risk of mould growth.

4.6 Influence of vapour content on the relative humidity

In some cases the differences between the measured and blindly calculated values is difficult to explain. Those cases generally 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) on the inside of the the vapour barrier, as shown in Figure 16. 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. By recalculating the measured and calculated temperature and relative humidity to vapour content, differences between measured and calculated values could be found, as shown in Figure 17. However, this is not as common, nor does it have as big influence as the differences in temperatures have on the relative humidity.

Figure 16. Example of comparisons between measured and blindly calculated RH and temperature in the installation layer on the inside of the vapour barrier in the interior part of a wall. Blindly calculated RH (turquoise) and measured RH (black). Blindly 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).
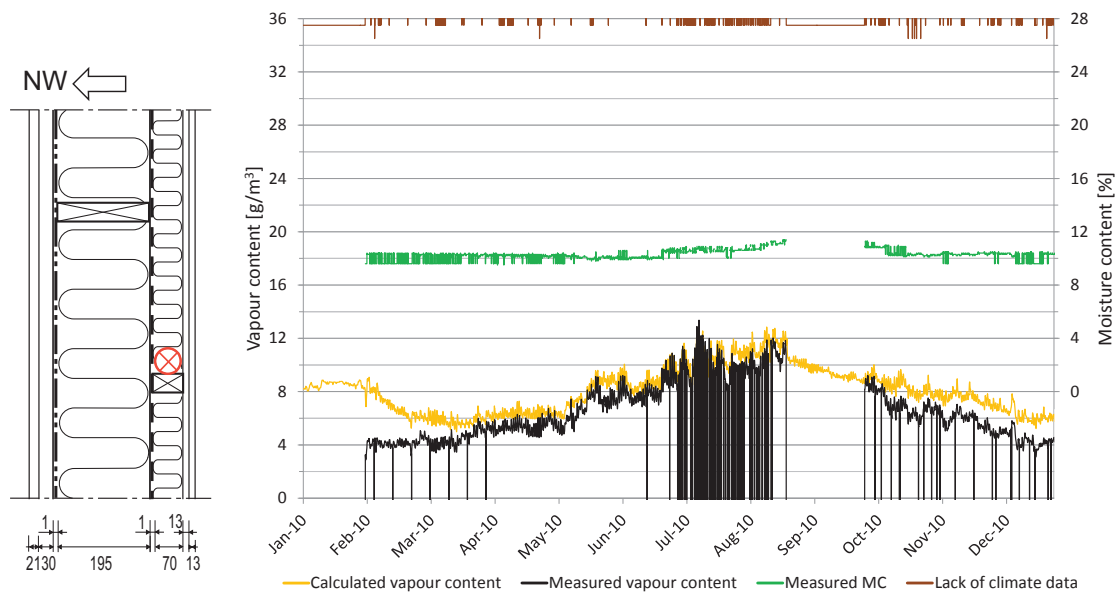
Figure 17. Example of comparisons and differences between recalculated vapour content for measured (black) and blindly calculated (yellow) values, periods with lack of climate data (brown), and measured (green) moisture content.

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4.7 Drying-out in installation layers in bathrooms between two vapour-tight membranes

In four positions in two of the studied designs sensors were mounted in the installation layer in bathrooms, between the vapour barrier and the interior waterproof membrane, (blue dashed line) as shown in Figure 18 and 19. Measurements in these positions indicated that the speed of the drying-out process was faster here than predicted by the blind calculations, as shown in Figure 18.
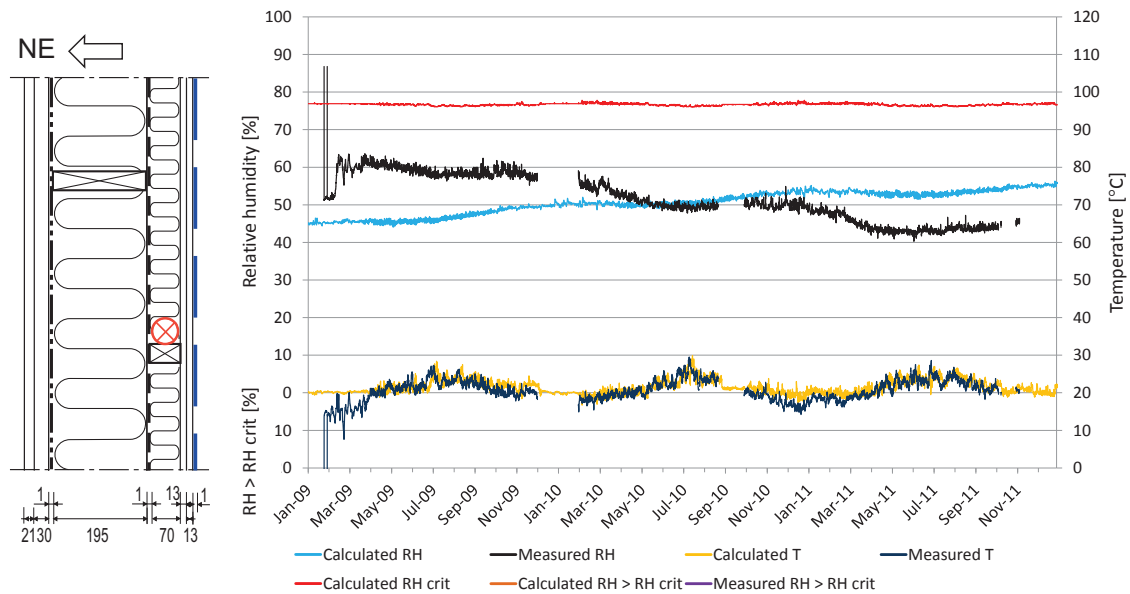
Figure 18. Example of comparisons between measured and blindly calculated RH and temperature in the installation layer between the vapour barrier and the interior waterproof membrane in the interior part of a bathroom wall over a period of three years. Blindly calculated RH (turquoise) and measured RH (black). Blindly 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).

One studied position in the installation layer in a bathroom, as shown in Figure 19, indicate that there was some kind of leakage from the inside since the relative humidity and the temperature rise during short periods mainly each second or third day.
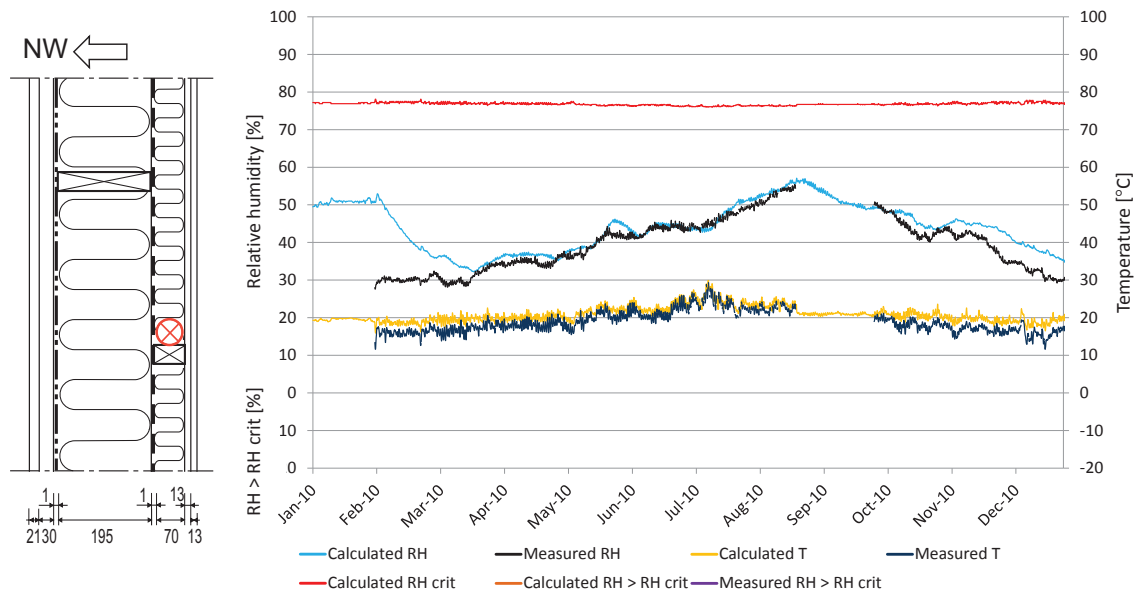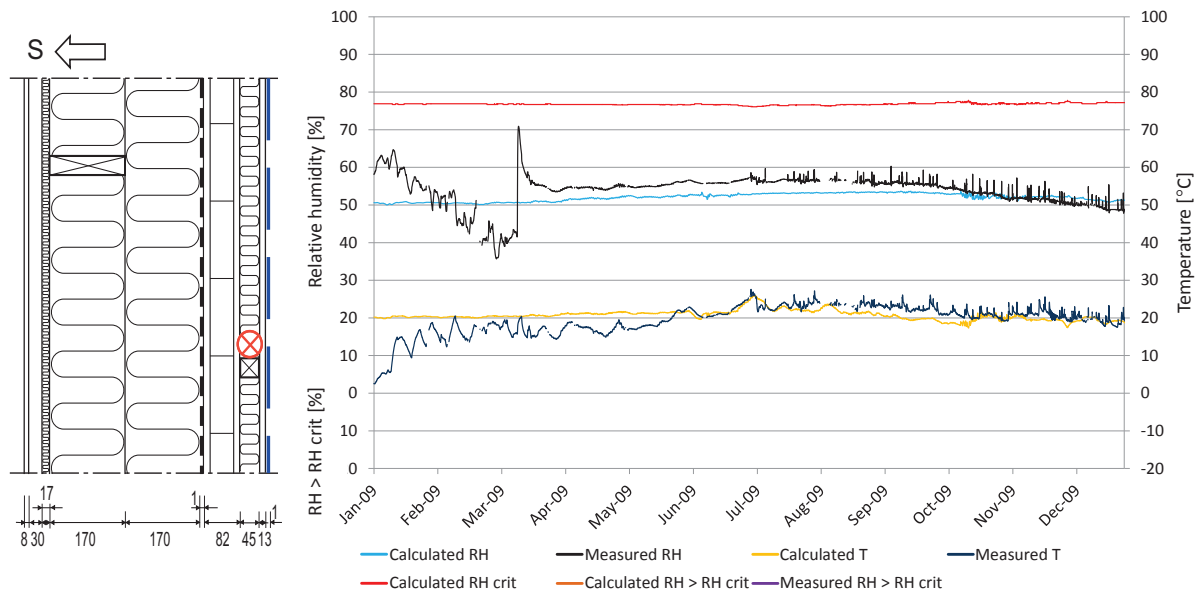
Figure 19. Example of comparisons between measured and blindly calculated RH and temperature in the installation layer between the vapour barrier and the interior waterproof membrane in the interior part of a bathroom wall where measured results indicate a leakage. Blindly calculated RH (turquoise) and measured RH (black). Blindly 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).

4.8 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 blindly calculated values were also carried out on the outside of the facade 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, as shown in Figure 20.

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 showed bigger differences than the other studied directions.
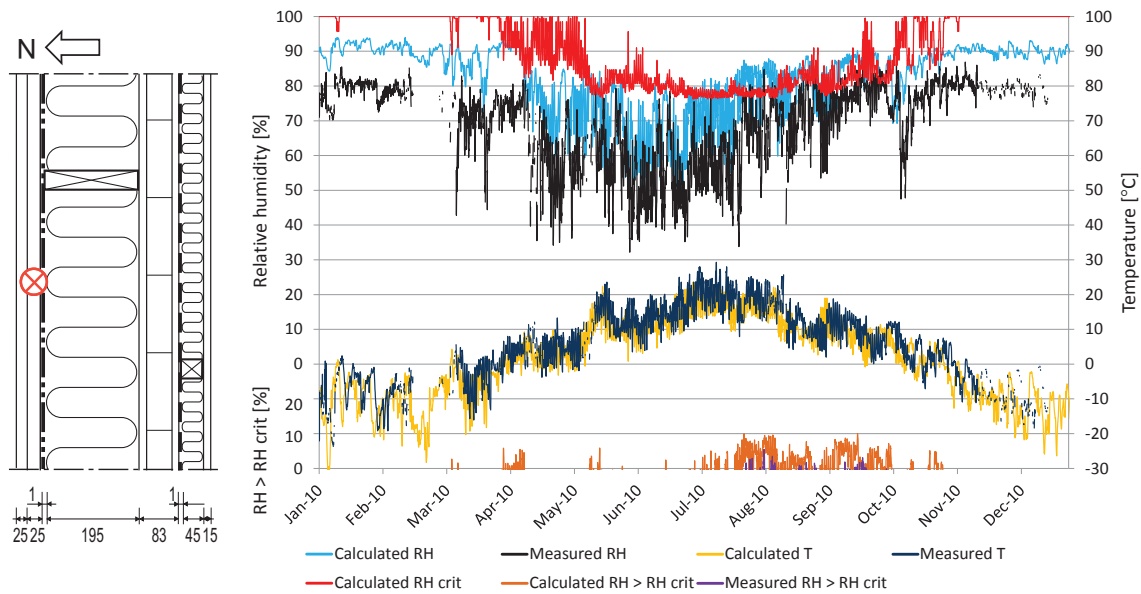
Figure 20. Example of comparisons between measured and blindly calculated RH and temperature in the air gap behind the cladding. Blindly calculated RH (turquoise) and measured RH (black). Blindly calculated temperature (yellow) and measured temperature (dark blue). RH$_{crit}$ derived from the calculated temperature (red). Calculated RH > RH$_{crit}$ (light brown) and measured RH > RH$_{crit}$ (purple).

4.9 Correlation between measured and blindly calculated moisture content

In studied positions with massive wood layers it was possible to compare measured and blindly calculated moisture content. The calculated moisture content was given in mass by volume [kg/m^3] and was then recalculated to mass by mass [%] using the density 455 kg/m^3 before it was compared to the measured results.

In general the measured and blindly calculated moisture content in studied positions in the walls followed each other, as shown in the example in Figure 21. However, there were positions without a perfect match and differences of up to five percent between measured and calculated values. Calculated values show a faster dry-out compared to measured values.

Figure 21. Example of comparisons between recalculated vapour content for measured (black) and blindly calculated (yellow) values, periods with lack of climated data (brown), and measured (green) and blind recalculated (red) moisture content in the massive wood layer.

Measured moisture content was also compared to blindly calculated values on the inside and outside of the facade in the studied house that was located in the northern part of Sweden. Comparisons between measured and calculated values on the facade did not match at all. In particular, the amplitude of the fluctuations in the measured values not reflected in the calculated values. However, there was a better correlation between measured and calculated values on the interior surface of the cladding. On the inside of the facade calculated values were following the measured, but with deviations up to eight percent, as shown in figure 22.
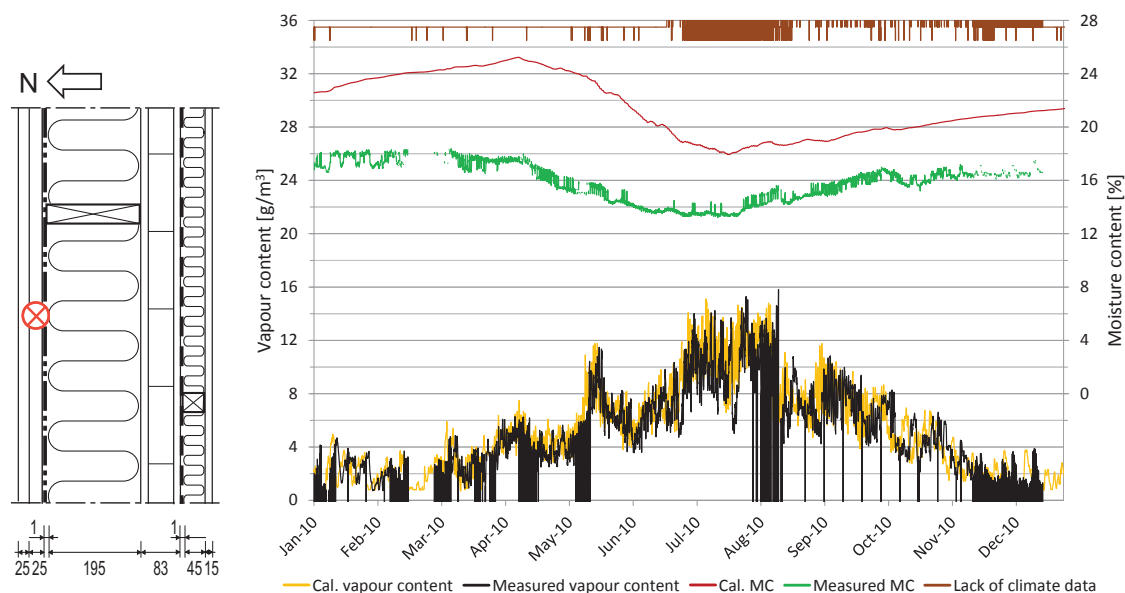
Figure 22. Example of comparisons between recalculated vapour content for measured (black) and blindly calculated (yellow) values, periods with lack of climate data (brown), and measured (green) and blind recalculated (red) moisture content on the inside of the wood panels.

4.10 Amplitude fluctuations in temperature and relative humidity

The amplitudes in different positions, as shown in the examples in Figures 8 to 20, 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 blindly calculated values, as shown in Figures 16 to 20. In the middle of the wall, the amplitudes are slightly larger, mainly in the measured values, as shown in Figure 9. Closer to the air gap, the amplitudes, mainly of the measured values, become significantly greater, as shown in Figures 8, 11, 12, 13 and 15. 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 20. The amplitudes of both the measured and calculated values in the studied positions in the outer part of the wall were also lower during the cold periods of the year, as shown in Figures 8, 11, 12, 13, 15 and 20. Comparisons, presented in the supporting technical background reports E and G, also show that there were larger amplitudes in the calculated and measured values in positions orientated towards the south.

4.11 Influence of variations in climate boundary conditions between different years

The outdoor surrounding climate affects the conditions in the exterior part of a wall, i.e. the most moisture critical position. Significant variations between different years were found by comparing the same positions over longer periods, as shown in the example in Figure 23. The results, as shown in Figure 23, show that there were significantly different behaviors in the same position during three different years (2009 to 2011).
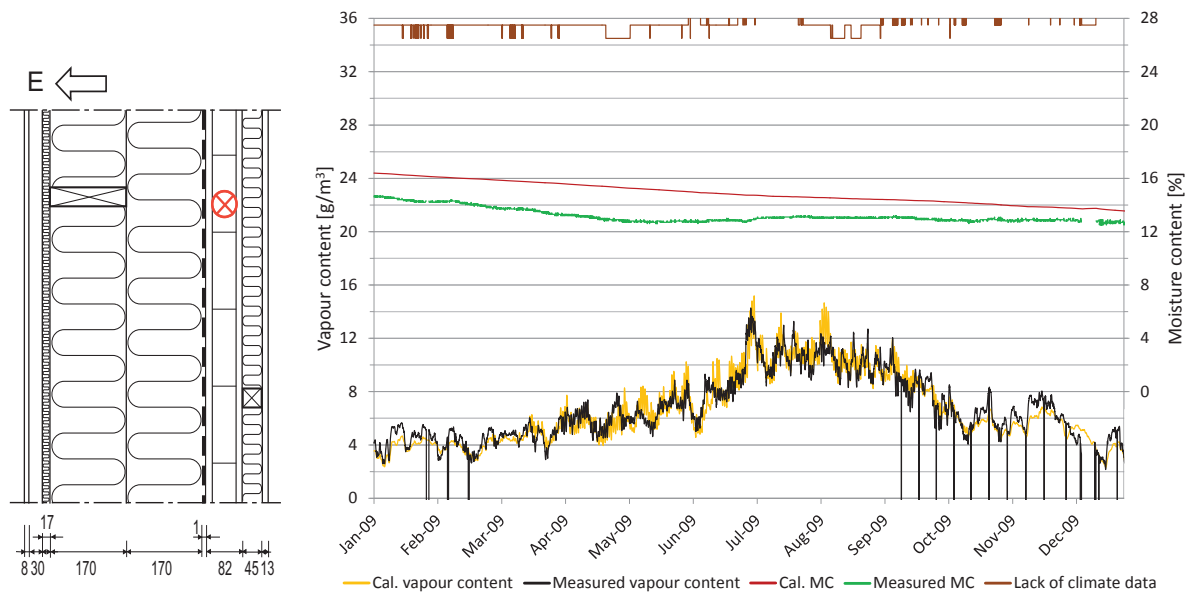

Figure 23. Example of comparisons between measured and blindly calculated RH and temperature behind a mould-resistant facade insulation board in the exterior part of a wall over a period of three years. Blindly calculated RH (turquoise) and measured RH (black). Blindly calculated temperature (yellow) 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).

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4.12 Influence of periods with lack of climate boundary conditions

During several periods replaced climate boundary data have been used in the blind calculations since real climate data from SMHI was lacking (SMHI 2012). The way of supplementing periods with lack of used climate boundary data was described in the sections 2.2.2, 2.2.3 and 2.2.4.

Shorter periods with replaced climate boundary data seems to have less influence on the result, as shown by comparing the results and periods with lack of climate data between Figure 16 and 17 and between Figure 20 and 22. However, longer periods with lack of real climate data and bad convergence between real climate and the replaced climate boundary data influence the correlation between measured and calculated values. These could be found comparing the differences between measured and calculated temperature, as shown in Figure 24, with the indoor climate boundary data used in the calculations, as shown in Figure 25, during January, November and December when the indoor climate boundary data have been replaced.
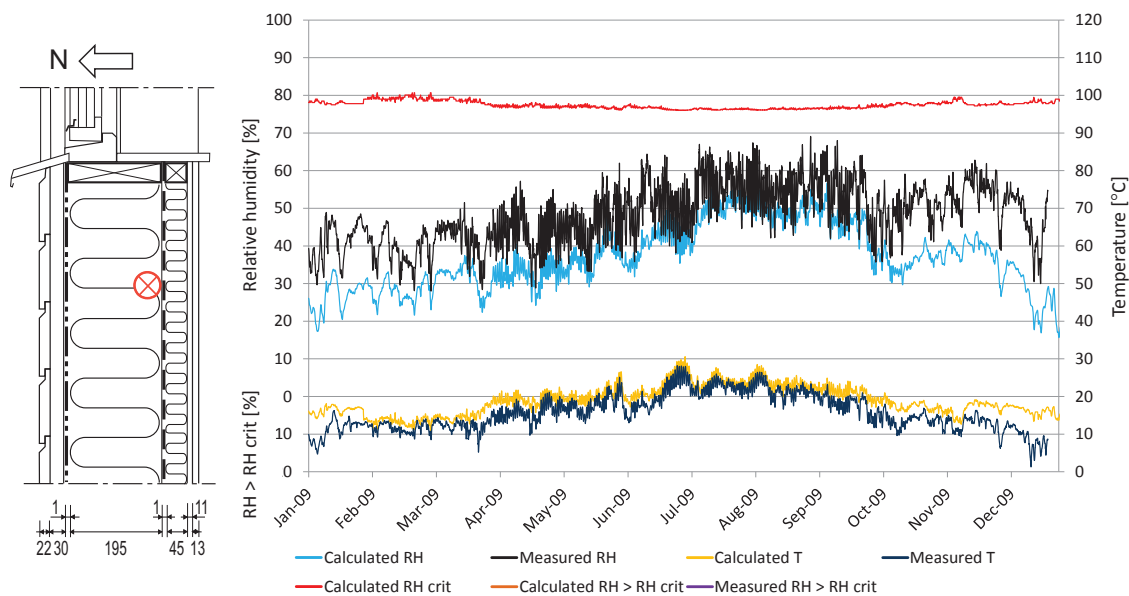
Figure 24. Example of comparisons between measured and blindly calculated RH and temperature outside vapour barrier in the interior part of the wall during periods with and without replaced climate boundary data. Blindly calculated RH (turquoise) and measured RH (black). Blindly calculated temperature (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).
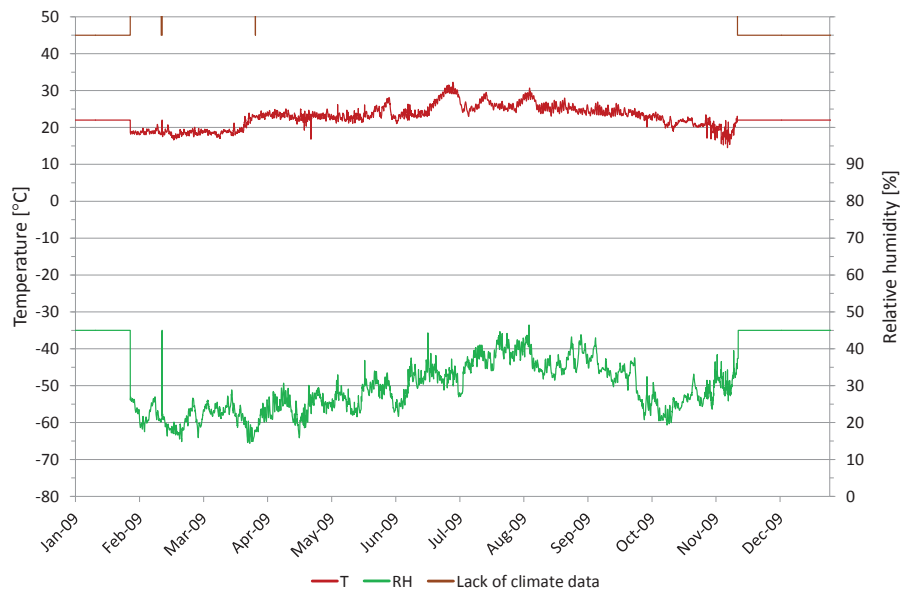
Figure 25. Example of used indoor climate boundary data including periods with and without lack of climate data where climate boundary data have been replaced during longer periods in January, November and December. Used indoor climate boundary data for RH (green) and temperature (dark red) in the blind calculations.

4.13 Influence of wind driven rain penetration in studied walls

For the blind calculations the wind driven rain penetration was assumed to be one percent of the amount of wind driven rain (ASHRAE 2009) and was located in the air gap behind the cladding. This means that the wind driven rain that is assumed to penetrate the facade will dry out fast since there it was also assumed that there was a well-ventilated air gap.

Some studied positions indicate leakages in the construction. Leakages were found behind the exterior mould-resistant facade insulation board in three studied positions. The climate parameters indicated that the leakages were caused by wind driven rain that penetrate both the facade, the air gap behind the cladding, and the exterior mould-resistant facade insulation board. Measurements and calculations in one of the positions that indicate leakages are shown in Figure 26 and 27 to be compared with the rainfall data shown in Figure 28. The high measured values that are pointed out in Figure 26 and 27 occur the same day, or day after, the rainfall pointed out in Figure 28. Notice that the amount of rain that might penetrate the facade is also affected by the wind speed and the wind direction, which is not shown in the figures below.
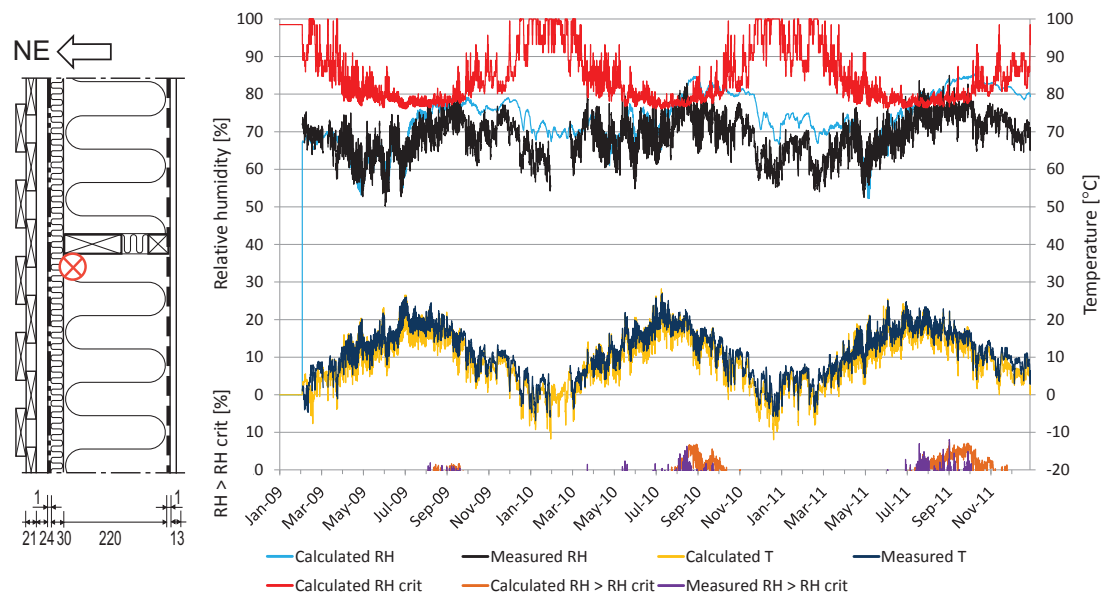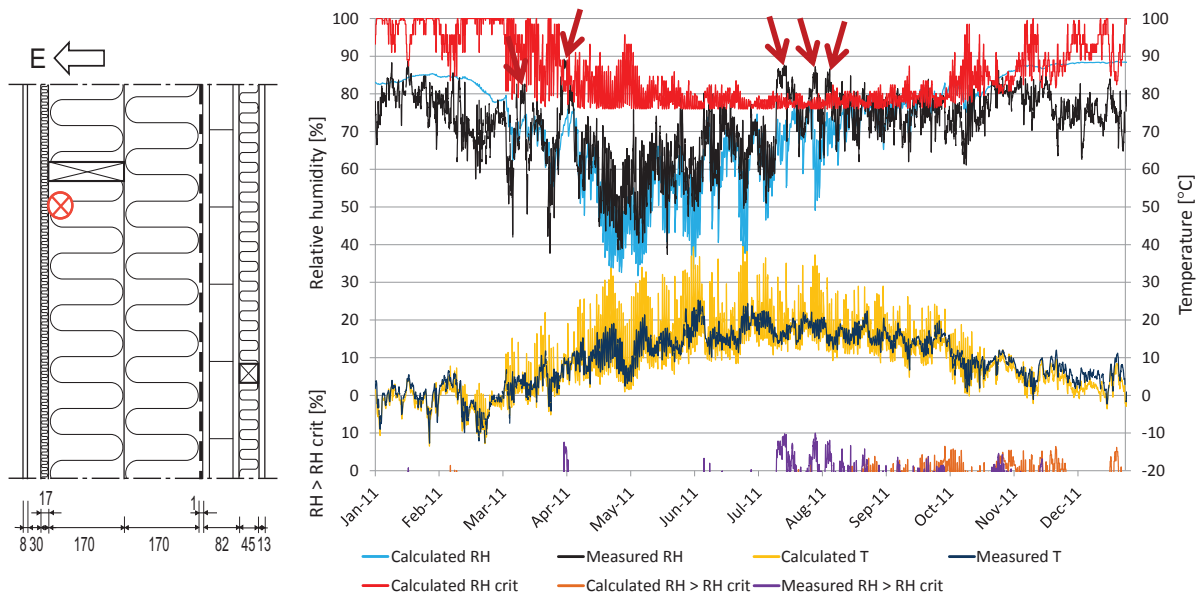
Figure 26. Example of comparisons between measured and blindly calculated RH and temperature behind the exterior mould-resistant facade insulation board where leakages from wind driven rain have increased the relative humidity (red arrows). Blindly calculated RH (turquoise) and measured RH (black). Blindly 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).
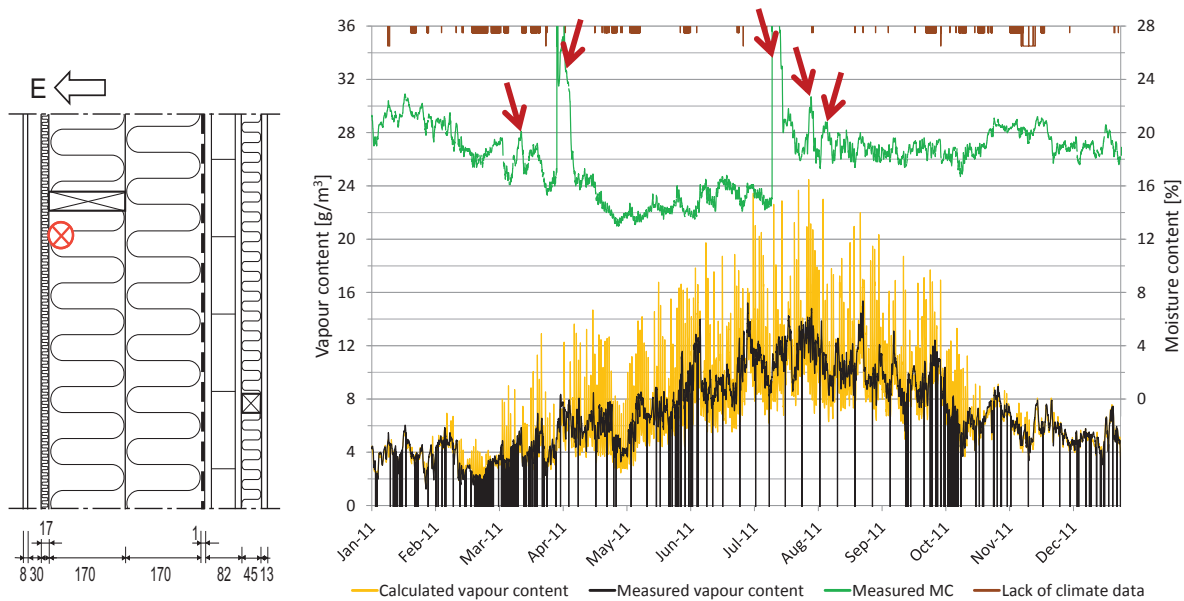
Figure 27. Example of comparisons and differences between recalculated vapour content for measured (black) and blindly calculated (yellow) values, periods with lack of climate data (brown), and measured (green) moisture content behind the exterior mould-resistant facade insulation board where leakages from wind driven rain have increased the moisture content (red arrows).

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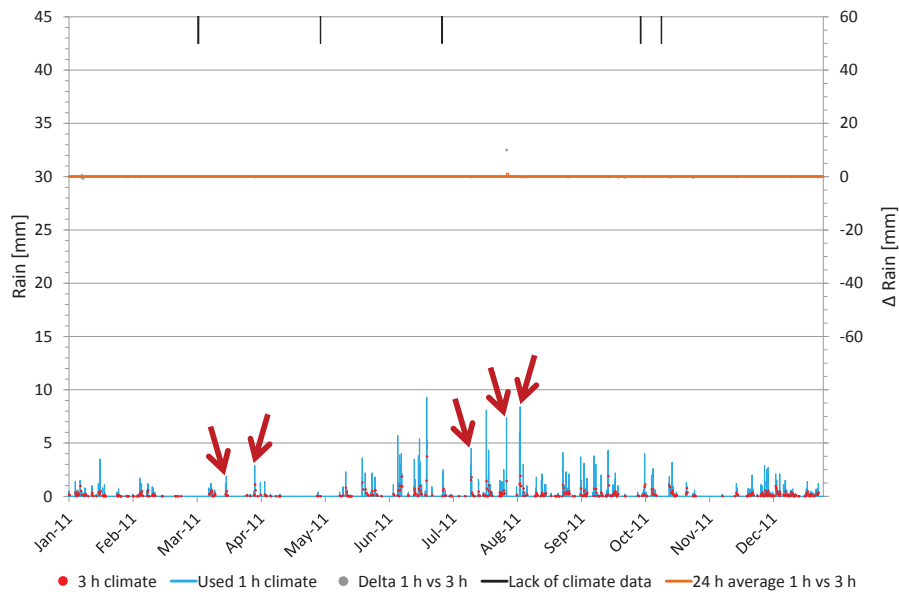
Figure 28. Exterior rainfall climate data during periods when leakages are noticed (red arrows) in the measured results behind the exterior mould-resistant facade insulation board.

4.14 The risk of mould growth based on the measurements

By using the Folos 2D visual mould chart for the studied positions it is also possible to evaluate the risk of mould growth in studied positions by both measurements and calculations. As mentioned above the most moisture-critical positions were located in the outer part of the wall.

In several positions in the studied houses there were climate conditions that allowed mould growth in the outer part of walls. The critical climate conditions, RH > RH_{crit}, mainly occur in three layers in the outer part of the wall, in the air gap behind the cladding, behind the wind barrier on the inside of the air, as shown in Figure 15 or on the inside of the exterior mould-resistant facade insulation between the studs and the air gap, as shown in Figure 8 and 9. The risk of mould growth is higher in the studied positions located in the air gap behind the cladding. However, according to the Swedish building code, mould growth could be accepted in the air gap behind the cladding (BBR 2011). The duration of the critical-conditions, RH > RH_{crit}, also influences the risk of mould growth (Viitanen et. al 2010), i.e. the incubation time for mould to germinate. The duration of the critical-conditions when mould growth is possible, RH > RH_{crit}, is shown in the Folos 2D visual mould chart, but the influence of duration is neglected.

It could also be established that there were different extents of critical-conditions, RH > RH_{crit}, between different years, as shown in Figure 23.

5 Results – Factors affecting the risk of mould growth

The investigation considering factors affecting the risk of mould growth was carried out as a parametric study with calculations made on differently designed wood frame walls in houses located in Northern European climate. The results are based on technical background report A and could partly also be found in paper III.

After the most moisture critical conditions were studied, the design and surrounding conditions of the reference case were varied. The effect of the changes in the most moisture-critical positions were then analyzed and compared to each other and to the reference case.

To limit the relative humidity, 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 vapour content, as described in paper V. Changes that increase the temperature or reduce the vapour content in order to achieve moisture-safe wooden designs were therefore implemented in the studied design changes.

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. Some of the changes could also be found in the studied wall designs shown in section 4 and the appended paper I – V.

5.1 Reference case

The reference wood frame wall is intended to be designed as a ordinary Swedish wall with mineral wool insulation (λ = 0.037 W/mK). This wall also imitates the basic design in the studied walls that was used in the previsuly blind validation and evaluation of the WUFI 5.0 in wood frame walls before they became modified with installation layers and exterior mould-resistant facade insulation boards.

The ordanary wall and its initial boundary conditions are henceforth referred as the "reference case". The materials used were retrieved from the WUFI 5.0 material data base (WUFI 2009a) and were specified in the Appendix I in section 9.1.

A horizontal cross-section and simplified one-dimensional calculation model are shown in Figure 29. Since WUFI 5.0 is a one-dimensional calculation tool, layers with mixed materials have been simplified. Wooden studs in the insulation layer and battens in the air gap behind the cladding were disregarded.

According to the technical background report A the most moisture-critical Swedish outdoor climate included in WUFI, from the city of Lund, was used during the entire study. Lund is located in the far south of Sweden and had a 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 20°C and a relative humidity that varies dependent on exterior vapour content using moisture load level 2, i.e. 4 g/m^3 is added to the exterior vapour content for temperatures below 0°C (SS-EN 13788:2001). The wall in the reference case was oriented towards the north and the influence of wind driven rain was taken into account by adding 1 % of the wind driven 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. The initial conditions were specified in Appendix I in the section 9.2.
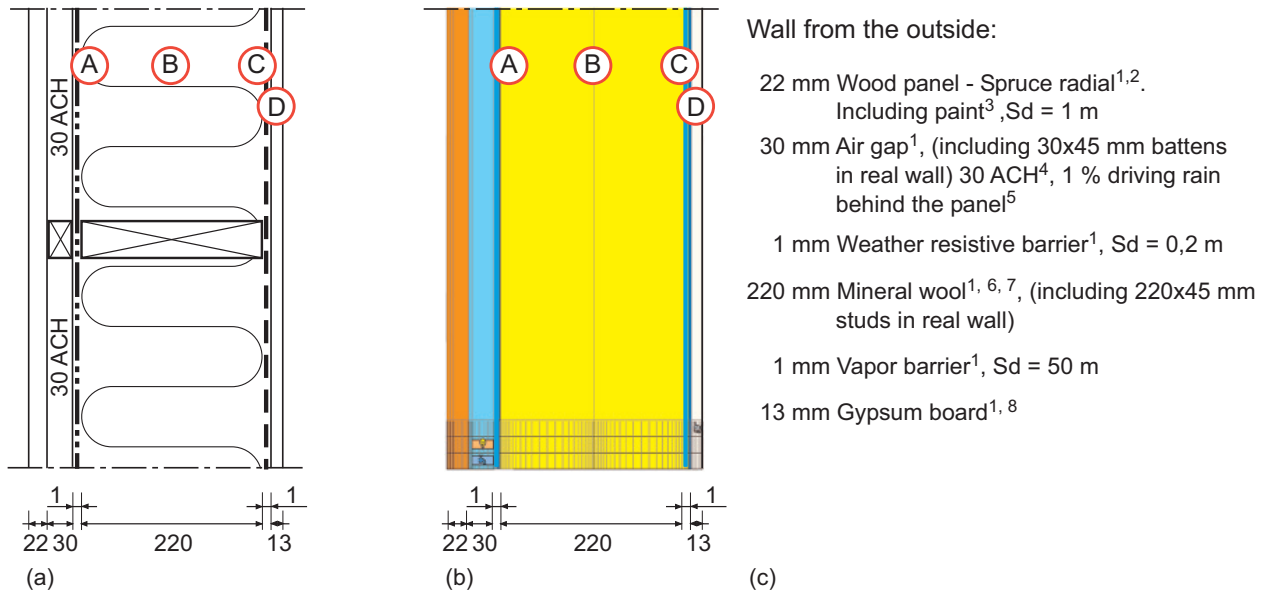
Figure 29. Reference case. (a) Cross sectional drawing of a ordinary Swedish wood frame wall. (b) Simplified one-dimensional WUFI 5.0 calculation model. (c) Material specification (1. WUFI 2009a; 2. Vik 1996; 3. Nevander and Elmarsson 1994; 4. Papaer IV; 5. ASHRAE 2009; 6. IEA Annex 24 1996; 7. Paroc 2002; 8. Krus 1996).

5.2 The most moisture-critical position

Initially, the most moisture-critical position in the wall was established in the reference case. To find the most moisture-critical area in the wall, climate conditions in four different positions, A-D in Figure 29, were calculated and plotted in an isopleth chart with a moisture-critical limit, RH_{crit}, as shown in Figure 30. The RH_{crit} line is defined as the limit above which mould 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).
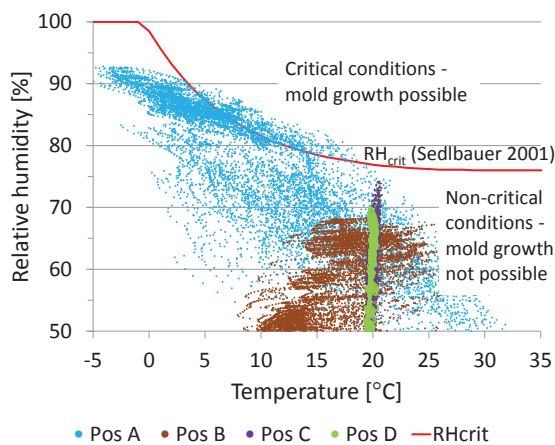
Figure 30. Calculated climate conditions in position A (turquoise), B (brown), C (purple) and D (green) compared to RH_{crit} (red) (Sedlbauer 2001).

The isopleth chart, in Figure 30, shows that the most moisture-critical conditions occur in position A, in the outer part of the wall. Further on, this parametric study focuses on position A and the exterior part of the wall.

The most moisture-critical conditions, RH > RH_{crit}, occur in the outer part of the wall, close to the air gap. Using the Folos 2D visual mould chart it was found that RH > RH_{crit} particularly occurs during longer periods in September, October and November, as shown in Figure 31.
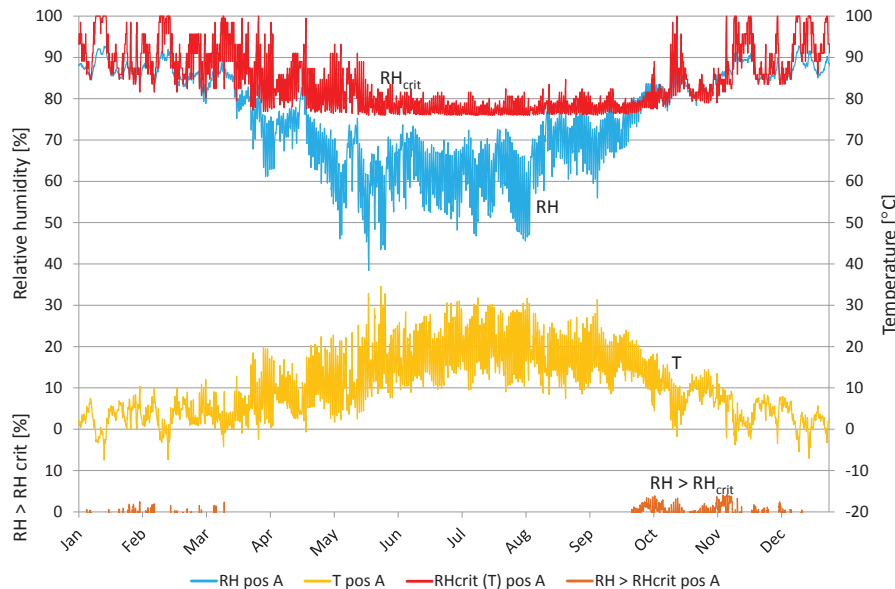
Figure 31. RH compared to RH_{crit} in position A. RH (turquoise), RH_{crit} (red), temperature (yellow), RH > RH_{crit} (light brown).

The critical conditions also depend on the moisture sensitivity of the material in this position. It should also be mentioned that the wooden studs shown in Figure 29 create thermal bridges that increase the temperature and reduce the relative humidity in the exterior parts of the stud, as discussed in section 2.6.4. The results in Figure 30 and 31 should therefore be seen as a worst case situation. Since the negative effect from thermal bridges on energy use is evident, the thermal bridges normally become "eliminated" by using lightweight studs or layers with separated studs, which make the one-dimensional worst case calculations appropriate.

5.3 Protection against mould growth by exterior mould-resistant insulation boards

By attaching exterior insulation boards to the outside of the wooden studs, as shown in paper III and IV the surrounding temperature on the exterior side of the studs will increase. The relative humidity and the risk of mould growth on the studs will then decrease as described in paper III and V. Figure 8 and 9 in section 4 also show examples of blind validation and evaluation of the WUFI 5.0 in wood frame walls, with the same exterior mould-resistance facade insulation boards, as included in paper III and IV. To achieve a higher temperature, and a lower relative humidity on the stud, the exterior insulation boards must be located on the outside of the wood studs, between the studs and the weather resistive barrier. The exterior insulation boards must be made of moisture-resistant materials so they are not damaged by the high relative humidity that occurs in position A on the inside of the weather resistive barrier.

The influence of increased total insulation thickness on the conditions in position A was studied. The required minimum thickness of the exterior insulation board on the outside of the wooden studs, in order to avoid mould 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 where mould growth might occur on the outside of a possible wood stud. The limit in position Q was chosen so that no relative humidity should be above RH_{crit}. The thermal conductivity and other material parameters was the same in both the exterior insulation board and the layer with mixed insulation and studs.

5.3.1 Relative humidity in position A and Q in a wall 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 was studied. The design was similar to the studied design in paper IV and the wall where measurements and blind calculations were carried out as shown in the example in Figure 8 in section 4. Calculation results from both position A and position Q are shown together in Figure 32.

By iteration it was determined that the thickness of the exterior insulation board in this specific case needs to be 33 mm order to avoid critical conditions in position Q if the wall has a total insulation thickness of 220 mm. 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.
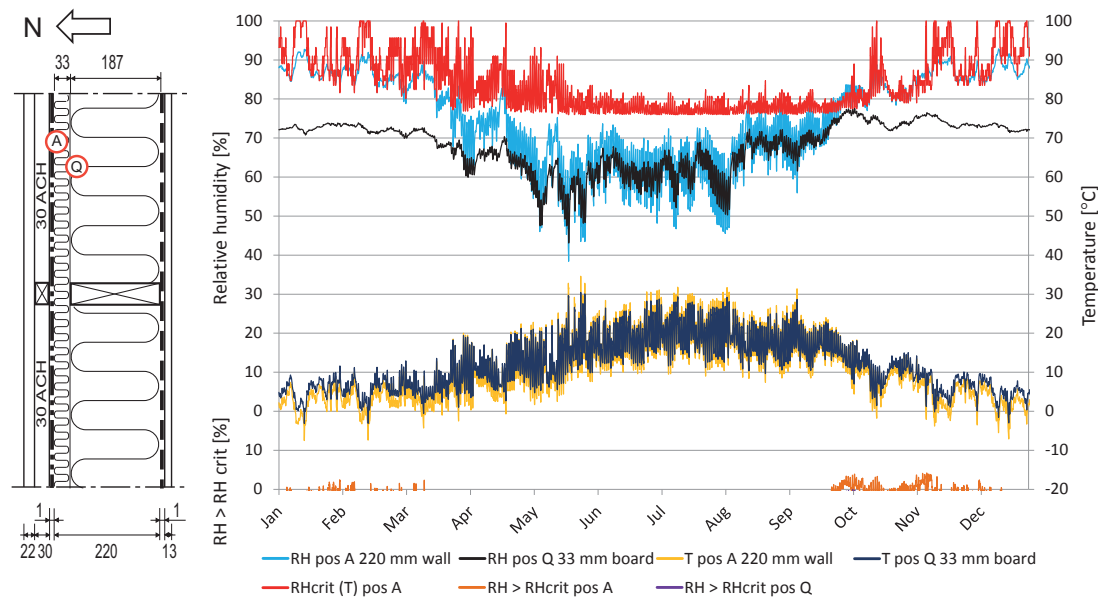
Figure 32. RH in position A (turquoise) and position Q (black) compared to RH_{crit} for a wall with a total insulation thickness of 220 mm. Temperatures in position A (yellow) and temperatures in position Q (dark blue). RH_{crit} is dependent on T in position A (red), RH > RH_{crit} in position A (light brown), RH > RH_{crit} in position Q (purple) is constant below the critical limit and not shown in the figure.

5.3.2 Relative humidity in position A and Q in a wall 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 design is similar to studied designs in paper III and the wall where

measurements and blind calculations were carried out as shown in the example in Figure 9 in section 4. The conditions in position A and required minimum thickness of the exterior insulation board for a wall with a total of 420 mm insulation were studied. Calculation results from both position A and position Q are shown together in Figure 33.

By iteration it was determined that the thickness of the exterior insulation board needs to be at least 52 mm order to avoid critical conditions in position Q, behind the insulation board, if the wall has a total insulation thickness of 420 mm. By comparing position A, behind the weather resistive barrier, in the examples in Figures 32 and 33 it can be concluded that the occurrence of critical conditions increased in the wall with thicker insulation.
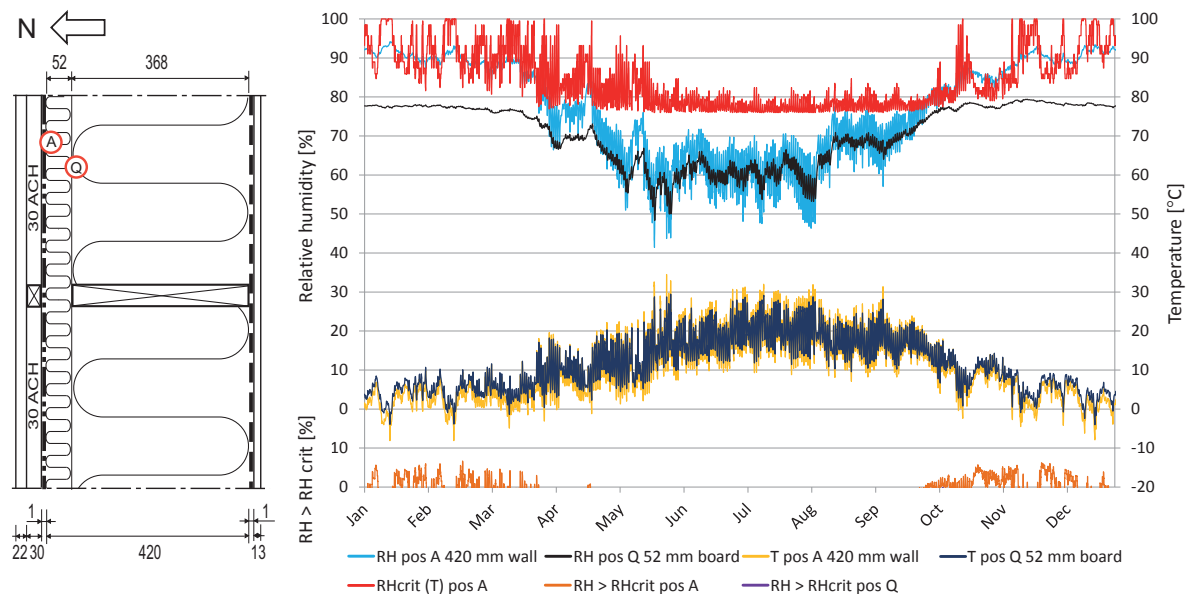
Figure 33. RH in position A (turquoise) and position Q (black) compared to RH$_{crit}$ for a wall with a total insulation thickness of 420 mm. Temperatures in position A (yellow) and temperatures in position Q (dark blue). RH$_{crit}$ is dependent on T in position A (red), RH > RH$_{crit}$ in position A (light brown), RH > RH$_{crit}$ in position Q (purple) is constant below the critical limit and not shown in the figure.

5.3.3 Required thickness of exterior insulation board with different total insulation thickness

Summarized results from several calculations, as discussed in the supporting technical background report A, 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 2.

Table 2. Required minimum thicknesses of exterior insulation board to reach non-critical conditions in position Q and the highest RH above RH$_{crit}$ in position A depending on the total insulation thickness of the wall. The results are valid for the specific studied cases with the specified climate conditions.

Total insulation thickness	Thickness of exterior insulation board RH < RH$_{crit}$ Position Q	Highest RH > RH$_{crit}$ in position A inside the weather resistive barrier
mm	mm	%
220	33	4.21
270	39	4.61
320	45	5.51
370	49	6.51
420	52	6.71
470	55	7.04
520	59	7.52

5.4 Different ventilated air gap behind the cladding

Paper I as well as several other studies discusses the importance of a well-ventilated air gap behind the cladding in wood frame walls. A high air flow in the air gap will vent out moisture that has penetrated the cladding and will contribute to increased drying out of a wood frame wall (Falk and Sandin 2013; Salonvaara et. al. 2007; Straube, van Straaten and Burnett 2004; Piñon et. al. 2004). The influence on critical conditions in position A was studied when there was a lower air flow 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 Figure 34. The assumption of 1 ACH was based on Falk (2010); Wadsö (1996); Sandin (1991); and Sandin (1993). Critical conditions in position A with an air flow of 30 ACH (turquoise) were equal to the reference case.
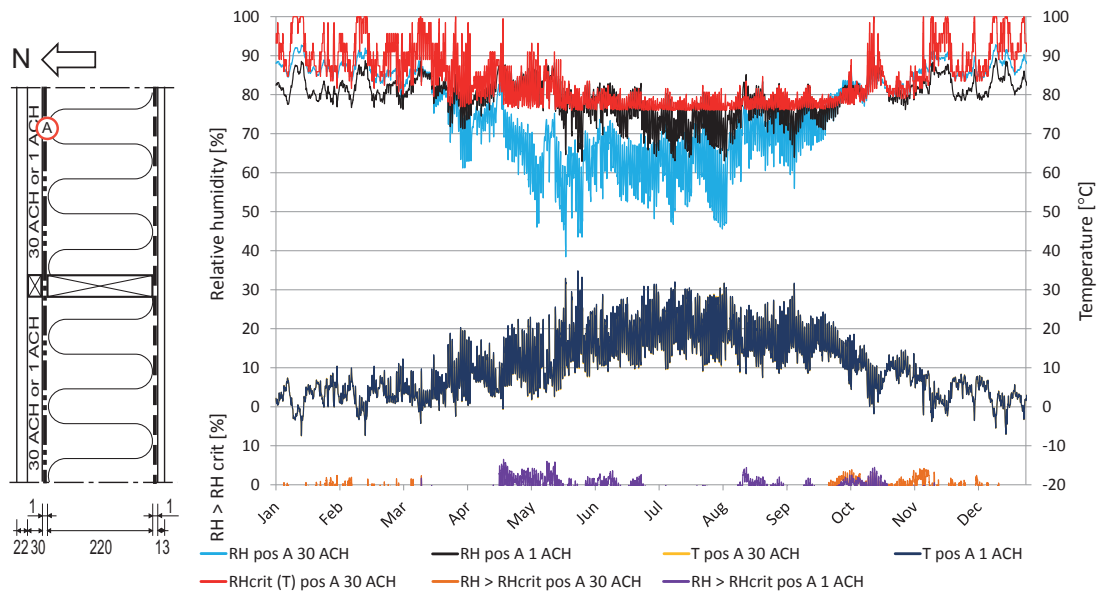
Figure 34. RH in position A compared to RH$_{crit}$ in a wall with 220 mm insulation, oriented towards the north with an air change rate of 30 ACH (turquoise) and 1 ACH (black) in the air gap. The temperature at 30 ACH (yellow) is hidden behind the temperature at 1 ACH (dark blue). RH$_{crit}$ (red) depends on T for 30 ACH, RH > RH$_{crit}$ 30 ACH (light brown), RH > RH$_{crit}$ 1 ACH (purple).

5.4.1 Effects of different ventilation of the 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 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. Position A (turquoise) in Figure 35 (a) are equal to the reference case.
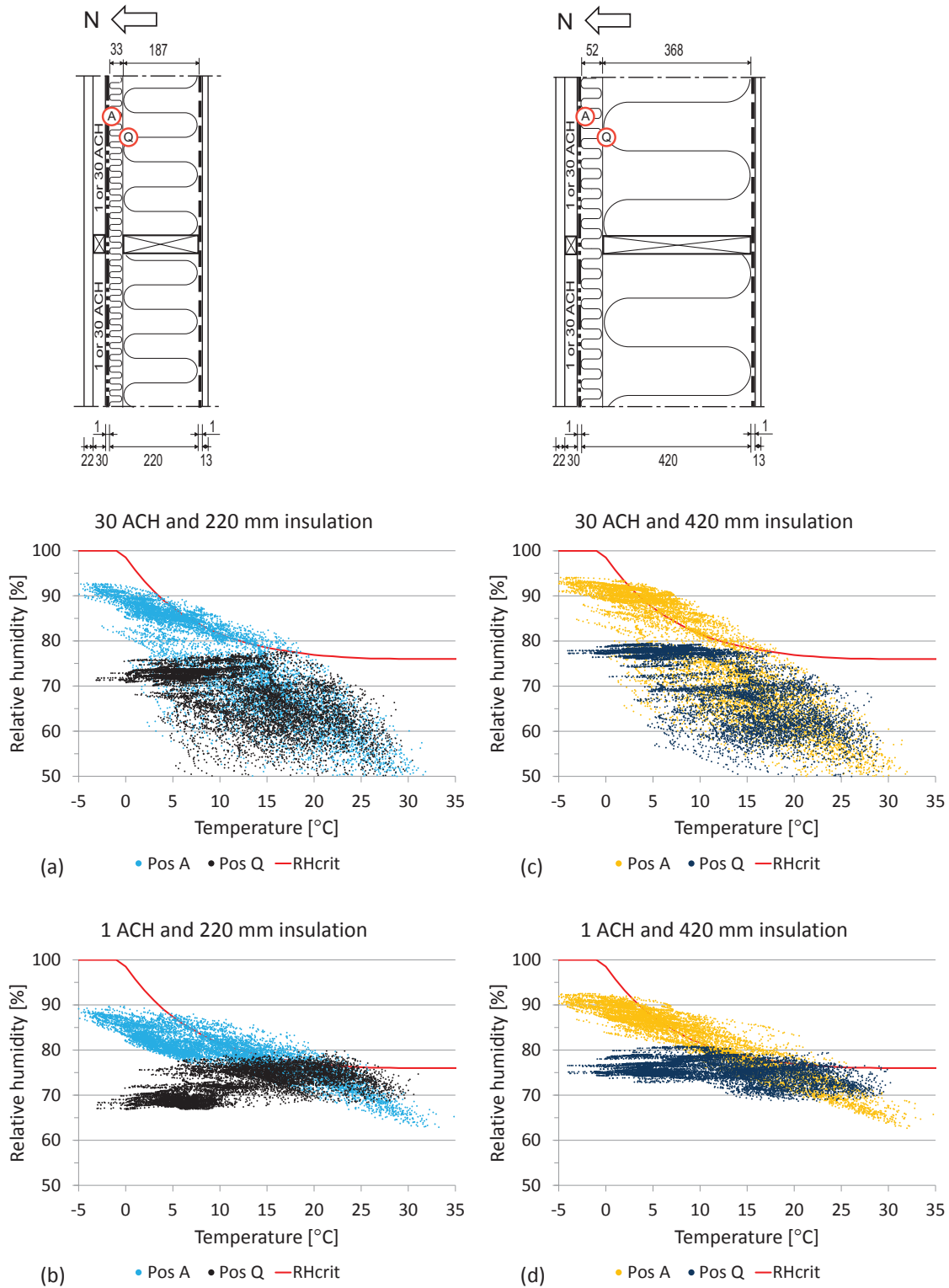
Figure 35. RH in positions A and Q compared to RH$_{crit}$ (red) for two different insulation thicknesses and two different air change rates in the air gap behind the cladding. (a) RH 220 mm insulation and 30 ACH, position A (turquoise) and position Q (black). (b) RH 220 mm insulation and 1 ACH, position 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).

5.4.2   The influence of wind driven rain and different ventilation rate in the air gap

Wind driven rain is caused by rain and wind acting at the same time. A wind driven rain load varies depending on the exterior climate conditions and the facade orientation. The climate data used showed a significantly higher wind driven rain load on the south-facing facade (450 mm/a) compared to the north-facing facade (100 mm/a). The influence of a higher amount of wind driven rain on a facade oriented towards the south and different air flows of 1 or 30 ACH in the air gap were studied in position A, as shown in Figure 36. The results, as shown in Figure 36, can be compared to those for the same wall with a lower amount of wind driven rain oriented towards the north, as shown in Figure 34.
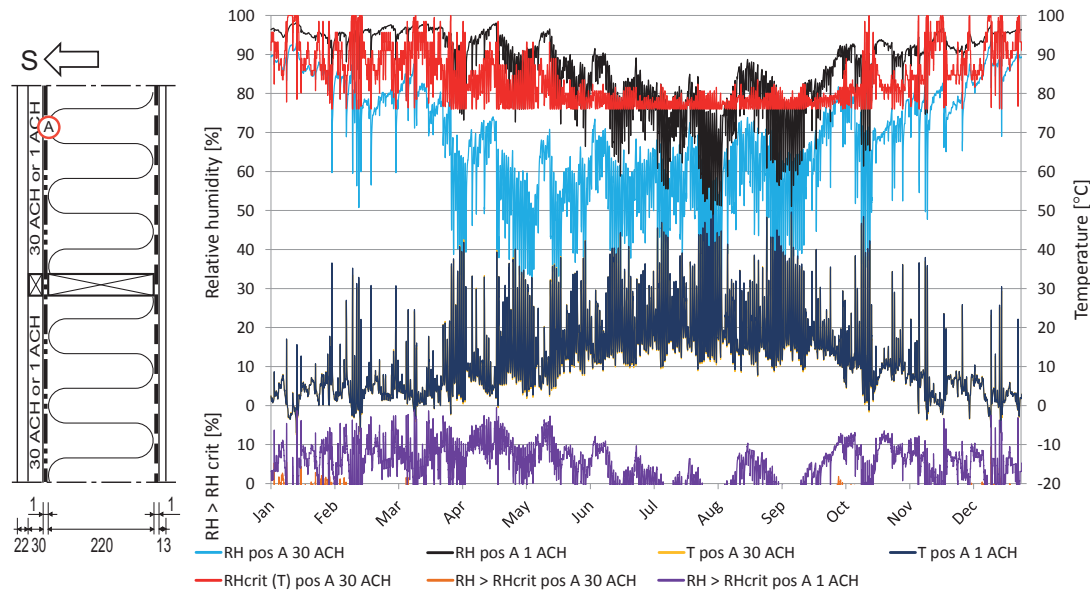
Figure 36. RH in position A in a wall with 220 mm insulation, oriented towards the south with an air change rate of 30 ACH (turquoise) and 1 ACH (black) in the air gap compared to RH$_{crit}$. The temperature at 30 ACH (yellow) is hidden behind the temperature at 1 ACH (dark blue). RH$_{crit}$ (red) depends on T for 30 ACH, RH > RH$_{crit}$ 30 ACH (light brown), RH > RH$_{crit}$ 1 ACH (purple).

5.4.3   Different facade materials and different ventilation rate in the air gap

The ability to store moisture in different cladding materials also affects the risk of mould 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 37, were therefore studied. The results in figure 37 can also be compared to the same type of frame with a wood facade as shown in Figure 34.
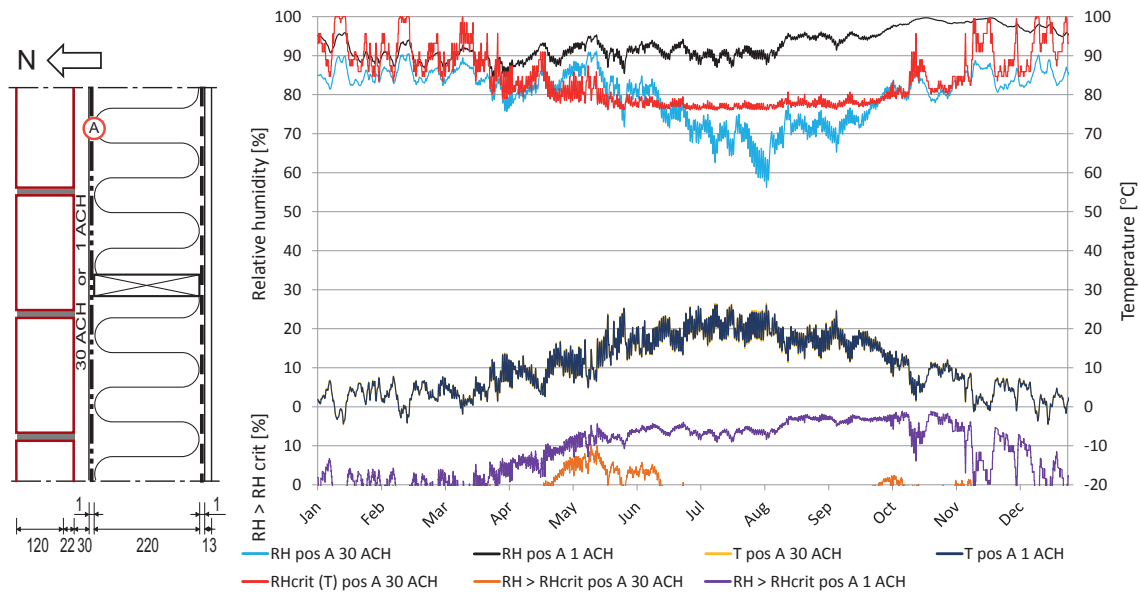
Figure 37. RH in position A in a wall with 220 mm insulation, a north oriented brick facade and air change rate of 30 ACH (turquoise) and 1 ACH (black) in the air gap compared to RH_crit. The temperature at 30 ACH (yellow) is hidden behind the temperature at 1 ACH (dark blue). RH_crit (red) depends on T for 30 ACH, RH > RH_crit 30 ACH (light brown), RH > RH_crit 1 ACH (purple).

5.5 Possibilities for drying out of water caused by leakages and initial moisture from the construction phase

Leakages into walls from rain or wind driven rain, as shown in example in Figure 26 and 27 might be more common than expected. In technical background reports C, E and F three additional similar cases with leakages are shown. It must 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 38, were compared in isopleth charts.

Two of the designs as shown in Figure 38 had insulation thicknesses of 220 and 420 mm insulation respectively. Two designs had an exterior mould-resistant insulation board of vapour-permeable mineral wool (λ = 0.037 W/mK). The other two designs had exterior mould-resistant insulation of rather vapour-tight expanded polystyrene, EPS, insulation board with the same thermal conductivity as in the first two designs (λ = 0.037 W/mK) and a density of 30 kg/m^3 (WUFI 2009a; Achtziger and Cammerer 1984).
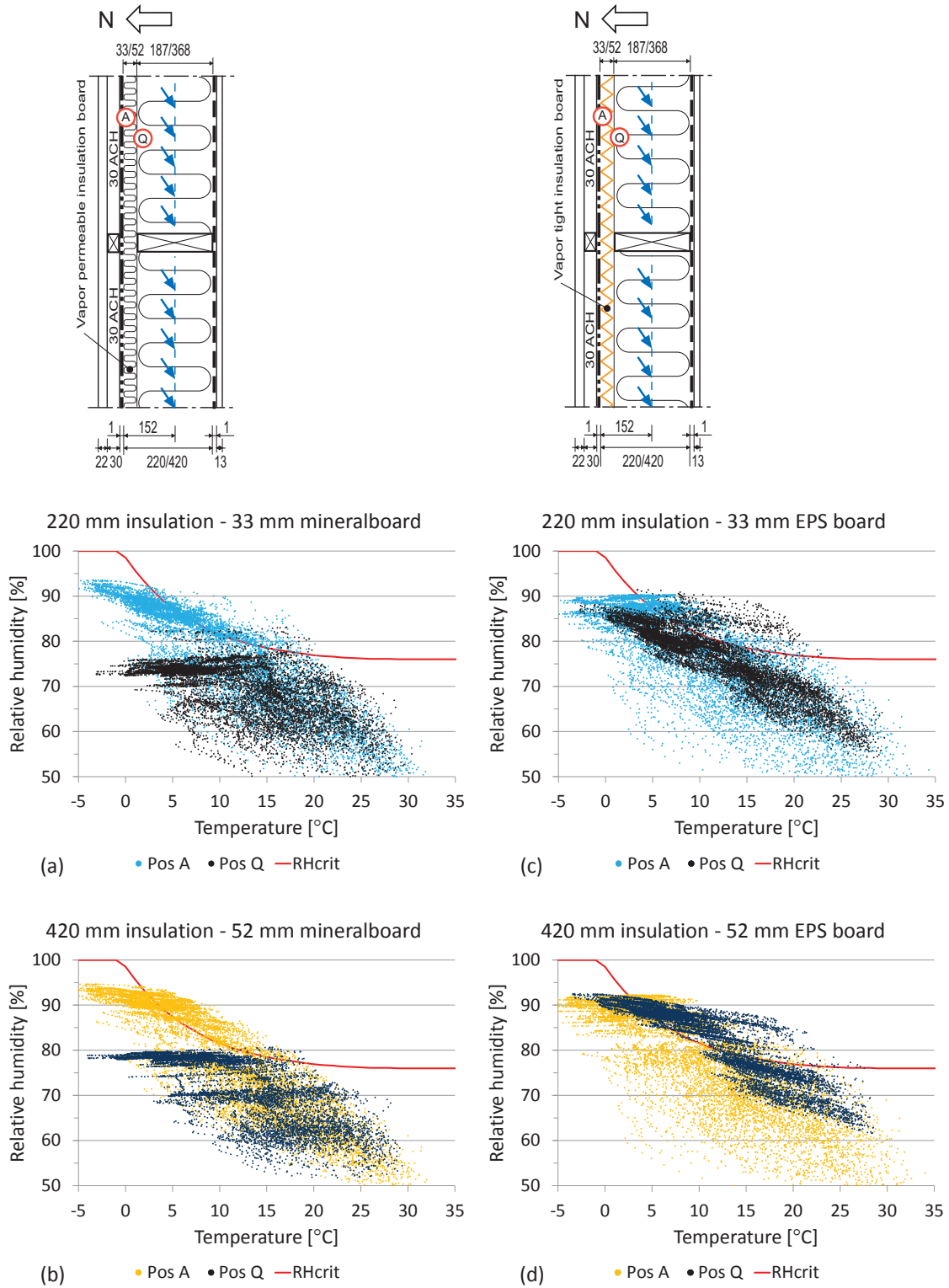
Figure 38. RH in positions A and Q compared to RH$_{crit}$ (red) for walls subject to a leakage with two different materials used for the exterior insulation board and two different insulation thicknesses, as shown in the cross sectional top view drawings. (a) RH 220 mm – 33 mm mineral insulation board, 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).

5.6 Cellulose fiber thermal insulation

The risk of mould growth in position A and Q using cellulose fiber insulation (WUFI 2009a) instead of mineral wool was studied. Since cellulose fiber is an organic material the exterior mould-resistant facade insulation board on the outside of the studs still consists of more mould-resistant mineral wool. An example with a total insulation of 220 mm where the interior 187 mm consist of cellulose fiber insulation, as shown in Figure 39, was studied. The results from a similar design with mineral wool are shown in Figure 32. The exterior mould-resistant facade insulation board of mineral wool and the cellulose fiber have the same thermal conductivity (λ = 0.037 W/mK). Cellulose fiber insulation has a higher heat and moisture capacity compare to mineral wool.
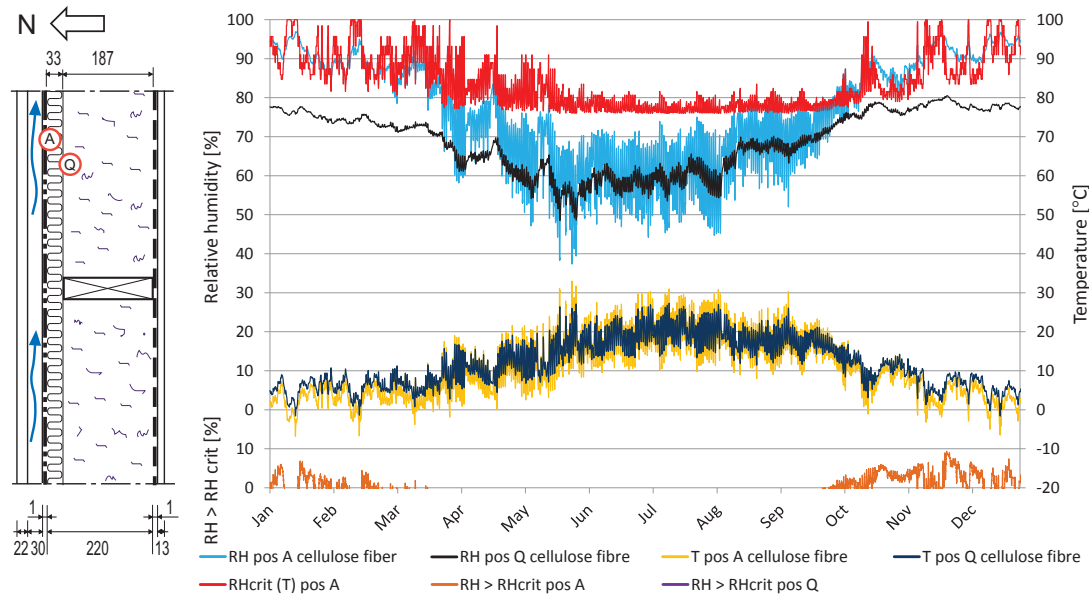
Figure 39. RH in position A (turquoise) and position Q (black) compared to RH$_{crit}$ for a wall with a total insulation thickness of 220 mm where 187 mm was cellulose fiber. Temperatures in position A (yellow) and temperatures in position Q (dark blue). RH$_{crit}$ is dependent on T in position A (red), 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.

5.7 Mean value climate compared to real climate

Calculations in the parametric study were carried out using WUFI standard climate for the Swedish city Lund. The Swedish climate files in WUFI were based on SMHI measured climate data during the years 1995 to 2005. The 10 years data was combined and adjusted to one mean climate year in a way which reduced extreme values. This is described in the technical background report A.

Differences in the results caused by WUFI standard climate compared to real climate data were studied. Figure 40 shows the extent of critical conditions in position A in the reference case using WUFI standard climate data (a) and using real climate data from the year 1994 (b). Periods with impaired climate data during 1994 were replaced with accurate climate data as described in section 2.2.2 and 2.2.3.
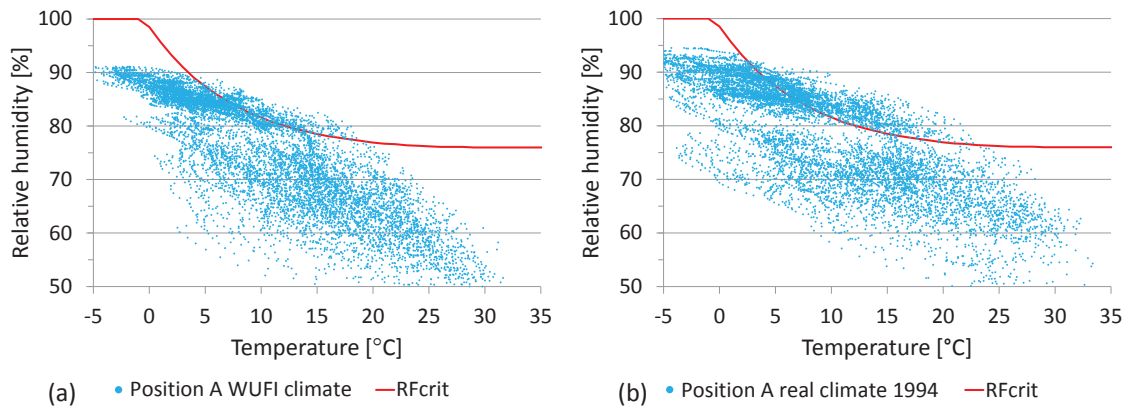
Figure 40. RH in positions A compared to RH$_{crit}$ (red) in the basic case using WUFI standard climate (a) and real climate data from 1994 (b).

6   Analysis and discussion

The purpose if this section is to discuss the overall results and present general results based on the findings in paper I – VI as well as in the presented results in section 3, 4 and 5.

Overall the entire results and its general analysis and discussion was based on approximately 300 simulations in WUFI 5.0 and measurements in real houses over a period of three years in 85 measuring positions.

The use of the Folos 2D visual mould chart to present results provides a direct analysis of the studied positions since it enables comparisons to be made between different designs and between measured and calculated values. At the same time it allows evaluation of the extent of critical conditions for mould growth and possible actions to reduce these.

6.1   Influence of temperature and vapour content on relative humidity

As described in paper V the level of relative humidity can mainly be affected by changing the vapour content or the temperature, which affects the vapour content at saturation. A lower level of vapour content or a higher temperature gives a lower relative humidity.

As expected, both parametric studies in section 5 and paper I, II and V show that the vapour content influences on the relative humidity was of importance for the risk of mould growth in the most moisture-critical position. Paper II shows that it is important to consider the vapour content to reach a proper correlation between measured and calculated relative humidity.

Regardless of whether the vapour content is correctly assessed, paper III and the example in Figure 11, 13 and 14, supported by the technical background reports C – G, show the influence of temperature on the relative humidity in the comparisons between measured and blindly calculated relative humidity. Based on the information in the paper V as well as several of the basic literature references (Nevander and Elmarsson 1994) it could be established that temperature has a high impact on the results since differences of 1 °C affect the relative humidity of approximately 5 percent under normally climate conditions. As noted in the examples given in Figure 11 – 14 minor differences in measured and blindly calculated temperature values thus led to larger differences when comparing measured and calculated relative humidity. As expected the parametric study and paper III also show that the temperature affects the risk of mould growth in the most moisture-critical position in the exterior part of the wall.

6.2   Most moisture-critical positions

The overall results in this thesis, both in the appended paper I – V, the examples in section 4 and the parametric study in section 5 confirm, in one way or another, that the most moisture critical position during normal situations was located in the outer part of studied wood frame walls. In case of a well-ventilated air gap and no influence of wind driven rain the critical conditions were caused by low temperatures in the exterior part of the wall which resulted in high relative humidity. Even if lower temperatures give a higher RH_{crit} limit, the negative influence of higher relative humidity in the air is greater.

By comparing measured and blindly calculated RH to the RH_{crit} limit in the appended paper III it can be established that the most moisture critical position on the interior side of the air gap is located in the outer part of the wood frame behind a 17 mm thick mould-resistant facade insulation board.

Papers I, II, and IV show that there is a higher relative humidity in the exterior part of the wood frame, behind the weather resistive barrier or the exterior mould-resistant facade insulation board, compared to other studied positions closer to the inside of the wall. However, measured and blindly calculated relative humidity in those papers was not compared to an RH_{crit} limit. Paper V shows that there was a high risk of mould growth according to both an RH_{crit} limit and a mould index definied by Viitanden et. al (2010) in calculations carried out in the outer part, inside the weather resistive barrier, of a wood frame wall with a brick facade.

Paper II and the example in Figure 20 as well as the technical background reports C – G supporting the thesis show results from both measurements and calculations in the air gap. Those results indicate that there were higher values of measured and calculated relative humidity in the air gap behind the cladding compared to the studied position on the inside of the weather resistive barrier or the exterior mould-resistant facade insulation board. Studied positions closer to the inside of the walls also show lower measured and calculated relative humidity. However, the Swedish building code allows moisture, mould growth and moisture-critical conditions in the air gap and on the cladding (BBR 2011). Positions in the air gap were therefore not treated as critical.

Literature in the area indicates that a critical area that has to be investigated in a moisture risk perspective is the exterior part of wood frame walls (Nevander and Elmarsson 1991). Finally the parametric study in section 5 confirms that the most moisture-critical conditions occur in the exterior part of the wood frame, behind the weather resistive barrier or the exterior mould-resistant facade insulation board, since possible risks of damages in the air gap was excluded from the study in accordance with the Swedish building code (BBR 2011).

Due to the higher risk of damages in the outer part of the wood frame walls, factors affecting the risk of mould-growth there is the focus in this study.

6.3   Most moisture-critical periods

As expected, and shown in paper I – IV, examples in section 4 supported by the technical background reports C – G and the parametric study in section 5, the most moisture-critical periods mainly occur during longer periods in the autumn in the most moisture-critical positions in the exterior part of the wall during normal climate conditions. However, there are factors that influence when the most moisture-critical periods occur. The parametric study in section 5 and the example in Figure 26 and 27 as well as the technical background report C, E and F indicate that wind driven rain penetrating the facade might cause critical conditions during other periods. The technical background reports C – G supporting the thesis also show that the variations in the exterior climate affect when the moisture-critical periods occur and that those vary during different years as well as the length and extent of the critical conditions.

6.4   Correlation between measured and blindly calculated values

This section only considers the correlation between measured and blindly calculated values and the most important possible factors and parameters that caused differences in the comparisons.

In general there was a good correlation between the measured and calculated temperature and relative humidity, as shown in the examples in Figures 8, 9 and 15. In some cases measured and calculated values followed each other but with significant differences, as shown in Figure 20.

However, there are also differences between measured and calculated values in many positions. Possible parameters and factors influencing differences are discussed in the following sub-sections below. Factors affecting the correlation between measured and calculated values are also discussed in a general context together with results from the appended papers and the results from the parametric study in section 6.5 – 6.13.

6.4.1 Differences between measured and blindly calculated temperature and relative humidity in studied wood frame walls

The most common parameter that caused differences between measured and blind values was differences in measured and calculated temperature. The differences in temperature affect the correlation between measured and calculated relative humidity, as shown in Figure 11 and 13. The temperature influence on relative humidity was discussed in section 6.1 above.

The differences between measured and blindly calculated relative humidity caused by differences in temperature mainly occur in the exterior part of the wall. Since this is the location of the most moisture critical positions it also becomes an important factor to consider. Especially since a low difference in temperature has a rather high influence on the relative humidity. There were generally higher measured temperatures, which lead to lower relative humidity, in studied positions. Those differences were also found in paper I, II and IV. However, paper III does not indicate such differences, probably because of several periods with lack of measured data in the position in the exterior part of the wall during the cold periods. A lower measured relative humidity caused by higher measured temperatures could be established since the results from several other positions located in the exterior part of the wall, as shown in the examples in Figure 11 and 13 and the technical background reports C – G, show the same behavior. The higher measured temperatures may depend on several of factors.

One such factor was that thermal bridges due to studs and beams are disregarded in the one-dimensional blind calculations. Studs and beams create thermal bridges that increase the temperature on the exterior part of the wood frame. Since studs and beams were located close to the measuring sensor in the exterior part of the wall those will cause higher temperatures which reduce the relative humidity.

Some sensors were located below windows in order to detect possible leakage. The one-dimensional calculation models were simulating a section with only thermal insulation, without possibilities to take the influence from the window niche into account, as shown in Figure 11 – 13. In this case the influences from the window niche decrease the insulation since the interior temperature becomes closer to the sensor in reality compared to the one-dimensional calculation model. The window niches were also surrounded by thermal bridges that also increase the temperature.

The sensor thickness of approximately fifty millimeters may also affect the temperature. Its size reduces the thickness of the surrounding thermal insulation which may result in 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. The sensor might also create heat during measurement processing.

The differences between measured values become higher during cold periods and were more common in the northern studied building, with a colder exterior climate. This might be expected since the influence of the thermal bridges and the reduced thermal resistance becomes more evident with bigger differences between interior and exterior climate.

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

In some places, in the interior part of studied walls, deviations between measured and blindly calculated relative humidity were found to be caused by differences in vapour content were found. Possible reasons for these deviations were difficult to establish. It 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. Further investigation and studies need to be carried out to find the cause for those differences. However, as mentioned above, this is not as common, or does not have as big influence as the differences in temperatures have on the relative humidity. Those positions were located in the interior part of the wall where moisture critical conditions do not occur during normal conditions.

Paper I shows that reducing the air flow in the air gap behind the cladding will increase the temperature during the cold periods and decrease the relative humidity. This makes measured values closer to blindly calculated values in the exterior part of the wall. However, the differences between measured and calculated values during the warm periods increase with such a low air flow. The low air flow of less than 5 ACH that is needed in order to reach correlation between measured and calculated values during cold periods is not reasonable according to Falk (2010; 2013) and Nore (2009). Since this phenomenon occurs on the north directed facades it is not possible that higher air flows were caused by solar radiation during the summer.

6.4.2 Differences and positive influence of under-floor heating

There were significant differences between measured and blindly calculated values in positions located on top or close to the sill, as shown in Figure 14. The differences in temperature are significantly higher during the cold periods of the year when there was a higher probability that the under-floor heating was switched on.

The differences between measured and calculated values clearly show that it is not possible to use one-dimensional calculation tools in all situations and that heating sources need to be included in the evaluation of a design.

The measurements also indicate that under-floor heating generates a positive effect in the sill and in the vicinity of the sill caused by higher temperature. Higher temperatures also improve the drying-out process and make the sill warmer. It is important to observe that this positive effect requires vapour-permeable exterior weather resistive barrier and insulation that allows the drying out process to take place.

Comparing walls on a slab with under-floor heating with and without an exterior mould-resistant facade insulation board on the outside of the studs indicates, as expected, that there was a better, warmer and dryer climate on top of the sill in the walls with the exterior insulation board.

6.4.3   Installation layers in bathrooms between two vapour-tight membranes

The faster drying-out process that was observed in the installation layers in bathrooms, as shown in Figure 18, may depend on the vapour barrier on the outside of the installation layer. The barrier might have been damaged or has a lower vapour resistance in reality than the vapour barrier used in the calculation model. Possible vertical or horizontal vapour transportion, which cannot be taken into account in the one-dimensional calculations, may also be a factor that speeds up the drying out process. The influence of convection may also be an important factor in the drying process.

Several of Swedish studies have been reported considering the vapour resistance in the interior waterproofing membranes on the inside of the bathroom and required vapour permeability on the vapour membrane on the exterior part of the installation layer. A summary of these studies concludes that if an additional interior waterproof membrane was installed in bathrooms, or other wet rooms, it is important to ensure that the interior waterproof membrane, closest to the interior surface, has a high vapour resistance in relation to the vapour barrier in the wall (Jansson 2005). The vapour resistance may have been tested using a method that neglects the fact that high RH generates a lower vapour resistance at the membrane (Jansson 2006). The choice of an appropriate vapour resistance for the exterior weather resistive barrier depends on the vapour resistance of the other membranes and the exterior climate. Other critical factors, with regard to membranes, depend to a great extent on the moisture tightness of joints, connections and other detailing (Jansson and Samuelson 2011; Jansson 2010). As mentioned in the literature review in paper VI there is a need for new waterproofing membranes and systems with high quality joints in bathrooms.

The recurrent temporary increased temperature and relative humidity that occurs at the same time, as shown in Figure 19, indicate a leakage in the bathroom inside the studied installation layer. The phenomenon starts directly after the apartment was occupied in June 2009. The possible leakage could also be traced to the bathroom in the same apartment since the temperature, probably caused by hot water, and relative humidity increase at the same time. This indicates that the increased values must be caused by increased vapour content. In case of a leakage from apartments above the temperature would probably be reduced during its transport and possible heat supply from the interior would not be possible to measure. The recurrent increased interval also make it easy to guess that the leakage occurs when the inhabitant taking a shower. However, although there seems to be a leakage, the critical limit is not exceeded in the studied position. An observation of the relative humidity over a three year period also indicates that there is an on-going drying-out process in the studied position. However, this does not ensure that possible in-leaking water dry out since the water or vapour might be transported and accumulated in some other place in the frame, such as the slab or connecting walls.

6.4.4   Correlation between measured and calculated values in air gaps behind the cladding and on the exterior facade

The correlation between measured and blindly calculated values in the air gap behind the claddings in general show that there is a higher temperature and a lower relative humidity in the measured values, as shown in Figure 20. In some studied positions there was more or less a constant difference. A minor number of positions show a better correlation between measured and calculated

values during the summer. In north directed facades measured temperatures were approximately 2 °C higher and the relative humidity approximately 10 % lower compared to calculated values. As expected the south directed facades measured temperatures were higher compared to calculated values and the measured relative humidity was lower, as shown in the technical background report D supporting the thesis.

The higher measured temperature in the air gap and on the surface of the facades facing south compare to the north directed facade and the lower calculated values indicate that the calculation tool might not take the entire influence of wind effects and solar radiation into account.

6.4.5   Differences between measured and blindly calculated moisture content

Comparisons between measured and blindly calculated moisture content in the frame show a correlation where measured and calculated values followed each other but with a difference of up to five percent, as shown in the example in Figure 21.

Comparisons between measurements and blindly calculated moisture content in the facade panel, carried out in a northern Swedish located building presented in the technical background report D, show two different behaviors. Measurement carried out in the facade panel from the inside, i.e. sensors mounted in the air gap, followed calculated values with differences of approximately 2 to 8 percent, as shown in Figure 22. Measurements of moisture content carried out from the outside did not show any correlation at all with the calculated values.

The differences may have been caused by the calculations where an assumption of constant density of 455 kg/m^3 on the wood was used when the moisture content mass by volume [kg/m^3] was recalculated to moisture content mass by mass [%].

The strict differences between measured values on the facade could not be further explained. It might be caused by bad assumption considering the influence of the exterior paint in the WUFI calculation model. Free water, such as rain or condensation, might be another factor that caused discrepancies in the comparison of moisture content.

Comparisons of measured and calculated moisture content on the exterior part of the facade indicate that the calculation tool does not give reliable results on the exterior part of the facade. However, there was no focus on evaluating differences and correlations between measured and calculated moisture content and the results need to be further analyzed.

6.4.6   Amplitude of fluctuations in temperature and relative humidity

Where moisture-critical conditions are considered, the amplitude of fluctuations might be of interest as mould growth is dependent on the duration of the critical conditions (Viitanden and Ojanen 2007; Isaksson et. al 2010).

Differences in amplitudes in both temperature and relative humidity during different periods of the year and for different orientations of the studied positions depended on differences in temperature. There were greater variations in temperature during the summer and these created larger amplitudes during those periods. As expected, the positions orientated towards the south were affected more by the heat variations created by solar radiation. This becomes obvious when comparing the results from positions in different directions located in the exterior part of the wall presented in the technical background report D supporting the thesis.

The studied positions in the exterior part of the wall were more affected by variations in the outdoor climate than the positions closer to the interior side of the wall, which were thermally more 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 depend on differences between real climate and influence of solar radiation compared to used climate boundary conditions in the calculations. The differences may also depend on the difference in heat and moisture capacity in the actual materials compared to the materials in the calculation model and the calculation model may not be able to consider solar radiation in a proper manner. 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 which is more quickly affected by temperature changes than the surrounding materials.

6.4.7 Climate boundary conditions

Several important findings concerning the climate are found in the case study. Some of those will be repeated when the influence of climate is further discussed in a wider context in section 6.9.

The variation in outdoor climate during different years created major variations in studied positions, as shown in Figure 23. The variations affected temperature, relative humidity and duration, all of which affect the risk of mould growth (Viitanden and Ojanen 2007; Isaksson et. al. 2010). This is of importance since it indicates that mean- or standard climate boundary conditions cannot be used in order to achieve reliable moisture calculations. Especially since the outdoor climate variations between different years especially affect the most moisture-critical positions in the exterior part of the wall.

The variations between different years show that real climate boundary conditions need to be used during validation of transient mould growth models and of transient heat and moisture calculation tools. It seems that other studies do not take into consideration the comparisons between measured and calculated values other than that both show the same effects (Geving and Holme 2010; Geving, Kvalvik and Martinsen 2011).

Comparing the agreement between measured and blindly calculated values in paper IV and the results in the technical background report C for the same positions, in the same house, located close to the west coast, indicates that differences between inland and coast climate conditions may need to be considered. The results in paper IV indicate better agreement with measured values. In this paper the climate boundary conditions were taken from a climate station in Gothenburg, located at the west coast approximately 100 km north of the house used in the calculations. In the technical background report C the climate boundary conditions were taken from a closer located climate station in Torup, located in the inland, 37 km east of the house, were used in the calculations. Besides differences in the studied house located on the west coast, the use of exterior climate data from a closely located climate station in the calculations does not seem to have any bigger influence on the results. Comparisons between used climate data and measured micro climate of temperature and relative humidity also show agreement.

The influence of periods with impaired climate boundary conditions, as shown as lack of climate data in brown in the additional charts, that affect the correlation between measured and blindly calculated values could also be found in some positions, as shown in Figure 24 and 25. However, as

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long as the period with impaired climate data does not became too long, it does not seem to have any major influence on the agreement between measured and calculated values. The positions closest located to the place with impaired climate boundary data also become more affected.

Analyzing the climate boundary outdoor climate that was received from SMHI, it was found that some parameters, such as the relative humidity, seems to slowly show bigger deviation over time, as could be seen in the technical background report C that supporting the thesis. It could also be found that those values suddenly decreased each four or fifth year, probably when there was a calibration.

6.4.8 Possible differences caused by incorrect assumptions of heat- and moisture sources in the calculation model

The wind driven rain penetration was assumed to be one percent of the amount of wind driven rain (ASHRAE 2009) and was located in the air gap behind the cladding. In three different positions, in different houses, the measurements indicate that leakage caused by wind driven rain occurs behind the weather resistive barrier and the exterior mould-resistant facade insulation board, as shown in Figure 26 and 27. This shows that wind driven rain may penetrate the cladding, the air gap and the exterior wind and heat defense and occur on the outside of the mould sensitive wooden studs. Several other positions located in the exterior part of studied walls do not indicate leakages behind the weather resistive barrier and the exterior mould-resistant facade insulation board, as shown in Figure 8 – 15.

The amount and influence of wind driven rain were discussed in several of other studies (Van Den Bossche, Lacasse and Janssens 2011). The importance to consider leakages of wind driven rain and damages that might occur, especially in wood frame walls without a drainage and ventilated air gap behind the cladding with outer EPS insulation, so-called ETICS or EIFS walls, is well known (Samuelson and Jansson 2009; Jansson 2011). There are also bad examples of calculation models without consideration of the influence of wind driven rain which falsely indicates that the walls works (Samuelson, Mjörnell and Jansson 2007).

Paper II shows that a correct air flow is needed in order to achieve reliable results that correspond to measured values in exterior part of studied walls. The influence of a proper air flow in the air gap is further discussed in wide context in section 6.6.

Differences between measured and blindly calculated values caused by bad calculation models by the user do not seem to occur since most of the values show agreement.

6.4.9 Possible differences caused by lack of possibilities for a second calibration

As mentioned above, all measuring sensors in the walls were built in into the walls and were not possible to calibrate a second time after measurements were completed.

Since 14 of a total of 16 calibrated sensors located in a roof show a lower relative humidity at high relative humidity conditions, indicating the relative humidity may in reality be some percentages higher under such conditions. It would also be of interest to see if there were higher deviations between measured and real temperature at lower temperatures. This would especially be of interest since it at least partly explains the differences between measured and blindly calculated values when there was a high relative humidity during lower temperatures in the cold periods in the exterior part of studied walls. I.e. explain some of the differences between measured and calculated relative humidity.

Since it is not possible to make any second calibration in the studied positions there is only an indication that may explain some parts of the differences between measured and calculated values when there is a high relative humidity.

6.4.10 Material data

In most of the studied walls a rather good agreement between measured and calculated values was found. Differences in the calculation results seem to mainly depend on deviations in temperature caused by other factors than material properties.

Possible differences caused by impaired material data could be found in the cases when measured and calculated moisture content was compared, as described in section 6.4.5.

Different thermal conductivity between real insulation materials and material properties in the calculations might also cause differences between measured and calculated temperature. However, other possible factors, as discussed in section 6.4.1, were assumed to have higher influence than possible differences caused by smaller variations in the thermal conductivity.

The material data for vapour permeability in the calculation model for exterior bathroom walls seems to be incorrect. The permeability greatly affects the agreement between measured and blindly calculated relative humidity. The faster dry out seen in the measurements in Figure 18 and discussed in section 6.4.3 indicate that the vapour barriers were more permeable.

The agreement between measured and calculated values shows that used material properties in general seem to be reliable in calculations in wood frame walls with a well-ventilated air gap behind the cladding. It may also be assumed that perfect material properties may not be the most important factor, as long as the material data between different material layers is high. I.e. different material parameters, such as vapour-permeable or thermal conductivity, became dominant in one material compared to other materials in other material layers. This might explain why less good agreement in the comparisons occurs between two materials with high vapour permeable- resistance and better agreement occurs in the same wall without one of the two permeable materials with high vapour resistance. Further sensitivity tests changing the material parameters are suggested in order to find the influence of deviations in material data.

6.4.11 Initial and boundary conditions

As expected, differences between measured and blindly calculated values were found in the initial comparisons since the calculations did not focus on perfect initial conditions in the calculation models. The initial differences that were noticed in both the calculations and the measurements were difficult to assume and apply in a reliable manner in the one-dimensional calculations.

Generally the calculations started before the houses where occupied. In some cases even before the house was built, due to numerical limitation. It seems to be differences between measured and calculated temperature that generally caused the main initial differences, as shown in Figure 18 and 19. A reliable indoor temperature to be used during the construction phase was also one parameter that was difficult to find.

6.5   The need of blind comparison

Software used as a tool to predict mould- and moisture-related damage before a house is built ought 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 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 other positive effects since the blind calculations are similar to the situation the designer has to deal with before a house is built. In addition, the blind calculations in this case study were carried out with real in- and outdoor climate data. In ordinary situations a mean standard climate was probably used by the designer. However, this was not possible in order to make calculated values comparable to real measured values as discussed in section 6.4.7.

The blind calculations provide 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, as mentioned in section 2.6.4. By using blind calculations, defects in used calculation models could be found, as shown in paper II. Errors like these could be avoided if they were known, by providing better default values, clearer instruction manuals or stricter parameter limit values in the software.

The initial comparison with wrong air change rate in the air gap behind the cladding in paper II also shows an important parameter that has a high influence on the results. Those parameters might also be found by sensitivity tests. If good correlation between measured and blind calculations where the only interest, parameters such as the air change rate would have been adjusted, without being mentioned, until good agreement had been reached between measured and blind values.

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.

6.6   Air flow in the air gap behind the cladding

Paper II shows that a correct air flow is needed in order to achieve reliable results that correspond to measured values in exterior part of studied walls. The horizontal battens in the construction studied in paper II made that a low air flow initially was assumed (Wadsö 1996; Sandin 1991; Sandin 1993). However, the results indicate that it was a higher ACH than expected, probably caused by vertical ventilation, because of horizontal battens in the air gap, and joints in between the wood panel (Kehl, Hauswirth and Weber 2011). In the following studies, carried out after paper II, paper III – VI as well as the technical background reports C – G supporting the thesis, an air flow above 30 ACH in the air gap was used.

The parametric study shows that a low air flow in the air gap behind the cladding has a negative influence and critical conditions occur more frequently and during other periods of the year in position A, as shown in Figure 34. 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 2010; Falk and Sandin 2013; Tichy and Murray 2007). Vertical battens and wide openings at the bottom also have the positive influence that wind driven rain becomes drained and also works as a capillary layer. As previously mentioned and shown in paper I an air change rate more than 30 ACH normally does not further improve the conditions in the wall since there is no more moisture available to dry out. Falk (2010) shows that a very high air flow of up to 300 ACH could be reached if there were vertical

battens, and the air gap behind the facade panel is thicker than 25 mm, and there are sufficient openings in the top and the bottom.

The low air flow has a negative influence in position Q, as shown when comparing Figure 35 (a) and (b). Comparing the isopleths charts in Figure 35 shows 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 pronounced negative influence on the conditions in the wall with 420 mm insulation. I.e. a low air flow in the air gap had a more negative influence when the walls were well-insulated. Results in position Q also showed that a high air change rate is favorable since the moisture levels in the whole wall decrease.

If there is a low air change rate, the negative impact of driving rain in position A is significantly higher, as shown in Figure 36, when compared to cases with a lower driving rain load, as shown in Figure 34. A sufficiently high air flow can also handle a high amount of penetrating driving rain. It is therefore very important to establish a sufficient air flow in the air gap behind the cladding if there is a high amount of driving rain. Comparing Figure 34 and 36 also shows that the colder north directed wall has slightly higher moisture conditions in case of a high air flow. This means that if there is a high air flow in the air gap behind the cladding and vertical battens that could handle penetration from wind driven rain the colder north directed wall become the worst case. In case of a low air flow in the air gap, the facade that becomes the most exposed to driving rain becomes the worst case.

The results in Figure 37 confirm previous results by Straube and Finch (2009) and Sandin (1991). The critical condition in position A is higher, longer and also occurs during other periods when a brick facade, as shown in Figure 37, was compared to the reference case. A low air change rate in the air gap behind the brick facade in Figure 37 created significantly more critical conditions compared to the case with a wood facade, as shown in Figure 34. 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. In case of a brick facade it is even more important to ensure a well-ventilated air gap behind the cladding. Previous studies indicate an air flow in the air gap behind the cladding of 0 – 5 AHC (Wadsö 1996; Sandin 1991; Sandin 1993). According to the results, as shown in Figure 37, this is significantly lower compared to the air change rate that is needed to avoid damage in the wood frame inside the air gap. The low ACH behind the brick facades is probable due to the lack of openings in the bottom of the facade where only each third or fourth joint between the bricks create an opening to the air gap. Previous studies indicate that there is a need for significantly larger openings in the bottom of brick facades and a 50 mm vide air gap is required in case of a brick facade, compared to 25 mm in case of wood panel, in order to reach a sufficient air flow in the air gap (Wadsö 1996; Sandin 1991).

Nore (2009); Falk (2010) and Falk (2013) show that the air flow in the air gap behind the cladding varies and is dependent on several factors. Besides the thickness and openings of the air gap the air flow mainly varies depending on the wind speed, wind direction and movement caused by temperature differences.

The influences of different air flows in the air gap were therefore investigated in paper IV. Measured temperature and relative humidity in a wall were compared to calculation of the same values with two different models; one with a constant air flow and one with a wind dependent varied air change

rate based on equations from Nore (2009). Since the air flow in the two calculated cases show similar results it was found that the air flows were high enough to dry out all available moisture that reach the air gap. I.e. the same result as shown in paper I.

The parametric study shows that a well-ventilated air gap behind the cladding is of great importance in order to build moisture proofed wood frame walls. A well-ventilated air gap, including drainage and capillary braking effect, behind the cladding also seems to be an important factor for robustness in the wood frame walls since it is important to ventilate and dry out initial construction moisture, and leakages and moisture that reach the air gap, mainly caused by driving rain. The rather fast dry out of leakage, as shown in the example in Figure 26 and 27, is probably caused by the high air flow in the air gap.

6.7 Protection against mould growth using exterior insulation boards

As expected, the results in Figure 32 and 33 in the parametric study show decreased moisture-critical conditions behind the exterior mould-resistant insulation board, position Q, compared to position A behind the wind recessive barrier further out in the wall. Analyzing the results show that the higher temperature decrease the relative humidity and further on the critical conditions in a manner as discussed in section 6.1 and in paper V. The favorable use of a mould-resistant vapour-permeable insulation board outside the wood studs could also be found in paper III and IV.

The results in paper III and IV, the example in Figure 20, and also results in the technical background report C and D supporting the thesis, indicate such a high critical limit that mould growth may occur in the air gap, and possibly also on organic material in the air gap. The mould-resistant insulation board outside the studs creates a situation without organic material in the exterior part of the frame and measurements and calculations inside the mould-resistant insulation board show a lower relative humidity caused by a higher temperature.

Even if there was better conditions behind the exterior mould-resistant insulation board, paper III show that critical conditions occurs anyway since the board was too thin. In the build house the board was 17 mm thick. Calculations, using real climate conditions, show that the board needs to be 57 mm thick in order to avoid most of the moisture-critical conditions and 87 mm thick to complete avoid critical conditions on the outside of the studs. The need of thicker exterior mould-resistant insulation boards in thicker insulated walls was also confirmed in the parametric study as shown in Figure 32 and 33 and Table 2. The results in Table 2 also confirm that more moisture critical conditions occur in the exterior part of walls with a higher thermal resistance. The precise needed thickness in practice of exterior mould-resistant insulation board, as shown in Table 2, is further discussed in section 6.11.

Exterior mould-resistant insulation boards limit the moisture-critical conditions on the outside of wood studs or other organic material in wood frame walls. However, the need of exterior mould-resistant insulation boards is a secondary parameter compared to the need of a well-ventilated air gap. I.e. it is more important that the wall design include a well-ventilated air gap. In well-insulated walls, with a thicker thermal insulation ($\lambda = 0.037$ W/mK) than approximately 220 mm, there was generally a pronounced need of both a well-ventilated air gap and an exterior mould-resistant insulation board in order to avoid moisture-critical conditions.

6.8 Dry-out potential with different facade board thermal insulation materials

All designs with leakages in Figure 38 showed a higher RH in positions A and Q compared to situations without leakages in Figure 35 (a) and (c). There is a significant difference in high RH in position Q between the cases with vapour-permeable mineral wool and an EPS rather vapour-tight exterior insulation board. In the case with a total insulation thickness of 420 mm there is a significantly higher RH in position Q compared to the case with thinner insulation of 220 mm.

As shown in the example in Figure 26 and 27, leakages that probably were caused by wind driven rain was noticed in the measurements behind the exterior mould-resistant board. This was also found in the technical background reports C and F supporting the thesis. Leakage was also indicated behind the weather resistive barrier behind the air gap as shown in the technical background report D. The amount of leakages was not investigated and need to be further studied, in addition to previous studies (Van Den Bossche, Lacasse and Janssens 2011) and standards (ASHRAE 2009) considering leakages penetrating the facade. At the same time the parametric study show that the influence on the moisture critical conditions become highly affected in case of a leakage behind a vapour-tight exterior mould-resistant board. The situation is similar to the problems concerning ETICS or EIFS walls (Jansson 2011; Straube et. al. 2004; Piñon et. al. 2004; Salonvaara et. al. 2007) even if the air gap in the parameteric study and showed in Figure 26 and 27 probably limit the amount of rain that finally penetrate the exterior insulation board.

The rather fast dry out of leakage, as discussed in section 6.7 and shown in the example in Figure 26 and 27 is probably caused by the high air flow in the air gap. This would not be possible in case of a vapour tight exterior mould-resistant insulation board or a vapour tight weather resistive barrier which would prolong the dry out-process.

In case of initial moisture or a fast dry-out in the sill caused by under-floor heating, as shown in Figure 14, a vapour-permeable exterior insulation board was also required. If the board became to vapour-tight condensation or high relative humidty, as shown in figure 38, would be a problem on the inside of the board where the mould sensitive studs are located.

To handle initial construction moisture and possible leakages, the exterior moisture-resistant board must be vapour-permeable. The influence of leakages from wind driven rain also have to be considered in the moisture safety design process and should be applied behind possible weather resistive barriers and exterior mould-resistant board in possible heat- and moisture calculations.

6.9 Different insulation materials and influence of moisture capacity

The design with cellulose fiber insulation and an exterior mould-resistant mineral wool insulation board show moisture-critical conditions in position A in the exterior part of the frame. Comparing the results in position A in Figure 32 and 39 show that there are slightly higher critical conditions in position A in the wall using cellulose fiber. However, since position A is a moisture-critical area there was no mould sensitive materials in this area. Comparing the more mould sensitive area in position Q in Figure 32 and 39, close to the studs and cellulose fiber insulation, there was the opposite situation where the design with cellulose fiber shows slightly lower critical conditions in positions Q.

The example in Figure 39, as well as the technical background report A supporting the thesis, indicate that there is no problem using cellulose fiber insulation as long as the exterior insulation board was

mould-resistant. However, it is not possible to use moisture sensitive cellulose fiber insulation in the entire wall since moisture-critical conditions occur in the exterior part of the wall. The technical background report A also shows that there is no problem if the insulation thickness was increased as long as the exterior mould-resistant insulation board became thicker.

Since the results from calculations using cellulose fiber insulation are similar to results using mineral wool insulation the results considering needed thickness of the exterior mould-resistant insulation board, as shown in Table 2, become applicable on designs with cellulose fiber insulation behind the mould-resistant board.

The higher heat- and moisture capacity in the cellulose fiber slightly decrease the moisture-critical conditions. The influence from heat- and moisture capacity in wooden studs may also be one factor that causes differences between measured and blindly calculated values. It would also affect the hourly differences in amplitudes between measured and blindly calculated values. However, the amplitude in measured values, close located to studs as shown in Figure 8, 9, 11 and 15, show higher amplitudes compare to blindly calculated values without studs. The influence on the heat- and moisture capacity on the measurements may therefore be questionable.

In a context the impact and influence of heat- and moisture capacity in beams and studs and minor differences in thermal insulation in the wood frame seems to be of minor importance.

The only noticed case where the heat- and moisture capacity influence the results was in case of exterior brick facade outside the wood frame, as shown in Figure 37 and discussed in section 6.6. The differences between measured and blindly calculated values in the interior part of a wall that was found in some places, as shown in Figure 16 may also have been influenced by the heat capacity in the surrounding wooden studs.

6.10 Influence of climate

The example in the parametric study, as shown in Figure 40, indicate a lower amount of moisture-critical conditions if WUFI Swedish mean climate data was used in the calculations compared to real climate data from 1994. The Swedish WUFI climate data was created as a mean climate without extreme values. I.e. important periods that may create critical periods was excluded from the climate boundary conditions in the parametric study. As discussed in the case study in section 6.4.7 and showed in the example in Figure 23, there were differences in the risk of mould growth in the same position caused by variations in the outdoor climate during the three studied years. This is also found in the technical background reports C – G supporting the thesis. As expected, different located house have different amount of critical conditions caused by variations in the outdoor climate. The outdoor climate seems to have a high impact on the moisture conditions in the most moisture-critical positions in the exterior part of studied walls, as discussed in the section 6.4.7. Previous studies also show the differences in risk of mould growth between different years and different cities (Hägglund, Isaksson and Thelandersson 2010). The outdoor climates also include the amount of wind driven rain, which have an impact on the moisture conditions as discussed in section 6.8.

Since the exterior climate have a high impact in the most moisture critical positions in the exterior part of the wall it may be questionable whether mean or standard climate boundary conditions should be allowed in a moisture-safety design process as it 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 mould 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 in calculations during the moisture-safety design phase. Methods to create climate boundary data to be used in moisture calculations were previously investigated by Harderup (1998).

6.11 Evaluated calculation tool to be used for dimensioning purposes

The possibility to use WUFI 5.0 for direct dimensioning purposes in the moisture safety design process might be questionable. As an example the precise thickness of needed exterior mould-resistant insulation board can be discussed. The precise thickness of the insulation boards, as shown in Table 2 and discussed in paper III and section 6.7, should in practice be evaluated for each specific case. Several factors influence the risk of mould growth and actions in order to limit the risk of damage as shown in previous sections.

As discussed in section 6.4.7, 6.10 and shown in Figure 23 and 40, the variations in the outdoor climate between different years have a high influence on the risk of mould growth. When investigating the needed thickness of the exterior mould-resistant insulation board possible future variations and changes in the outdoor climate need to be considered. Different directions, as shown in Figure 30 and 34, as well as other individual factors such as surrounding topography might also affect the risk of mould growth in the wall.

Even if the thickness in Table 2 was based on results using a strict mould growth limit and without accepting moisture critical conditions they should only be seen as guidelines and not be used in dimensioning purposes, since outdoor climate boundary conditions without extreme conditions were used in the calculations.

Besides the chosen RH_{crit} limit from (Sedlbauer 2001) and different methods of considering duration and germination of mould growth there is a complete lack of safety margins. Possible safety margins related to: variations in exterior climate, defects caused by poor workmanship, different mould models and robustness or way of treating leakages from wind driven rain have not been found at all. The area considering reasonable safety margins and reliable outdoor climate boundary conditions need to be further studied.

6.12 The risk of mould growth in studied walls based on field measurements

The risk of mould growth in the studied walls included in the case study was carried out using the Folos 2D visual mould chart. Measurements and calculations indicate slightly moisture-critical conditions in walls in the most critical position in mainly two of the studied houses, as shown in the examples in Figure 8, 20, 23 and the technical background reports C – G. In one studied house it seems to mainly be the outdoor climate that cause high risks. In the other design the critical conditions seems to be caused by a thick thermal insulation. A qualitative analyze of those indicate that the duration and amount of critical conditions is too short to germinate mould growth. Leakages into the frame that were found, as shown in the example in Figure 26 and 27 as well as other measured leakages shown in the technical background reports C, E and F, seems to dry out so fast that mould growth do not occur. However, in many positions in the exterior part of the frame,

measured and calculated values show that the critical-conditions is on the critical limit, or slightly above or below it. Rather small changes in the exterior climate may cause damage.

6.13 The use of the Folos 2D visual mould chart

The invented Folos 2D visual mould chart, as shown in paper V, seems to be useful. The intention to: evaluate several parameters, compare different designs, compare measured and calculated values and evaluate factors affecting the risk of mould growth, at the same time as the risk of mould damage was shown was successful.

The difficulties to quantitatively establish the risk of mould growth germination and predict damage when analyzing the walls in the field studies show that the Folos 2D visual modul chart need to be complemented with a mould growth index, as shown in paper V. It may also be discussed if different safety margins could be added.

It may also be discussed if the RH > RH_{crit} should be presented below moisture-critical conditions.

The used moisture critical limit, RH_{crit}, in the Folos 2D visual mould chart may be discussed. In this thesis, mainly all cases were evaluated using the LIM I limit invented by Sedlbauer (2001). The limit is rather strict and motivated by the precautionary principle and Swedish building code that indicate that safety margins and uncertainties in the calculation models should be considered (BBR 2011).

7   Conclusions and recommendations

Although there are a number of differences between the measured and blindly calculated values shown above, it must be stated that most of the blind comparisons, as shown in the technical background reports C – G supporting the thesis, show good correlations, as presented in the examples in Figures 8, 9 and 10. 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 vapour barrier.

The study assessed a number of important factors that must be taken into account if moisture-safe and well-insulated wood frame walls are to be built. As expected there is a higher risk of moisture damage in well-insulated wood frame walls and the occurrences of moisture-critical conditions increase as the thickness of thermal insulation in walls is increased. The most moisture critical positions are normally located on wood or other organic material in the exterior part of the wood frame. The risk of mould growth can be reduced by implementing suitable designs in which a well-ventilated air gap behind the cladding and the addition of a vapour-permeable exterior moisture-resistant insulation board between the studs and the air gap are of great importance.

Important factors affecting the moisture-safety and parameters that affect the calculation results that need to be taken into account in order to build moisture proof wood frame walls and when WUFU 5.0 is to be used for moisture safety purposes are listed below:

1. Parametric studies included in the thesis indicate that there is a great need for a well-ventilated air gap behind the cladding in order to build well-insulated walls with good moisture-safety.
    a. A well-ventilated air gap behind the cladding may be ensured by a 25 mm, or thicker, wide air gap created by vertical battens with openings in the bottom and the top of the cladding. In case of a brick cladding a thicker air gap of at least 50 mm is recommended.
    b. The need for a well-ventilated air gap increases with higher thermal resistance of the wall.
    c. It is especially important when there are high amounts of driving rain.
    d. It is especially important when the facade material has a significant moisture storage capacity, such as a brick facade.
2. Temperature has a great influence on the relative humidity.
    a. In the studied positions in the case study the measured temperature was, in general, higher than calculated values, which make the measured relative humidity lower than the calculated values.
    b. The temperature affects the moisture critical conditions in the exterior part of the wall. A higher temperature in a moisture-critical area in the frame could be used in order to create more moisture-proof design solutions.
    c. Under-floor heating had a positive influence on the studied walls if combined with vapour permeable materials on the outside.

3. In Northern European climate moisture-critical conditions in wood frame walls mainly occur in the exterior part of the wall.
    a. The moisture-critical conditions in the exterior part of the wall were mainly caused by low temperatures that increase the relative humidity. The risk increases despite a lower risk for mould growth at lower temperature.
    b. The occurrences of moisture-critical conditions increase as the thickness of thermal insulation in walls is increased.
    c. The amplitudes of the fluctuations in the measured values was higher than in the calculated values, especially in moisture-critical positions in the exterior part of the wall.
4. Studs and other organic material in the exterior part of a wood frame wall can 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.
    b. Table 2 indicates required thickness of the exterior moisture-resistant insulation board in case of different total insulation thicknesses where the insulation materials have a thermal conductivity of 0.037 W/mK.
    c. Exterior moisture-resistant insulation boards must have high vapour permeability to allow initial construction moisture and water from possible leakages to dry out.
5. Cellulose fiber insulation with a higher thermal and moisture capacity can be used as long as an exterior moisture-resistant thermal insulation board is used outside the cellulose fiber insulation.
6. In general a good agreement was found in the comparisons between measured and blindly calculated temperature and relative humidity.
    a. Comparisons between measured and blindly calculated moisture content did not show good agreement.
    b. The comparison between measured and blindly calculated values did not initially show good agreement due to influence of initial moisture and problems with accurate climate boundary conditions.
7. A correct 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. Average or standard outdoor climate boundary conditions without extremes should not be used when comparing with field measurements.
    c. It should be investigated whether it is possible to use other safety limits combined with average 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.
    e. There is a need to develop climate boundary conditions that could be used for dimensioning in the moisture safety calculation process since using standard climate without extremes is questionable.
    f. There is a need to investigate and create reliable safety margins in relation to used climate boundary conditions and existing mould-growth models.

8. Wind driven rain causes leakages into the wood frame behind the exterior mould-resistant insulation board and the weather resistive barrier.
    a. The recommendation of a position to apply leakages caused by wind driven rain should be changed from the air gap to a position behind the exterior mould-resistant insulation board and the weather barrier or to a pre-defined depth in the wood frame wall.
    b. The dry out possibilities of water to the frame need to be considered during the moisture safety design process.
    c. The amount of leakage into the wood frame construction behind the exterior mould-resistant insulation board and the weather resistive barrier caused by wind driven rain need to be further investigated
9. The installation layer in studied walls seems to have a faster dry-out process compared to what was expected in the calculations.
10. One-dimensional models cannot be used in all situations and influence of heating sources need to be considered in the hygrothermal calculations.
11. Comparisons between measured and calculated values over time must be made using real climate boundary conditions as there are significant variations in annual climate that affect the results between different years.
12. Blind methods are valuable in order to create and verify reliable calculation tools
    a. Blind methods help the developer to find parameters and factors that highly influence the results.
    b. Blind methods help the developer to learn how an ordinary user uses the tool.
    c. Blind methods give indications of needed limitation or default values that may be needed.
    d. Blind methods help the developer to further develop studied calculation tool.

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9 Appendix I – Initial and boundary conditions and material data

Appendix I present and describe boundary and initial conditions that were used in the calculations. Used materials and material data in the calculation models were also linked to references.

9.1 Used material parameters and material data in WUFI 5.0 calculations

Below the material parameters and material data that were used in the WUFI 5.0 calculations are specified. Each material was described with basic values, such as: Bulk density [kg/m^3], Porosity [m^3/m^3], Specific heat capacity – dry [J/kgK], Thermal conductivity – dry 10 °C [W/mK] and Water vapour diffusion resistance factor [-]. No hygrothermal functions were specified below, such as: moisture storage function, suctions liquid transport coefficients, redistribution liquid transport coefficient, moisture dependent water vapour diffusion resistance factor, moisture dependent thermal conductivity, temperature dependent thermal conductivity and temperature dependent enthalpy. Those functions could be found in the WUFI 5.0 material database (WUFI 2009a).

9.1.1 Facade materials

Concreate board – Fibercementskiva
Material Source: LTH Lund University
Bulk density = 1580 kg/m^3
Porosity = 0.2 m^3/m^3
Specific heat capacity – dry = 850.0 J/kgK
Thermal conductivity – dry 10 °C = 0.13 W/mK (Paroc 2002)
Water vapour diffusion resistance factor = 83.3
Initial moisture: 95 kg/m^3
References: WUFI 2009a; Hedenblad 1996

Solid brick masonry (including mortar joints)
Material Source: Fraunhofer-IBP – Holzkirchen; Germany
Bulk density = 1900 kg/m^3
Porosity = 0.24 m^3/m^3
Specific heat capacity – dry = 850.0 J/kgK
Thermal conductivity – dry 10 °C = 0.6 W/mK
Water vapour diffusion resistance factor = 10
Initial moisture: 100 kg/m^3
References: WUFI 2009a; IBP 1994

Facade panel – Spruce, radial
Material Source: Fraunhofer-IBP – Holzkirchen; Germany
Bulk density = 455 kg/m^3
Porosity = 0.73 m^3/m^3
Specific heat capacity – dry = 1500.0 J/kgK
Thermal conductivity – dry 10 °C = 0.09 W/mK
Water vapour diffusion resistance factor = 130
Initial moisture: 80 kg/m^3
References: WUFI 2009a; Vik 1996

Paint included in the facade panel – Spruce radial

A thin layer of 1mm simulation paint was added in the facade panel

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 455 kg/m^3

Porosity = 0.73 m^3/m^3

Specific heat capacity – dry = 1500.0 J/kgK

Thermal conductivity – dry 10 °C = 0.09 W/mK

Water vapour diffusion resistance factor = 1000 (Nevander and Elmarsson 1994)

Initial moisture: 80 kg/m^3

References: WUFI 2009a; Vik 1996; Nevander and Elmarsson 1994

9.1.2 Air gap materials

Air gaps were modeled by three different layers. This way of modeling the air gap was made in order to make it possible to handle free water and moisture capacity. Two thin layers with additional moisture capacity were added on the exterior and interior surfaces in the gap. Another reason for the three different layers was to simulate a construction with a ventilated air gap at the same time as the influence from wind driven rain was taken into account. An air change source as ventilation was added in the layer in the middle of the air gap at the same time as a leakage from wind driven rain was added in the exterior thin layer in the air gap.

All three layers have the same initial thickness in the material data base. Afterwards the thickness was reduced in such a manner that the total thickness of the three layers became the same as the initial thickness. On the interior and exterior surface two thin layers of 2 mm air gap was modeled. In the middle a thicker layer of 26 mm was modeled. This give a total thickness of 30 mm. Used material parameters as listed below.

2 mm air gap – Air layer 30 mm

Material Source: Generic materials

Bulk density = 1.3 kg/m^3

Porosity = 0.999 m^3/m^3

Specific heat capacity – dry = 1000.0 J/kgK

Thermal conductivity – dry 10 °C = 0.18 W/mK

Water vapour diffusion resistance factor = 0.46

Initial moisture: 0 kg/m^3

References: WUFI 2009a

26 mm air gap – Air layer 30 mm; without additional moisture capacity

Material Source: Generic materials

Bulk density = 1.3 kg/m^3

Porosity = 0.001 m^3/m^3

Specific heat capacity – dry = 1000.0 J/kgK

Thermal conductivity – dry 10 °C = 0.18 W/mK

Water vapour diffusion resistance factor = 0.46

Initial moisture: 0 kg/m^3

References: WUFI 2009a

9.1.3 Insulation materials

EPS (heat cond.: 0.04 W/mK – density: 30 kg/m^3)

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 30 kg/m^3

Porosity = 0.95 m^3/m^3

Specific heat capacity – dry = 1500.0 J/kgK

Thermal conductivity – dry 10 °C = 0.037 W/mK

Water vapour diffusion resistance factor = 50

Initial moisture: 0 kg/m^3

References: WUFI 2009a; Achtziger and Cammerer 1984

Cellulose fibre (heat cond.: 0.04 W/mK)

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 70 kg/m^3

Porosity = 0.95 m^3/m^3

Specific heat capacity – dry = 2500.0 J/kgK

Thermal conductivity – dry 10 °C = 0.037 W/mK

Water vapour diffusion resistance factor = 1.5

Initial moisture: 12 kg/m^3

References: WUFI 2009a;

Mineral wool (heat cond.: 0.04 W/mK)

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 28 kg/m^3

Porosity = 0.95 m^3/m^3

Specific heat capacity – dry = 850.0 J/kgK

Thermal conductivity – dry 10 °C = 0.037 W/mK (Paroc 2002)

Water vapour diffusion resistance factor = 1.3

Initial moisture: 0 kg/m^3

References: WUFI 2009a; Paroc 2002; IEA Annex 24

9.1.4 Wood based materials

Massive wood – Spruce, radial

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 455 kg/m^3

Porosity = 0.73 m^3/m^3

Specific heat capacity – dry = 1500.0 J/kgK

Thermal conductivity – dry 10 °C = 0.09 W/mK

Water vapour diffusion resistance factor = 130

Initial moisture: 80 kg/m^3

References: WUFI 2009a; Vik 1996

Chipboard

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 600 kg/m^3

Porosity = 0.5 m^3/m^3

Specific heat capacity – dry = 1500.0 J/kgK

Thermal conductivity – dry 10 °C = 0.11 W/mK

Water vapour diffusion resistance factor = 70

Initial moisture: 1.5 kg/m^3

References: WUFI 2009a

9.1.5   Membrane materials

Weather resistive barrier (sd = 0.2 m)

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 130 kg/m^3

Porosity = 0.001 m^3/m^3

Specific heat capacity – dry = 2300.0 J/kgK

Thermal conductivity – dry 10 °C = 2.3 W/mK

Water vapour diffusion resistance factor = 200

Initial moisture: 0 kg/m^3

References: WUFI 2009a

Vapour retarder (sd = 50 m)

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 130 kg/m^3

Porosity = 0.001 m^3/m^3

Specific heat capacity – dry = 2300.0 J/kgK

Thermal conductivity – dry 10 °C = 2.3 W/mK

Water vapour diffusion resistance factor = 50000

Initial moisture: 0 kg/m^3

References: WUFI 2009a

Waterproofing membranes – vapour retarder (sd = 100 m)

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 130 kg/m^3

Porosity = 0.001 m^3/m^3

Specific heat capacity – dry = 2300.0 J/kgK

Thermal conductivity – dry 10 °C = 2.3 W/mK

Water vapour diffusion resistance factor = 100000

Initial moisture: 0 kg/m^3

References: WUFI 2009a

9.1.6   Interior surface materials

Gypsum board

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 850 kg/m^3

Porosity = 0.65 m^3/m^3

Specific heat capacity – dry = 850.0 J/kgK

Thermal conductivity – dry 10 °C = 0.2 W/mK (Paroc 2002)

Water vapour diffusion resistance factor = 8.3

Initial moisture: 8 kg/m^3
References: WUFI 2009a; Krus 1996

Cement plaser (stucco)
Material Source: Fraunhofer-IBP – Holzkirchen; Germany
Bulk density = 2000 kg/m^3
Porosity = 0.3 m^3/m^3
Specific heat capacity – dry = 850.0 J/kgK
Thermal conductivity – dry 10 °C = 1.2 W/mK
Water vapour diffusion resistance factor = 25
Initial moisture: 280 kg/m^3
References: WUFI 2009a

9.1.7 Moisture and air change sources added in materials

Moisture and air change sources were used in all calculations in the thesis. A moisture source of 1 % of the wind driven rain was always located in a thin air gap, on the inside of the cladding (ASHRAE 2009). In some specific calculations in the parametric study, a leakage was also simulated by adding 1 % of the wind driven rain in the middle of the studied wall. The air change source varies in different cases but was always located in the middle of the air gap.

9.2 Used initial and boundary conditions in WUFI 5.0 calculations

Below is the initial and boundary conditions that was used in the WUFI 5.0 calculations listed. Further information can also be found in WUFI 5.0 manual (WUFI 2009c).

- Orientation – Orientation. The facade direction was specified in each specific case.
    - Studied walls from the field measurements were facing its real direction as far as possible in the case study.
    - North and south directed walls were studied in the parametric study.
- Orientation – Wall inclination. Walls are 90 degrees i.e. vertical. WUFI default value (WUFI 2009c).
- Orientation – Building Height.
    - Short building, height up to 10 m, was used in the parametric study and in the calculations made for single-family houses in the case study.
    - High building, the height was set to simulate the same height as the location of the studied position in the multi-family houses in the case study.
- Orientation – Driving rain coefficients. Indicate the amount of wind driven rain that hits the facade. WUFI default values were used (WUFI 2009c).
    - Wind driven rain coefficient R1 = 0. WUFI default value (WUFI 2009c).
    - Wind driven rain coefficient R2 = 0.7 s/m. WUFI default value (WUFI 2009c).
- Surface transfer coeff. – Exterior surface – Heat resistance.
    - 0.0588 m^{2}K/W. WUFI default value (WUFI 2009c).
    - Wind dependent.
    - External wall.
- Surface transfer coeff. – Exterior surface – Sd-value. No Sd-value was set on the exterior surface. However, the Sd-value from a layer of paint was set into claddings with wood panel as mentioned in section 9.2.

- Surface transfer coeff. – Exterior surface – Short-wave radiation absorptivity. Depends on the color of the facade.
    - In the parametric study all walls where assumed to be red with at short-wave radiation absorptivity of 0,67.
    - In the case study the short-wave radiation absorptivity was adjusted to the color of each specific house.
- Surface transfer coeff. – Exterior surface – Long-wave radiation emissivity. Set to 0.9 which is WUFI default value (WUFI 2009c).
- Surface transfer coeff. – Exterior surface – Explicit radiation balance. Turned on using WUFI default values (WUFI 2009c).
    - Ground short-wave reflectivity = 0.20. WUFI default value (WUFI 2009c).
    - Ground long-wave emissivity = 0.90. WUFI default value (WUFI 2009c).
    - Ground long-wave reflectivity = 0.1. WUFI default value (WUFI 2009c).
    - Cloud index 0.66. WUFI default value (WUFI 2009c).
- Surface transfer coeff. – Exterior surface – Rain water absorption factor. According to inclination and construction type = 0.7. WUFI default value (WUFI 2009c).
- Surface transfer coeff. – Interior surface – Heat resistance = 0,125 m^2K/W. WUFI default value (WUFI 2009c).
- Surface transfer coeff. – Interior surface – Sd-value. No Sd-value was set on the interior surface. In case of an exterior bathroom wall the interior water proofing membrane was set as a material, presented in section 9.1.
- Initial conditions – Initial moisture in component.
    - In each layer that was used.
    - Typical built-in moisture was assigned.
    - Water content was based on material properties as presented in section 9.1.
- Initial conditions – Initial temperature in component.
    - Constant across component.
    - Initial temperature in component 17 °C.
- Control – Calculation period / Profiles.
    - Start and end.
        - The calculations in the parametric study were carried out over a period of five years using WUFI standard climate. i.e. the same climate boundary conditions all five years.
        - The start and end of calculations in the case study was adjusted as far as possible to when the house was built in order to reach as real conditions as possible.
    - A time step of one hour was always used.
- Control – Numerics – Mode of calculation.
    - Heat transport calculation. Turned on.
    - Moisture transport calculation. Turned on.
    - For thermal conductivity – Use temperature and moisture dependency. Turned on.
- Control – Numerics – Hygrothermal special options. No hygrothermal special options was used.
- Control – Numerics – Numerical parameters.
    - Increased accuracy. Turned on.

- o   Adapted convergence. Turned on.
- Control – Numerics – Adaptive time step control.
  - o   Enable. Turned on.
  - o   Step = 3.
  - o   Max stages = 5.
- Control – Numerics – Geometry.
  - o   Cartesian.

10 Appendix II – Appended conference papers

I.   S. Olof Hägerstedt, Lars-Erik Harderup, Importance of a proper applied airflow in the facade air gap when moisture and temperature are calculated in wood framed walls, 5th International Symposium on Building and Ductwork Air-tightness October 21th – 22th 2010, Copenhagen/Lyngby, Denmark, 2010.

II.   S. Olof Hägerstedt, Jesper Arfvidsson, 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, Brno University of Technology, Faculty of Chemistry, November 3rd – 5th 2010, 978-80-214-4166-8.

III. S. Olof Hägerstedt, Lars-Erik Harderup, Control of moisture safety design by comparison between calculations and measurements in passive house walls made of wood, XII DBMC, International Conference on Durability of Building Materials and Components April 12th – 15th 2011 – Conference proceedings, Porto, Portugal, 2011, 978-972-752-132-6.

IV.   S. Olof Hägerstedt, Lars-Erik Harderup, Comparison of measured and calculated temperature and relative humidity with varied and constant air flow in the facade air gap, 9th Nordic Symposium on building Physics NSB, May 29th – June 2th 2011, Tampere, Finland 2011, 978-952-15-2574-2.

V.   S. Olof Mundt-Petersen, Petter Wallentén, Tomi Toratti, Jorma Heikkinen, 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, Brno University of Technology, Faculty of Chemistry, October 31th – November 2nd 2012, ISBN 978-80-214-4599-4.

VI.   S. Olof Mundt-Petersen, Lars-Erik Harderup, Moisture safety in wood frame constructions – What do we know today? – A literature overview, Sustainable Building Conference 2013, SB13, May 22th – 24th 2013, Oulu, Finland 2013.

Paper I

S. Olof Hägerstedt, Lars-Erik Harderup

Importance of a proper applied airflow in the facade air gap when moisture and temperature are calculated in wood framed walls

5th International Symposium on Building and Ductwork Air-tightness

October 21th – 22th 2010

Copenhagen/Lyngby, Denmark

Importance of a Proper applied Airflow in the Façade Air Gap when Moisture and Temperature are Calculated in Wood Framed Walls

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ABSTRACT

The airflow in the air gap behind the façade panel has shown to be of importance when risks of moisture and mould damages in wood frame walls are calculated. This study demonstrates the importance of a properly applied outdoor air flow in the air gap behind the façade panel when temperature and moisture conditions are calculated. The paper present and compare how variations in airflow in the air gap influence temperature and moisture conditions in a modern Swedish wood framed wall. Different references present various air flows that are adapted in the air gap. Calculations are made in the one dimensional temperature and moisture calculation program WUFI 4.2. The results shows that the air flows in the air gap behind the panel affect relative humidity in all positions outside the vapour retarder. At the same time temperature in the whole construction and relative humidity inside the vapour retarder is not affected by different air flows in a significant way. The conclusion is that a correct airflow in the façade air gap is of importance for calculated moisture conditions in modern Swedish wood constructions. An incorrect air flow can also give significant errors for calculated moisture conditions.

KEYWORDS
Wood Framed Walls, Airflow, Air gap Moisture calculations, WUFI.

INTRODUCION

Background

In order to prevent moisture damages, the revised regulations in Sweden require a moisture design process in the early planning process (Boverket, 2008). A consequence of increased insulation for energy saving reasons is that critical parts of the building envelop become more exposed to higher relative humidity and increased risk of mould growth. To minimize the risk for mould and moisture damages the Swedish wood house industry need a reliable method to predict moisture conditions in wood constructions.

A great number of simulations with WUFI show that the outdoor air flow in the air gap behind the façade panel is of great importance when the moisture conditions in the wall are calculated (Hägerstedt, O., 2010, Nore, K., 2009). In order to make a good assessment of future moisture conditions in Nordic climate it is of vital importance to assume a proper air flow in the air gap behind the façade panel.

Aim

The purpose of this study is to show how the air flow, in an outdoor ventilated air gap behind the façade panel affects calculated results of relative humidity and temperature in modern wood house walls. This is shown by repeating calculations in the same model with different air flows in the air gap. The report compares differences of calculated relative humidity and temperature with different air flow in the air gap.

Illustrations of the importance of using a proper air flow in the air gap in calculations are shown by comparing calculated relative humidity for two different air flows with measurements in the same position.

Limitations

This study does not discuss how airflows are affected by the design of the air gap. Detailed function and data for parameters and boundary conditions in used calculation program are not concerned. All calculations are limited to a one dimensional case.

The construction refers to a modern Swedish exterior wall made of wood. The façade is facing north because it usually becomes the most critical direction for moisture conditions in this type of wall. Apart from the example is WUFI 4.2 standard climate data used. A comparison with actual climate data between calculated and measured values of temperature and relative humidity are presented in Thermophysic conference 3 to 6 November 2010, Valtice, Czech Republic.

RELATIVE HUMIDITY AND RELATION TO TEMPERATURE

Climate conditions with a relative humidity above 75% can cause mould growth on organic materials. There are a several factors that affect if mould growth arises but temperature seems to have a big importance of possibility and intensity of mould growth. Lover temperatures generally reduce the risk of mould growth and increase the critical level of relative humidity. Normally there is no mould growth at 0°C, or lower. In contrast gives higher temperature increased probability of mould growth. Higher temperature also provides a faster establishment of mould spores. Below 75% relative humidity the general opinion is that there is no risk of mould growth regardless of temperature (Boverket, 2008). Besides temperature the material structures and exposed time are also factors of importance when the risk for mould is estimated. (Viitanen, H., 1996)

METHOD

In this chapter is a briefly method description given. A complete detailed method description, with defined sources of error and specified parameters, is given in a separated report (Hägerstedt, O. 2010)

Calculations of relative humidity and temperature have been carried out for different air flows in three positions, B, C and D, in a modern wood framed wall with WUFI 4.2 (WUFI 2009). In the air gap behind the panel, position A, is a constant outdoor air flow of 0, 1, 5, 10, 20 or 50 air changes per hour applied for each calculation. Used air flow in the air gap behind the panel is based on available literature in the field. In real cases the air flow is not constant and depends on several factors such as air gap design, wind and other climatic factors. The airflow could also vary in different parts of the air gap. (Wadsö, L. 1996, Nore, K. 2009) The wall and calculations are supposed to reflect a real case. From the outside the wall are constructed by: 21 mm Spruce radial (IBP) including paint Sd = 1 m (Nevander, L-E. et al. 1994), 30 mm Air layer with varied air flow (IBP), 1 mm Weather resistive barrier Sd = 0,2 (IBP), 195 mm Mineral wool (IEA Annex 24 1996), 1 mm Vapour retarder (IBP), 70 mm Mineral wool (IEA Annex 24 1996), 13 mm Chipboard (IBP), 13 mm Gypsum board (Krus, M. 1996). (Hägerstedt, O, 2010)
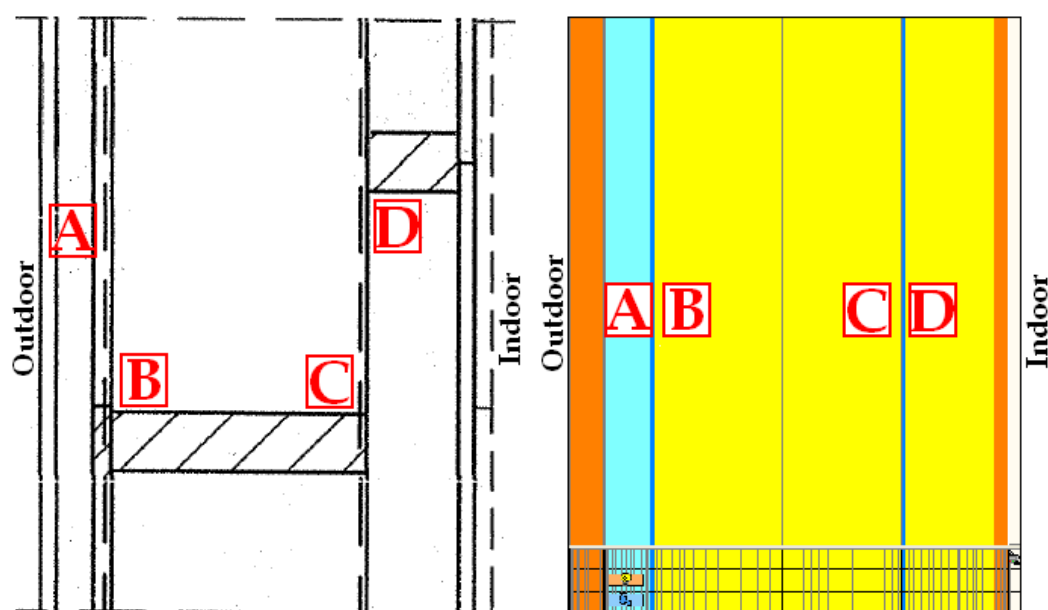

Figure 1: Drawing of estimated wall construction and WUFI 4.2 model. Air gap with different air flow for each calculation (A). Calculated positions (B, C and D).

The calculations are carried out with the one dimensional moisture and temperature calculations program WUFI 4.2. (WUFI 2009). Calculated results for stable conditions after four years loops are presented. Used outdoor climate come from WUFI 4.2 (WUFI 2009) climate data base and concern the Swedish city Växjö. Indoor climate are based on standard EN 15026 (EN 15026) and set to normal moisture load and dependent on outdoor climate. Calculations are performed hour by hour. Since the Swedish climate used in WUFI does not include radiation we have used a built in function in WUFI 4.2 (WUFI 2009) for the radiation balance.

Sources of error

Besides the example connected to measured values this is a parameter study. This mainly limits the sources of error to deficiencies in WUFI 4.2 physical model and input errors. Compared to real conditions there is a number of other sources that can

end in errors. The most general errors can be traced to errors in boundary conditions, the model conformity with real conditions and that the calculations are made in one dimension.

RESULT

The results shows one dimensional calculations in WUFI 4.2 (WUFI 2009) for relative humidity and temperature for three positions in a modern wood wall when different air flows with outdoor air are applied in the air gap behind the panel.

Comparison between calculated relative humidity and temperature with different air flow in the air gap for position B are shown in chart 1.
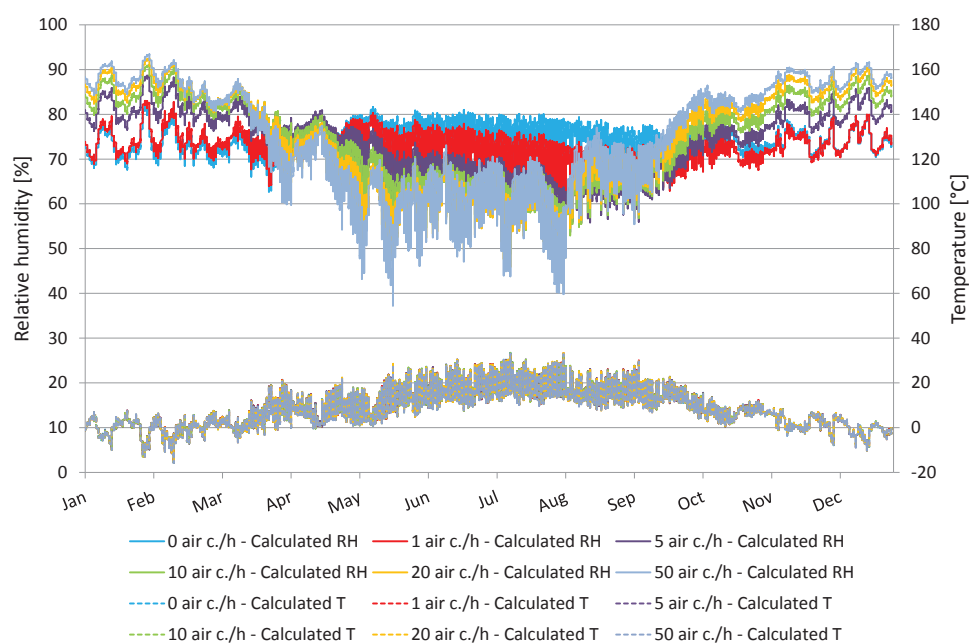

Chart 1: Position B. Calculated relative humidity and temperature with different applied air flow in the air gap. Different colors show different flow.

In order to increase transparency fore temperature calculations the difference between temperature for the lowest air flow, 0 air changes per hour and maximum air flow of 50 air changes per hour are presented in chart 2. Other temperature differences between used air flows in the air gap are lower than what is shown in chart 2.

Chart 2: Difference between calculated temperature in position B for the lowest air
flow of 0 air changes per hour and maximum air flow of 50 air changes per hour.

Comparison between calculated relative humidity and temperature with different air
flow in the air gap for position C are shown in chart 3.

Chart 3: Position C. Calculated relative humidity and temperature with different
applied air flow in the air gap. Different colors show different flow.

In order to increase transparency for temperature calculations the difference between
temperature for the lowest air flow, 0 air changes per hour and maximum air flow of
50 air changes per hour are presented in chart 4. Other temperature differences
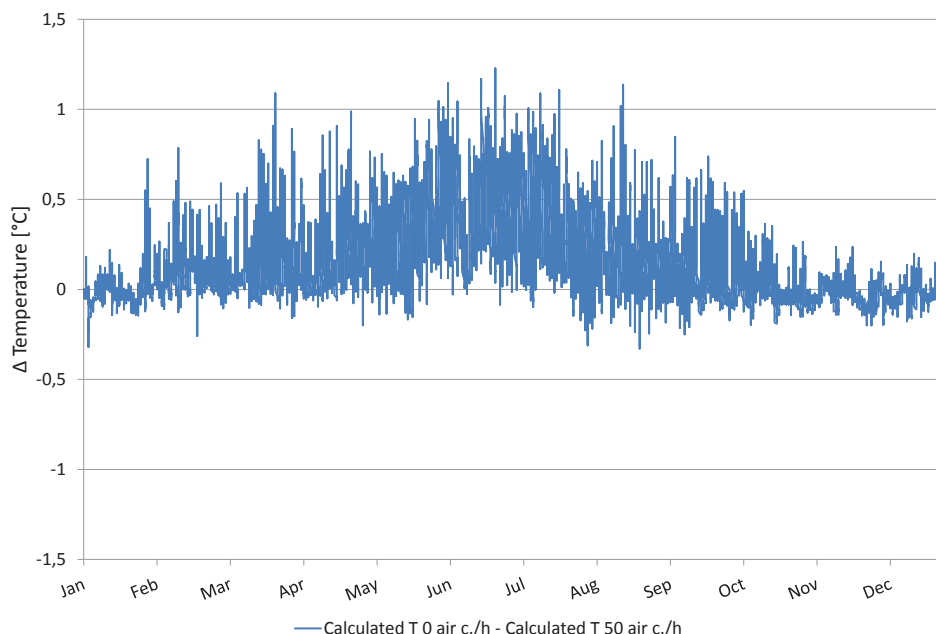between used air flows in the air gap are lower than what is shown in chart 4.
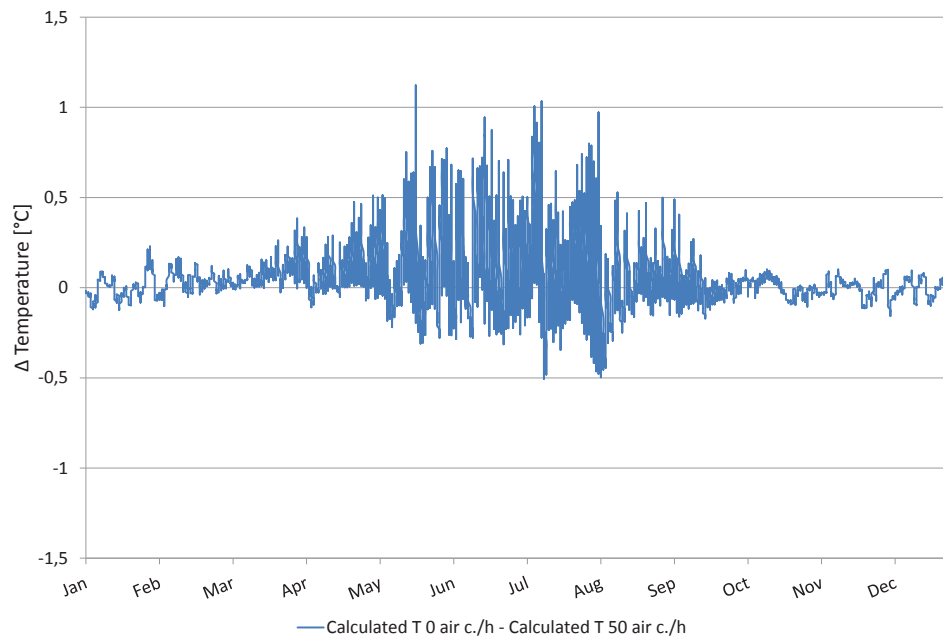
Chart 4: Difference between calculated temperature in position C for the lowest air flow of 0 air changes per hour and maximum air flow of 50 air changes per hour.

Comparison between calculated relative humidity and temperature with different air flow in the air gap for position D are shown in chart 5.
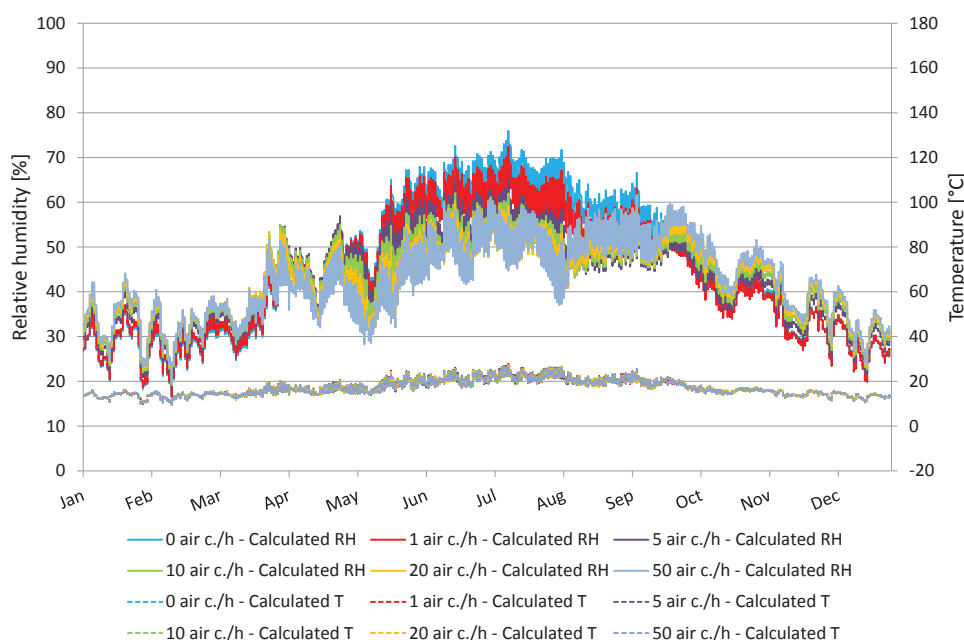

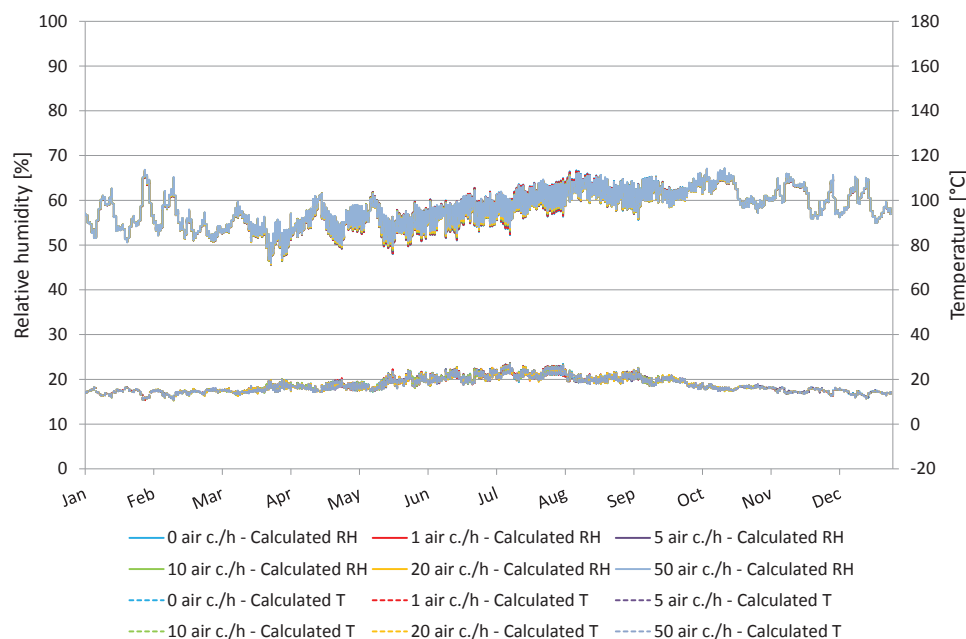Chart 5: Position D. Calculated relative humidity and temperature with different applied air flow in the air gap. Different colors show different flow.

Temperature difference between the lowest air flow, 0 air changes per hour and maximum air flow of 50 air changes per hour in position D are almost the same as for position C as shown in chart 5. A closer illustration is therefore unnecessary.

COMPARISON BETWEEN MEASUREMENTS AND CALCULATIONS

In order to demonstrate consequences of an incorrect airflow in the air gap behind the façade panel an example is shown below. Both measurements and calculations are based on construction in figure 1 above. Chart 6 shows a comparison between measured and calculated relative humidity for two different flows.
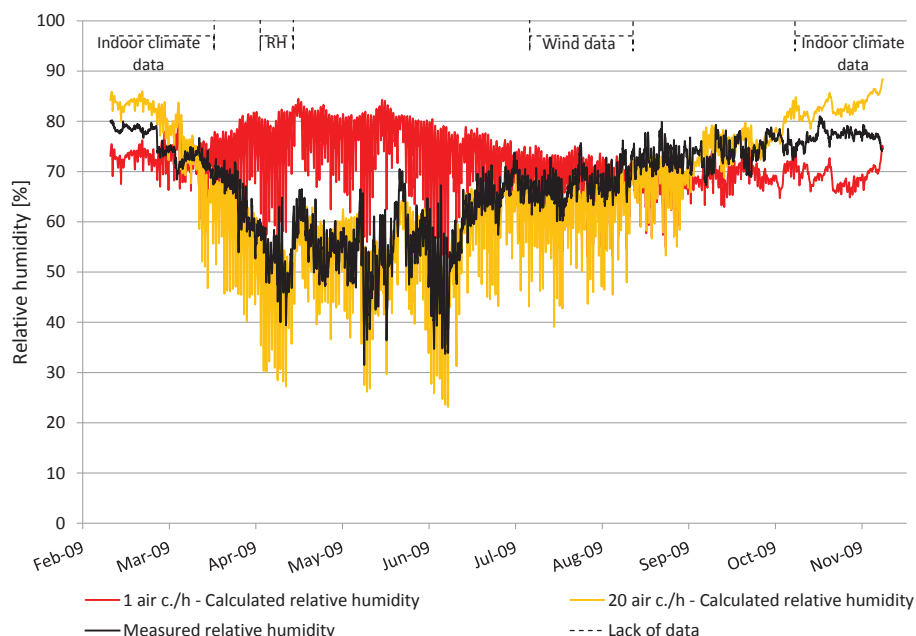

Chart 6: Example on comparison in position B. Measured relative humidity (black). Calculated relative humidity for 1 air changes per hour (read). Calculated relative humidity for 20 air changes per hour (yellow). Periods with gaps in boundary conditions are shown in the top.

ANALYSIS

Comparison of calculated relative humidity in position B and C, outside the vapour retarder, during summer shows that one air change per hour or less in the air gap results in higher relative humidity compared to higher air flows over five air changes per hour. During the winter period the conditions are reversed which means that for higher air flows a higher relative humidity is calculated in both position B and C. In positions outside the vapour retarder is calculated relative humidity with five air changes per hour close to the results from calculations for higher flows in the air gap behind the panel. Calculated relative humidity with flows of 20 air changes per hour and 50 air changes per hour are consistent. For position D inside the vapour retarder is calculated relative humidity independent of the flow in the air gap behind the panel.

Calculated temperature has compliance in all positions for all applied flows in the air gap. During the period October to April the difference is not more than 0,3°C. During the summer the biggest difference is 1,5°C. Calculated temperature is constant or higher for flows lower than one air change per hour. Therefore it cannot be differences in temperature that causes higher relative humidity in positions outside the vapour retarder for flows below one air change per hour in the air gap behind the

panel. If that would be the case, the higher temperature should instead make the relative humidity to decrease. Calculated relative humidity is also different and acting different on the inside of the vapour retarder compared to outside of the vapour retarder. This ensures that the air flow in the air gap behind the panel only affect calculated relative humidity in positions outside the vapour retarder.

Calculated relative humidity with air flow of five air changes per hour in the air gap are nearly similar to the same calculations with higher air flow in the air gap. Comparison for calculated relative humidity with flows at 20 to 50 air changes per hour show a good agreement. This depends on that air flows from five air changes per hour in the air gap makes the excess moisture to start move away. From 20 air changes per hour there is no more moisture left and 50 air changes per hour compared to 20 air changes per hour doesn't make any difference in this case.

Calculations show that position B is the most critical. Bad moisture conditions mainly occur with air flows below one air change per hour during the summer. The reason is a high relative humidity at the same time as the temperature is high. The high calculated relative humidity for flows over ten air changes per hour during the winter might be a problem. During the winter the temperature is also lower in position B and therefore it could be possible to avoid mould growth. The high relative humidity in position B during the winter could be traced to the fact that the air gap is ventilated with outdoor air that has high relative humidity in the winter. To ensure that there is no risk of mould growth in position B there has to be a careful moisture design process in this case where relative humidity and temperature are weighted together.

The example shows measured relative humidity compared to two cases of calculated relative humidity with different flow in the air gap behind the panel. The graphs in chart 6 clearly show that the calculation with one air changes per hour deviate significantly from the other two curves.

CONCLUSION

The main conclusion of this study is that calculated relative humidity in positions outside the vapour retarder is affected by the air flow in the air gap behind the panel. In order to make reliably moisture calculation for modern Swedish wood frame houses a relevant air flow in the air gap behind the panel is of great importance. The example also shows that an incorrect assumption of the air flow in the air gap behind the panel could give significant errors in the result.

Calculated moisture conditions inside the vapour retarder are not affected significantly by the air flow in the air gap behind the panel. The temperature in all positions is either not significantly affected by different air flow in the air gap.

Flows above 20 air changes per hour do not have any big impact of calculated relative humidity because there is no more excess moisture that can be transported.

The calculations also show that relative humidity become lower further into the wall, from the outside. This mainly depends on a higher temperature which gives a lover relative humidity.

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Because it is important to consider the airflow in the air gap in moisture calculation it could also be relevant to discuss if the moisture part of Glaser calculation is applicable to outdoor ventilated facades with air gap.

According to the calculations the best conditions is achieved if the air flow in the air gap behind the panel are high during the summer period and low during the winter period. A higher air flow in the air gap is preferable because it gives low relative humidity during the summer and the high relative humidity during the winter is not a big problem because of the low temperature.

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Paper II

S. Olof Hägerstedt, Jesper Arfvidsson

Comparison of field measurements and calculations of relative humidity and temperature in wood framed walls

Comparison of Field Measurements and Calculations of Relative humidity and Temperature in Wood Framed Walls

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Abstract: Energy efficient wood frame buildings give besides a number of positive effects also risks for moisture damages. To avoid moisture damage in wood houses some parts of the Swedish construction industry use WUFI 1D calculation tool in the design phase. The purpose of this study is to demonstrate the coupling between measured and WUFI 1D calculated values of relative humidity and temperature. The first step presents a comparison between measurements and blind calculations of relative humidity and temperature at different positions in a wooden wall with an air gap. In the second step has boundary conditions for calculated values been adjusted in order to achieve better agreement. The result of the comparisons between calculated and measured values are analyzed. The general conclusion of this study is that it is of great importance to apply a correct airflow in air gap. Results also show that it is possible to obtain reliable calculated values with a proper flow in the air gap.

Keywords: Moisture, Wood framed hoses, WUFI, Relative humidity.

Introduction

Background

New laws and demands from consumers have increased the interest in well insulated wood frame houses. Besides a number of positive effects of reduced energy need there are also risks with well insulated wood frame houses. Critical parts of the building envelope become more often exposed to higher relative humidity than before. That provides increased probability for the occurrence of mould growth. To minimize the risk of moisture damages the Swedish wood house industry need a user friendly and reliable moisture calculation tool. This paper show the possibilities to use WUFI 1D to calculate the moisture performance for Swedish conditions.

Aim

The purpose of this study is to demonstrate the coupling between measured values of relative humidity and temperature compared with the same parameters calculated in WUFI 1D. The intension is to show if WUFI 1D is a tool that is suitable for the Swedish house industry during the design of wooden framed houses.

Limitations

The limitations for the measurements in this study are governed by the project schedule and building location. Measuring period, instrumentation and production schedule allows only data for one design and one building section, exposed to central Swedish climate, to be presented. This study does not deal with detailed information about functions and parameters used in the calculation program.

Method

In this chapter is a briefly method description given. A complete detailed method description with defined sources of error is given in a separated report (Hägerstedt, O. 2010, in press)

Relative humidity and temperature has been measured at different positions in a wall. Calculations of relative humidity and temperature have been carried out for the same positions with WUFI 1D 4.2 (WUFI 2009). Measured and calculated values for the relative humidity and temperature are then compared hour by hour in two steps. The first step is a blind comparison. In the second step the boundary conditions for calculated values have been adjusted in order to get better agreement. The comparisons between calculated and measured values are analyzed.

Measurements are carried out in the northwest facade for different depths in positions A to D as shown in figure 1. Northwest facade has been chosen because it often becomes the most moisture critical. This facade is also exposed to least amount of short wave radiation, which is a missing boundary condition. Measurements of temperature and relative humidity have been carried out every hour using a wireless Protimeter Hygro Trac system (Fjellström, P. et al. 2009; GE Sensing 2006; Hoogenboom, C. 2009). Measurements in position A to D, started 2008-11-08.

21 mm Spruce radial[1], including paint Sd = 1m[2]
30 mm Air layer[1], step 1 = 0,5 air/h, step 2 = 20 air/h
1 mm Weather resistive barrier[1], Sd = 0,2m
195 mm Mineral wool[3]
1 mm Vapour retarder[1], Sd = 100m
70 mm Mineral wool[3]
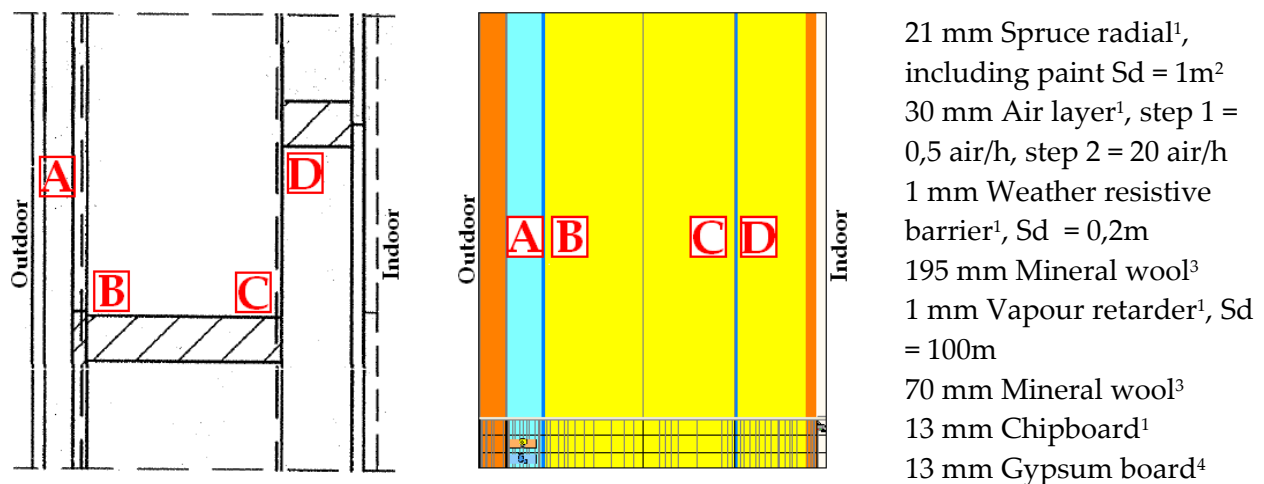13 mm Chipboard[1]
13 mm Gypsum board[4]

Figure 1: Wall construction, measuring positions (A to D) and calculation model showing calculated positions (A to D). (1. IBP, 2.Nevander, L. et al. 1994, 3. IEA Annex 24 1996 4. Krus, M. 1996)

Boundary conditions in the calculation model are set to match measurement conditions. Applied outdoor climate for calculations are taken from SMHI, Swedish meteorological and hydrological institute, at a climate station nearby. Lack of data for longer periods has been replaced with the previous year's values for the period. Measured indoor climate have been possible to use for indoor boundary conditions from 2009-04-07. Previous period has constant values of 22°C and 40% relative humidity in calculations. Monitor position has also been changed 2009-09-23. Periods of significant lacks of climate data are shown in result charts.

Sources of error

Losses of climate data are the biggest sources of error. The constant conditions in the air gap are also of importance. Those losses in boundary conditions are bigger in a normal design phase and not reasonable to solve in context of this project. Deficiencies in WUFI physical model and bad coincides between calculated material and real material is seen as a part of the limitations. The loss of wooden beams in the 1D model, as show in figure 1, is also difficult to affect.

Result Blind Test

In order to limit the report only characteristic comparisons between blind calculated and measured values are presented. A short written result explanation is presented for all positions. Complete results are presented on the website www.framtidenstahus.se.

Comparison between blind calculated and measured values for relative humidity and temperature for position C are shown in chart 1 and for position D in chart 2.
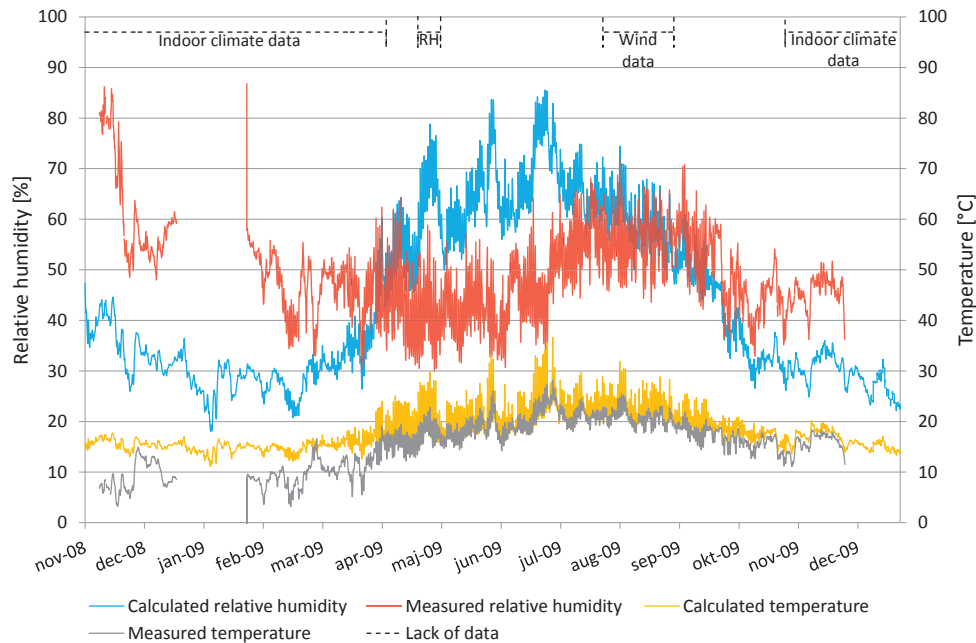

Chart 1: Position C. Relative humidity: Blind calculated (blue), measured (red). Temperature: Blind calculated (yellow), measured (grey). Periods without measured boundary conditions are shown in top.
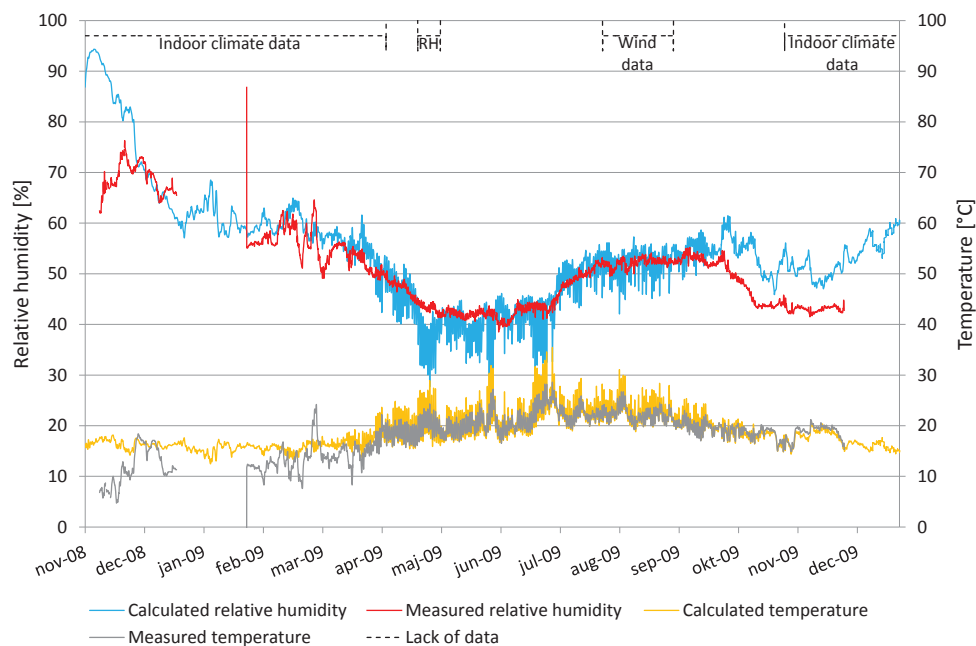

Chart 2: Position D. Relative humidity: Blind calculated (blue), measured (red). Temperature: Blind calculated (yellow), measured (grey). Periods without measured boundary conditions are shown in top.

Results for position C, as shown in chart 1, are characteristic for positions A, B and C outside the vapour barrier. Estimated and measured values follow each other for temperature but do not comply for relative humidity. Comparison of blind calculated and measured values in position D, as shown in chart 2, complies in both temperature and relative humidity.

Analysis Blind Test

Estimated and measured relative humidity does not match for positions at the cold side of the vapour barrier. At the same time there is a good correlation between calculated and measured temperature for all positions and relative humidity on the warm side of the vapour barrier.

This means that outdoor temperature and complete indoor climate seem to be correct applied. The relative humidity generally follows the temperature. That means that the reason for the mismatch of the relative humidity in position A, B and C has to do with additional or removed moisture outside the vapour barrier. The two possibilities for this in the calculation model are the amount of construction moisture or the airflow rate in the air gap behind the panel. Construction moisture should be dried out early in the calculation and is affected by the airflow in the air gap. The conclusion is therefore that the bad compliance in relative humidity in positions A, B and C depends on incorrect estimated airflow.

Adjustment of airflow

The airflow of 0,5 air changes/h, used in blind calculations, is taken from previous studies (Wadsö, L. 1986) and are assumed because of the horizontal wood strips in the air gap. Used airflow can be improperly adopted because the measuring points are located near a corner and a window which create leaks. The air in the air gap could also move more horizontally than expected.

Calculations with varied airflows are therefore made and compared with measurements from the air gap. Comparison shows that 20 air changes/h is a more reasonable value in terms of the whole year. During colder periods of the year, a lower flow of about 10 air changes/h give a better agreement. By changing the airflow in the air gap during the year gives the possibility to obtain very good correlations in all points over the whole year. A higher number of air changes than 20 air changes/h does not affect the calculated results significant.

Note that the airflow in both initial blind and adjusted calculations is constant during the calculation period, which itself gives rise to a source of error. It is not possible to further measure or study changes of airflow in context of this project.

Result with Adjusted Airflow

In the following comparisons the airflow in the air gap behind the wood panel are adjusted to 20 air changes/h in all calculations. In order to limit the report a characteristic period is chosen for each position to show the comparison between calculated and measured values. This is a short period for some positions and the entire period for other positions. Complete results are presented on the website www.framtidenstrahus.se. Results from this study are summarized and discussed in the analysis section.

In order to show the influence of the amplitude in calculated values carts have been extended with 12 hourly averages.

Position A – Air gap

Calculated and measured relative humidity and temperature in position A are shown in chart 3.
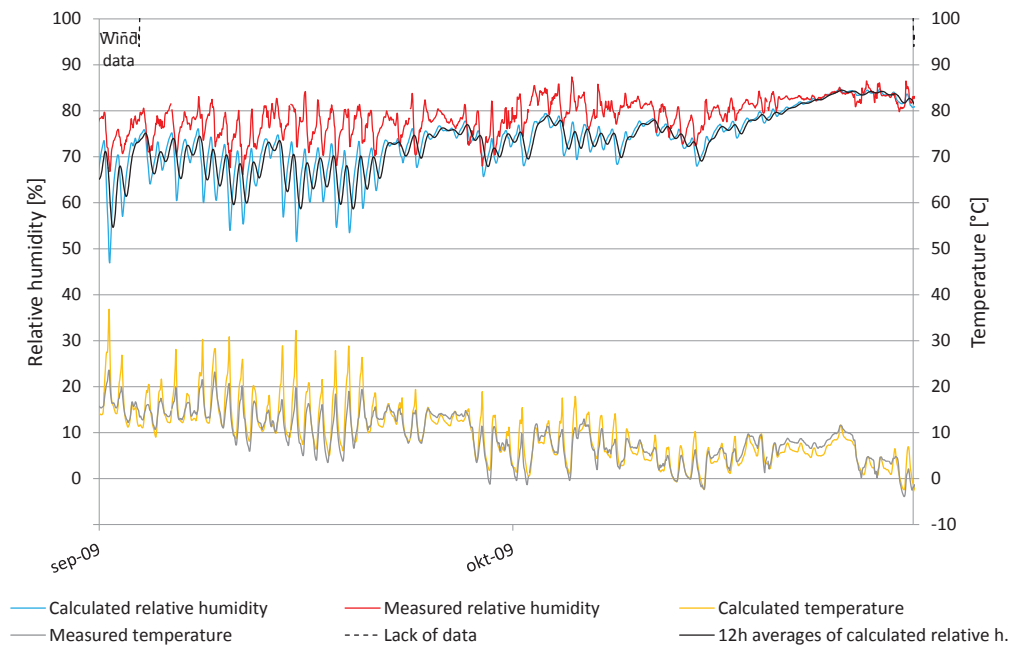

Chart 3: Position A – Air gap. Period: September - October. Relative humidity: Calculated (blue), measured (red). Temperature: Calculated (yellow), measured (grey). Periods without measured boundary conditions are shown in top. 12 hourly averages for calculated relative humidity (black).

Position B – Outside frame

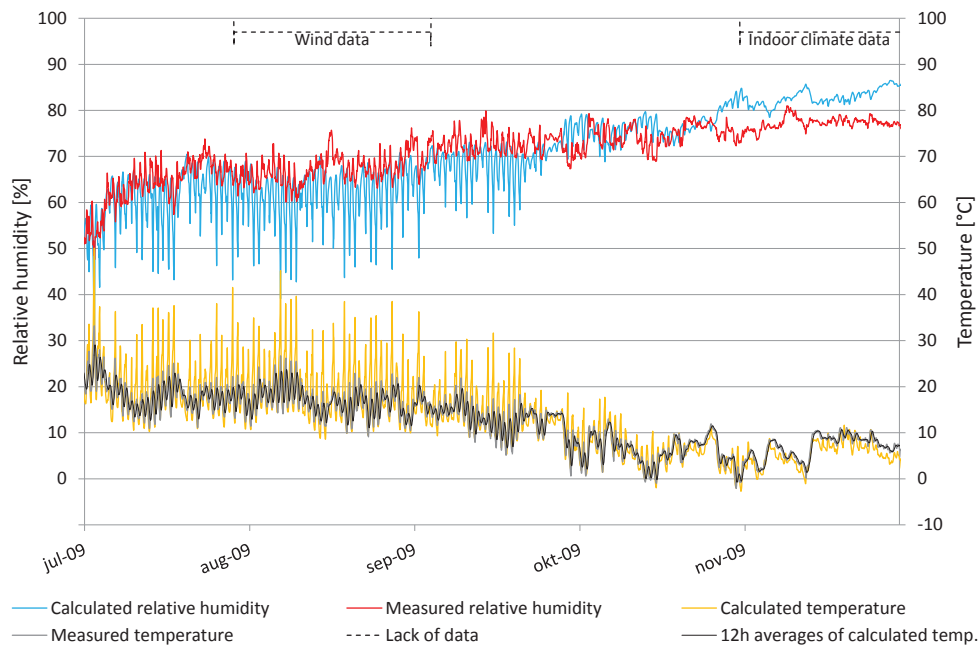Calculated and measured relative humidity and temperature in position B are shown in chart 4.

Chart 4: Position B – outside frame. Period: July - November. Relative humidity: Calculated (blue), measured (red). Temperature: Calculated (yellow), measured (grey). Periods without measured boundary conditions are shown in top. 12 hourly averages for calculated temperature (black).

Position C – Cold side of vapour retarder

Calculated and measured relative humidity and temperature in position C are shown in chart 5.

Chart 5: Position C – Cold side of vapour retarder. Period: November 2008 – December 2009. Relative humidity: Calculated (blue), measured (red). Temperature: Calculated (yellow), measured (grey). Periods without measured boundary conditions are shown in top.

Position D – Warm side of vapour retarder

Calculated and measured relative humidity and temperature in position D are shown in chart 6.
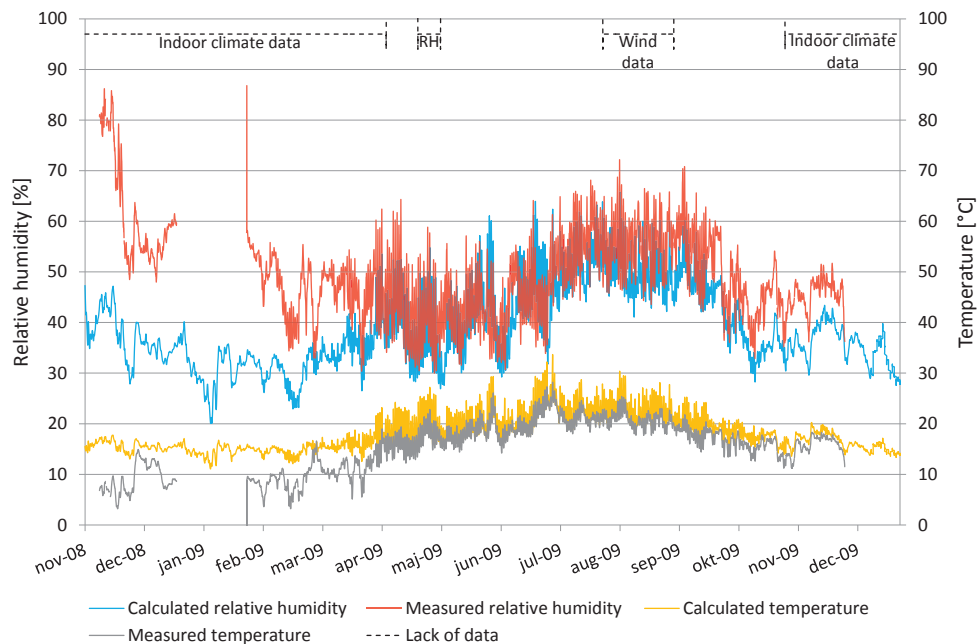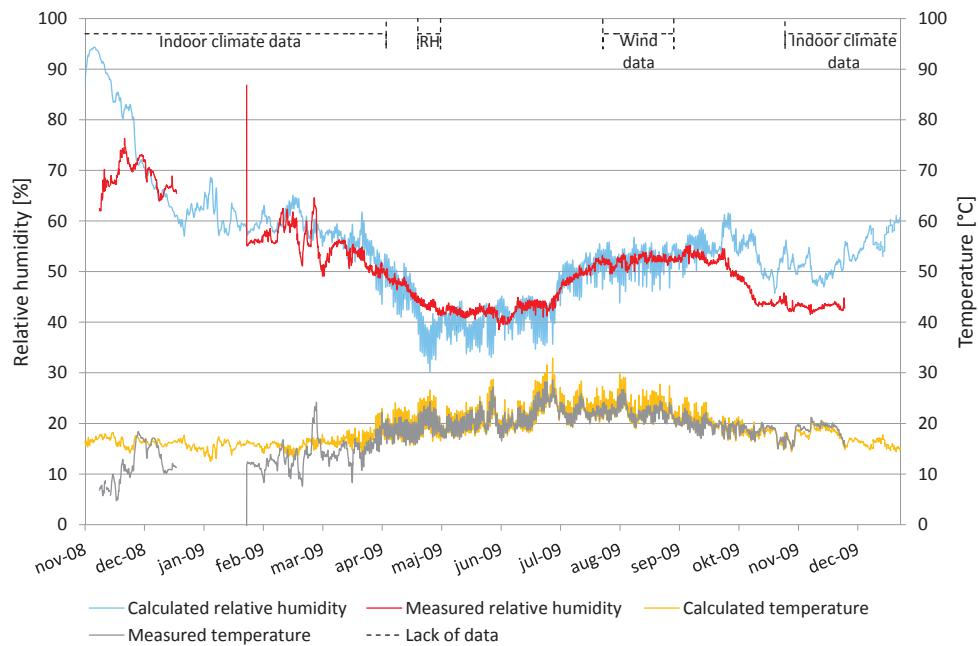

Chart 6: Position D – warm side of vapour retarder. Period: November 2008 – December 2009. Relative humidity: Calculated (blue), measured (red). Temperature: Calculated (yellow), measured (grey). Periods without measured boundary conditions are shown in top.

Analysis – with adjusted airflow

Besides some individual periods, and the size of amplitude for daily values, there is at good correlation between calculated and measured temperature in all studied positions. By adding the mean value for every 12 hours on calculated temperature, as shown in chart 4, the daily amplitude size is reduced and gives a perfect agreement with measured values.

Apart from some individual periods, and the size of amplitude for daily values, calculated and measured relative humidity follows each other. Calculated values of relative humidity are constantly five to ten percent lower compared to measured values for positions A, B and C, outside the vapour barrier. The mean value for every 12 hours in calculated relative humidity, as shown in chart 3, reduce the size of the daily amplitude to corresponds to the measured amplitude.

Deviations between calculated and measured values outside the vapour barrier during the cold period could, as mentioned earlier, be remedied by reducing the airflow in the air gap. The effort to indentify the impact of outdoor climate on the conditions in the air gap was not possible to do within the context of this project.

The lack of boundary conditions for relative humidity in the end of April could be noticed in position C and D, as show in chart 5 and 6.

Especially position C and D shows a bad correlation between calculated and measured values for both relative humidity and temperature until indoor climate is applied 2009-04-01 in the calculations. Position C and D are closer to the inside and therefore more affected of the lack of boundary conditions compared to positions further out in the construction. Besides the loss of boundary conditions for indoor climate during this period, the house is not inhabited, and construction moisture may retain and effect measurements.

The comparison between calculations and measurements in position D, as shown in chart 6, clearly shows that the monitor for indoor boundary conditions has been moved 2009-09-23.

The amplitude of the daily calculated values for both relative humidity and temperature are bigger than measured in all positions during the warm period. During the cold period the amplitude of calculated and measured values is equal. Lower daily amplitude obtains for positions deeper into the construction. This probably depends on a more even temperature distribution from the indoor climate. The amplitude for calculated and measured values also has a better correlation deeper into the construction. The reason for constant higher amplitude for calculated values is unknown. Installations of monitors in the wood frame with higher heat and moisture capacity may cause the amplitude of the measurements to be lower. The monitors may also have a weak ability to register rapid temperature shifts, or calculation could be more sensitive to temperature fluctuations compared to measurement. In positions A, B and D there is also higher amplitude on calculated relative humidity compare to measured. It is easy to assume that the high amplitude of the calculated temperature gives corresponding errors to calculated relative humidity. It is therefore surprising that the amplitude of the calculated relative humidity is the same as the measured relative humidity in position C, while there is a difference in amplitude of the calculated and measured temperature. By adding the floating mean value for every 12 hours on calculated values, as shown in chart 3 and 4, the amplitude is reduced which give a better correspondence to measured values.

Conclusion

The general conclusion of this study is that conditions of the airflow in the air gap behind the panel must be known to give a good correlation between calculated and measured values.

The difference in results for the relative humidity between blind calculations with airflow of 0.5 air changes/h and the calculated values with an adjusted airflow for 20 air changes/h shows the great importance using a correct air flow in the model. The use of a relevant airflow in the air space is essential for evaluation of the risk for moisture damages and mould growth. Applied airflow in the air space has a big influence in all points of the frame that are located on the outside of the vapour retarder.

Deviations and differences between calculated and measured values can be attributed to relevant sources. It is entirely possible that the airflow in the air gap behind the panel varies in a manner which gives a good correlation between calculated and measured values. Since the condition in the air gap is not measured it is not possible to confirm that this is the case. In respond to known and unknown sources of error the correlation between calculated and measured values are considered as good.

Future work on development of WUFI 1D should focus on designing a model for airflow in air gaps behind facade layer. Another solution could be to look for context in settled airflow in other studies where comparisons between calculated and measured values in facades with underlying air space made. It would have been helpful if a general model of varying airflow in air gaps could be created and applied in calculations.

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Paper III

S. Olof Hägerstedt, Lars-Erik Harderup

Control of moisture safety design by comparison between calculations and measurements in passive house walls made of wood

Control of moisture safety design by comparison between calculations and measurements in passive house walls made of wood

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ABSTRACT

The use of passive house technique has been used in a new wood framed building in Sweden. Besides the positive effect of reduced energy need, highly insulated wooden houses often have a higher risk of moisture and mould problems. The reason is that critical positions is more exposed to higher relative humidity compared to ordinary houses with thinner insulation. To investigate if an external wall has been correctly designed and constructed it has been investigated both with hourly measurements and by calculations with WUFI 5.0.

The aim of this study is to investigate the result of the moisture design process and the way changes in the design influence the moisture safety with real climate conditions. The study also investigates if WUFI 5.0 is a reliable tool to use in the construction design process. This was investigated by comparisons between measured and calculated relative humidity and temperature in different positions in an exterior wooden wall from April 2009 to October 2010.

In the original design the outer wooden studs have no protecting layer from the ventilated air gap behind the façade. Results from calculations with WUFI 5.0 shows that it is sufficient with a thin protecting thermal insulation on the outside of outer studs to considerably improve the moisture conditions in the outer parts ot the wall. If we never want the relative humidity to be above the critical level, at least 87 mm of insulation have to be applied on the outside of the wooden studs.

Comparisons between measurements and calculations show that WUFI 5.0 can be a reliable tool in moisture design of highly insulated wood framed walls. To get safe results it is important to use reliable climate and correct assumption about the air flow in the air gap behind the façade material.

KEYWORDS

moisture, measurements, WUFI, comparisons, mould

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1 INTRODUCTION

1.1 Background

The use of passive house technique in new wood framed buildings increases in Sweden. Besides the positive effect of reduced energy need passive house often have a higher risk of moisture and mould damages. The reason is that critical positions with organic material in the frame becomes more exposed to higher relative humidity compared to ordinary houses with thinner insulation. In order to minimize risk for moisture damages in a new passive house made of wood experts were given the opportunity to implement moisture design and suggest changes throughout the design phase of a major wood build project. This paper show possibilities to use the one dimensional heat and moisture calculation program WUFI 5.0 [WUFI] in the moisture design process and the effects it could result in concerning moisture safety.

1.2 Aim

The aim of this study is to use real climate conditions and show how changes in the design will influence the moisture safety, and consequences if no changes are made. Another aim is to investigate if WUFI 5.0 is a reliable tool to use in the moisture design process. This is demonstrated with comparisons between measured and calculated relative humidity and temperature in different positions in a highly insulated exterior wooden wall in an apartment building in Sweden, in 2009.

1.3 Limitations

The limitations in this study are primarily related to conditions for the measurements. Project schedule, production plan, construction type and building location only admit data for one design in one location. The limited duration of the measurements also affects the reliability of the results. The study does not include detailed information about parameters and functions used in the calculations.

2 METHOD

During the moisture design process [Mjörnell, K. 2007] a number of calculations was carried out for an initial proposal of wall construction, shown as "Initial wall" in Fig. 1. One challenge in the moisture design process was to protect the outside of the wood studs, position B, from mould growth. This was made by adding a insulation board on the outside of the wood studs, shown in "Build wall" in Fig. 1. Conditions in the design phase limited the thickness of the insulation board to 17 mm. To study moisture conditions in the wall and to compare with results from WUFI 5.0, measurements have been carried out in positions B to E in the modified wall, shown as "Build wall" in Fig. 1.

Wall from outside:
8 mm Concrete board[1]
30 mm Air gap 40 ACH[2]
(17 mm Insulation board)[34]
170 mm insulation/studs[34]
170 mm insulation/studs[34]
1 mm Vapour retarder[2]
82 mm Massive wood[2]
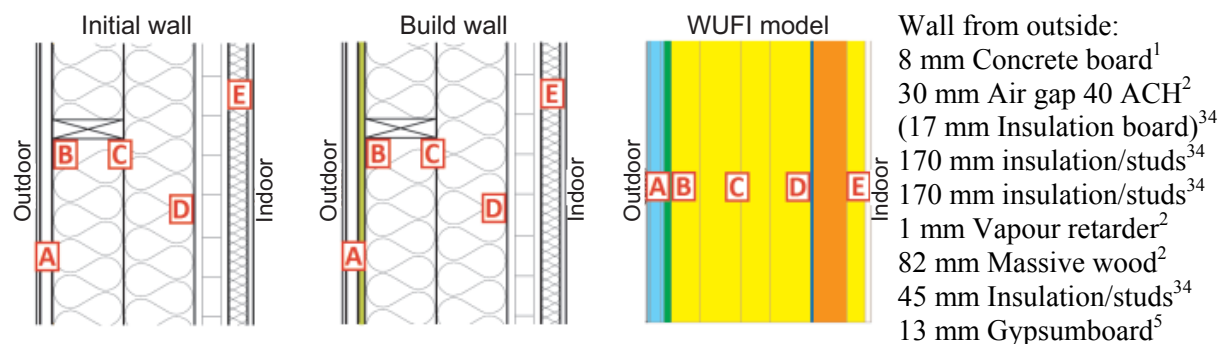45 mm Insulation/studs[34]
13 mm Gypsumboard[5]

Figure 1. Initial wall without insulation board and Build wall with insulation board (green). Air gap A and measuring positions B to E. Calculation model with insulation board, air gap A and calculated positions B to E. [1. Hedenblad, G. 1996, 2. IBP, 3. IEA Annex 24, 4. Paroc, 5. Krus, M. 1996].

As a first case conditions for positions B to E in the initial wall were calculated in WUFI 5.0 with real climate as boundary conditions. To get a similar model to the wall that was built, a 17 mm insulation board was added, as shown as "WUFI model" in Fig. 1, and calculations in position B to E were repeated. Calculated results from the initial wall and the built wall were analysed. Since 17 mm of board was not enough to avoid critical relative humidity levels a number of calculations were carried out to investigate the minimum thickness of the board to avoid critical relative humidity levels.

To validate the calculations and show the possibilities to use WUFI 5.0 in the design process calculations of relative humidity and temperature for position B to E are compared with measured values. The comparisons are blind, i.e. measured results have not been available until calculations were completed. Calculations and measurements have been carried out and compared hour by hour. The agreement between measured and calculated relative humidity and temperature are presented and analysed.

Measurements are carried out at sixth floor in the north façade at different distances from the outside, shown as position B to E in Fig. 1. The north façade is supposed to be the most critical regarding the risk of moisture related problems. It is also less exposed to short wave radiation, which is excluded in the calculations. Measuring sensors have been applied during the production at the same time as constructions were controlled for deviations to drawings. Measurements of temperature and relative humidity have been carried out every hour using a wireless Protimeter Hygro Trac system [Sandberg, K. et al. 2011; GE Sensing 2006]. Measurements in position B to E started 2009-05-01 and are still running.

Boundary conditions and a model for the calculations are shown in Fig. 1 as "WUFI model" and set to match build wall and measured conditions. The house is built under a tent so no initial construction moisture is added in the calculations. According to the height and earlier studies the air flow in the air gap, position A, are set to 40 air changes per hour [Hägerstedt & Arfvidsson 2010]. Used outdoor boundary conditions are taken from SMHI, Swedish meteorological and hydrological institute, at a climate station nearby [SMHI]. All indoor boundary conditions are based on measurements from October 2009 to October 2010. The apartment, where the indoor climate is measured, has not been inhabited during the measurement period. Lack of in- and outdoor climate conditions are replaced with relevant data [Hägerstedt O. 2010, A, in press]. Periods with lack of outdoor climate data are shown in the top of Figs. 4 to 8. Lack of temperature and relative humidity are shown separated because of its impact.

A complete detailed method description with defined sources of error is given in a separate report [Hägerstedt, O. 2010, in press].

2.1 Sources of error

The main sources of error can be summarized as follow: Lack of measured boundary conditions for parts of the time and lack of some material data. Possible defects in WUFI´s physical model, convergence errors and bad correspondence between material data used in calculations and real material is also treated as possible errors. In the one dimensional model wooden beams have been neglected, as shown in Fig. 1, which is a simplification. The use of field measurements both as boundary conditions and as a part of the comparison also creates unknown possible sources of error.

3 RESULTS - MOISTURE DESIGN

In this report only results from the most moisture critical position on the outside of the wall studs, position B, is presented. Other positions, C to E, are not so exposed to moisture critical conditions. Complete results for all positions are shown on the webpage www.framtidenstrahus.se.

A critical relative humidity limit, as a function of temperature [Zedlbauer, K. 2001], is shown as a green line for the initial wall in Fig. 2 and for a test calculation with 87 mm board in Fig. 3. Difference

between the critical and calculated relative humidity at specific times for each case are shown in the bottom of Figs. 2 and 3. The level of critical relative humidity as a function of temperature [Sedlbauer, K. 2001] for one studied case is also added in Figs. 2 and 3. Specific time and difference between critical and actual relative humidity is also shown.
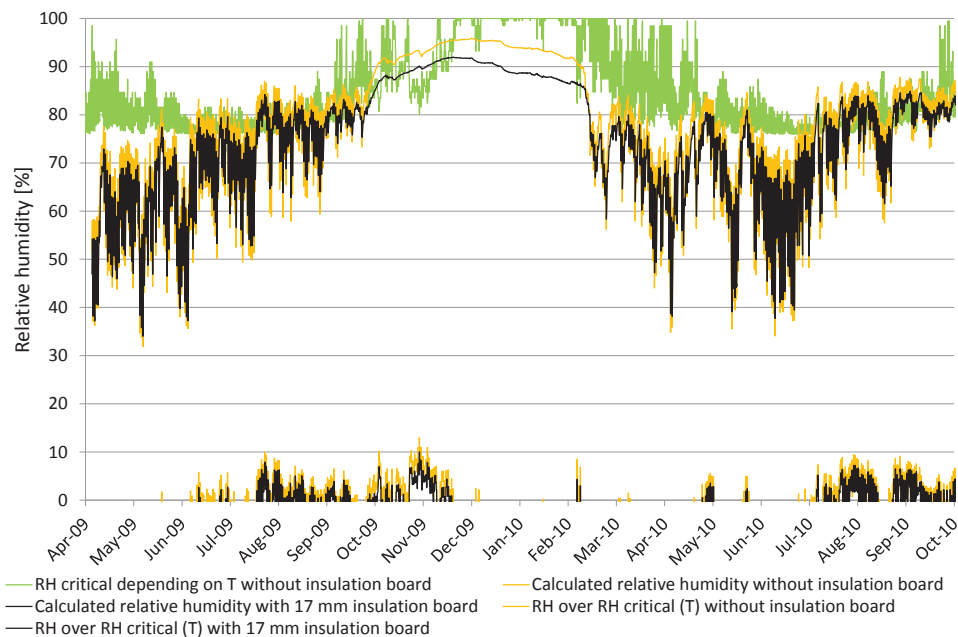

Figure 2. Position B. Calculated RH without insulation board and exceeded to critical RH (yellow). Critical RH level as a function of temperature for calculated RH without insulation board (green). Calculated RH with 17 mm insulation board and exceeded to critical RH (black).
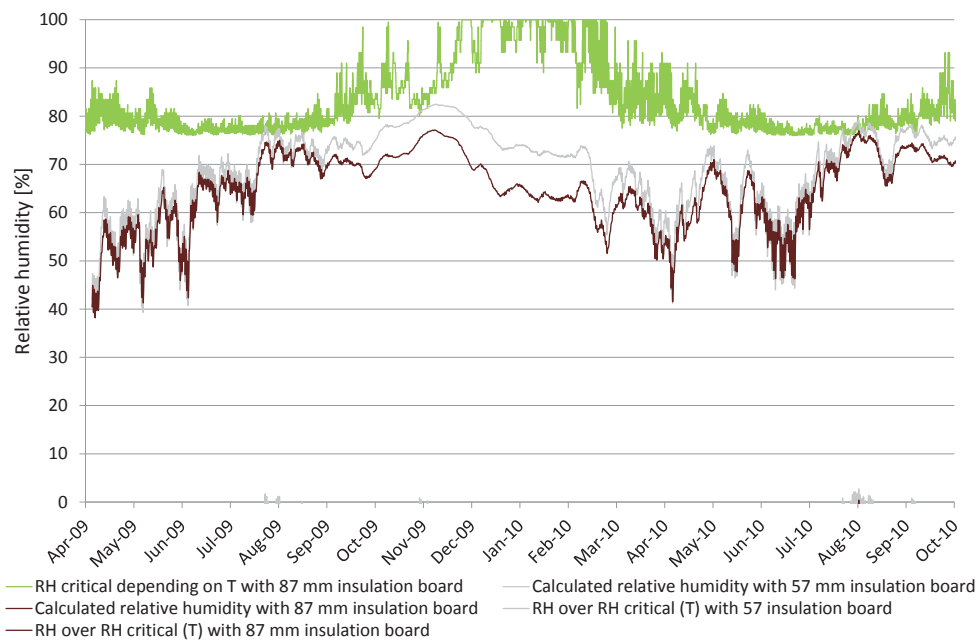

Figure 3. Position B. Calculated RH with 57 mm insulation board and exceeded to critical RH (grey). Critical RH level as a function of temperature for calculated RH with 87 mm insulation board (green). Calculated RH with 87 mm insulation board and exceeded to critical RH (dark red).

4 RESULTS - VALIDATION OF CALCULATIONS

Comparison between calculated and measured relative humidity and temperature are presented.

4.1 Position B - Outside of the wood studs

Comparison between calculated and measured relative humidity and temperature are show in Fig. 4. In Fig. 5 a more detailed comparison from March 2010 to June 2010 is shown.

Figure 4. Position B - Outside of the wood studs. Relative humidity: Calculated (blue), measured (red). Temperature: Calculated (yellow) measured (purple). Lack of boundary condition (green/black).
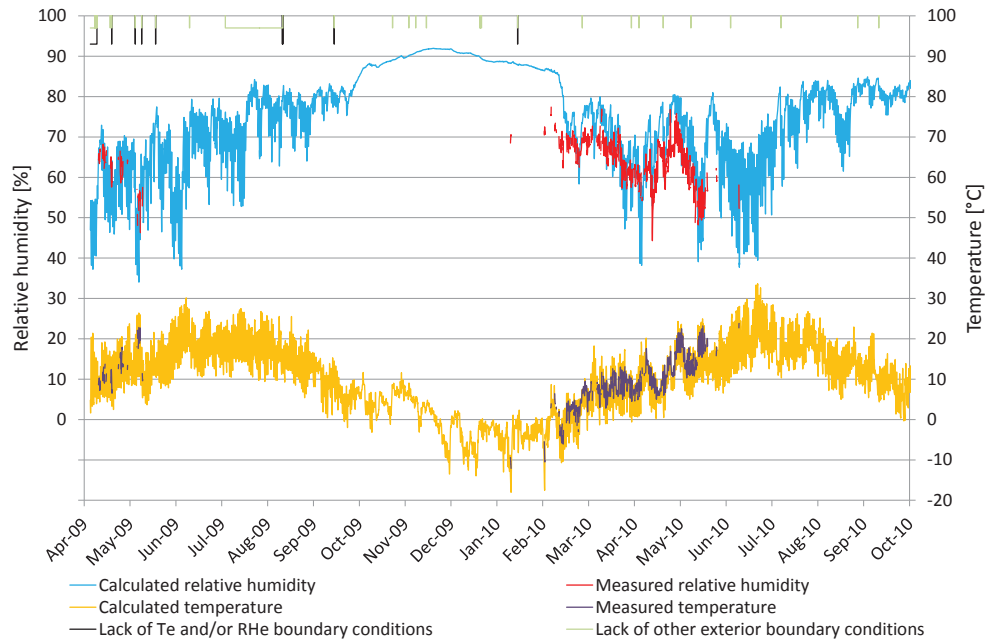

Figure 5. Position B - Outside of the wood studs. Relative humidity: Calculated (blue), measured (red). Temperature: Calculated (yellow) measured (purple). Lack of boundary condition (green/black).

4.2 Position C - In the middle of insulation

Comparison between calculated and measured relative humidity and temperature are show in Fig. 6. Unfortunately there is an extensive lack of measurements in position C.
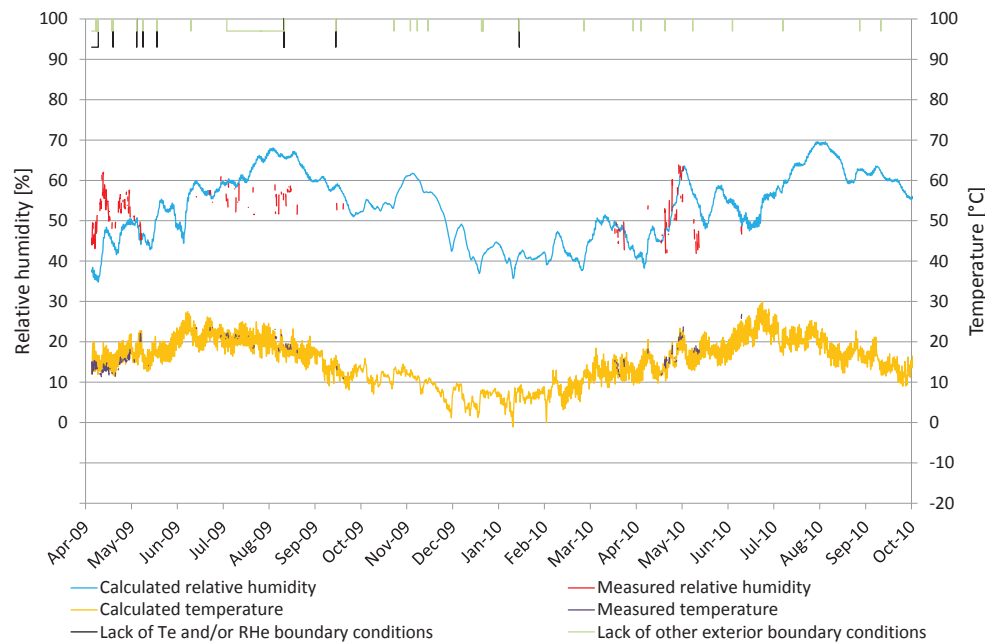
Figure 6. Position C - The middle of insulation. Relative humidity: Calculated (blue), measured (red). Temperature: Calculated (yellow) measured (purple). Lack of boundary condition (green/black).

4.3 Position D - Cold side of the vapour retarder

Comparison between calculated and measured relative humidity and temperature are show in Fig. 7.

Figure 7. Position D - Cold side of vapour retarder. Relative humidity: Calculated (blue), measured (red). Temperature: Calculated (yellow) measured (purple). Lack of boundary condition (green/black).
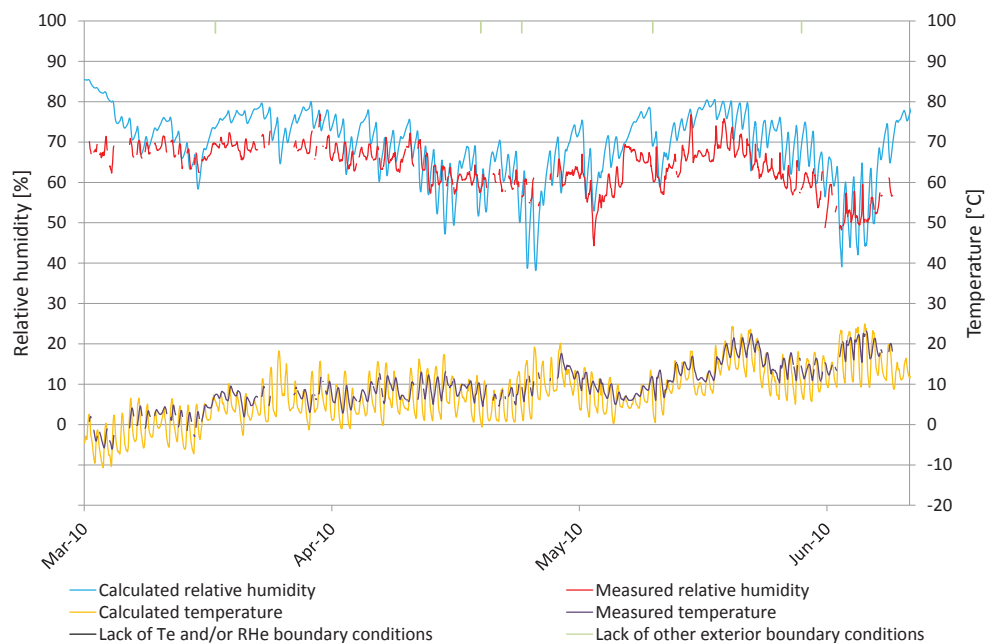
4.4 Position E - Installation layer on the warm side of the vapour retarder

Comparison between calculated and measured relative humidity and temperature are show in Fig. 8.

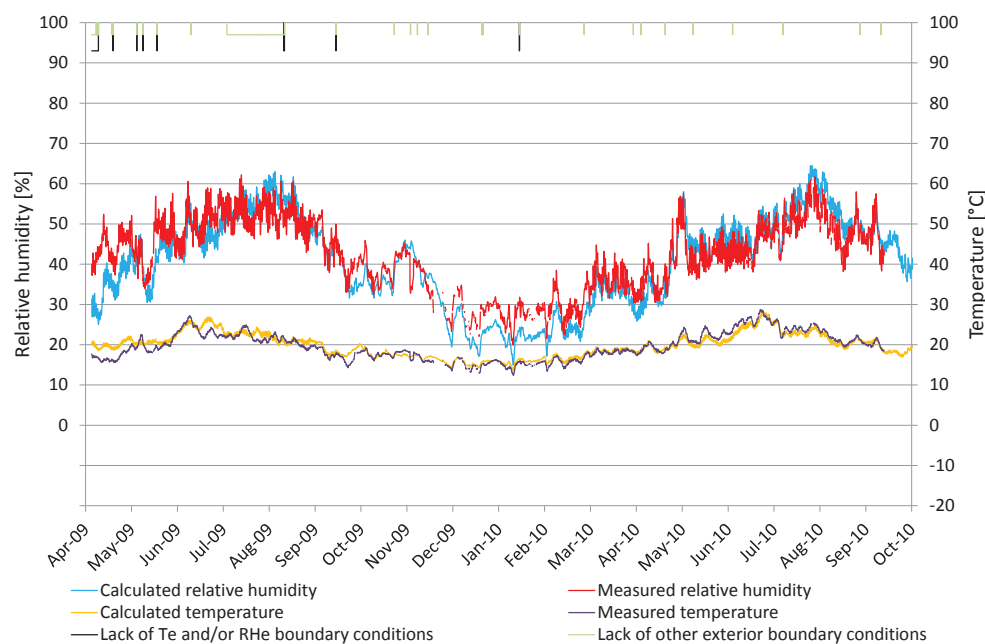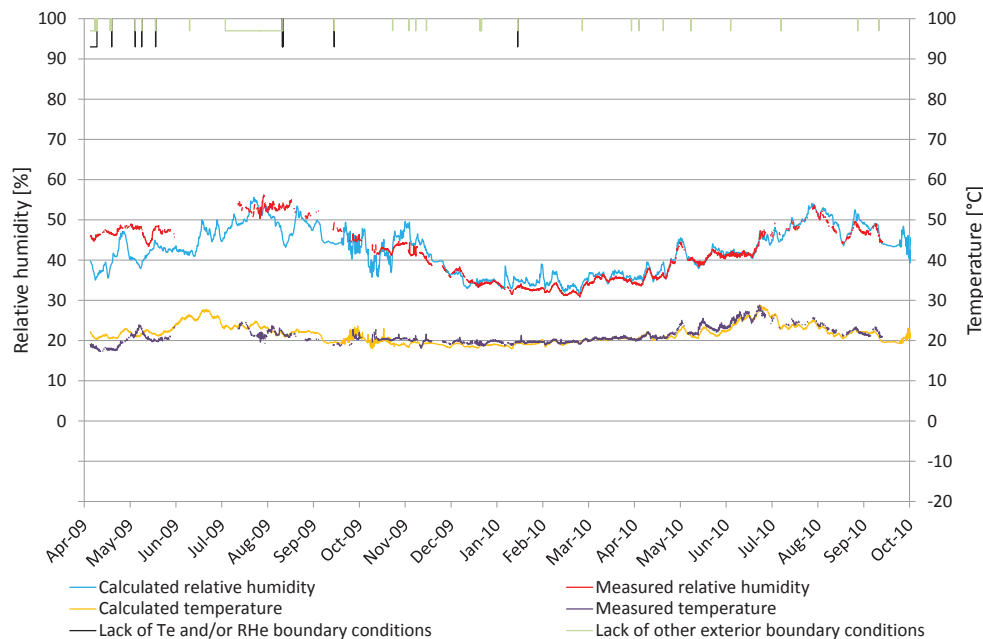**Figure 8.** Position E - Installation layer on the warm side of the vapour retarder. Relative humidity: Calculated (blue), measured (red). Temperature: Calculated (yellow), measured (purple). Lack of boundary condition (green/black).

5 ANALYSIS

The evaluation, as shown in Fig. 1, shows that an extra 17 mm insulation board improves the moisture conditions in position B. However, the evaluation also shows that 17 mm is insufficient to protect the exterior part of the wooden studs from moisture damages.

Calculations in Fig. 3 shows that an 87 mm thick insulation board is needed to prevent mould growth on the outside of the wooden studs. Fig. 3 also shows that 57 mm thick insulation board reduces the risk of mould growth significantly. Not presented initial calculations with standard climate data shows a need of about 65 mm insulation board. Today the building system allows 80 mm insulation board.

The results in Figs. 2 and 3 shows that August is the most critical period although critical conditions occur in other parts of the year to. Because of defective measurements no moisture critical conditions have been measured. For all that we have to assume that mould growth on the studs may occur.

The comparison between calculated and available measured values of relative humidity and temperature in Figs. 4 to 8 shows a considerable convergence witch validates the use of WUFI 5.0. Deficiencies in measurements make positions C impossible to use and position B weaker in analyze.

Divergence in position D and E from April to October 2009 can be explained by the indoor boundary conditions. During this period the indoor boundary conditions are based on the following April to October 2010.

The amplitude of daily calculated values for both relative humidity and temperature are bigger compared to available measured ones in position B and C during the warm period. Daily amplitude of calculated and measured values in position D and E shows agreement throughout the whole period. As

shown in a previous study the daily amplitude is low during the winter (Hägerstedt & Arfvidsson 2010). All used measurement sensors are located close to solid wood. In the calculation model it is only possible to take account of the solid wood structure near position D and E. The fact that calculated daily amplitude in position D and E converges with measured when solid wood is close supports the theory that nearby wood reduce the daily amplitude (Hägerstedt & Arfvidsson 2010). In the calculations model the solid wood is separated from position C by a vapour barrier. This means that the heat capacity of the wood that affects the daily amplitude but not the moisture capacity.

6 CONCLUSIONS

The first conclusion of this study is that the moisture design process has both exposed bad design and improved moisture conditions in critical positions. Unfortunately the modifications in the construction do not seem to be good enough to ensure that no moisture or mould damages will occur.
Today the wall manufacturer has change the design that will allow 80 mm thick insulation board.

The second conclusion is that WUFI 5.0 can be used as a tool in the moisture design process of passive wood framed houses with an open air gap behind the façade material. When using WUFI 5.0 in those cases it is of great importance that proper assumptions, materials, models and boundary conditions are used. The importance of accurate climate data has been shown. The study also shows that it is reasonable to believe that wooden material reduces the daily amplitude inside the wall.

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Comparison of measured and calculated temperature and relative humidity with varied and constant air flow in the facade air gap

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Paper IV

Comparison of measured and calculated temperature and relative humidity with varied and constant air flow in the façade air gap

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KEYWORDS: *Comparison, measurements, moisture, WUFI 5.0, calculations mould*

SUMMARY:
Calculation of relative humidity and temperature in an early stage of the design process is important to avoid moisture damages in wooden walls. Previous studies show that a sufficient air flow in the air gap behind the façade panel is important to ensure a moisture safe construction. This study investigates if blind WUFI 5.0 calculations with a varied air flow in the air gap behind the façade give a better correlation to measured values compared to calculations with a constant air flow. Calculations for two cases are compared to measured values in single family house. The results show that calculations with a wind dependent air flow does not necessary give better correlation to measured values compared to calculations with a constant air flow. However, the calculated values are confirmed with measured values during the warm period and there are deviations in the outer part of the wall during the cold period. Variations in measured values at the same depth in different places in the studied wall are larger compared to differences between calculated values with or without a wind dependent air flow in the façade air gap.

1. Introduction

1.1 Background

Higher demands for more energy efficient buildings in Sweden has led to more thickly insulated houses (BBR 16 2008). Thicker insulation can increase the risk of moisture and mould damage in the outer part of wood walls when organic material becomes more exposed to high levels of relative humidity. The regulations also require that the critical parts of the construction with respect to moisture should be investigated and modified during the design phase (BBR 16 2008). In order to handle this, there is a great need of validated calculation methods and models that are missing today.

This study is a part of a larger research project called "The future wooden houses" where climate conditions in wood framed walls are studied. The project will investigate and validate calculation tools and calculation methods to be used in the moisture safety design process. In this study, WUFI 5.0 (WUFI) was used as calculation tool. The studied house is a newly built single family wood-framed house located outside a small town on the Swedish West coast.

Previous studies with the moisture calculation program WUFI 5.0 show good correlations between measured and calculated values (Hägerstedt 2010 A). Hägerstedt (2010 A) showed that applied air flow in the air gap behind the façade panel is of great importance for the result. In those studies the airflow is constant and differences in compliance may be implied when the climate shifts between seasons (Hägerstedt 2011). Further studies show that the airflow in the air gap behind the façade panel varies depending on wind and thermal conditions and therefore can be different in different places in the air gap behind the façade (Falk 2010) (Nore 2009).

1.2 Aim

The aim of this study is to investigate the correlation between measured and calculated values for temperature and relative humidity in a Swedish standard wood-framed construction. This study includes an investigation to determine if a wind dependent flow of air changes per hour, ACH, in the air gap behind the façade panel, affects calculated climate conditions in the wall compared to if a constant ACH is applied.

The study also investigates if WUFI 5.0 is an appropriate moisture safety calculation tool by comparing measured and calculated values for temperature and relative humidity. Differences between measured temperature and relative humidity at the same wall depth but at different places in the same wall are also presented.

1.3 Limitations

This study does not contain detailed information about functions, parameters and boundary conditions in the calculation program besides differences in used ACH in the air gap behind the façade. Lack of data has not been possible to affect since measurements are made in a real house project. The house construction and location have also determined other boundary conditions in the study.

2. Method

In order to see if there are climatic variations in different parts of the wall, temperature and relative humidity was measured at three different places at the same depth, depth B. In the following section, measurements for temperature and relative humidity at two depths are compared with calculated values from a model with a constant ACH in the air gap behind the façade and another set of calculations with a wind dependent ACH in the air gap. Note that only the main boundary conditions are described as this study focuses on the correlation between measurements and the two blind calculations with different ACH conditions in the air gap. A complete method description with more detailed boundary conditions and limitations are given in Hägerstedt (2010 C).

To show the variation in the local climate conditions in the same wall, temperature and relative humidity were measured and compared at three different points in the wall at the same depth. The three measurement points B.1, B.2, and B.3 are placed as shown in Figure 1, and are located close to wood studs behind the 30 mm outer massive insulation mineral wool board as shown in Figure 2.
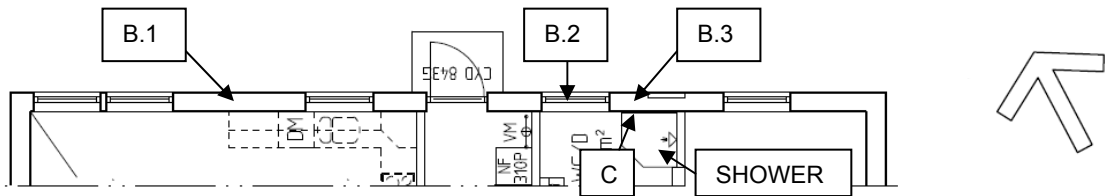

FIG 1. Location of measured places and positions, B.1, B.2, B.3 and C in the North-North West wall.

Measured temperature and relative humidity in positions B.3 and C are compared every hour with the same values from two different calculation models. The measured positions B.3 and C are located at the same point but at different depths in the wall, as shown in Figures 1 and 2 "Built wall". The first calculation model has a constant 30 ACH in the air gap, position A in Figure 2, and the second has a wind dependent ACH in the air gap, position A in Figure 2. Besides the variations in ACH, used calculation models are made to mimic real conditions.

In order to have the same conditions as in the design phase, all calculations with WUFI 5.0 are made blind, i.e. measured values have not been available until they were compared to calculations. The first calculation model has a constant air flow of 30 ACH (Hägerstedt 2010 A) in the air gap behind the

façade, position A, in Figure 2. The second calculation model has a wind dependent ACH in the same air gap. The wind dependent ACH has two modes. If the wind blows away from the façade or is below 1 m/s there are 10 ACH in the air gap. If there is a wind higher than 1 m/s in any direction towards the façade the ACH is 100 ACH (Nore 2009). Although the 100 ACH normally is too low it will not have a big influence on the result as long as the flow can remove penetrated moisture (Hägerstedt 2010 A).

Wall from outside:
15/21 mm Facade panel - Spurce radial[1] including paint Sd=1m[2]
24 mm Air gap with ACH[1]
1 mm Weather resistive barrier[1], Sd=0,2m
30 mm Mineral insulation board[34]
220 mm Light studs/ Mineral insulation[34]
1 mm Vapour retarder[1], Sd=50 m
13 mm Gypsum board[5]
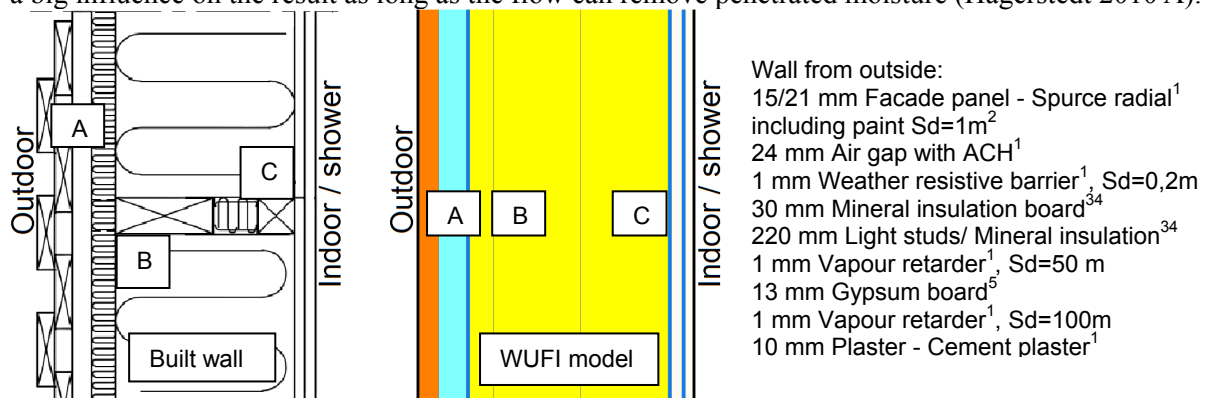1 mm Vapour retarder[1], Sd=100m
10 mm Plaster - Cement plaster[1]

FIG 2. Built wall and WUFI model of wall. Air gap A and measured depth/ positions B and C. (1. IBP) (2. Nevander 1994) (3. IEA Annex 24 1996) (4. Paroc 2002) (5. Krus 1996)

In order to derive deviations, vapour content is calculated from measured and calculated temperatures and relative humidity using the saturation vapour content (Nevander 1994). Measurements and calculations are carried out on a North-North West façade because it is generally the most moisture critical and is less exposed to short wave radiation that affects thermal air transport in the air gap.

Measurements for temperature and relative humidity have been carried out every hour using a wireless Protimeter Hygro Trac system (Sandberg 2011) (GE Sensing 1996). Measurements started 2009-02-02, the same day as the house was mounted and are still running. A great number of measurement sensors have been applied during production at the same time as the constructions were controlled for deviations to drawings.

Calculations for temperature and relative humidity have been made every hour using WUFI 5.0. Climate is from SMHI, Swedish meteorological and hydrological institute (SMHI). Losses of complete hourly climate data and radiation data led to that the nearest climate station not could be used. Differences between local outdoor measured temperature and relative humidity and used outdoor boundary conditions for temperature and relative humidity are shown in the results.

Indoor temperature boundary conditions are based on measurements during the periods 2009-03-12 to 2009-06-10 and 2010-04-28 to 2010-11-30. During the periods with lack of indoor climate data the temperature is assumed to be 22°C, based on known indoor climate data. Periods with a lack of indoor boundary temperature are shown in Figures 4 and 6. Indoor relative humidity has been set to 99 percent because there is a shower with tiled walls and previous studies show a constant wet plaster behind the tiles (Jansson 2006).

3. Measurement result in depth B

3.1 Comparison between measurements in the places B.1, B.2 and B.3

Figure 3 shows measured relative humidity and temperature in the places B.1, B.2 and B.3. The aim is to show if the climate conditions at the same depth in different places in the same wall deviates from each other. The three upper lines show measured relative humidity and the three lower lines shows measured temperature for the same places. The three lines in the middle show vapour content calculated from measured values.
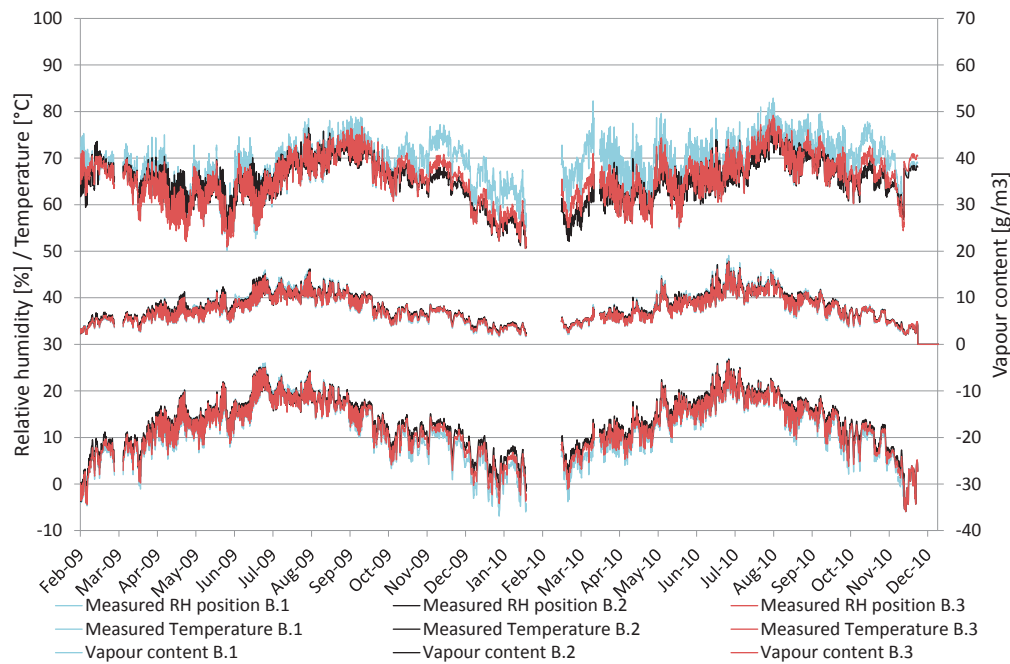
FIG 3. Depth B – Measured relative humidity and temperature at B.1, B.2 and B.3. Vapour content is calculated from RH and T. B.1 light grey B.2 black and B.3 dark grey.

3.2 Measurements results in position B.1, B.2 and B.3

Overall there is a correlation between measured values at all three points. However, there is a stronger correlation between values for B.2 and B.3, which are located close to each other. The largest deviations between measured temperatures and relative humidity occur during the period October -09 to April -10 and October -10 to November -10. Vapour content calculated from measured relative humidity and temperatures show good correlation for all three places. This means that the reason for deviations in relative humidity are due to different temperatures. The influence of thermal bridges, different air flows in the air gap or a higher indoor temperature could be possible explanations.

4. Comparison of measured and two cases of calculated values

This section shows comparisons of measured and calculated relative humidity and temperature in positions B.3 and C with a constant ACH and a wind dependent varied ACH in the air gap. Calculations are carried out for two different cases with a constant air flow of 30 ACH, position A, and a wind dependent air flow of 10 or 100 ACH, in the air gap, position A. Position B.3 and C are located in the same area but at different depths as shown in Figures 1 and 2.

The results are shown in Figures 4 and 6. The three upper lines show measured and calculated relative humidity while the three lower lines show measured and calculated temperature. Calculated values, in black and light grey should correlate to the measured ones presented in dark grey.

In order to explain the causes of deviations, vapour content based on presented relative humidity and temperature are shown in Figures 5 and 7. Those figures also include differences between local outdoor climate data (three hour measurement data) and used outdoor boundary conditions in the calculations (one hour measurement data). A high positive or negative value means a big difference between real outdoor climate conditions and used conditions in the calculations. At the bottom of Figures 4 to 7 are the used ACH for the calculation case with a wind dependent ACH shown. At the top of Figures 4 and 6 periods with lack of data in indoor climate and assumed temperatures of 22 degrees are shown.

4.1 Measured and two cases of calculated relative humidity and temperature in position B.3

Measured temperature and relative humidity compared to the same calculated values for two cases with constant 30 ACH and a wind dependent ACH of 10 or 100 ACH in the air gap behind the façade.

FIG 4. Position B.3-Relative humidity/ Temperature outside of the wood studs: Measured (dark grey), calculated with 30 ACH in the air gap (light grey), calculated and wind dependent ACH in the air gap (black), 10 or 100 ACH (light grey in bottom). Periods with lack of indoor data (black in top).

Figure 5 shows vapour content from measured and calculated values in Figure 4. Differences between local measured outdoor climate (3 h data) and used boundary conditions in calculations (1 h data).

FIG 5. Position B.3-Vapour content outside of the wood studs: Measured (dark grey), calculated with constant 30 ACH in the air gap (light grey), calculated and wind dependent ACH in the air gap (black). Variation in local outdoor T /RH (3h) and used T/RH in calculations (1 h) (in top black/grey).

4.2 Measured and two cases of calculated relative humidity and temperature in position C

Measured temperature and relative humidity compared to the same calculated values for two cases with constant 30 ACH and a wind dependent ACH of 10 or 100 ACH in the air gap behind the façade.
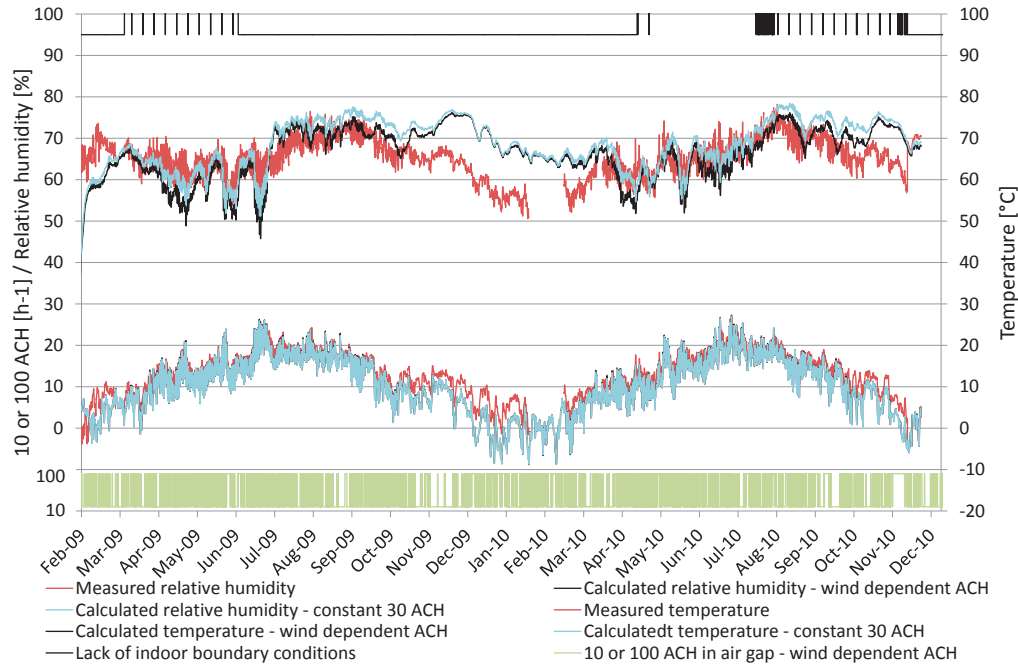

FIG 6. Position C-Relative humidity/ Temperature outside of the wood studs: Measured (dark grey), calculated with 30 ACH in the air gap (light grey), calculated and wind dependent ACH in the air gap (black), 10 or 100 ACH (light grey in bottom). Periods with lack of indoor data (black in top).

Figure 7 shows vapour content from measured and calculated values in Figure 6. Differences between local measured outdoor climate (3 h data) and used boundary conditions in calculations (1 h data).
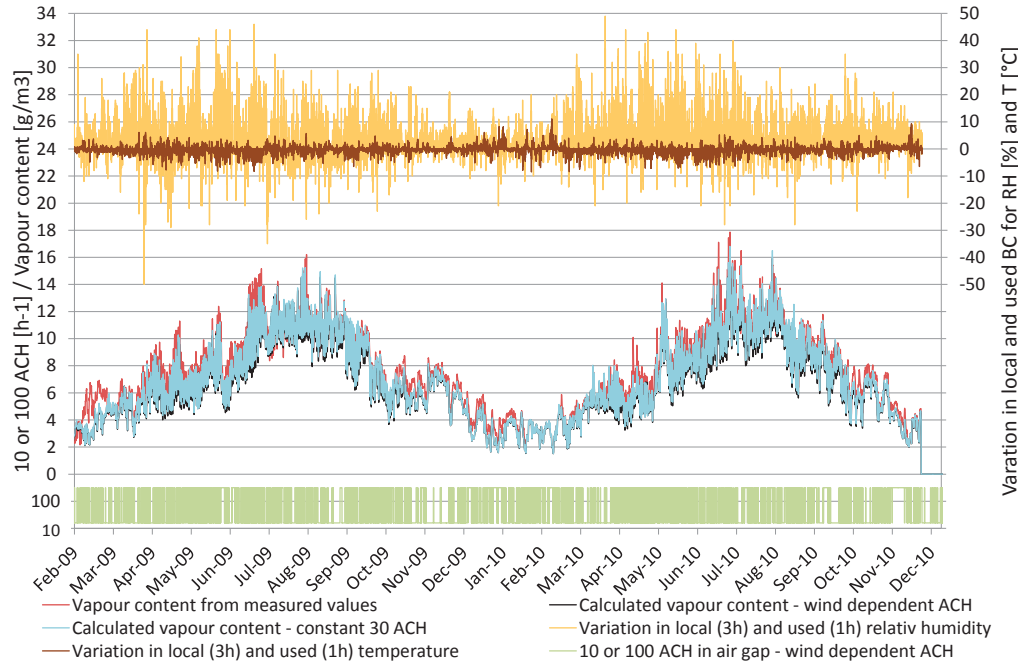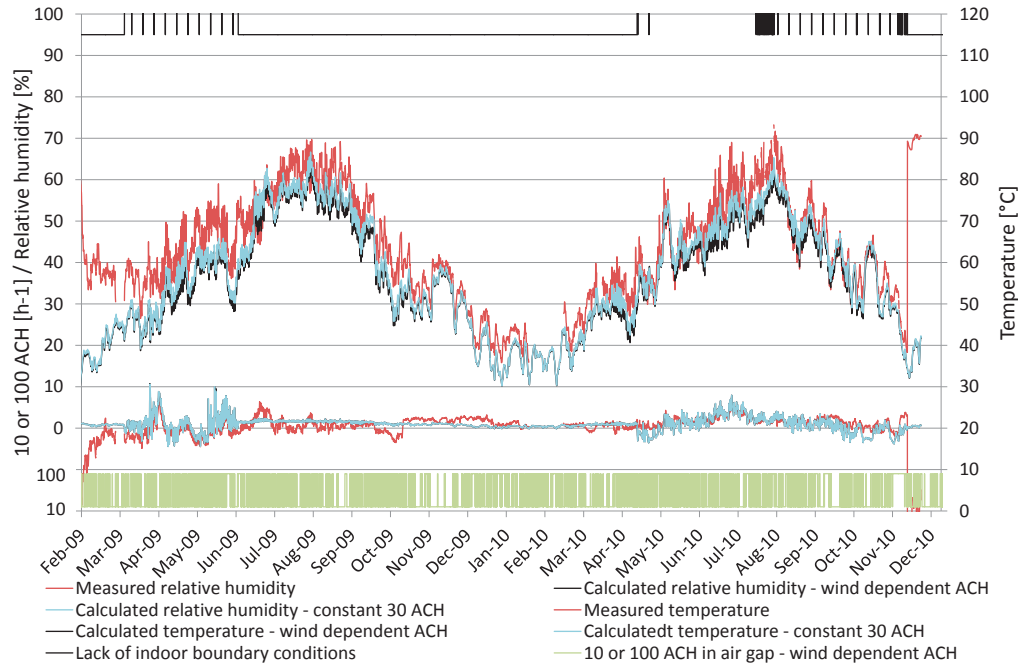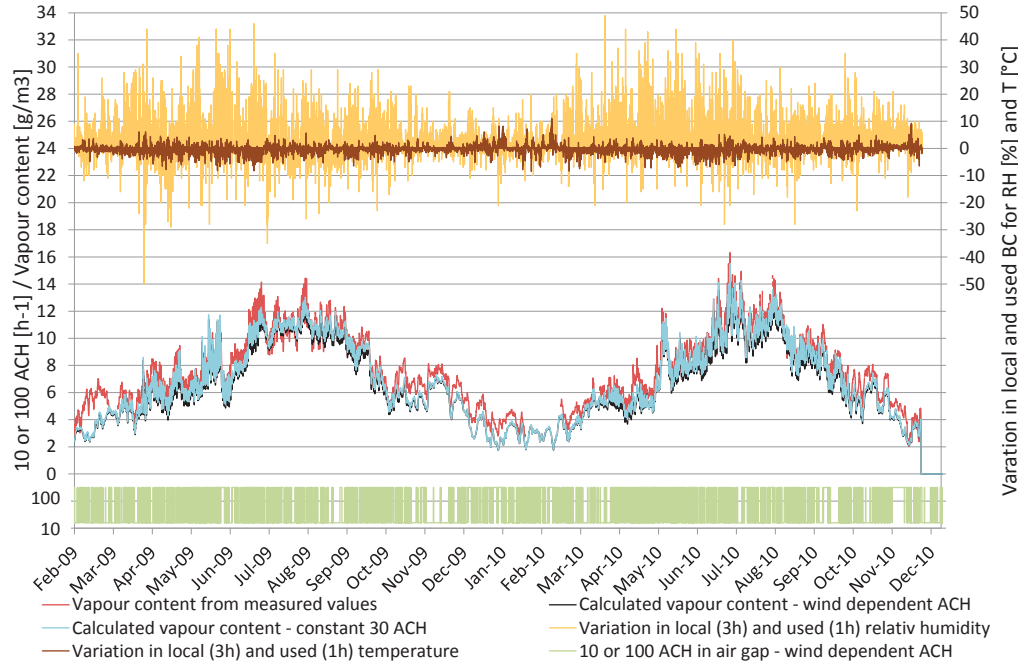

FIG 7. Position C-Vapour content outside of the wood studs: Measured (dark grey), calculated with constant 30 ACH in the air gap (light grey), calculated and wind dependent ACH in the air gap (black). Variation in local outdoor T /RH (3h) and used T/RH in calculations (1 h) (in top black/grey).

4.3   Comparison between measured and calculated values in position B.3 and C

Beside the cold periods between October -09 to April -10 and October to November -10 there is a good correlation between measured and calculated values for the two different cases in position B.3. In position C, deeper into the wall, measured and calculated values correlate during the whole period.

Previous studies have indicated that there might be less correlation between measured and WUFI 5.0 calculated values in the outer part of the wall during the winter (Hägerstedt 2010 B). In this case the deviation becomes clear. The correlation in vapour content during the period show that deviations in relative humidity depend on temperature differences. Position B.1 at the same depth but at a different part of the wall, also shows the same pattern compared to other positions. The reason for the deviation cannot be determined but a higher indoor temperature compared to set boundary conditions as shown in Figure 6 could be a factor. Thermal bridges or an incorrect ACH are also possible explanations.

In position C, the measured relative humidity tends to remain a little higher compared to calculated values because of a higher vapor content, as shown in Figure 7. Correlation between measured and calculated temperatures in position C, in Figure 6, show that assumed temperature of 22°C is good. There are no differences between the two calculated cases, with constant 30 ACH and a wind dependent ACH. During certain periods the curves cover each other. This is expected because the air flow in the air gap has a lower influence of the climate conditions deeper into the wall.

The two calculated cases show good correlation with measured values during different periods in position B.3. Differences between the two calculated cases are smaller compared to the variances between B.1, B.2 and B.3. Calculated relative humidity with a constant air flow of 30 ACH tend to have higher relative humidity compared to the case with a wind dependent ACH, and would have correlated better with position B.1 in Figure 3. Differences in calculated values for the two cases shows that the ACH affect the calculated values in position B.3 but the variations could not be connected to specific periods with 10 or 100 ACH in the wind dependent case.

Differences between local outdoor measured climate data and used outdoor boundary conditions in the calculations cannot be traced to deviations between measured and calculated values. In fact the opposite, since the largest deviations in October -09 to April -10 occur when there are low differences between used boundary conditions and local measured climate.

Differences in amplitude in Figure 4 between measured and calculated relative humidity shows a notable deviation compared to previous studies. In this case the measured relative humidity has higher amplitude compared to calculated values. Normally it should be the opposite. (Hägerstedt 2011) The use of light beams with lower thermal bridges and lower thermal load might be the explanation.

Values before June -09 might not be full representative because the house was not inhabited. The initial period is probably more affected by moisture from the construction process.

5. Conclusions

Comparison between measurement places at the same depth, B.1, B.2 and B.3 show that the climate conditions in a wood framed wall near the façade can vary in different places. In this case the relative humidity varies up to 10 percent, depending on different temperatures, between the places.

In this study WUFI 5.0 tends to generate low temperatures compared to measured values in the outer part of the wall during the cold period of the year. This gives a higher calculated relative humidity compared to measured values. Besides the cold periods there is good correlation between measured and calculated values.

A wind dependent ACH in the air gap behind the façade does not necessary give better correlation between measured and calculated values. Differences between calculated relative humidity with constant 30 ACH and a wind dependent ACH in the air gap is smaller than the differences between

measured values in different places at the same depth in the wall. This means that the local conditions in air gap and the wall can be of greater importance than calculations with a wind dependent ACH in the air gap, as long as the flow is high enough to dry out incoming moisture (Hägerstedt 2010 A).

The correlation between measured and calculated values, although the differences between used boundary conditions and local measured climate, shows that the calculations tend to be stable as long as outdoor climate data are similar to the local climate.

6. Acknowledgements

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Moisture risk evaluation and determination of required measures to avoid mould damage using the Folos 2D visual mould chart

Paper V

Moisture risk evaluation and determination of required measures to avoid mould damage using the Folos 2D visual mould chart

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Abstract: There is an increased interest in and awareness of mould growth damage in buildings. Today's mould growth models are limited to only presenting the risk of mould growth. They do not take into account underlying factors and other parameters that make it possible to establish necessary measures to limit or avoid the risk of mould growth. This paper presents a chart that can be used to determine these measures, both to reduce the risk of mould growth in buildings and, at the same time, indicate the risk of mould growth. The chart can be based on all known risk models for mould growth. No new mould growth model is presented; only an illustration of how it is possible to use known models in practical moisture safety design processes. The chart can also be used to compare different structural designs, measured and calculated values, and to show how mould growth risk prediction depends on which mould model is used.

Keywords: Mould model, risk of mould growth

1. Introduction

1.1 Background

Newly introduced laws and requirements, in combination with observed mould growth damage in buildings, has meant increased interest in the factors affecting mould growth in buildings [1, 2, 3]. Furthermore, recent studies also show that today's highly insulated buildings are more sensitive to mould growth damage [4]. Several models showing conditions for, and risk of, mould growth on building materials have also been developed. Most of the models are relatively similar, as shown in figure 1 [5]. However, many models are limited to only showing whether or not there is a risk of mould growth, below or above the critical lines in Figure 1, without presenting the underlying factors affecting the risk of mould growth or when the risk of mould growth would occur. The lack of knowledge about the underlying factors hides required measures to avoid mould growth and makes it difficult to compare different design solutions. Furthermore, there are different views on how the influence of duration should be regarded and how possible risk levels regarding mould growth should be dealt with [5, 6, 7, 8].

1.2 Aim

The purpose of this article is to present a chart that illustrates the underlying factors affecting the risk of mould growth in a specific location in a construction. Knowledge of these underlying factors makes it possible to evaluate the measures that can be taken to limit or avoid the risk of mould growth. Furthermore, the chart aims to make it possible to compare the conditions in different locations within a structure as well as different designs and different mould models. The risk of mould growth can be presented according to any chosen mould growth model.

1.3 Limitations

This article is limited to presenting a chart that includes the factors used to evaluate the risk of mould growth and the measures that might be required in order to avoid mould growth. No new mould growth models are presented. However, the chart has been constructed in such a way that it can be used for any mould growth model.

2. Fundamentals

2.1 Factors affecting mould growth

The risk of mould growth depends on several different factors. Besides different materials having different resistance to mould growth, there is wide agreement that the dominating factors affecting mould growth are the temperature, relative humidity (RH) and duration above critical conditions, i.e. the length of time when temperature and RH allow mould growth to occur [9, 10]. As mentioned above, the different mould growth models show similar behaviour where the influence of temperature and RH is concerned, as shown in Figure 1 [5]. Critical conditions (RH_{crit}) are defined as the conditions when mould growth is possible. RH_{crit} varies depending on temperature, as shown in Figure 1 [5, 8]. RH_{crit} occurs when the RH, at a specific temperature and time, is above the specific RH_{crit} curve for each mould growth model. RH_{crit} does not necessary lead to mould growth. Different materials have different RH_{crit} lines [9].
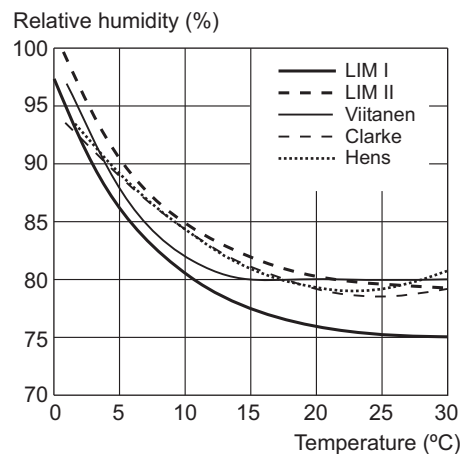

Figure 1: Different mould models show similar behaviour with respect to temperature and RH [5].

Differences between existing mould growth models mainly concern the way in which the influence of duration is treated, if at all. The influence of duration includes both the conditions above RH_{crit} and the possible decline of mould growth during non-critical conditions.

Besides each material having specific limits for RH_{crit} and the influence of the main factors temperature, RH and duration above RH_{crit}, there are other factors that affect the risk of mould growth. Examples of such factors are the amount of dirt or dust on the surface of the material, surrounding microbial conditions, shortwave radiation and moisture content in the material [9].

2.2 Examples of existing mould models

Several mould models investigate the risk of mould growth using charts, as shown in Figure 1, to present their findings [5, 8]. During the evaluation of mould risk, isopleth dots, indicating an RH level and temperature at one specific time, are normally plotted on a chart similar to that in

Figure 1. Hourly based evaluation over one year will give 8760 dots. Dots above the line indicate RH$_{crit}$ conditions and dots below indicate non-critical conditions [7, 8]. However, the point in time when critical conditions occur or the influence of duration is not shown.

Mould models including the influence of duration mainly refer to a mould index (MI) or relative dose that must not be exceeded if mould growth is to be avoided. Some models take into account the effect of duration both during RH$_{crit}$ conditions, with regard to germinating mould growth, and during non-critical conditions with regard to the decline in mould growth, as shown in Figure 2 [5, 6]. Other models only deal with the influence of duration during RH$_{crit}$ conditions and do not take into account any decline of mould growth [5, 7]. However, factors that affect the mould index or relative dose, such as RH or temperature or the vapour content, are not shown. There are also models that calculate the probability of mould growth in relation to duration time [12]. Some models only present a number as mould growth risk [13].
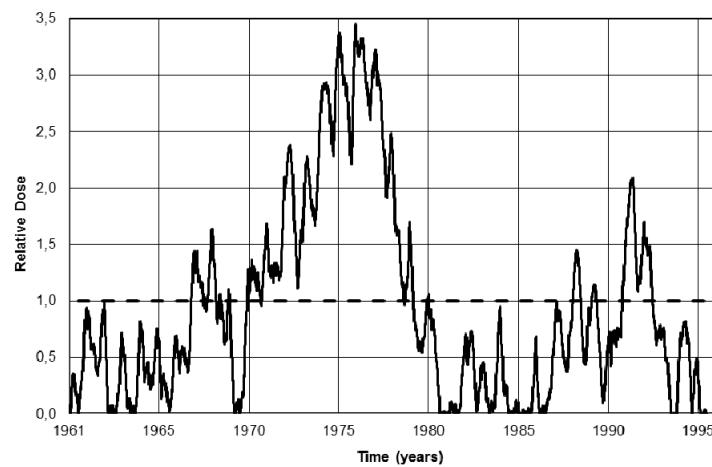

Figure 2: Mould model that takes into account the influence of duration on mould growth and decline of mould growth without showing the factors affecting the risk of mould growth [6].

3. Description of the Folos 2D visual mould chart

3.1 Parameters in the Folos 2D visual mould chart

The Folos 2D visual mould chart, shown in Figure 3, visualizes the factors temperature (yellow) on the right y-axis and RH (turquoise), RH$_{crit}$ (red), the RH > RH$_{crit}$ difference (light brown) and MI divided by 10 (green dotted line) on the left y-axis. The time presented on the x-axis indicates the conditions at each specific time and particularly the periods when RH > RH$_{crit}$.

When a moisture risk evaluation is carried out in the design phase, temperatures and RHs are calculated. Normally, the calculated RHs for one year are shown as 8760 isopleth dots in a chart similar to that in Figure 1. The same RH isopleth dots create a line when presented over time in the Folos 2D visual mould chart. The temperature is also given for each specific point in time.

RH$_{crit}$ conditions occur, and mould 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 1, i.e. the chosen RH$_{crit}$ line from Figure 1 is converted over time by using the actual temperature at each point in time. This means that RH$_{crit}$ conditions depend on the prevailing RH and temperature, where a high temperature gives a low RH$_{crit}$ line and vice versa. Depending on the legislation in different countries, the RH$_{crit}$ line could be used to define

a limit [2, 14]. The RH$_{crit}$ line in Figure 3 is based on the Viitanen curve shown in Figure 1. However, it is easy to use another mould growth model by choosing another appropriate curve.
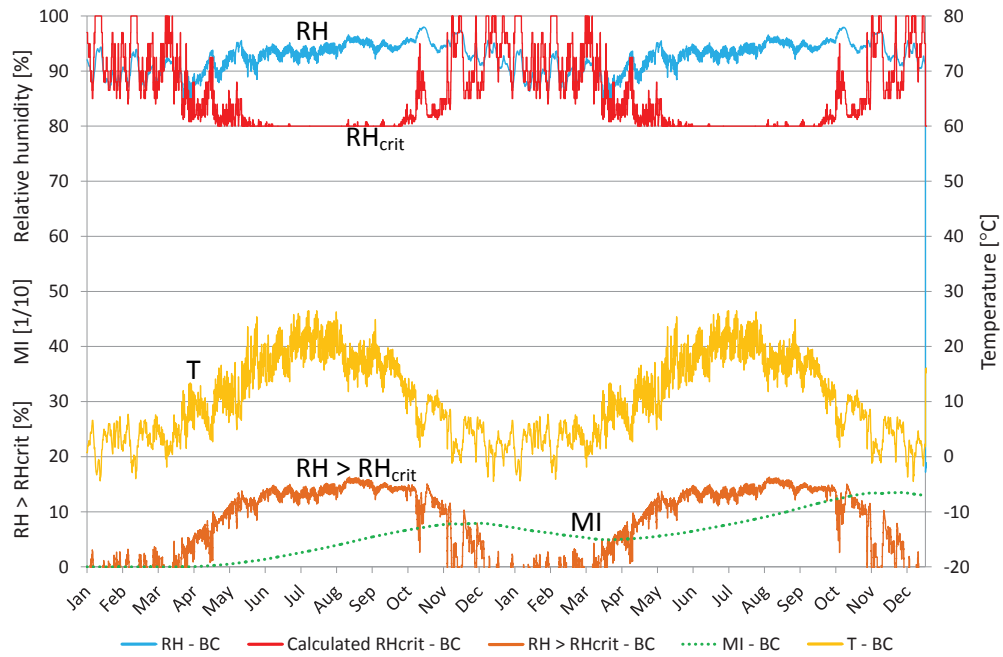

Figure 3: The Folos 2D visual mould chart with calculated values for the basic construction (BC) shown in Figure 4 including the parameters temperature (yellow), RH (turquoise), RH$_{crit}$ (red), RH > RH$_{crit}$ (brown) and MI (green dotted line).

The parameter RH > RH$_{crit}$ shows how much, when and for how long RH exceeds RH$_{crit}$.

The parameter MI shows the mould index as described in [11, 15]. In order to read the correct MI value, the scale number on the left-hand y-axis must be divided by 10, i.e. 10 = 1, 20 = 2 etc.

Furthermore, the vapour content could also be of interest. This can be easily calculated from the temperature and RH using Equation 1 and added to the chart.

$$RH = \frac{v}{v_s} \qquad\qquad (1)$$

where *RH* is the relative humidity, *v* the vapour content and *v$_s$* the vapour content at saturation, depending on the temperature [16]. RH and temperature are known from the initial calculated conditions.

Other factors that affect the risk of mould growth, such as climate conditions or moisture content, could also be added to the Folos 2D visual mould chart.

3.2 Evaluating the risk of mould growth and required measures to limit the risk of damage

RH$_{crit}$ periods, when mould growth is possible, are shown as periods when RH > RH$_{crit}$ in the Folos 2D visual mould chart. The greater the RH > RH$_{crit}$ differences and the longer the periods when RH > RH$_{crit}$, the higher the risk of mould growth.

The level of RH and, furthermore, the risk of mould growth on a specific material can mainly be affected by changing the vapour content or the temperature, which affects the vapour content at

saturation. A lower level of vapour content or a higher temperature gives a lower RH as shown in Equation (1) [16]. By using this relationship it is easy to define what measures are needed.
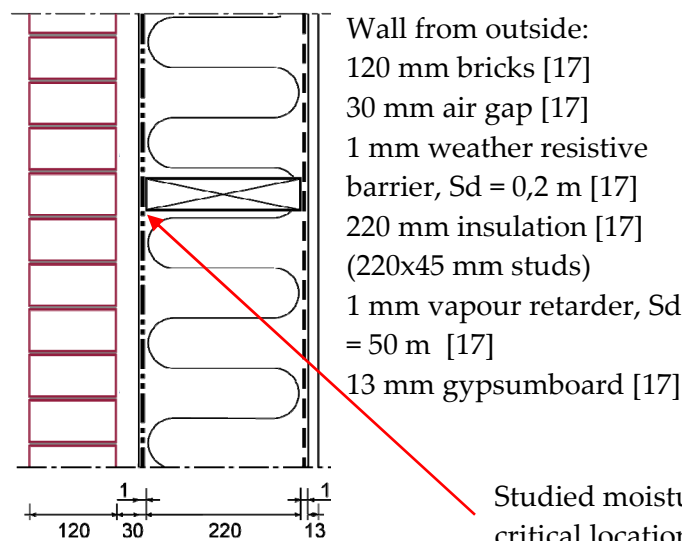
Periods with RH > RH$_{crit}$ and high temperatures, June to September in Figure 3, have to be dealt with using measures that reduce the vapour content, such as higher rates of ventilation in the façade air gap, as shown in Figure 4.

Periods with RH > RH$_{crit}$ and low temperatures and low vapour content, October to November in Figure 3. This period could be dealt by applying measures that result in higher temperatures, such as fitting a mould-resistant insulation board onto the outer frame, as shown in Figure 4.
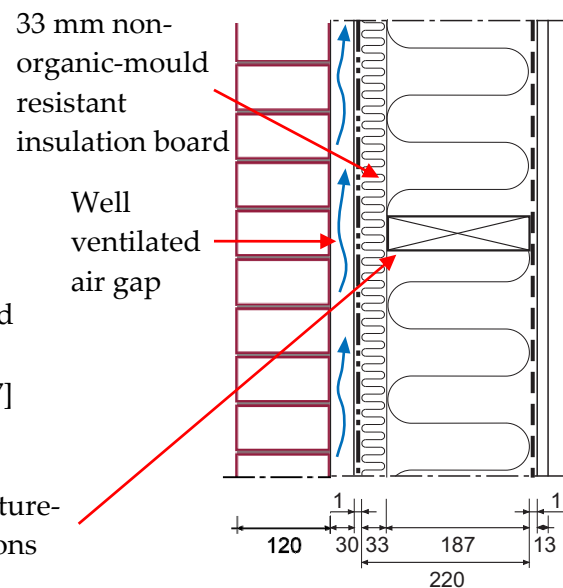
Shorter periods with RH > RH$_{crit}$, December to March in Figure 3, would probably not need to be dealt with as the duration of RH > RH$_{crit}$ is not long enough to create mould growth. However, in some cases, measures are required that can create both lower vapour contents and higher temperatures.

If it not is possible to create non-critical conditions, or the risk of mould growth is not predicted to be eliminated by a model that includes the influence of duration, the design might have to be changed. Materials could be replaced by materials with higher resistance to mould growth, i.e. a material that has a higher RH$_{crit}$ limit. The design could also be changed in such a way that more or less vapour transport, dependent on the design, through different material layers is possible.

Basic Construction (BC)   *Modified Construction (MC)*

Wall from outside:
120 mm bricks [17]
30 mm air gap [17]
1 mm weather resistive barrier, Sd = 0,2 m [17]
220 mm insulation [17] (220x45 mm studs)
1 mm vapour retarder, Sd = 50 m [17]
13 mm gypsumboard [17]

33 mm non-organic-mould resistant insulation board

Well ventilated air gap

Studied moisture-critical locations

Figure 4: Example of possible measures that could be used in Swedish climate conditions to eliminate or reduce the risk of mould growth [4]. Calculations made using WUFI 5.0 [17].

4. Other possible comparisons using the Folos 2D visual mould chart

The Folos 2D visual mould chart could also be used to compare different locations within structures or different structural designs, different mould models with different risk levels of mould growth, and differences between measured and calculated temperature and RH in actual structures. Figure 5 shows a comparison carried out using WUFI 5.0 calculations for the Basic Construction (BC) and the Modified Construction (MC) shown in Figure 4. Figure 6 shows an

example of how the Folos 2D visual mould chart could be used to compare measured and blind calculated values.
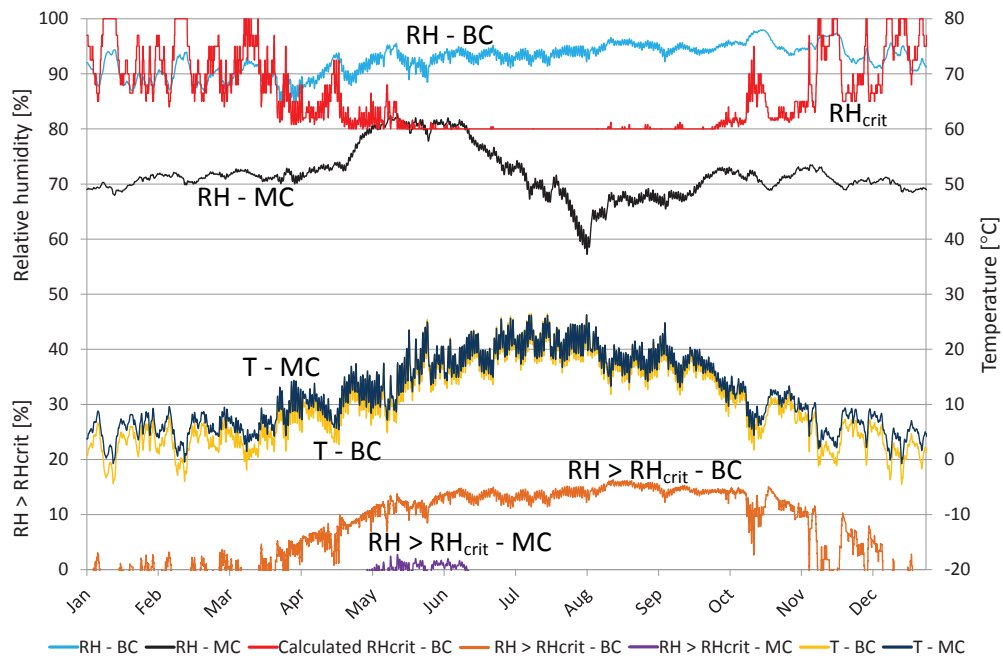
Figure 5: Folos 2D visual mould chart with comparison of critical location in the basic (BC) and modified (MC) structure. BC temperature (yellow), MC temperature (dark blue), BC RH (turquoise), MC RH (black), RH$_{crit}$ depending on BC temperature (red), MC RH > RH$_{crit}$ (brown), MC RH > RH$_{crit}$ (purple).
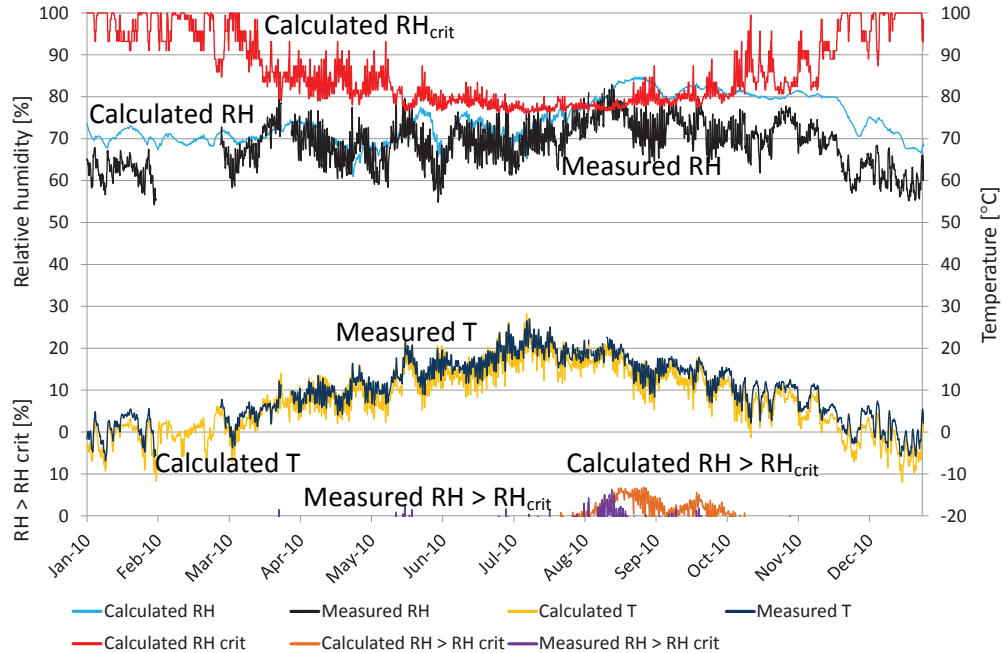
Figure 6: Folos 2D visual mould chart with comparisons of measured and calculated temperatures and RH in a construction [18]. Levels of RH$_{crit}$ from LIM I in Figure 1 [8]. Measured temperature (dark blue), calculated temperature (yellow), measured RH (black), calculated RH (turquoise), RH$_{crit}$ depending on calculated temperature (red), measured RH > measured RH$_{crit}$ (purple), calculated RH > RH$_{crit}$ (brown).

In order to limit the number of plots, there is only one RH_{crit} plot and no mould index (MI) in Figures 5 and 6. Gaps in the comparison between measured and calculated values indicate a lack of measured values.

In the comparisons between measured and calculated values, differences can be seen in the Folos 2D visual mould chart, as shown in Figure 6. By using the relationship in Equation 1, it is easy to determine whether the differences between the measured and calculated RH depend on the differences between measured and calculated temperature, or vapour content, or both. A separate plot for calculated vapour content might need to be added to the chart.

5. Discussion

The article demonstrates how the Folos 2D visual mould chart might be used to evaluate the risk of mould growth and, at the same time, establish what measures need to be taken to limit or avoid the risk of mould growth. This is done by investigating the underlying factors, such as temperature and RH. The Folos 2D visual mould chart could also be used to compare different structural designs, measurements and calculations, and different mould models. To encourage the use of the Folos 2D visual mould chart it could be introduced as a tool when implementing the ByggaF moisture safety design recommendations during the design phase [19].

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Moisture safety in wood frame constructions – What do we know today? – A literature overview

Paper VI

Moisture safety in wood frame constructions – What do we know today? – A literature overview

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Summary

This paper intends to offer an overview of current knowledge in practical moisture safety in wood frame house. Books, journal articles, reports and other documents at different levels regarding moisture and moisture safety in different aspects are summarized. Possible gaps and flaws in existing knowledge, such as, lack of blind verifications of moisture safety calculation tools, the need to separate quantitative and qualitative issues in the moisture safety design processes and the fact that mould growth model handle the influence of duration in different manners are reported.

Keywords: Moisture safety, mould growth, wood frame constructions, literature overview

1. Introduction

1.1 Background

The interests of using wood frame constructions have increased during the last decade depending on the intention to build more carbon dioxide, CO_2, efficient houses [1]. In Northern European countries there is also a tradition of wood frame houses and plenty of wood as raw material that can be used in buildings [2] [3].

Regardless what materials or design system is used there is a need to build moisture safe constructions. Moisture damages are linked to negative consequences, extra costs and cause sickness and bad health because of inadequate indoor climate and Sick Building Syndrome [4].

Today, there is a relative good basic knowledge in the area of building physics, moisture transport and factors affecting mould growth [5] [6] [7] [8] [9]. However, since moisture related damages still is common and cause high costs and bad indoor climate it may be questioned if there are areas with lack of knowledge and if or how knowledge in the moisture safety area are implemented in the building industry [4] [10] [11].

1.2 Aim

The aim of this paper is to give an overview of current knowledge in the moisture safety area in wood frame constructions. The intention is also to present new insights into underlying factors, results from field studies and strategies to avoid mould and moisture damages as well as to discuss mould models and calculation tools that can be used to predict mould and moisture damages in wood frame constructions. Furthermore, the paper aims to show weaknesses and gaps in existing knowledge and research in the moisture safety area and suggest direction of further research.

1.3 Limitations

The paper does not include a complete review of all knowledge in the field and it is instead more a kind of "state-of-the-art" that overviews and presents the latest knowledge. The study does not aim to discuss and evaluate basic building physic knowledge. Furthermore, it is limited to focus on wood frame constructions. Material data and boundary conditions are not considered. Additional steps have been taken to especially present literature that is useful and applicable to applied research and possible to use in real building constructions, without any further development. Some references are given in national languages such as Swedish, Finnish and German.

2. Literature search method

This paper consists of studies and research documents at different levels. The connection between and effects of qualitative and quantitative factors also make it necessary to include studies at different levels. Therefore the study includes doctoral theses and international reviewed journal articles as well as national institute reports, conference papers and master- and bachelor theses.

Initially, searches in open access data bases in the area were carried out, but mostly with poor results. The only open database that showed relevant and reasonable hits was Google Scholar. This may depends on that the topic of applied building physics seem to be primarily published for national use since the construction sector is strongly national. In the area of mould and moisture, the local climate has a big influence, and, consequently, only Nordic research is useful in the Nordic area. Furthermore, the construction sector acts conservatively and in a closed manner [10] [11], i.e. findings and knowledge are not supposed to be spread to competitors. Instead of a random literature search on Google Scholar, references and authors in known documents were used to find new relevant documents. A risk with this kind of search is that critical articles may have been excluded.

Furthermore, conference proceedings from the latest conferences in the area have been used and scanned. This has given both an overview of the present knowledge level and a good picture of the most recent research results that have been published.

The fact that some research in the area is connected to national experience or local conditions and traditions have made that national institute reports and master's and bachelor's theses also have been studied. In addition, the SP Technical Research Institute of Sweden database was used.

3. Summary of studied representative papers, articles and documents

Below are important facts from several studied journal articles, conference papers, thesis and other documents summarized in different groups depending on their content. A more detailed description of total 146 documents is shown in a separate report [12].

3.1 Laws, Rules and Regulations, Enquiries and National Investigations and Reports

By studying building laws, rules and regulations concerning mould and moisture in some European countries it seems that there is variation in demands, structure and limitations. Some countries focus on qualitative limits and some connect mould and moisture risks to inhabitant's health. Furthermore, there are countries that give recommendations, qualitative or quantitative, how to avoid mould and moisture related damages. In general, studied laws, rules and regulations seem to be underdeveloped compare to regulations in other building areas such as statics, availability, fire safety and energy use [13] [14] [15].

Furthermore, studied Swedish national investigations show that there is a lack of knowledge in the moisture safety area and unclear responsibilities [10] [16]. Verified methods and calculation tools to predict and avoid moisture damages are also required [4].

3.2   Moisture Safety Design Methods

Different moisture safety design processes and methods to avoid moisture related damages have been found. Some methods concern qualitative issues, i.e. practical or basic knowledge, and some quantitative issues, i.e. measurable [12]. Only one moisture safety design method that concern both qualitative and quantitative issues and cover the entire building process has been found [17]. Studied quantitative methods focus on a maximum relative humidity with respect to duration limits to avoid mould growth in buildings [18] or use statistic methods calculating the risk of mould growth [19] [20]. There are also moisture safety design methods that focus on qualitative issues [21]. General guidelines in order to achieve high quality timber buildings where moisture related questions are briefly discussed have also been found [22].
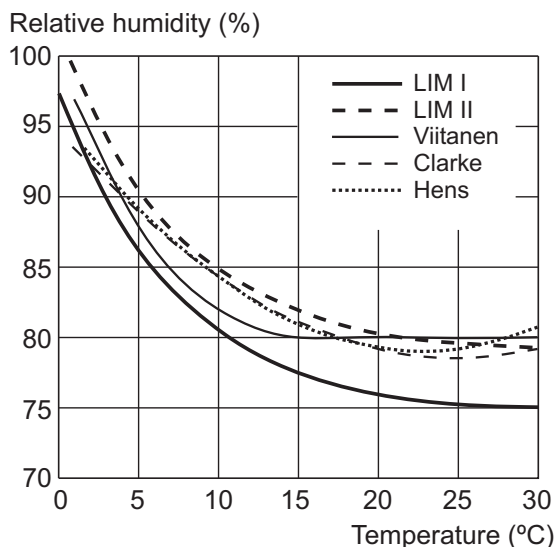
3.3   Mould Growth Models

Fig. 1 Example of different mould growth models dependent on relative humidity and temperature [23].

There is a broad agreement that different material has various sensitivity to moisture and that temperature, relative humidity, and duration are the main factors affecting the risk of mould growth [23]. Several of mould growth models have also been invented based on those facts, as shown in Figure 1. However, the models have a number of different theories and models about reducing, if this is at all possible, the amount of mould growth during non-favourable mould growth climate conditions. Furthermore, different critical levels with regard to the effects of duration are presented and none of studied mould growth model include the influence of short time climate variations [24] [25] [26] [27]. The mould growth models mainly show if there is a risk of mould growth or not, without presenting underlying factors affecting the risk of mould growth and possible actions in order to avoid or reduce the risk of moisture damages [28].

3.4   Water Proofing Membranes in Wet Rooms/ Bathrooms

Bathrooms, and other wet rooms, are pointed out as an area where mould and moisture damages have high cost [4]. Many bathrooms with exterior walls made of wood in Nordic European countries have three different vapour resistance membranes. To avoid damages, the interior waterproofing membrane in bathrooms has to have a higher vapour resistance compared to the other vapour membranes in the wall. Studies show that many waterproofing membranes has to low vapour resistance compare to other vapour retarder membranes in the wall. Therefore penetrating vapour become locked in, between the interior waterproofing membrane and the vapour retarder, and creates mould damages [29]. Acceptable vapour resistance of weather or wind resistive barrier in the outer part of the wall depends on the vapour resistance on the other membranes and the exterior climate. Furthermore, the vapour resistance is often given by a test method that neglects the influence of high relative humidity. Unfortunately, waterproofing membranes have shown significantly higher vapour diffusivity if there is a high relative humidity, which naturally occurs in bathrooms. This increase the risk of moisture related damages in exterior bathroom walls [30].

Many damages also occurs dependent on detailing errors. Several waterproofing membrane systems have been tested for leakages in or close to installations, pipes penetrations or other details with bad results. None of the systems had acceptable solutions for detailing [31]. The influence of detailing errors is also shown in damages investigations where the main cause of damage was poor sealing around or close to the floor drainage point. An interesting result from a limited study shows that "amateur" work appeared to be better than work carried out by professional workers [32].

3.5   Airtightness in Buildings

The quality of airtightness in buildings mainly depends on good detailing and a building design or building system that allows good joints between airtight membranes. Plenty of examples with constructions detailing and solutions of how joints can be put together and sealed have been found, both as literature and in forms of mounting instructions from material industry [33] [34] [35]. There are also validations made of different sealing methods [36]. New materials, especially membrane tools for joints and detailing, seem to be constant developed by the industry. Furthermore, methods handling air tightness during the entire building process, including verifications, have been found [37].

3.6   Rendered Non-Drained and Unventilated Facades

It is well known that rendered non-drained wood frame walls without a ventilated cladding, so-called ETICS design, are a risk construction [38]. A great number of moisture damages have been found in houses with this design [39]. The main causes of damages are detailing error, poor workmanship and leakages of penetrating driving rain. Suggestions of possible moisture safe repairs for damaged walls [40] as well as studies showing the positive effects and importance of a well-ventilated air gap behind the claddings have been found [41] [42].

3.7   Moisture Risks During the On-Site Construction Phase

Recent Swedish field studies show that mould growth are noticed in wood frame houses that have become exposed to only one rain during the on-site production of wood element, even in cases where the mounting have been completed in one day. The risk of mould growth is highly dependent on the prevailing weather conditions during the on-site production until the house is made weather tight [43]. Furthermore, laboratory studies show that if sills or studs become exposed to rain during the construction phase they also become damaged by mould growth [44]. However, there are general and detailed methods, descriptions and measuring methods of how to control and handle moisture in wood material during the on-site construction phase [17] [43] [45].

3.8   Well-insulated Wood Frame Houses

Well-insulated constructions are generally more sensitive to mould- and moisture damages compared to less insulated constructions [46]. This depends on several factors such as higher amount of initial construction moisture, longer dry out times and a higher amount of cold parts in the construction. To build moisture safe well-insulated wood frame houses there have to be a well-ventilated and drained air gap behind the cladding, the influence of driving rain have to be considered and organic materials in the outer part of walls have to be protected by mould resistant thermal insulation. Furthermore, there is a need of an interior vapour barrier in cold climate and the outer parts of walls have to have vapour diffuse open materials to facilitate the dry out process of in-leaking water and initial construction moisture [8] [47]. However, the risk of increased moisture damage is not significantly higher in newly build Swedish cold attics since they are already normally well-insulated [48]. The influence of long wave radiation and the air ventilation rate in cold attics also have a major influence on the risk of mould growth damages in attics [49].

3.9   Air Flow Rate in the Air Gap in Ventilated Cladding

Different studies establish the need of a well-ventilated and drained air gap behind the cladding for several moisture safety reasons. The service life of the facade is positively affected of a well-ventilated air gap [50]. The dry out potential from both the façade and the wood frame wall on the inside of the air gap increase if the air gap is well-ventilated [42]. In case of a brick façade with a wood frame construction behind the air gap it is even more important to establish a proper air flow in the air gap, which gives a high air ventilation rate, in order to achieve a moisture-safe building [51]. A 25 mm wide air gap behind wood façades and a 50 mm wide air gap behind brick façades is suggested [42] [47] [52]. Furthermore, the importance of a well-ventilated air gap increases in well-insulated wood constructions. A well-ventilated air gap with vertical or perforated battens also has positive effects on drainage and decreasing the air pressure difference over the cladding [47].

3.10 Moisture Calculation Programs

There is a need of reliable and user friendly calculation tools that could be used to predict and avoid moisture related damages [4]. Several moisture calculation programs with coupled heat- and moisture transport have been found [12]. Most of the programs use forward differential equations methods [6] [53] [54] [55] [56]. The availability of using forward differential equation method in real cases has been known since the 70´s. However, it has not been possible to apply this knowledge to real conditions because of the lack of computer capacity [53]. Some programs based on the finite element calculation method have also been found [12] [57]. Many programs seem to be based on the same general equations and then further developed from each other. Most of the programs also seem to be made for research purposes. Three, WUFI, DELPHIN and COMSOL, of eleven studied programs seems to be user friendly and could be used as moisture safety tools in the design phase by the industry. COMSOL is based on the finite element method [12]. COMSOL and DELPHIN are also perceived as more complex compare to WUFI. More complex two-dimensional versions also exist of some programs. There are plenty of studies where calculated values have been compared with measured values. Both independent and dependent comparisons made by the developer were found [6] [53] [58] [59] [60]. However, none of over 50 known studies seems to make blind comparison between measured and calculated values, i.e. not knowing measured results before the calculation is made [12]. Furthermore, some studies show the importance of using appropriate boundary conditions to get reliable results, such as air flow in the air gap and the influence of driving rain [40] [47] [58] [61] [62].

4. Summary, discussion and conclusions

The summary, discussion and conclusions intend to point out examples of relevant knowledge and to give examples of gaps where there is a lack of knowledge and suggest further research. Based on the studied journal articles, conference papers, dissertations, theses, standards, books and other documents, knowledge could be summarized and several conclusions could be established based on the contents of several documents.

In general it is obvious that there is lot of Swedish knowledge that only is national published and not widely spread to the international research society. It is also obvious that basic knowledge exists in the area of heat, moisture, moisture transport and mould models. However, there are several documents that establish the need of further research in the area since moisture related damage is common and has a great effect on both financial and health issues. Furthermore, the construction industry needs to carry out further work with regard to moisture protection in existing construction systems. Investigations also show that attitude, unclear responsibilities and deficiencies handling moisture safety issues in the industry are a part of the problem.

There is broad agreement about the main factors affecting the risk of mould growth. However, possible ways of reducing mould growth and its influence on health need to be further investigated as well as critical levels with regard to the effects and duration. The effects of short-time variations between critical and non-critical conditions also have to be further studied. Mould models also need to be further developed to direct or indirect show possible actions how to reduce or avoid the risk of mould growth in critical constructions.

Moisture safety design process is needed to reduce the risk of mould and moisture related damages. It is established that both qualitative and quantitative issues need to be considered in the moisture safety design process and it needs to be in focus and dealt with from the planning phase, throughout the entire building process.

New waterproofing membranes and systems with high quality joints in bathrooms need to be developed. There is also a need to ensure the vapour tightness when the membranes are in contact with high relative humidity. The difference in vapour resistance between different membranes in exterior bathroom walls also needs to be handled in the design and construction phase.

Generally there are good materials, tools and detailing solutions to build airtight constructions. It

also seems to be a positive ongoing developing process with new materials and new tools in the material industry. However, it is always best to try to find design solutions with good opportunities for easy made airtight joints and membrane connections.

Experience and studies from rendered non-drained and unventilated facades with wood frame walls, so-called ETICS constructions, could be summed up with that those kinds of constructions should be avoided in order to build moisture safe wood frame constructions. The importance of a ventilated air gap behind the façade in order to reach a long service life is also established. No matter the design the influence of driving rain have to be considered, which can be made by a well-ventilated and drained air gap behind the façade.

It is possible to build wood frame constructions with high thermal resistance, but there is an increased risk of mould and moisture damage. A number of specific factors affecting the moisture safety of well-insulated wood frame houses have been identified and must be considered. For instance, the organic materials in the outer part of the wall needs to be protected, preferably by a mould resistance vapour diffuse open insulation board. Furthermore, the importance of a well-ventilated air gap behind the façade cladding increases with well-insulated wood frame walls.

Wood frame houses cannot become exposed to rain during the construction phase in order to safely avoid the risk of mould growth. By build under tent or concentrate the on-site construction to a day without rain in case of building element houses, this risk could be neglected. This is especially important in well-insulated houses which are more sensitive to moisture.

I order to predict and avoid moisture damage it is also shown that there is a need for user-friendly and reliable moisture calculation tools and methods. User-friendly tools exist but do not seem to be widely spread in the construction industry. However, none of the studied moisture calculation tools, no matter if they are commercial or used for research, seems to be verified to real conditions by blind comparisons.

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