



LUND UNIVERSITY

Moisture Safety in Wood Frame Buildings - Blind evaluation of the hygrothermal calculation tool WUFI using field measurements and determination of factors affecting the moisture safety

Mundt Petersen, Solof

2015

[Link to publication](#)

Citation for published version (APA):

Mundt Petersen, S. (2015). *Moisture Safety in Wood Frame Buildings - Blind evaluation of the hygrothermal calculation tool WUFI using field measurements and determination of factors affecting the moisture safety*. [Doctoral Thesis (compilation), Division of Building Physics]. Byggnadsfysik LTH, Lunds Tekniska Högskola.

Total number of authors:

1

General rights

Unless other specific re-use rights are stated the following general rights apply:

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

Read more about Creative commons licenses: <https://creativecommons.org/licenses/>

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

Moisture Safety in Wood Frame Buildings

Blind evaluation of the hygrothermal
calculation tool WUFI using field
measurements and determination of
factors affecting the moisture safety

S. Olof Mundt-Petersen

Report TVBH-1021 Lund 2015
Building Physics, LTH



LUND
UNIVERSITY

Moisture Safety in Wood Frame Buildings

**Blind evaluation of the hygrothermal
calculation tool using field
measurements and determination of
factors affecting the moisture safety**

S. Olof Mundt-Petersen

Doctoral thesis

Building Physics LTH
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

ISRN LUTVDG/TVBH--15/1021--SE(284)
ISSN 0349-4950
ISBN 978-91-88722-57-7

To Vesslan, Kerminator and upcoming Wolves

the more complicated design
the less likely it will be built as planned
limit the amount of engineering Christmas trees!

Preface

This doctoral thesis presents the results of my research studies which began in June 2008. The work was carried out both as theoretical and applied research at on-site construction projects and wood frame house industry factories. I found the variety in my work and the applied research attractive and valuable even if the differences between “pure” and “applied” research have been confusing and difficult to handle during some periods.

I would like to thank my supervisor Professor Jesper Arfvidsson who has given me confidence and freedom during the work. Many thanks also to my co-supervisors; to Petter Wallentén for his mentorship and to Lars-Erik Harderup who gave good support and always took time for feedback.

Furthermore I would like to thank Lars Olsson and Simon Dahlquist at SP, Technical Research Institute of Sweden, and the project partnership companies in the timber industry – Myresjöhus, Götenehus, Martinson, Willa Nordic and Hyresbostäder i Växjö – for a successful cooperation. Thanks also to Lilian Johansson who drew the figures and was a great help in the layout process. Many thanks to John Bitton and Christina and Peter Goodacre for your time and valuable spelling and grammar checks.

The work was supported by Vinnova (the Swedish Government Agency for Innovation Systems), the Swedish Forest Industries Federation and their partnership with representatives of the timber industry, who initiated the research projects “Framtidens trähus” (Wood frame buildings of the future), Woodbuild and “ECO2 – Carbon-efficient timber constructions”.

Rådmansö-Västernäs, January 2015

S. Olof Mundt-Petersen

Abstract

Due to increased awareness of climate change and higher energy costs, well-insulated buildings have become more common. Furthermore, interest in the use of wood in building to produce more carbon dioxide-efficient buildings has increased. However, thicker thermal insulation in building envelopes increases the risk of high relative humidity levels and the risk of mold-related damage in wood frame buildings. In order to predict the risk of 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 validation 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 in wood frame walls and roofs carried out in Northern European climates.

The thesis shows and discusses examples of how the validated tool can be applied as a tool in the moisture safety design process in practice. Furthermore, 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 designs are compared to more energy-efficient designs with thicker thermal insulation, and alternative designs and important factors affecting the risk of mold growth in well-insulated wood frame constructions are presented.

In general, the comparisons of measured and blindly calculated values show a good correlation. The results indicate that the validated tool can be used during the moisture design process in a reliable manner. However, factors such as the influence of impaired temperature readings on relative humidity have to be taken into account. There is also a need for developing outdoor climate boundary conditions that include critical periods and variations between different years. Unexpected human behavior, poor workmanship and poor design may have major influences on the hygrothermal conditions in the wood frame construction. Several unexpected leakages caused by driving rain penetrating deep into different wooden frame walls, on the inside of the air gap, were noticed. It has to be discussed and further investigated what appropriate safety margins should be used in future hygrothermal calculations.

It has been found that there is a higher risk of moisture-related damage in thicker insulated walls and roofs. However, this risk can be reduced by choosing more suitable designs in which well-ventilated air gaps behind the cladding and exterior vapor-permeable moisture-proof thermal insulation boards are of great importance in walls. Wooden roof constructions were found to be very sensitive to all kind of leakages, both from exterior precipitation penetrating the roofing felt and interior humid air penetrating cracks or poorly executed joints in the interior vapor membrane. The ventilation rate in a cold roof air gap or cold attic must, primarily, be sufficiently high to remove all moisture. However, high ventilation rates decrease the temperature which, in turn, increases the relative humidity and this may cause damage. An unnecessarily high ventilation rate in the cold attic or air gap in roofs should therefore be avoided. This is possible to achieve if the exterior and interior membranes are water- and vapor-tight. The results also show that exterior insulation, on the outside of tongued and grooved wooden roof boarding limits the risk of damage.

Sammanfattning

Hårdare krav på lägre energianvändning i byggnader samt ökade energipriser har gjort att välisolerade hus har blivit vanligare. Ökad medvetenhet om koldioxidens påverkan på klimatförändringarna har också ökat intresset för trähus. Tjockare isolering ökar dock risken för höga fukttillstånd och med detta också risken för fuktskador. För att förutse och undvika fuktskador finns 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 ett omfattande projekt med jämförelser mellan resultat från fältmätningar och blinda beräkningar av temperatur och relativ fuktighet redovisas. Avhandlingen visar också på hur beräkningsverktyg kan användas i praktiken som en del av fuktsäkerhetsprojekteringen. I jämförelsen visas även om, när och varför förhållanden uppstår som gör mögelpåväxt möjlig på olika platser väggar och tak i fem studerade hus på olika orter i Sverige.

I studien redovisas också faktorer och parametrar som har stor inverkan på risken för mögelpåväxt på organiskt material i trähus. Fuktkritiska positioner i traditionella svenska väggar och tak studeras i en parameterstudie med hjälp av kopplade fukt- och värmeberäkningar. Utformningen och omgivande förutsättningar för de vanligt förekommande träkonstruktionerna modifieras med en mer energieffektiv design och resultatet från beräkningar med de nya förutsättningarna jämförs med varandra och med den ursprungliga designen.

Resultaten från jämförelsen visar generellt 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 ånghalten eller temperaturen som kan ha stor betydelse för förutsättningarna för att göra en korrekt bedömning. Vidare påverkar variationerna i utomhusklimatet risken för skador i de mest kritiska positionerna långt ut i konstruktionerna 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. Faktorer som påverkar från oväntade boende vanor, dålig design eller undermåligt och icke-fackmannamässigt utförande kan också ha stor påverkan på uppskattade hygrotermiska förhållanden, och risken för skador, i trähus. Vidare har oväntade läckage från slagregn, tämligen långt in i träregelväggar och innanför luftspalten, noterats. Behovet av säkerhetsmarginaler i beräkningarna eller mögelmodeller behöver diskuteras.

Resultaten visar att det är en högre risk för påväxt av mögel i väggar och tak med tjock isolering. Genom att ha en väl ventilerad och dränerad 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. Trätak har visat sig vara mycket känsliga för alla typer av inläckage, såväl från nederbörd från utsidan som från fuktig luft som tränger igenom den invändiga ångspärren. Luftomsättningen på kallvindar och i luftspalter i parallelltak skall vara så pass hög att fuktig luft ventileras ut men samtidigt så pass låg att temperaturen inte sänks. Resultaten visar också att en utvändigt isolering på utsidan av råspotnen reducerar den relativa fuktigheten på insidan av råspotnen under perioder då mögelpåväxt är möjlig.

Contents

Preface.....	5
Abstract	7
Sammanfattning.....	9
Contents	11
1 Introduction.....	13
1.1 Background.....	13
1.2 Aim	14
1.3 Limitations	14
1.4 Intended readers	15
1.5 Structure of the thesis and reading guide.....	15
1.6 List of publications.....	16
2 Methodology and methods.....	19
2.1 Literature review search strategy	19
2.2 Methods and analysis tools for the blind validation	20
2.3 Hygrothermal calculation tool in practice.....	22
2.4 Method to determine important factors affecting moisture safety	22
2.5 Definition of used moisture-critical limit	23
2.6 Analysis tools.....	23
2.7 Possible sources of errors affecting the calculations and measurements	26
3 Results and analyses.....	29
3.1 Major findings of importance in the literature review	29
3.2 Blind validation and evaluation of WUFI in wood framed buildings.....	30
3.3 Hygrothermal calculation tools in practice	38
3.4 Important factors affecting the risk of moisture damage.....	39
4 Discussion.....	53
4.1 Reflections on the literature review.....	53
4.2 Reflections on the blind validation and evaluation of WUFI.....	53
4.3 Reflections on hygrothermal calculation tools in practice.....	57
4.4 Reflections on important factors affecting the risk of moisture damage	58
5 Conclusions and recommendations	61
6 Nomenclature.....	63
7 References.....	65

8	Appendix I – Boundary conditions, initial settings and material data	71
8.1	Used material parameters and material data in WUFI calculations	71
8.2	Used initial and boundary conditions in WUFI calculations.....	81
9	Appendix II – Appended papers	83

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 (CO₂-efficient) buildings (Dadoo, 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, 2009). The awareness of climate changes, increased energy costs and new energy demands have made well-insulated (U-value < 0.15 W/m²K) houses more common (BBR 2011). Besides the positive effects of reduced energy needs, thicker insulation results in a building envelope in which critical parts more often become exposed to high levels of relative humidity (RH) (Nevander and Elmarsson 1991; Paper VIII; IX; XII and XIII; Technical Report G). Higher relative humidity leads to the increased probability of occurrences of mold growth. Since wood has low mold growth resistance compared to other building materials, the risk of mold damage in well-insulated wood constructions will increase (Nielsen et al. 2004; Johansson et al. 2005; Johansson 2014).

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). Mold and moisture-related damage are linked to high costs and huge amounts of money are spent each year by individual owners, 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 mold and moisture damage in order to reduce the risk of such problems. Moisture conditions that create odors, unhealthy indoor climates and mold growth that affect the health of occupants are forbidden. It is strongly recommended that these factors be taken into account and are verified before a house is built using a moisture-safety design process (BBR 2011).

To predict and minimize the risk of moisture damage, a reliable and validated user-friendly hygrothermal calculation tool is needed. A tool that could be used to estimate future hygrothermal performance in the construction in order to limit and eliminate situations where mold growth is possible before the house is built (BBR 2011; Boverket 2009; Mjörnell, Arfvidsson and Sikander 2012). There are two software programs which are commercially available and could be seen as user friendly, WUFI and DELPHIN, and could be used to predict climate conditions in constructions (Paper IV; Technical Report A). Neither of these tools was found to be independently verified by blind methods, as presented and recommended in Paper I, i.e. not verified by the developer and without knowing the measurement results before making comparisons with unadjusted calculated results.

A blind validation is similar to the situations met by the designers applying the tool in the design phase, i.e. without knowing the future results (Paper I). In general there are a limited number of verified calculation tools for real-life field conditions in houses occupied by ordinary people in Northern European climates (Papers I and IV; Technical Report A). A calculation tools should be tested in its anticipated operating environment to determine whether the system is acceptable for operational use. It should be determined how to use the tool in practice. Furthermore, external factors and parameters, such as boundary conditions, user or occupant behavior, affecting the

results in addition to the tool's equations, must not be advertently or inadvertently ignored (Paper I; OECD 1995). By using reliable hygrothermal calculation tools it is possible to decrease the lack of awareness in the entire construction industry of factors that highly affect the risk of mold growth and moisture-related damage (Arfvidsson and Sikander 2002).

1.2 Aim

The aim of this study was to show whether it might be possible to use the WUFI transient heat and moisture calculation tool as a tool in the moisture safety design process in order to predict and evaluate the risk of mold growth and moisture damage. The purpose was also to show how the tool can be applied in practice, i.e. analyze under what conditions the tool can be used and try to evaluate possible important factors that highly affect the correlation between calculated and measured values from field measurements.

The thesis also aims to present important factors that need to be taken into account and to 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 also evaluated the moisture safety in five different new wood framed houses. This was carried out parallel to the validation of the WUFI calculation tool by comparing measurements from the five new houses both to blindly calculated values and to conditions when mold growth are possible.

1.3 Limitations

The thesis considers wood frame walls and cold roofs with an interior vapor barrier in locations with Northern European climate. The walls have an air gap behind the cladding and the cold roofs have a ventilated air gap or ventilated cold attic below the tongued and grooved wooden roof boarding. The designs studied were limited to a number of common Swedish designs and houses in which measurements were carried out. The studied walls were assumed to be the results of perfect workmanship when compared to the drawings and when used in the calculation models.

The designs were studied from a quantitative, i.e. calculable, aspect and possible influences of qualitative issues were excluded. In general, the calculations were one-dimensional; the influence of the wooden studs, beams, battens and other thermal bridges as well as detailing in joints, wall-corners etc. and the possible influence of convection were deemed negligible. One-dimensional calculations applied to two- and three-dimensional wood frame walls and roofs limit the possibilities of considering the possible influence of initial moisture from the construction phase.

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

The part of the study carried out as a case study, where measurements were made in five real houses with occupants, was limited to the conditions and specific designs of the studied houses. The measurements were governed by the specific conditions and properties in each specific studied house, i.e. each specific project schedule, production plan, building location, building orientation, instrumentation of measuring sensors and construction type. Measurements and calculations in the case studies were carried out and compared during the period 2008 to 2011. The studied houses,

including each specific measuring position, are not presented in the thesis but are presented in detail in five separate reports, Technical Reports B to F. Local factors that might affect the measurements were not possible to check. Comparisons between measured and blindly calculated moisture content were possible, and were carried out by Mundt-Petersen (2013) and are presented in the Technical Reports B to F, but excluded from this study since this was not one of the main objectives.

The definition of the moisture critical limit, RH_{crit} , in the study was limited to showing the conditions when mold growth on wood-based materials was possible. The background to the chosen RH_{crit} limit is given in section 2.5.

Possible sources of error are mentioned and discussed. Some known parameters which might create errors were analyzed in order to find factors that would highly affect the calculation results and correlation between measured and blindly calculated values. However, a complete analysis of all possible sources of error and their effects on the results has not been carried out since it would require extensive work.

1.4 Intended readers

The thesis is primarily intended to be read and used by consultants and the timber house industry. It is also meant to be used by researchers in the areas of house construction, wood-based materials and wooden and wood framed houses. Major parts of the thesis could be used in teaching and education at different levels. The conclusions and recommendations presented can be used by local authorities as they are obliged to prevent buildings with poor moisture safety designs from obtaining building permission. Technical Report G, which gives recommendations for moisture-safe wood frame wall designs, was specially written in Swedish to be more accessible to the Swedish timber house industry, consultants dealing with wood frame houses and Swedish authorities.

1.5 Structure of the thesis and reading guide

The thesis consists of 13 papers in which the major findings are summarized and linked to the results and analyses, to the discussions and to the conclusions and recommendations. Several of the 13 papers are supported by seven Technical Reports. However, the Technical Reports do not form part of the thesis but could be used for further reading.

The initial section of this report gives an introduction to the thesis. The second section presents the methodology and methods used and refer to Papers I and II. Furthermore, the second section also includes a description of the analysis tools used in the entire study, as presented in Paper III. The third section concludes the study and presents the results and an analysis of the major findings with reference to Papers IV to XIII. The fourth section discusses findings from the thesis in a broad respect. Finally, general conclusions and recommendations concerning the entire study are given in Section 5. Section 6 presents the nomenclature for the specific terms used in the thesis and Section 7 contains the references. Appendix I, in Section 8, presents boundary and initial conditions that were used in the calculations. Materials and material data in the calculation models are also presented and linked to references. Papers appended to the thesis are listed in Appendix II in Section 9.

The thesis includes four major parts all of which all are numbered as Sub-sections in the following main Sections 2 to 4, as given below:

1. Current knowledge from a literature review, as presented in Paper IV.
2. A blind validation of the hygrothermal calculation tool, presented in Papers V to X. Some extra important results from the Technical Reports B to F, which did not fit into the appended papers, were also added.
3. Examples of how to apply the studied tool in the moisture safety design process in practice, presented in Papers X and XI.
4. Important factors affecting the risk of mold and moisture related damage in wooden frame walls and roofs, refer to Papers XII and XIII.

The Technical Reports present background data and detailed descriptions. Technical Report A has a detailed literature study/state-of-the-art study including a short description of each studied document and is summarized in Paper IV. The five Technical Reports B to F present results from comparisons between hourly measured and blindly calculated temperatures and relative humidities and an evaluation of moisture safety over a period of approximately three years in 148 positions located in five different wood frame houses. Each of the 148 studied positions is described in detail in the Technical Reports B to F and the general results from each specific house are summarized. The major findings in the Technical Reports B to F are presented in Papers VIII and IX. Technical Report G, in Swedish, deals with moisture-safe wood constructions and gives guidelines for wall design, and is summarized in Paper XII.

1.6 List of publications

1.6.1 Appended papers

The thesis consists of the following papers:

- I. S. Olof Mundt-Petersen, Lars-Erik Harderup. A method for blind validation of hygrothermal calculation tools. XIII DBMC 2014, International Conference on Durability of Building Materials and Components. September 2nd – 5th 2014, Sao Paulo, Brazil.
- II. S. Olof Mundt-Petersen, Petter Wallentén. Methods for compensate lack of climate boundary data. XIII DBMC 2014, International Conference on Durability of Building Materials and Components. September 2nd – 5th 2014, Sao Paulo, Brazil.
- III. 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, 17th International Meeting of Thermophysical Society. October 31th – November 2nd 2012, Podkylava, Slovak Republic.
- IV. S. Olof Mundt-Petersen, Lars-Erik Harderup. Moisture safety in wood frame constructions – What do we know today? – A literature overview. SB 13, Sustainable Building Conference 2013. May 22th – 24th 2013, Oulu, Finland.
- V. S. Olof Hägerstedt, Jesper Arfvidsson. Comparison of field measurements and calculations of relative humidity and temperature in wood framed walls. Thermophysics 2010, 15th International Meeting of Thermophysical Society. November 3th – 5th 2010, Valtice, Czech Republic.

- VI. 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.
- VII. 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. NSB 2011, 9th Nordic Symposium on Building Physics. May 29th – June 2th 2011, Tampere, Finland.
- VIII. S. Olof Mundt-Petersen, Lars-Erik Harderup. Validation of a 1D transient heat and moisture calculation tool under real conditions. Thermal Performance of the Exterior Envelopes of Whole Buildings XII – International Conference 2013. December 1st – 5th 2013, Florida, USA.
- IX. S. Olof Mundt-Petersen, Lars-Erik Harderup. Predicting hygrothermal performance in cold roofs using a 1D transient heat and moisture calculation tool. Submitted to Journal of Building and Environment.
- X. 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 – Conference proceedings. April 12th – 15th 2011, Porto, Portugal.
- XI. S. Olof Mundt-Petersen, Lars-Erik Harderup. Moisture safety in corners and walls in well-insulated wood framed houses. Submitted to Journal of Building and Environment.
- XII. S. Olof Mundt-Petersen, Lars-Erik Harderup, Jesper Arfvidsson. Important factors affecting the risk of mold growth in well-insulated wood frame walls in Northern European climates. Thermal Performance of the Exterior Envelopes of Whole Buildings XII – International Conference 2013. December 1st – 5th 2013, Florida, USA.
- XIII. S. Olof Mundt-Petersen, Lars-Erik Harderup. Important factors affecting moisture safety in well-insulated wood framed cold roofs in northern European climates. Submitted to Journal of Building and Environment.

All work in the above listed papers was carried out by the first author, i.e. the author of this thesis, in addition to the collection and storage of measurement values and work on the chapter concerning long wave sky radiation in Paper II. The second, third and fourth authors have proofread the Papers and worked as discussion partners. The two different family names of the first author are due to a name change after marrying in the autumn of 2012. Papers III, IV, V, VI, VII and X were included in the author's licentiate thesis, presented in May 2013.

1.6.2 Technical reports

The thesis and several of the listed Papers above were also based on the following Technical Reports:

- A. S. Olof Mundt-Petersen, Literature study/State-of-the-art – Mould and moisture safety in constructions. Department of Building physics, Report TVBH-3053, Lund University 2012, ISBN 978-91-88722-44-7.
- B. S. Olof Mundt-Petersen, Comparison of hygrothermal measurements and calculations in a single-family wooden house on the west coast of Sweden. Department of Building physics, Report TVBH-3054, Lund University 2013, ISBN 978-91-88722-45-4.

- C. S. Olof Mundt-Petersen, Comparison of hygrothermal measurements and calculations in a multi-family wooden house on the north-eastern coast of Sweden. Department of Building physics, Report TVBH-3055, Lund University 2013, ISBN 978-91-88722-46-1.
- D. S. Olof Mundt-Petersen, Comparison of hygrothermal measurements and calculations in a single-family wooden house in the Swedish town of Växjö. Department of Building physics, Report TVBH-3056, Lund University 2013, ISBN 978-91-88722-47-8.
- E. S. Olof Mundt-Petersen, Comparison of hygrothermal measurements and calculations in a multi-family wooden house in the Swedish town of Växjö. Department of Building physics, Report TVBH-3057, Lund University 2013, ISBN 978-91-88722-48-5.
- F. S. Olof Mundt-Petersen, Comparison of hygrothermal measurements and calculations in a single-family wooden house in the Swedish municipality of Upplands-Bro. Department of Building physics, Report TVBH-3058, Lund University 2013, ISBN 978-91-88722-49-2.
- G. S. Olof Hägerstedt, Moisture-safe wood constructions – guidelines for wall design, Fuktsäkra Träkonstruktioner – Vägledning för utformning av träbaserade ytterväggar. Department of Building physics, Report TVBH-3052. Lund University 2012, ISBN 978-91-88722-43-0. In Swedish.

1.6.3 Other publications

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

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. 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.
3. S. Olof Mundt-Petersen. Moisture safety in wood frame walls – Blind evaluation of the hygrothermal calculation tool WUFI 5.0 using field measurements and determination of factors affecting the moisture safety. Licentiate thesis. Department of Building physics, Report TVBH-3059, Lund University, Sweden, 2013.
4. S. Olof Hägerstedt. Calculations of relative humidity and temperature in wood framed beam structures with under floor heating. Department of Building physics, Report TVBH-7235, Lund University, Sweden, 2011.
5. Wood in carbon efficient construction, Chapter 7, Editors: Matti Kuittinen, Alice Ludvig, Gerhard Weiss. ISBN: 978-9-0820-9080-2. CEI-Bois, Brussels, Belgium 2013.

2 Methodology and methods

This chapter presents the overall methodology, detailed methods for each specific part of the thesis, definitions and the developed analysis tools. The methodology consists of four parts as presented below:

1. A literature study was initially carried out in order to offer an overview and summarize known facts, create a base of knowledge to work from and show possible gaps and flaws in the area of moisture safety. A reference-to-reference method was used where new documents of interest were found using references in known documents. Papers of interest were then summarized in the literature study, as presented in Paper IV.
2. The second part, which is the main part of the thesis, consists of a blind validation in real conditions of the hygrothermal calculation tool. The validation was carried out in order to establish whether and during what conditions the studied tool could be applied. Possible factors that affect the calculations, both sources of error and factors affecting differences between measurements and blindly calculated values, were discussed and established if possible. The validation was also necessary in order to create credibility for the two upcoming steps where the tool was applied in practice and used in order to establish factors which highly affect the moisture safety. The validation was carried out as a case study and presented in Papers V to X.
3. The third part shows how the tool can be applied in practice during the moisture safety design process. The applied part was carried out as a combined case study, investigating two real well-insulated designs, and a parametric study in order to obtain a suitable design. Papers X and XI show examples of how to use the tool in practice in a moisture safety design process (Mjörnell, Arfvidsson and Sikander 2012).
4. The fourth part clarifies important factors and parameters which affect moisture safety in wooden framed wall and roof designs. The different factors and parameters were compared to the possible risk of damage and compared in relationship to each other. The establishment of the most important factors affecting moisture safety was determined by parametric studies in which the consequences of variations in a basic design were evaluated with respect to moisture safety. The fourth part is presented in Papers XII and XIII.

The different parts of the methodology require different methods, analysis tools and evaluating principles. As a consequence, some minor separate methods were developed.

Comparisons between the different papers, sections and Sub-sections were possible since similar analysis tools, principles and moisture-critical limits were used in the entire study, as discussed in Paper III.

2.1 Literature review search strategy

Since moisture safety consists of both qualitative and quantitative issues both of these sub-areas were included in the literature study. The connection between the sub-areas also made it necessary to include documents at different levels, which resulted in the inclusion of doctoral theses and internationally reviewed journal articles as well as national institute reports, conference papers and master and bachelor theses.

Relevant papers, theses and technical reports were found using a reference-to-reference search strategy. Conference proceedings from the latest conferences in the area and local databases of institutes were scanned for relevant papers and reports. The papers and reports found of interest were reviewed and their relevant references were followed up in the next step in order to find further interesting papers and reports in the area. By continually following up, reading and analyzing interesting references, the literature review gradually expanded. In total, the literature review consists of 146 documents which were analyzed and briefly summarized in Technical Report A and Paper IV. A detailed description of the literature review search strategy can be found in Paper IV and the Technical Report A.

2.2 Methods and analysis tools for the blind validation

The study was influenced by the Good Laboratory Practice, GLP, system which is governed by law and complies with the EU directives for chemistry, food, drugs and medicine etc. The GLP says that computerized systems should be tested in their anticipated operating environments to determine whether they are acceptable for operational use (Robinson 2013; OECD 1995). In order to implement and apply GLP in this context, the validation of the studied tool was carried out as a case study under the same conditions as would be met by the possible users, i.e. design engineers, when designing real houses to be occupied during real indoor and outdoor climate conditions (Papers I; VIII and IX). The validation investigates whether the studied tool is deemed to be sufficiently good to be used in a reliable manner in situations that correspond to the conditions met by designers in the moisture safety design process by comparing measured and blindly calculated values.

The validation was carried out as a case study in five different houses, located in four different towns. Hygrothermal calculations were made blind, i.e. made without knowing the results of the measurements to be compared to. Blind calculations are similar to the situations when the designers carry out the heat- and moisture calculations before a house is built (Paper I). However, in order to attain results that are possible to compare to measurements, available real indoor and outdoor climate boundary conditions have to be used in the calculations (Paper II). Blind comparisons could also be called single-blind. All calculations and comparisons in this study were made single-blind and were carried out by independent organizations and testers. During the validation process, the studied tool was also, if possible, evaluated in a context which included possible factors influencing the results.

Comparisons after the completed blind calculations and after the measured values had been received were evaluated using the Folos 2D visual mold chart, as presented in Paper III. After comparing the measured and the blindly calculated values, it was possible to make adjustments to the calculation models to achieve a better correlation, or a perfect match. However, this was not a part of the study. If adjustments to the calculation models were made after the first comparison, the calculations would not be blind anymore. A more detailed description of the method and its importance in order to reach independent, reliable and powerful validations is found in Paper I. The results of the validation are presented in Papers V to X and Technical Reports B to F, in which short descriptions of the blind method and examples of how to apply the method are found.

2.2.1 Blind comparison between measured and blindly calculated values

In practice, the blind validation was carried out by sensors, measuring the temperature and relative humidity, which were installed at different depths and locations during the construction phase in the walls and roofs in the studied houses. The position of each sensor was well documented in drawings and photos, as shown in Technical Reports B to F. The construction phases for each house were monitored to establish possible deviations between the drawings and the real conditions in the built houses. Measurements were carried out using a wireless Protimeter Hygro Trac system (GE Sensing 2006; Sandberg, Pousette, and Dahlquist 2011; Mundt-Petersen 2013). Hourly measurements of temperature and relative humidity for each specific position were then separately stored by a measurement collector, inaccessible to the persons involved in validating the calculation tool. Over a three year period, 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 conditions as close to reality as possible. After the period of three years, calculations were carried out for each of the studied positions for the entire measuring period without knowing the measured results in the constructions. The calculations were made using indoor and outdoor climate boundary conditions, as shown in Technical Reports B to F, collected from indoor measurements and closely located outdoor climate stations (SMHI 2014). The results of the blind calculations were sent to the measurement collector, from where the previously inaccessible measurements were retrieved. Finally, comparisons were made between the measurements and the calculated temperature and relative humidity over time by using the Folos 2D visual mold chart (Paper III). The entire process for the blind validation is presented in Paper I.

2.2.2 Checking and supplementing lack of indoor and outdoor climate data

In accordance with GLP, measurements were carried out in real, occupied houses with real indoor and outdoor climate conditions. To achieve agreement between measured and calculated values, the use of the standard outdoor climate in the calculation tool was avoided (Paper II). Real measured climate data from climate stations closely located to the studied houses was collected during the measuring period and then used in the calculations (SMHI 2014). The measurement data was checked against other available climate data in order to find occurrences of possible inadequate climate data or deviations (Technical Reports B to F). Unfortunately, periods with impaired or lack of boundary climate data were found that varied in length from single hours to longer periods of up to months. In order to get a continuous series of climate boundary conditions, to be used in the calculations, when there were periods with impaired data and lack of data simple methods, as presented in Paper II, was developed to compensate for missing data. Basically, periods with a lack of or impaired data were supplemented with data from previous hours, weeks or years. The methods was used to create a complete series of climate boundary conditions to be used in Papers V to X, i.e. the part of the study concerning the validation of the hygrothermal calculation tool. Periods with flawed climate data or a lack of climate data were replaced and are shown in Technical Reports B to F.

Besides periods with impaired or lack of climate data, there was a complete lack of long wave night radiation values to be used in the hygrothermal calculations. A detailed method to create appropriate long wave night radiation values was developed by Wallentén, as presented in Paper II. The calculation results using the detailed method for estimating long wave radiation developed by Wallentén, a simplified default method for estimating long wave radiation (WUFI 2012a) and

situations with no long wave radiations at all were compared to measured values. The results show that the influence of long wave radiation should be taken into account when carrying out hygrothermal calculations in order to reach better correlations to measured values. However, the simplified default method for calculating long wave radiation works as well as the detailed method in Northern European climates (Paper II). The simplified default method as implemented in the hygrothermal calculation tool (WUFI 2012a) was therefore used during the entire study and in appended papers.

2.3 Hygrothermal calculation tool in practice

Examples were compiled of how hygrothermal calculation tools can be applied in practice in a moisture safety design method (Mjörnell, Arfvidsson and Sikander 2012) in a case study in combination with parametric elements. The studies were carried out as case studies in two real designs located in two different towns. Moisture-critical positions were evaluated using the Folos 2D visual mold chart, as presented in Paper III. Based on knowledge from the literature review or the appended papers, measures to limit the risk of moisture related damage were proposed. The effects on the moisture safety of the proposed measures were later evaluated as a parametric study in two real walls. The risk of moisture critical conditions in the studied positions were compared before and after the proposed measures in the calculation models to see any possible effects of the measures, using the Folos 2D visual mold chart. Examples of how to apply the tool are presented in Papers X and XI. Paper X presents both results from the validation of the tool and how to implement the tool in the moisture safety design process. As mentioned in the limitations, the two-dimensional hygrothermal calculation tool was not blindly validated in this study.

2.4 Method to determine important factors affecting moisture safety

The investigations to find and evaluate factors affecting the moisture safety and risk of moisture related damage were carried out as parametric studies in different building components and different designs. Calculations were carried out on differently designed wood frame constructions using the previously validated one-dimensional transient heat and moisture calculation tool WUFI (WUFI 2012a). Materials and climate boundary conditions were retrieved from the calculation tool material database (WUFI 2012b) and climate database (WUFI 2012c).

A reference wood frame wall and roof, intended to imitate an ordinary Swedish wall and roof design, was designed in the calculation tool. The reference case also intended to imitate some of the previously studied roofs and walls where measurements were carried out. Initially, the most moisture-critical positions in the wall and roof were established for the reference cases. The design and surrounding conditions of the reference cases were then varied and the effects of the changes in the most moisture-critical positions were analyzed and compared to the reference cases. Possible measures in order to achieve better moisture-safe designs were also studied. The variations of conditions and designs that are presented were 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.

In total, a great number of simulations with different designs were carried out. The most important factors influencing the risk of moisture related damage were summarized and compared to the

reference cases and a moisture-critical limit regarding mold growth in Papers XII and XIII, using the Folos 2D visual mold chart and isopleth chart as presented in Paper III.

2.5 Definition of used moisture-critical limit

Organic materials, such as wood, are the most moisture-sensitive materials prone to damage compared to other building materials, and the primary risk is mold growth (Johansson 2014; Johansson et. al 2005). The moisture-critical limit for wood in the building envelope is therefore, in practice, when mold growth occurs on the material. Since this study considers the moisture risk in wood frame constructions, where wood is the most moisture-sensitive building material, the moisture critical limit focuses on the risk of mold growth on wood.

Besides the exposed materials themselves, temperature, relative humidity and duration are the main factors affecting the risk of mold growth (Viitanen et. al 2010). Recently, i.e. after this study was initiated, models estimating mold growth using climate conditions such as temperature and relative humidity over time were developed (Thelandersson and Isaksson 2013). There are also different theories and models about reducing the amount of mold growth during non-favorable mold growth climate conditions, as discussed in Papers III and IV.

This study primarily focuses on the reliability of hygrothermal calculation tools and whether, and during what conditions, hygrothermal calculation tools can be used in the moisture safety design process. Furthermore, the study focuses on factors and parameters affecting moisture safety. The definition of the critical limit, further on called moisture-critical conditions, RH_{crit} , was therefore defined as “climate conditions when mold growth is possible on wooden material”. The influences of temperature and relative humidity were considered for the RH_{crit} limit but without taking into account the influence of duration. The critical limit indicates when mold growth is “possible” at any specific time, but not when mold growth actually “occurs”. The duration is shown and its influence could also be included in the analysis tool using results from mold growth models (Paper III).

Since possible uncertainties should be taken into account (BBR 2011), the most moisture-sensitive mold growth model developed by Sedlbauer (2001), as shown in Figure 1 in the next Sub-section, was used as the RH_{crit} limit in this study. However, other sensitivity levels for mold growth, with respect to other materials and other mold growth models, can be included in the analysis tool.

2.6 Analysis tools

Two ways of validating the studied tool and evaluating the risk of mold growth due to climate conditions, isopleth charts and the Folos 2D visual mold chart, were used in the study, as presented in paper III.

2.6.1 Isopleth chart

The isopleth chart, as shown in Figure 1, illustrates where critical conditions occur, and mold growth is possible, 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. The moisture critical limit, RH_{crit} varies depending on temperature (Sedlbauer 2001; Viitanen et. al 2010) and different materials have different RH_{crit} lines (Johansson 2014; Johansson et. al 2005).

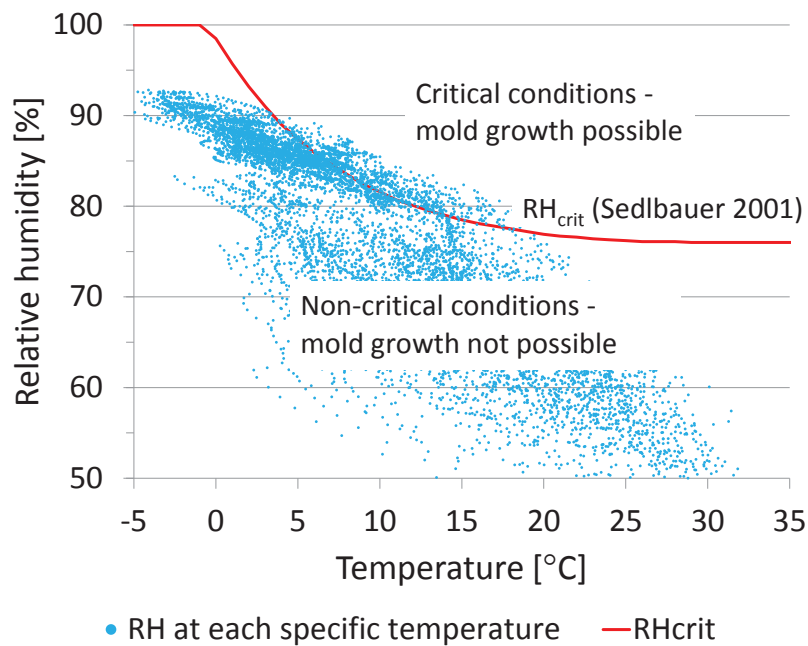


Figure 1. Example of an isopleth chart showing hourly dots for hourly values of temperature and RH (turquoise) and the RH_{crit} limit (red) (Sedlbauer 2001).

However, the isopleth chart does not show when the RH_{crit} conditions occur in time and whether there could be a risk of mold growth, if the influence of duration is considered. Furthermore, the isopleth chart does not show underlying factors, such as the possibilities of reducing the vapor content or increasing the temperature, making it possible to limit or avoid the risk of mold growth.

2.6.2 Folos 2D visual mold chart

Besides the isopleth chart, another tool, the Folos 2D visual mold chart, was developed in order to compare and analyze results in a way that satisfy the aims and intention of the study. The chart was used in both the case study and the parametric study and allows different analyses and comparisons. At the same time, the main underlying factors affecting the risk of mold growth, such as temperature, relative humidity and duration, were visualized. The Folos 2D visual mold chart is presented in Paper III. A brief description of the tool, which can also be found in Papers VII, IX, XII and XIII, is presented below.

The Folos 2D visual mold chart, in Figure 2, visualizes temperature (yellow) on the right y-axis and RH (turquoise), RH_{crit} (red) and the $RH > RH_{crit}$ difference (light brown) on the left y-axis. The time presented on the x-axis indicates the conditions at any specific time, and of particular interest are the periods when $RH > RH_{crit}$ showing the extent, when and for how long the relative humidity exceeds the RH_{crit} conditions. The hourly RH isopleth dots (turquoise) for one year (8760 hrs), in Figure 1, resulted in a line when presented over time in the visual mold chart in Figure 2.

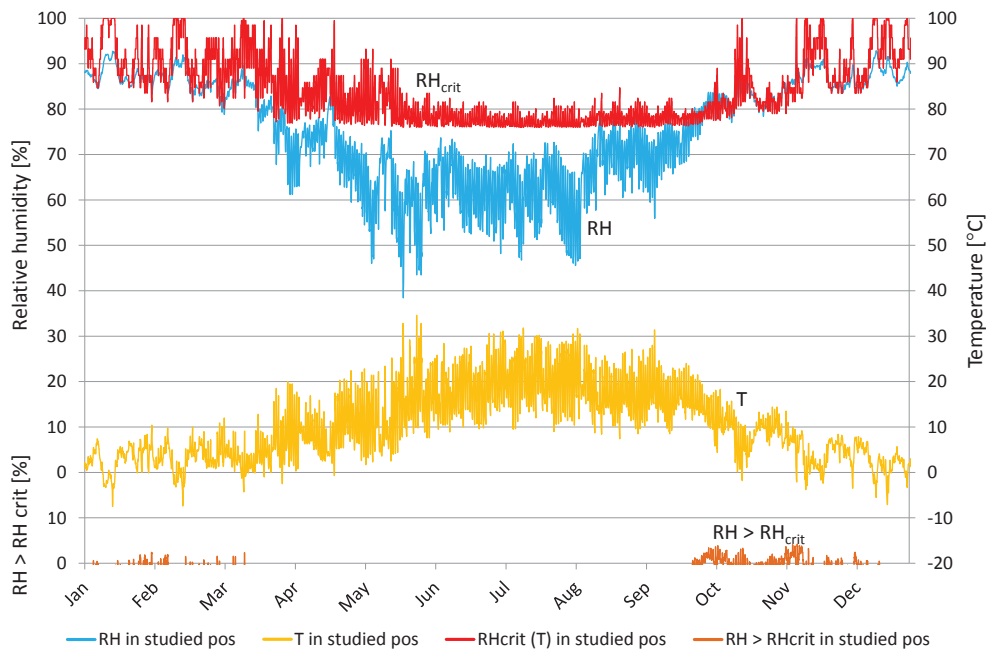


Figure 2. Example of the Folos 2D visual mold chart including the parameters temperature (yellow), RH (turquoise), RH_{crit} (red) and $RH > RH_{crit}$ (light brown).

Critical conditions occur, and mold growth is possible, when the RH is above the RH_{crit} line. The RH_{crit} line is defined by the temperature that, at any specific time, exceeds the RH_{crit} limit as shown in Figure 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 critical conditions depend on the prevailing RH and temperature, where a high temperature gives a lower RH_{crit} line and vice versa. The RH_{crit} line in this study is based on the LIM I curve developed by Sedlbauer (2001). It should be mentioned that it might take months or longer before mold growth occurs if the RH is only slightly above RH_{crit} , especially at low temperatures. Single short periods, even with RH high above RH_{crit} , do not cause damage since mold needs more than a few hours above the RH_{crit} limit to germinate (Johansson 2014; Sedlbauer 2001). Depending on the moisture resistance of different materials and regulations in different countries, another mold growth limit could be applied by choosing another appropriate RH_{crit} curve.

By plotting additional dots in the isopleth chart or additional lines with relative humidity (black), temperature (dark blue) and $RH > RH_{crit}$ (purple), comparisons to the initial calculations were possible. In the part of the study concerning the validation, as presented in Papers V to X and Technical Reports B to F, the additional lines consist of measured values which easily become comparable to blindly calculated values in the visual mold chart. In the case of the parametric studies, the calculation results consist of the results from both the reference case and the additional lines of relative humidity, temperature and $RH > RH_{crit}$, from an equivalent position in an adjusted or different design. When analyzing the results, the Folos 2D visual mold chart could also be supplemented with investigations of other parameters or charts showing factors such as specific climate parameters, vapor content, moisture content, mold growth etc. as presented and carried out in Papers III, VII, XI and Technical Reports B to F, and by Mundt-Petersen (2013).

To decrease the relative humidity, and the critical conditions, there are generally two types of measures that can be taken according to the relationship in Equation 1; increasing the temperature or reducing the amount of vapor content.

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

where RH is the relative humidity, v the vapor content and v_s the vapor content at saturation depending on the temperature.

Measures which increase the temperature increase the vapor content at saturation, which, in turn, reduces the relative humidity, and measures which decrease the vapor content reduce the relative humidity, as exemplified in Papers X to XIII, in which measures influencing the risk of damage are presented.

Deviations between the parameters temperature or vapor content could be used to trace the reason for the deviations between the measured and blindly calculated relative humidity, as presented in Paper III and exemplified in Paper V.

A complete description of the Folos 2D visual mold chart, how it should be applied and possible additional parameters etc., are presented in Paper III and by Mundt-Petersen (2013). Different colors indicating the parameters temperature, relative humidity, RH_{crit} , $RH > RH_{crit}$, may have been used in the figures in the appended papers.

2.7 Possible sources of errors affecting the calculations and measurements

There are several possible factors and sources of errors which may cause deviations when comparing measured and blindly calculated values. Some of these factors and sources of errors were not possible to affect or to check. All possible sources of error and influencing of the results were not seen as possible to analyze completely in multi-variable analyses. One part of the purpose of this study was also to find such factors and possible sources of errors affecting the calculations and measurements. Possible sources of errors are discussed in Paper IX, by Mundt-Petersen (2013) and by Sandberg, Pousette, and Dahlquist (2011).

2.7.1 Measurement sensors

Deviations between measured and calculated values may depend on weaknesses or flaws in the measurement sensors. Most of the sensors were built-in into the walls and roofs during the construction phase, and were impossible to remove and recalibrate after the measurements had been completed. However, 16 sensors in a cold attic were accessible and were recalibrated (Nordtest method 1998; SP Eti-QD). In accordance with the user manual (GE Sensing 2006), the calibration indicated lower accuracy when the relative humidity was high. Almost all sensors had the same trend and magnitude with a mean deviation of 3.3 % at 85.1 % relative humidity (Mundt-Petersen 2013). The measuring sensors were also enclosed in a ventilated plastic shell, which was insulated from its surroundings by two surface resistances. The plastic shell also reduced the influence of wind. These factors may increase the temperature, which reduces the measured relative humidity and therefore might create deviations between measured and calculated values. The lack of a second calibration means that all such results were excluded in this study. However, the influence on the deviations

could be investigated in detail for both specific sensors and, in general, by using a mean calibration curve from the 16 calibrated sensors.

2.7.2 Measurements

The thickness and volume of the sensor may have affected the measurements in the studied positions. Since its size reduces the thickness of the surrounding thermal insulation the sensor might primarily affect the temperature, especially in thinner insulated designs, and the relative humidity. Sensors mounted close to thermal bridges may be affected by a higher measured temperature compared to the one-dimensional calculations. The measurement sensors might also have created heat during measurement processing that affected both temperature and relative humidity. There are also local factors, impossible to check, such as the influence of changes in the surrounding topography and vegetation (Mundt-Petersen 2013).

2.7.3 WUFI calculation tool

Possible flaws in the WUFI calculation tool, and in the numerical and physical models, might have created systematic errors that were not taken into account but may have constituted some of the errors.

2.7.4 WUFI 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 walls, cause higher temperatures and lower relative humidity in reality (Mundt-Petersen 2013). The one-dimensional calculation also limits the possibilities to consider the influence of initial construction moisture and how it might have been affected by the excluded wood studs and wood beams.

The air flow in the air gap behind the cladding was, in general, constant in the calculations. In reality, the air flow is affected by wind, temperature differences, the size of in- and out air openings, the width of and possible barriers in the air gap (Falk and Sandin 2013). The influence of a varied air flow in the air gap behind the cladding was investigated in Paper VII and seems to be of minor importance as long as the air flow is high enough to remove all moisture penetrating the wall. The amount and direction of driving rain in the calculation models might be different compared to reality (Mundt-Petersen 2013).

Leakages from the outside caused by driving rain penetrating the cladding are expected in walls and taken into account by adding 1 % of the rain load in the air gap behind the cladding (ASHRAE 2009) in the calculation models in Paper VIII and Technical Reports B to F. The air gap behind the cladding is expected to drain out leaking water and have a capillary breaking effect that prevents the water from reaching the frame.

Insufficient or poor calculation models, due to unawareness or lack of knowledge, may be the fault of the user. The knowledge and capacity to handle the tool and make reliable calculation models is always of importance to get an accurate result as discussed in Paper I.

2.7.5 Material parameters used in the WUFI calculations

Material parameters were retrieved from the WUFI material database (WUFI 2012b). Possible deviations between material properties used in the calculations and real materials used in the

investigated buildings are possible. There are also limitations in the way the hygrothermal calculation tool handles different material properties during the calculations, such as using only one sorption curve for each material (WUFI 2012a; Mundt-Petersen 2013).

2.7.6 Climate, and initial and boundary conditions used in the WUFI calculations

Poor initial conditions used in the calculation models may have created initial deviations between the measured and calculated results before equilibrium was reached. In the case study, the calculations for some of the houses had to start before the houses were built, due to numerical limitations or only when the exterior climate boundary conditions were available, i.e. after the house was built. None of the calculations in the studied houses take into account the influence of initial moisture content. Details concerning calculation periods and calculation starts can be found in Technical Reports B to F supporting the thesis and by Mundt-Petersen 2013. Boundary conditions that were not possible to estimate or consider in the calculations may also have created deviations in the calculation results when compared to real conditions. Initial and boundary conditions that were used in the calculations are specified in Appendix I in section 8.2.

2.7.7 Differences between drawings and the walls and roofs as built

Differences between the drawings and real walls and roofs as built were not regarded as probable. As mentioned, the construction phases were thoroughly followed up and no deviations between the drawings and the real conditions were noticed. Perfect workmanship was therefore assumed in the calculation models.

3 Results and analyses

This section summarizes the general and most important results from the entire study. Only the major findings are highlighted and further detailed information of specific interest can be found in the appended papers.

3.1 Major findings of importance in the literature review

The major findings of importance in the literature review, which comprises 146 reviewed documents, are briefly summarized and presented below.

A basic knowledge exists in the area of heat- and moisture-transport and mold models (Nevander and Elmarsson 2007; Viitanen 1996; Vinha 2007; Krus 1996; Künzel 1995). However, there are several documents that call attention to 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 attitudes, unclear responsibilities and shortcomings when handling moisture safety issues in the industry are parts of the problem (SOU 2002:115; Stadskontoret 2009; Arfvidsson and Sikander 2002).

A moisture safety design process is needed, and has been included in the Swedish building regulations, in order to reduce the risk of mold and moisture related damage. It is established that both qualitative and quantitative issues need to be considered in the moisture safety design process and must be in focus and dealt with from the planning phase and throughout the entire building process (BBR 2011; Mjörnell, Arfvidsson and Sikander 2012).

It is possible to build wood frame constructions with high thermal resistance, but there is an increased risk of mold and moisture damage. According to Papers IV to XIII, several other documents show that a number of 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 buildings cannot be exposed to rain during the construction phase if the risk of mold growth is to be avoided. By constructing under a tent or concentrating the on-site construction to a single day without rain when building prefabricated houses, this risk could be avoided. This is especially important in well-insulated houses which are more sensitive to moisture (Paper XII and XIII; Mjörnell, Arfvidsson and Sikander 2012; Olsson. 2014; Brander, Esping and Salin 2005).

In order to predict and avoid moisture damage it has also been shown that there is a need for user-friendly and reliable moisture calculation tools and methods (Boverket 2009; Mjörnell, Arfvidsson and Sikander 2012). According to Paper IV and Technical Report A, user-friendly tools exist but do not seem to be widely spread at present in the construction industry. None of the studied moisture calculation tools, no matter whether they are commercially available or used for research, were found to have been independently verified to real conditions by blind comparisons in Northern European climates (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).

3.2 Blind validation and evaluation of WUFI in wood framed buildings

This section presents the major results of comparisons between measurements and blind calculations of studied positions in several different wood framed walls and roofs. All calculations and comparisons in this section were made blind although this is not specifically highlighted in each specific case. The results generally refer to Papers V to X and are supported by Technical Reports B to F.

3.2.1 Evaluated tool

The criteria for choosing the hygrothermal calculation tool were that it should be user-friendly and available to the Swedish timber industry (Boverket 2009). The most user-friendly and commercially available software seems to be WUFI (Paper IV; Technical Report A; Mundt-Petersen 2013), which was chosen for the blind validation. The chosen tool was also specifically mentioned as a possible tool in previous investigations (Boverket 2009; Samuelson and Jansson 2009). Material properties which were used in the calculation models were chosen from the calculation tool material database (WUFI 2012b). All calculation models, including the materials and material data used, the results from comparisons between measurements and calculations over the entire investigated period, and other positions not included in the thesis and appended papers, are found together with the description of the studied positions in Technical Reports B to F. Boundary conditions and material data are listed in Appendix I in Section 8.

3.2.2 Materials

Measurements and calculations for the blind validation case study were carried out in five different wood frame houses. The measurement and calculation positions were located at different depths and locations in the walls and roofs, which had different designs and faced different directions. All the studied designs and positions are shown in detail in the Technical Reports B to F and in Papers V to X in its context together with the results. The houses were located in four different towns in Sweden, as shown in Figure 3, each with different climate conditions.

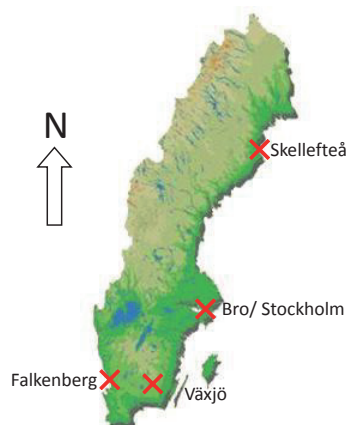


Figure 3. Locations of the studied houses in Sweden.

3.2.3 Correlation between measured and blindly calculated values

When evaluating the results in Papers V to X and Technical Reports B to F, a clear correlation between measured and blindly calculated temperature and relative humidity in walls and roofs, as shown in Figures 4 to 6, was found in general. Even if a perfect correlation was not reached, the results obtained are deemed to be sufficiently good to show that the validated calculation tool could be used in a reliable manner in situations that correspond to the conditions met by designers in the

moisture safety design process. The lengths of the studied periods and the high number of studied positions in the entire project confirm the reliability in the results.

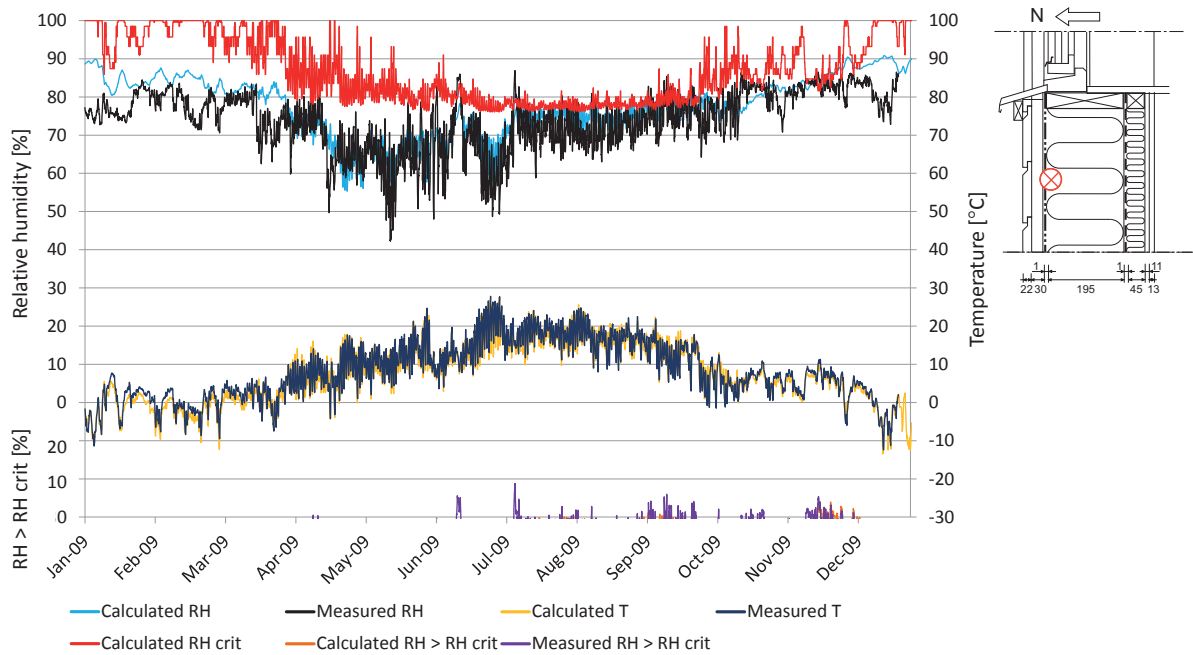


Figure 4. Comparisons between measured and calculated RH and temperature behind a mold-resistant facade insulation board in the exterior part of a wall (Paper VIII; Position 6 in Technical Report F). Calculated RH (turquoise) and measured RH (black). Calculated temperature (yellow) and measured temperature (dark blue). RH_{crit} derived from the calculated temperature (red). Calculated $RH > RH_{crit}$ (light brown) and measured $RH > RH_{crit}$ (purple).

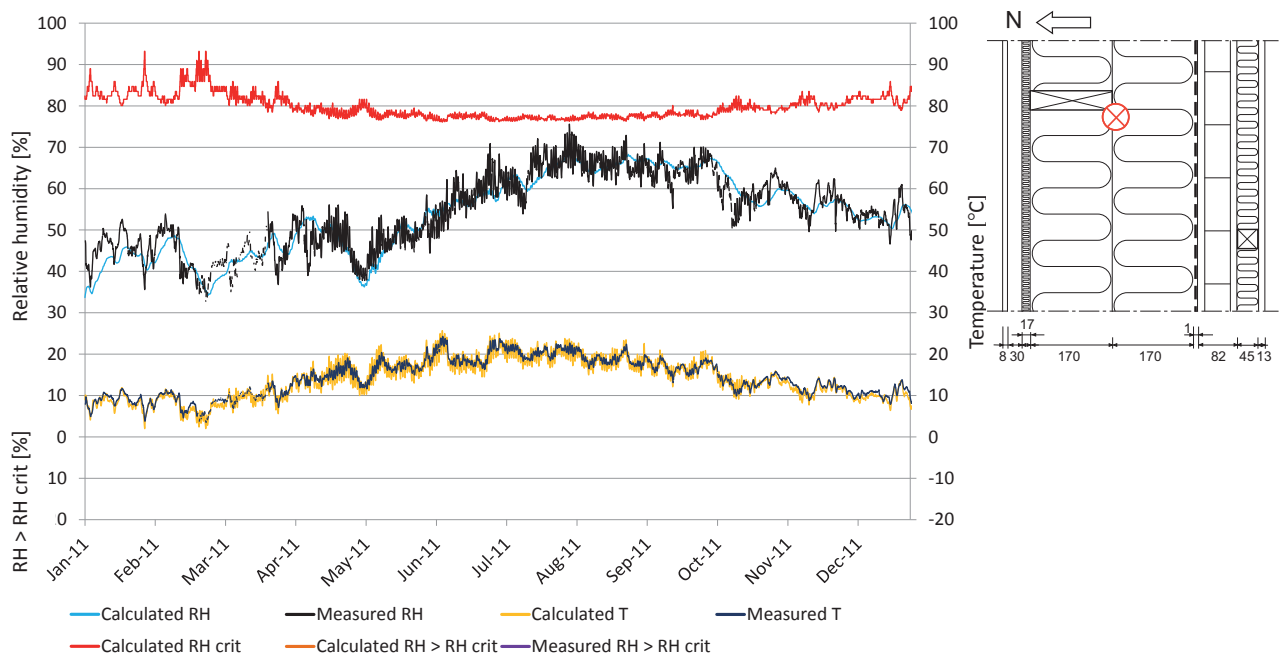


Figure 5. Comparisons between measured and calculated RH and temperature in the middle of a wall (Paper VIII; Position 27 in Technical Report E). Calculated RH (turquoise) and measured RH (black). Calculated temperature (yellow) and measured temperature (dark blue). RH_{crit} derived from the calculated temperature (red). Calculated $RH > RH_{crit}$ (light brown) and measured $RH > RH_{crit}$ (purple).

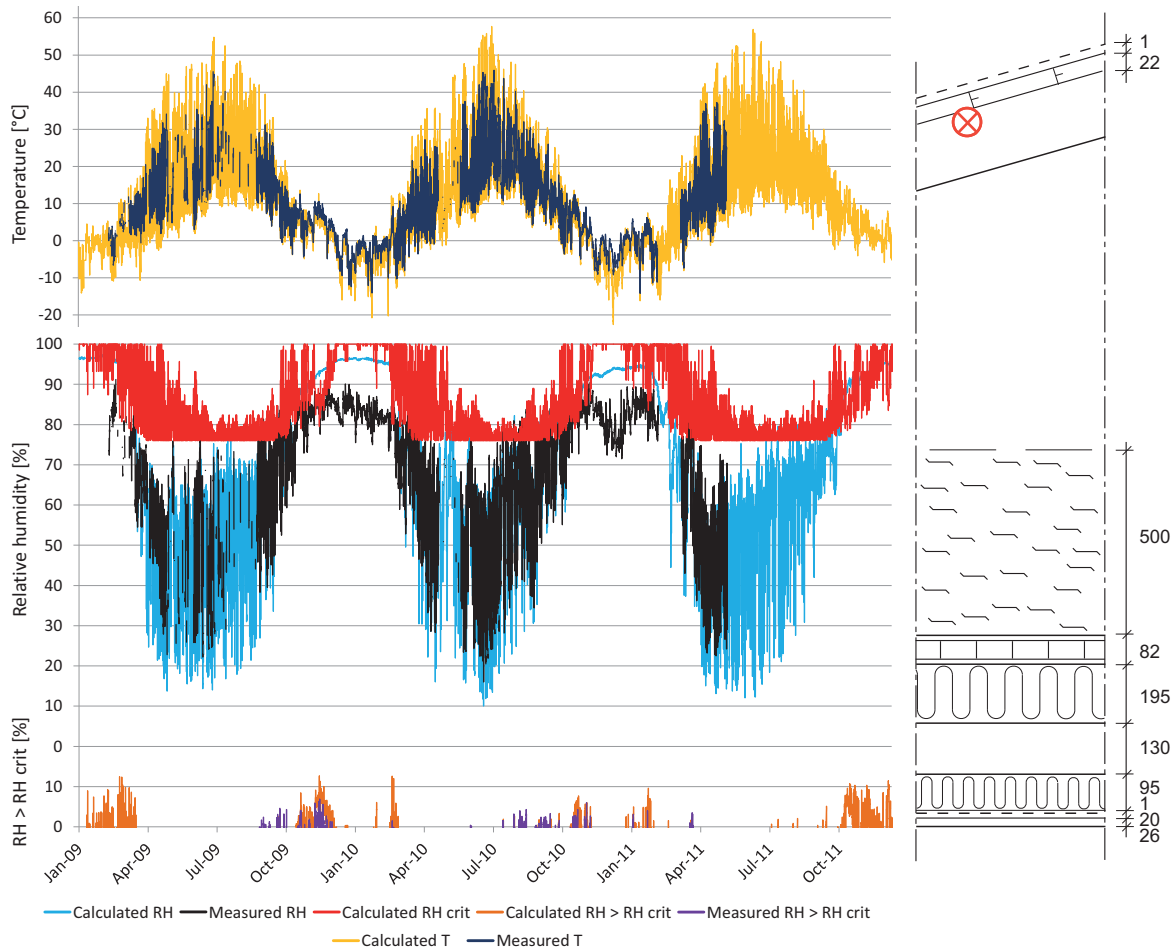


Figure 6. Comparison between measured and calculated RH and temperature in a cold attic (Position P-43 in Paper IX and Technical Report E). Calculated RH (turquoise) and measured RH (black). Calculated temperature (yellow) and measured temperature (dark blue). RH_{crit} derived from the calculated temperature (red). Calculated $RH > RH_{crit}$ (light brown) and measured $RH > RH_{crit}$ (purple).

In general, a better correlation was found closer to the interior part of the design, probably depending on reduced influence from temporary solar radiation on surfaces and other variations in the outdoor climate. A better correlation was also found during the spring, summer and autumn compared to the winter periods.

Differences between measured and blindly calculated relative humidity depend on vapor content and temperature, which affect the vapor contents at saturation, according to Equation 1. Generally, differences between measured and calculated temperatures create differences in the relative humidity. I.e. the vapor content is the same but different measured and calculated temperatures give different vapor contents at saturation. This particular effect of temperature on relative humidity can be found in all the studied designs and houses. In most of the studied positions the measured temperature is higher than the calculated one, which in turn results in a lower relative humidity, as shown in Paper VII.

The higher measured temperature during the winter, reducing the relative humidity, as shown in Figures 4 and 6, may depend on factors such a lower air flow in the air gaps or a lower thermal resistance than expected, which increase the temperature compared to calculated values. In roofs,

any exterior snow layers, equivalent to insulation, may increase the temperature in the attic during the winter period. With respect to the risk of moisture-related damage, the calculated results were on the safe side, i.e. a lower measured relative humidity compared to the calculated (Papers V to X; Technical Reports B to F).

Besides a rather good correlation being found in most of the studied houses and positions, there were several limitations and factors that influenced the measured and calculated values to such an extent that they should be taken into account in order to reach reliable results in the moisture safety design process. The most important factors are presented below but several others may be found in the appended Papers V to X. Several of the additional factors and parameters could be investigated further to create even more reliable calculation results.

3.2.4 Proper hygrothermal calculation model

It may sound obvious, but in order to reach accurate calculation results a proper hygrothermal calculation model has to be used. Poor parameters in the calculation model, such as an incorrectly applied air flow as shown in Paper V or the exclusion of leakages from driving rain (Samuelson and Jansson 2009), might have a significant influence on the calculation results. The results of an inadequately applied air flow in the air gap, as shown in Paper V, indicates the need for blind validations, as discussed in Paper I. As mentioned, the validation process should preferably be carried out by independent researchers, since it is easy for the developer to only report proper results without mentioning the adjustments carried out in order to reach acceptable correlations. Finding and adjusting the important parameters to reach accurate results, as shown in Paper V, using the relationship presented in Equation 1 and the method presented in Paper III, show that the Folos 2D visual mold chart works.

As expected, deviations between measured and blindly calculated values occur when comparing measurements in some two- or three-dimensional situations, such as corners, to one-dimensional calculations (Mundt Petersen 2013). Several of the studied positions were located in the sill slightly above floors with under-floor heating in a two-dimensional situation which was not, as expected, possible to calculate in a proper manner using one-dimensional calculation tools. However, the measurements show that a positive effect was generated by a higher temperature on the outside of the sills reducing the relative humidity, as shown in Paper VIII. Higher temperatures also improve the drying-out process. It is important to observe that this positive effect requires vapor-permeable insulation that allows the drying out process to take place before mold growth can occur.

3.2.5 Air flow in air gaps and cold attics

Results from the calculations in Papers V and VI show that a too low applied air flow rate in the air gap behind the cladding, in the calculations for walls, has a major influence on the correlation between measured and calculated relative humidity. At the same time, the results in Papers V and VI, as well as the parametric study in Paper XII, show that there is a great need of a high air flow in the air gap behind the cladding in order to obtain a moisture-proof wall construction. In reality, the air flow rates vary and depend on several factors (Falk and Sandin 2013; Nore 2009). Calculations including a varied wind-dependent air flow in the air gap were therefore made, as presented in Paper VII. If there is a high air flow in the real air gap, the results, as presented in Papers V to VII, indicate that as long as the air flow in the air gap was high enough to remove all moisture which had reached

the air gap, the specific air flow is of minor importance in the calculation models since it is not possible to remove further “non-existing” moisture from the air gap.

Modeling the air flow in the air gap in cold roofs was carried out in a similar way to the walls, with an air flow of approximately 30 ACH. When cold attics were modeled a narrower air gap was used than in the real design but with an increased air flow, i.e. the higher air flow compensated for the narrower air gap and the ventilated air volume became equal to that estimated in reality (Paper IX; Technical Reports B, C, E and F). Based on results by Walker and Forest (1995), the ventilation rate in the air gap was set to approximately 30 ACH, which corresponds to a ventilation rate of approximately 3 AHC in a cold attic space. Considering the rather good correlation between measured and blindly calculated values in roofs, the estimated ventilation rates seem to be appropriate, as shown in Figure 6 and Paper IX.

The influence of different air flows on the moisture safety in the air gaps was further discussed using parametric studies in Papers XII and XIII.

3.2.6 Deviations caused by possible inadequate material data in the calculation models

Some cases with initial moisture in the installation layer in bathrooms, between the vapor barrier and the interior waterproof membrane, were studied. Measurements in these positions indicated that the speed of the drying-out process was lower than in vapor-permeable designs but, at the same time, faster than predicted by the calculations, as shown in Paper VIII and Technical Report D. The faster drying-out process may have depended on a lower vapor resistance in the vapor barrier in the real built wall compared to the material properties for the vapor barrier used in the calculation model. This creates a higher vapor transport through the vapor barrier, and a faster drying out process in reality compared to what was estimated in the calculations. However, several of other factors may speed up the drying-out process in reality, such as: convection and vertical or horizontal vapor transport, which cannot be taken into account in the one-dimensional calculations, and possible poor joints or damage. The risks associated with double membranes, i.e. a vapor barrier and an interior waterproof membrane, and possible measures to reduce the risk of any moisture becoming trapped between the two membranes, were thoroughly investigated by Jansson (2005; 2010; 2011) and is discussed in Paper IV and therefore not investigated further in detail in this study.

3.2.7 Unexpected leakages caused by driving rain

During the blind calculations, the penetration through the facade was assumed to be one percent of the amount of driving rain falling on the facade (ASHRAE 2009) and this amount was also added as a load in the air gap behind the cladding in the calculation models. This means that the driving rain that is assumed to penetrate the facade will dry out quickly since it was also assumed that there was a well-ventilated air gap behind the cladding.

Some studied positions indicated leakages caused by driving rain penetrating deeper into the walls than expected. Unexpected increased relative humidity and moisture content was noticed on the inside of the air gap behind the wind barrier or behind the exterior mold-resistant facade insulation board in three of the studied positions, in three different houses. Climate parameters indicated that the leakages were caused by driving rain which penetrated both the facade, the air gap behind the cladding and the wind barrier or the exterior mold-resistant facade insulation board outside the studs. Measurements and calculations in one of the positions are shown in Figure 7. The rainfall data

and moisture content at specific times is shown in Figure 8. The high measured values that are pointed out in Figures 7 and 8 occur directly after the rainfall, as shown in Figure 8 in Technical Report E.

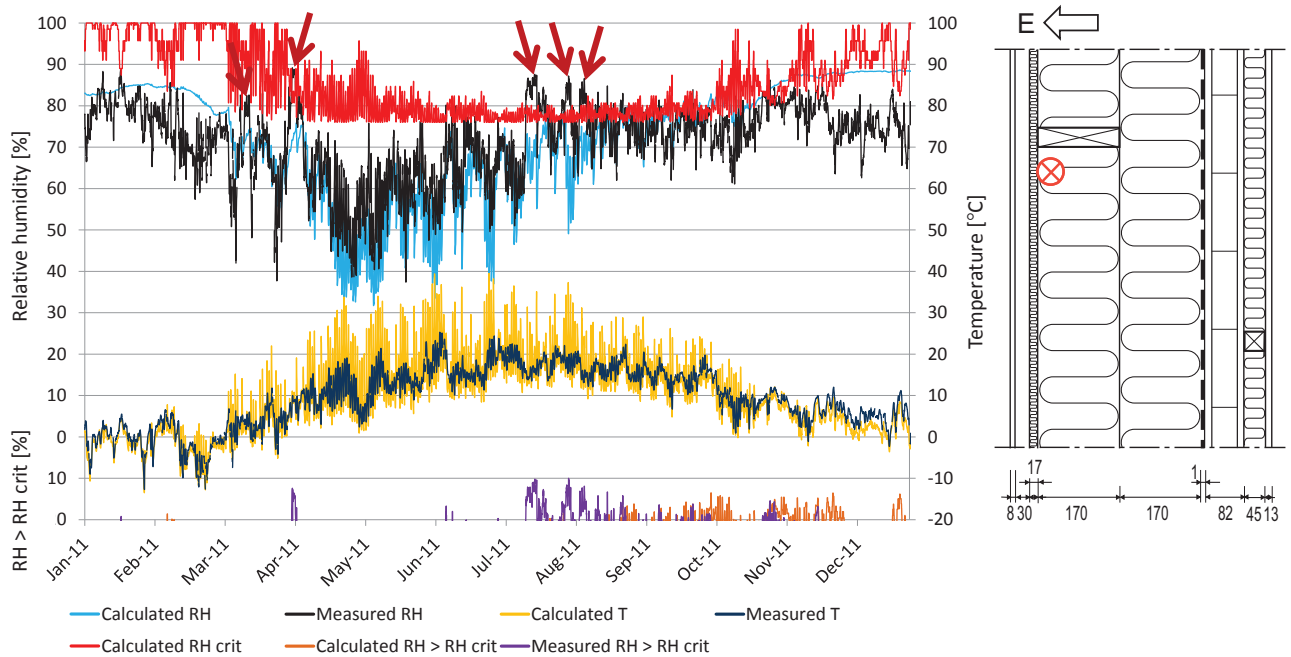


Figure 7. Comparisons between measured and blindly calculated RH and temperature, in Position 16 in Technical Report E, behind the exterior mold-resistant facade insulation board where leakages from driving rain have increased the relative humidity (red arrows). Blindly calculated RH (turquoise) and measured (black). Blindly calculated temperature (yellow) and measured (dark blue). RH_{crit} derived from the calculated temperature (red). Calculated $RH > RH_{crit}$ (light brown) and measured $RH > RH_{crit}$ (purple).

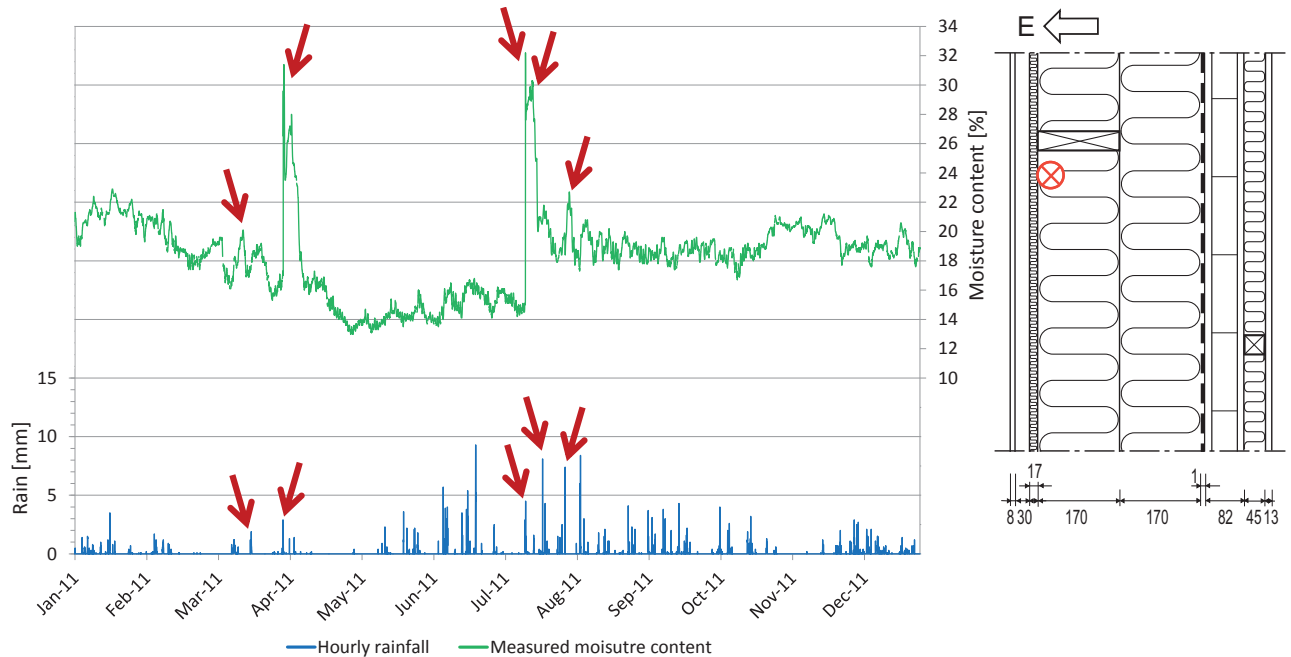


Figure 8. Measured moisture content (light green) in Position 16 in Technical Report E compared to exterior rainfall climate data (blue) during periods when leakages were noticed (red arrows) in the measured results behind the exterior mold-resistant facade insulation board.

Besides the leakage and increased measured relative humidity and moisture content directly after the rainfalls, a rather fast drying out process, both in measured relative humidity and moisture content, was observed. The fast drying out process probably depended on a high air flow in the air gap behind the cladding in combination with a vapor permeable façade insulation board according to the findings in Paper XII. The amount of rain that might penetrate the facade is also affected by the wind speed and the wind direction.

Although it was not specifically investigated, and needs to be studied further using the data in Technical Reports B to F, it may be mentioned that no leakage of particular interest was found in the studied roof constructions.

3.2.8 Amplitudes in measured and calculated values

As can be seen in Figures 4 to 6, as well as discussed in Papers VIII and IX, and clearly visible in Technical Reports B to F, the amplitudes in the studied positions vary during the day and their general heights vary during different times of the year. The differences in amplitude between measured and calculated relative humidity mainly depend on differences in the temperature affecting the relative humidity according to the relationship in Equation 1.

According to Paper VIII, which compares the results in the Technical Reports, it can be seen that there were, in general, greater amplitudes in the measured temperature and relative humidity than in the blindly calculated values in the constructions. Close to the inside of the wall and roof there were low amplitudes in both the measured and calculated values. In the middle of the wall, the amplitudes were slightly greater, mainly in the measured values. Closer to the air gap, the amplitudes, mainly of the measured values, become significantly greater. In the air gaps and on the outside of the facade and in the roof constructions the measured and calculated amplitudes were mainly of the same magnitude when the measured and calculated values were compared. The studied positions in the exterior part of the wall were more affected by the variations in the outdoor climate than the positions closer to the interior side of the wall, which were thermally influenced by the more stable indoor climate. The indoor humidity conditions were of less importance, since well-functioning interior vapor barriers limited its influence deeper in the wall. Comparisons of the results in Technical Reports B to F also show that there were larger amplitudes in the calculated and measured values in positions oriented towards the south, due to solar radiation. There were also higher variations in temperature during the day in summer, which later on created higher amplitudes in the relative humidity during those periods.

The lower amplitudes during the winter may have depended on a more stable outdoor climate, with a limited influence of solar radiation, during those periods. The reason for different amplitudes between measured and blindly calculated values in the studied walls and roofs may depend on the difference in heat and moisture capacity in the actual materials when compared to the materials in the calculation model. The specific measurement sensors were also protected by a plastic shell and not directly exposed to the surrounding material. This material may include a volume of air which was affected more quickly by temperature changes than the surrounding materials.

3.2.9 Risk of moisture damage

In accordance with the results from the parametric studies (Papers XII and XIII), Papers V to X and the results in Technical Reports B to F, it was seen that the most moisture-critical positions were located

in the exterior part of the constructions and primarily occurred during the autumn and the winter when studying the measured results.

Since this study focuses on investigating the correlation between measured and blindly calculated values and the influence of possible measures to reduce the risk of moisture-related damage, the analysis tool, i.e. Folos 2D visual mold chart, only shows when mold growth is possible or not.

Several positions in the study, with an expected risk of damage, were investigated for possible mold growth by Olsson (2014). Material samples have been analyzed in a laboratory for mold growth from chosen positions without any observations of mold growth being observed under the microscope. Furthermore, calculations using the MRD model (Thelandersson and Isaksson 2013), indicated mold growth germination in some positions, but these did not exceed the critical limit of 1 to be defined as damage (Olsson 2014), as presented in Paper IX.

3.2.10 Influence of the exterior climate boundary conditions on moisture safety

As shown in Figure 6, and discussed in Papers II, VIII and IX, the different outdoor climates during different years create variations in the most moisture-critical positions, which affect and vary the risk of mold growth during different years. Some years are more critical than others. It may, therefore, be questionable whether mean climate boundary conditions should be used in the moisture-safety design process since they may reduce or ignore the influence of moisture-critical periods. As mentioned previously and in Paper II the consequences of variations in measured and calculated values during different years also indicate that correct climate boundary conditions must be used when comparing measurements to calculated values.

The overall good agreement between measured and blindly calculated values indicates that the method, presented in Paper II, of supplementing periods with flawed climate data or a lack of climate data was found to work in this context.

3.2.11 Unexpected factors and occupant behavior

By studying the entire material in Technical Reports B to F, on which this study is based, deviations between measured and calculated values caused by unexpected factors were found in several positions. Such an example was the high measured relative humidity in the insulation material caused by a low temperature during the cold period in a roof, as shown in Figure 9. The lower temperature probably depended on the room below the roof being unheated during the winter periods in order to limit energy costs.

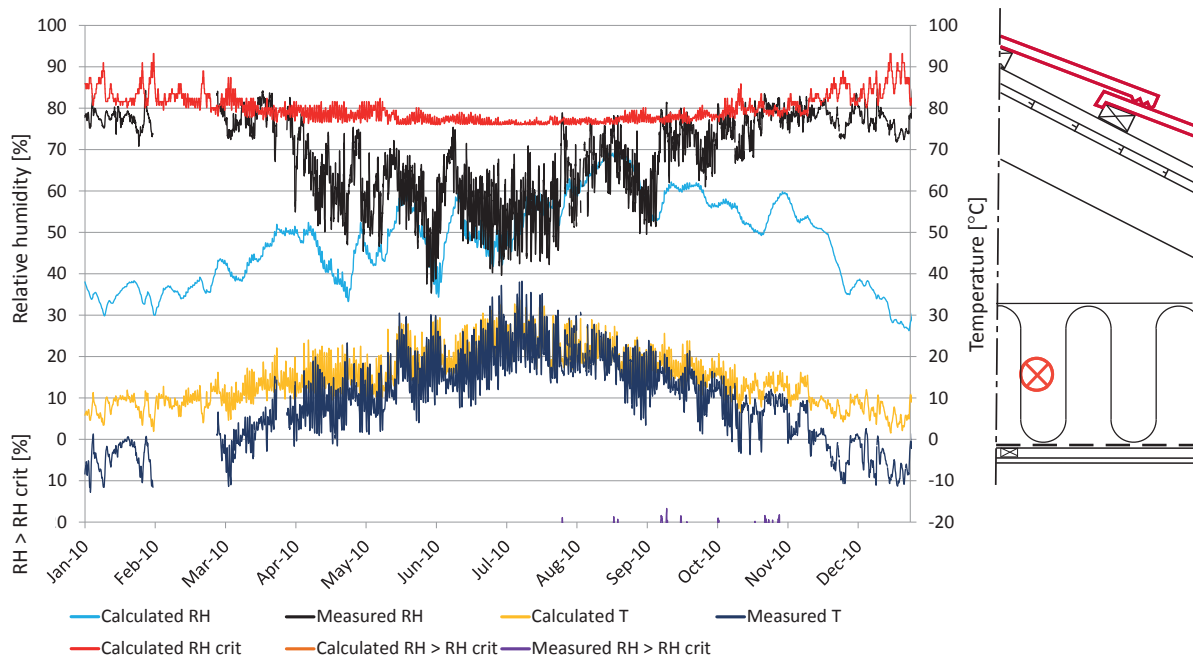


Figure 9. Comparisons between measured and blindly calculated RH and temperature in the middle of the roof insulation (Position 19 in Technical Report B). Unexpected lower temperatures during wintertime increase the relative humidity. Calculated RH (turquoise) and measured RH (black). Calculated temperature (yellow) and measured temperature (dark blue). RH_{crit} derived from the calculated temperature (red). Calculated $RH > RH_{crit}$ (light brown) and measured $RH > RH_{crit}$ (purple).

Different safety margins should be discussed if the occupants do not use the entire building during the winter since this may create moisture-critical conditions. Other unexpected factors affecting the correlation between measured and blindly calculated values, such as ventilation ducts in the insulation materials, were presented in Paper IX. However, the deviation as discussed in Paper IX could also be connected to the possible influence of incomplete information in the calculations.

3.3 Hygrothermal calculation tools in practice

This section summarizes the major results and conclusions from Papers X and XI about how the validated tool may be applied in practice. The parts in Papers X and XI concerning how to apply the tool should only be regarded as examples. Furthermore, the use of hygrothermal calculation tools, does not cover the entire scope of the work involved in carrying out a proper moisture safety design process for a new house.

The influence on the hygrothermal conditions of an actual external, vapor-permeable facade insulation board on the outside the studs are presented. The results proposing adjustments to the design indicate the need to consider the moisture safety questions in the design process. Furthermore, an approach regarding the determination of the thickness of the exterior insulation board was presented. In the specific case, real exterior outdoor climate boundary data was used, which, in practice, is not possible in the design phase before the house is built. However, designing for the case due to real climate conditions was valuable, since the strict comparison using real climate conditions also shows how reliably the tool can be applied in real situations.

Paper XI presents a description of the process when a well-insulated wall was evaluated, observations of the possible risk of moisture-related damage and investigates the effects of measures taken to reduce the risk of damage. The evaluation process of the studied wall in Paper XI indicates, in accordance with Papers V, X, XII and XIII, that the Folos 2D visual mold chart can be used in order to find and evaluate possible measures to reduce the risk of damage in real cases.

The results in Paper XI show the differences between one- and two-dimensional calculations. As expected, and in agreement with previous findings (Forsberg 2011; Olsson 2011; Olsson 2014), there was a reduced risk of damage in the outer part of the studs in a flat wall in two-dimensional situations. I.e. the increased temperatures in the exterior part of the studs which was caused by thermal bridges in the wooden studs reduce the relative humidity and the risk of damage. However, the situation in corners was found to be of more interest since an increased risk of damage was observed. The periods and the patterns of periods when mold growth was possible did not correlate with the cases on the flat wall. As expected, and in accordance with the findings in Paper VIII and the results presented in Technical Reports B to F, this indicates that one-dimensional calculations are not always sufficient in more complicated two-dimensional situations.

The most interesting results in Paper XI were the differences in calculation results, in corners, over time and the subsequent patterns compared to the flat wall, and the indications of a worse situation occurring in corners. In practice, this means that there is a need of two-dimensional calculation tools or reliable safety margins using one-dimensional tools in two- or three-dimensional situations. The rather fast drying out of leakages caused by driving rain, which was observed in corners, was a positive indication. The increased drying out rate probably occurred since moisture in the outer part of the corner may have dried out in two directions. It may be mentioned that the results also indicate that the risk of damage was found to be strictly connected to the specific detailing of the corner design.

3.4 Important factors affecting the risk of moisture damage

This section presents the observations concerning the most important factors affecting the risk of moisture-related damage in wood frame building envelopes. Different wall and roof designs were compared and evaluated with regard to the risk of moisture-critical conditions, i.e. periods when mold growth was possible. The observations mainly refer to findings in Papers X to XIII and Technical Report G.

3.4.1 Most moisture critical position in the reference cases

Two reference cases, intended to simulate a traditional Swedish wall and roof were modeled. The wall had a ventilated air gap behind the cladding and the roof had a ventilated air gap below the tongued and grooved spruce boarding below the roofing felt. The reference cases assume leakages from the exterior due to rain. Both reference cases also had an interior vapor membrane,. However, in the roof reference case, minor holes of $\varnothing 2 \text{ mm/m}^2$ in the interior vapor membrane were assumed. A cross-section and simplified one-dimensional calculation model are shown in Figure 10 and 11. The most moisture-critical Swedish climate, from the city of Lund, was used for the exterior climate and the indoor climate was based on the SS-EN-13788 standard (Paper XII and XIII; Technical Report G; WUFI 2012c; SS-EN 13788 2001).

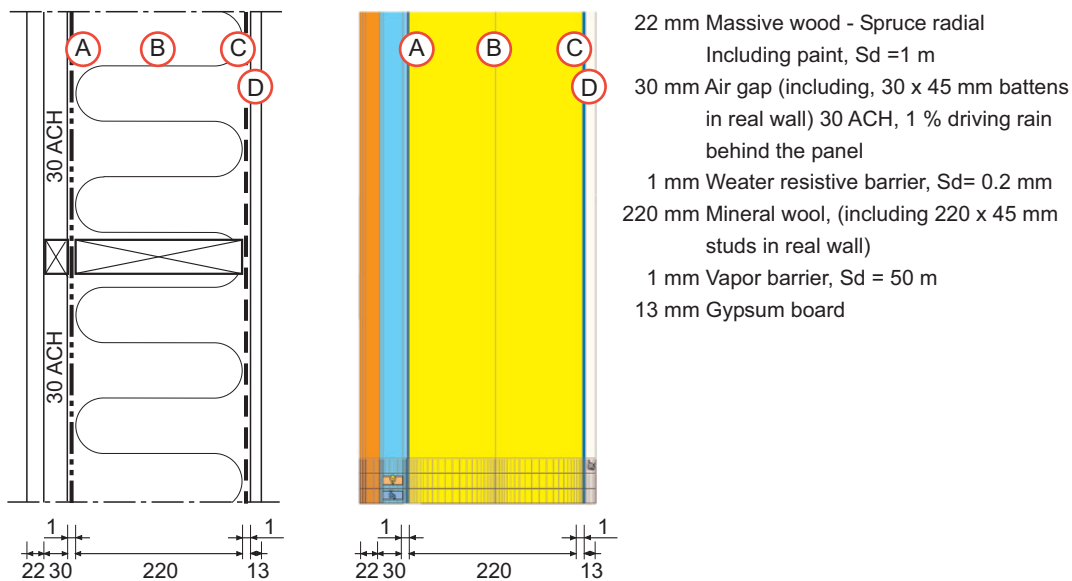


Figure 10. Horizontal cross-section top view drawing and simplified one-dimensional calculation model for the wall reference case (Paper XII).

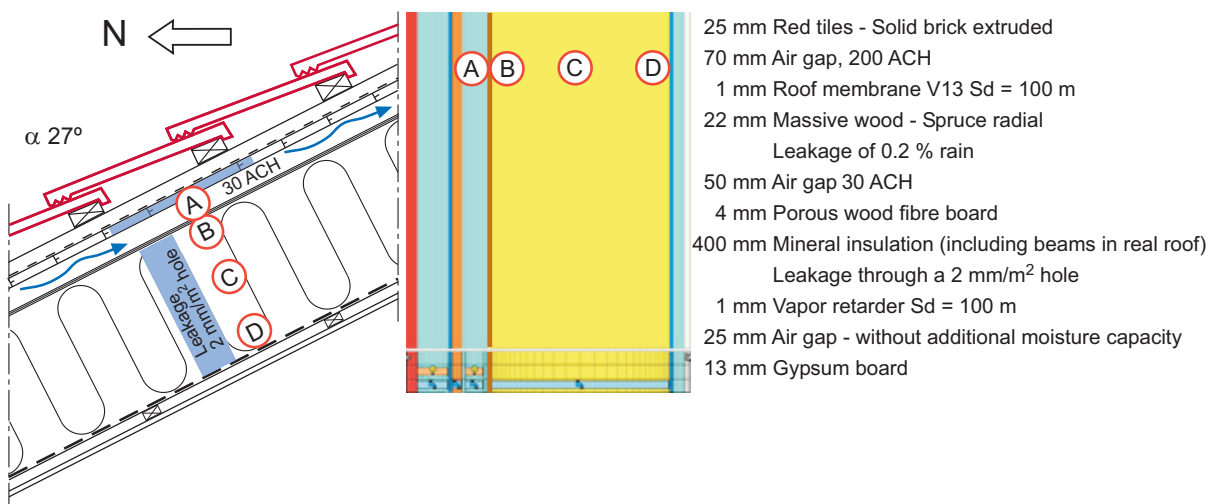


Figure 11. Cross-section drawing and simplified one-dimensional calculation model for the roof reference case (Paper XIII).

Since a one-dimensional calculation tool was used, layers with mixed materials have been simplified and wooden beams in the insulation layer and battens in the air gaps were disregarded. A more detailed description of the reference cases was found in Paper XII and XIII.

Evaluating the studied positions A to D in the two reference cases it was found that the most moisture-critical positions occur in the organic material in the exterior part of the designs, i.e. primarily position A, as shown in Figure 10 and 11 (Paper XII and XIII). It may be mentioned that the facade cladding in the wall was excluded as a critical position since the Swedish building regulations allow mold growth outside the air gap in walls (BBR 2011). The most moisture-critical position established in the exterior part of the designs in the parametric study corresponded to the findings when analyzing the results in the case studies presented in Papers V to X. The most moisture-critical position was also affected by different orientations. North-oriented walls and roofs must always be checked since these are the coldest, because of limited exposure to solar radiation, which gives a

higher relative humidity and risk of damage. Referring to the results in Paper XII, walls oriented towards the direction with the highest amount of driving rain must also be investigated, since this has a major influence on the climate conditions in the wall and the risk of damage. Changes in the designs, in general to more vapor tight materials, may also remove the most critical position to the inside of the vapor tight material, as shown in Papers XII and XIII.

There are several possible measures that can be taken to reduce the risk of moisture-related damage as well as factors that increase the risk of damage. The most important factors affecting the hygrothermal conditions in the most moisture-critical position, referred to Papers XII and XIII, are presented below.

3.4.2 Insulation thickness in walls and roofs

Several studies indicate an increased risk of damage in the case of thicker insulated constructions, as reported in Paper IV and Technical Report A. Similar results showing increased relative humidity conditions with a higher probability of possible mold growth were found in both roofs and walls, as presented in Papers XII and XIII. An example of increased highest relative humidity, above the critical limit when mold growth was possible in the case of thicker insulated walls is given in Table 1 in the next Sub-section.

3.4.3 Exterior facade insulation boards in walls

By attaching exterior vapor-permeable insulation boards to the outside of the wooden studs, as shown in Figure 12, the surrounding temperature on the exterior side of the studs will increase and the relative humidity and the risk of mold growth on the outer part of the studs, position Q, will decrease (Paper VII; X; XI and XII; Technical Report G). Exterior insulation boards must be located on the outside of the wood studs, between the studs and the weather resistive barrier, and must be made of moisture-resistant materials so they are not damaged by the high relative humidity that occurs in position A.

The required minimum thickness of the exterior insulation board for walls without any critical conditions at all outside the wooden studs was established by iteration, as shown in Table 1. For the reference case with a total insulation thickness of 220 mm, the exterior insulation board needs to be 33 mm thick in order to avoid critical conditions in position Q, as shown in Figure 12.

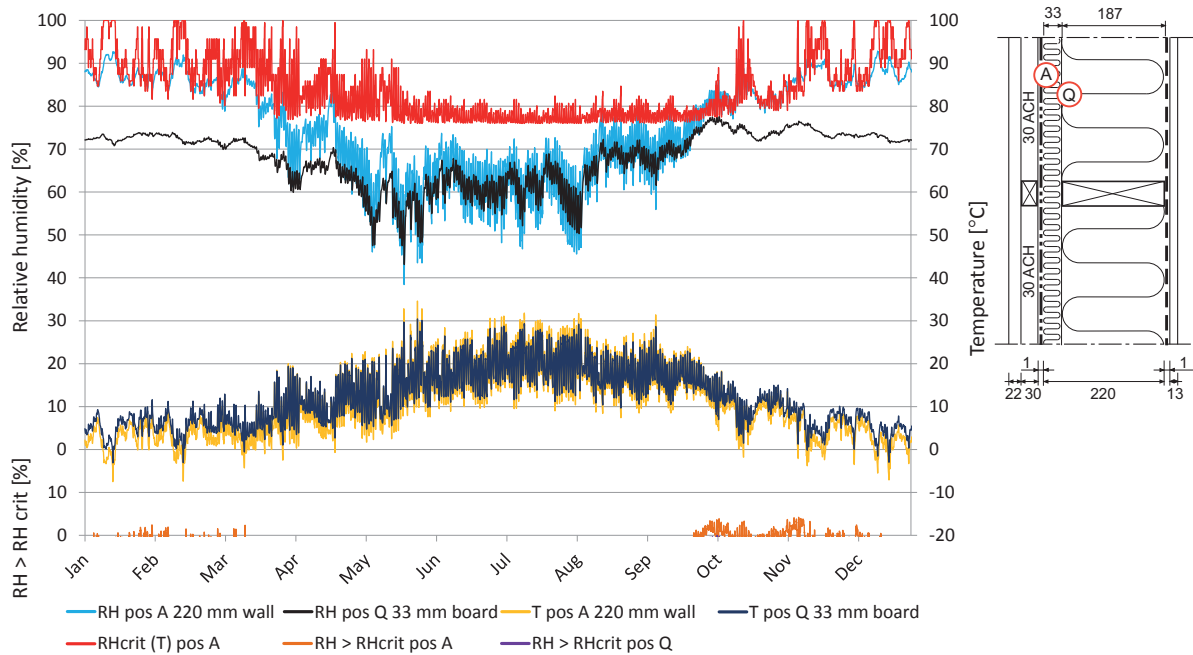


Figure 12. RH in position A (turquoise) and position Q (black) compared to RH_{crit} for a wall with a total insulation thickness of 220 mm. Temperature in position A (yellow) and in position Q (dark blue). RH_{crit} dependent on T in position A (red), $RH > RH_{crit}$ in position A (light brown), $RH > RH_{crit}$ in position Q (purple) is always below the critical limit and not shown in the figure.

Calculations in order to establish different thicknesses of the exterior facade insulation board with regard to different total insulation thicknesses were carried out by iteration for several cases as shown in Table 1, Paper XII and Technical Report G. Similar results were also found in the combined case and parametric study as presented in Paper X.

Table 1. 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 in Lund (WUFI 2012c).

Total insulation thickness	Minimum 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	4.2
270	39	4.6
320	45	5.5
370	49	6.5
420	52	6.7
470	55	7.0
520	59	7.5

3.4.4 Exterior insulation on top of the tongued and grooved wooden roof boarding

Increased temperatures, reducing the relative humidity and risk of damage in position A in roof constructions, might be created in a similar manner as in walls, i.e. by attaching exterior insulation boards to the outside of the tongued and grooved roof boarding, as shown in Figure 13 and Paper XIII

(Harderup and Arfvidsson 2008; Persson Lindgren 2010; Hansson and Lundgren 2009; Nik 2012). In general, the insulation material was mineral wool or polystyrene boards, which were installed below or above, or in between two layers of roofing felt, as shown in Figure 13.

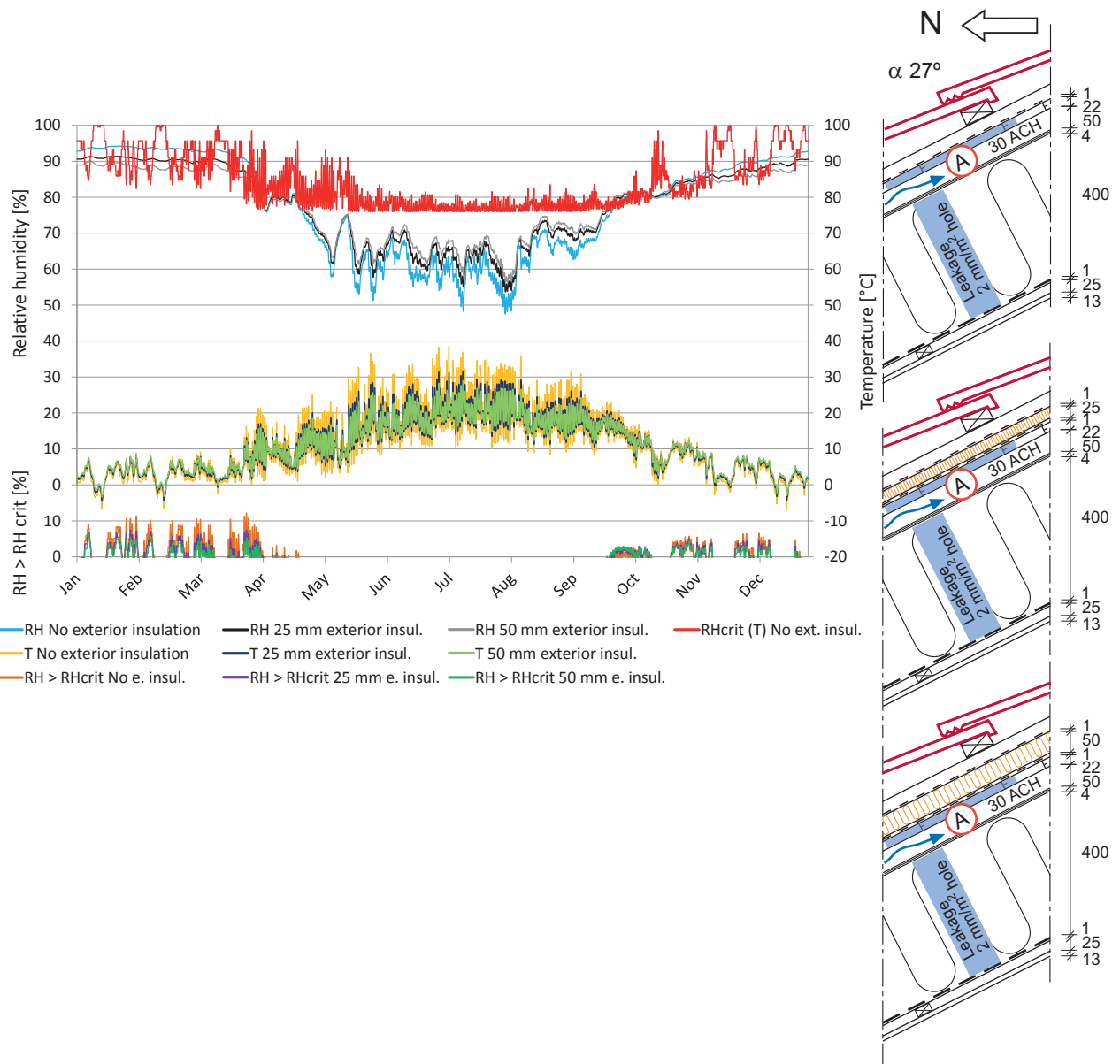


Figure 13. Comparing the climate conditions in position A with and without exterior insulation on top of the tongued and grooved wooden roof boarding. RH without, 0 mm (turquoise), 25 mm (black) and 50 mm (grey) exterior insulation. T without, 0 mm (yellow), 25 mm (dark blue) and 50 mm (light green) exterior insulation. RH_{crit} dependency on T without exterior insulation (red), $RH > RH_{crit}$ without (light brown), 25 mm (purple) and 50 mm (dark green) exterior insulation.

The findings in Paper XIII confirm previous results (Harderup and Arfvidsson 2008; Persson Lindgren 2010; Hansson and Lundgren 2009; Nik 2012) in which the critical conditions, in position A, were reduced when exterior insulation was installed on the outside of the tongued and grooved roof boarding, as shown in Figure 13, compared to the reference case without external insulation. The reduced relative humidity was caused by higher RH temperatures as a consequence of the exterior

insulation. The thicker the exterior insulation, the fewer the critical conditions during the period November to April. During the warm non-critical period, the exterior insulation increases the relative humidity, but without any risk of mold growth.

3.4.5 Air flow in the air gap behind the facade cladding

Several studies discuss the importance of a well-ventilated air gap behind the cladding in wood frame walls. A high air flow in the air gap will remove moisture that has penetrated the cladding and will contribute to an increased drying out rate in a wood frame construction (Salonvaara et. al. 2007; Straube, van Straaten and Burnett 2004; Piñon et. al. 2004; Falk and Sandin 2013; Paper IV; VI; VII and XII; Technical report G). The influence on critical conditions in position A is shown in Figure 14 when there was a lower air flow in the air gap, of 1 ACH, behind the cladding compared to the reference case, with an air flow of 30 ACH in the air gap.

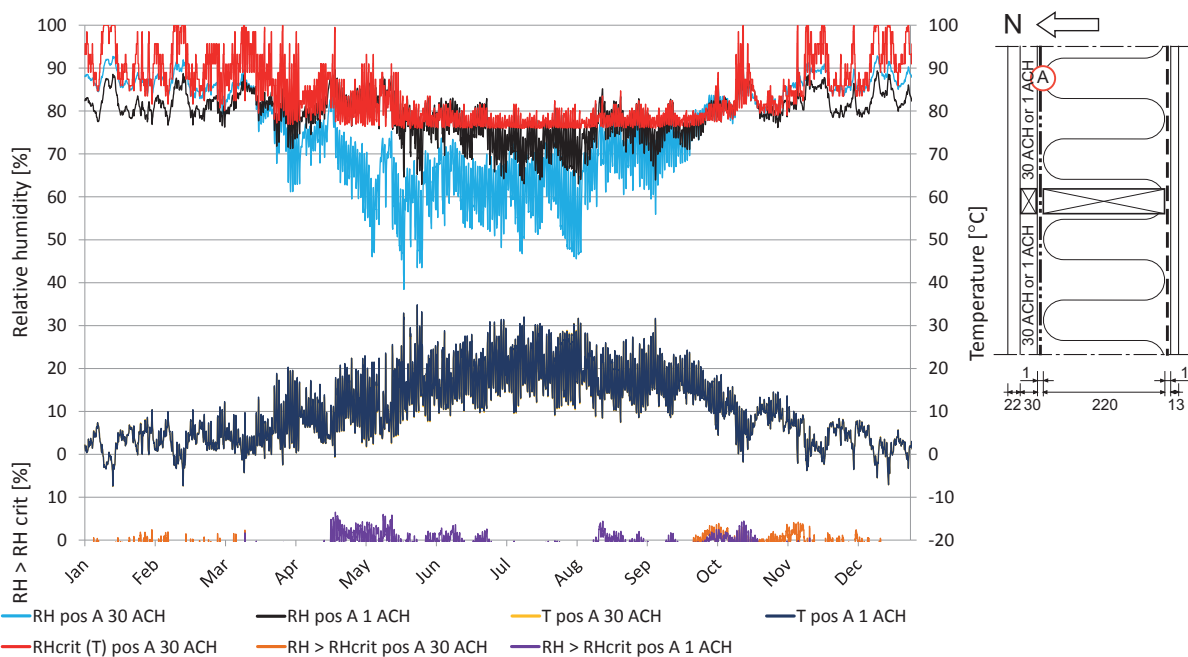


Figure 14. RH in position A compared to RH_{crit} in a wall with 220 mm insulation oriented towards the north with an air change rate of 30 ACH (turquoise) and 1 ACH (black) in the air gap. The temperature at 30 ACH (yellow) is hidden behind the temperature at 1 ACH (dark blue). RH_{crit} (red) dependent on T at 30 ACH, $RH > RH_{crit}$ at 30 ACH (light brown), $RH > RH_{crit}$ at 1 ACH (purple).

A low air flow in the air gap behind the cladding has a negative influence and the critical conditions occur more frequently and during other periods of the year in position A, as shown in Figure 14. In a well-ventilated air gap with vertical battens and wide openings at the bottom and top there is normally a higher air change rate than 30 ACH (Falk 2013; Tichy and Murray 2007). According to Papers VI and VII, high ventilation rates, i.e. more than 30 ACH, do not further improve the conditions in the wall as long as there is no more moisture available to dry out. Differences in the critical conditions in positions A and Q in walls with increased insulation in combination with a low and high air change rate in the air gap were studied in Paper XII and Technical Report G. Four cases, as shown in Figure 15, 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 a total insulation thickness of 420 mm.

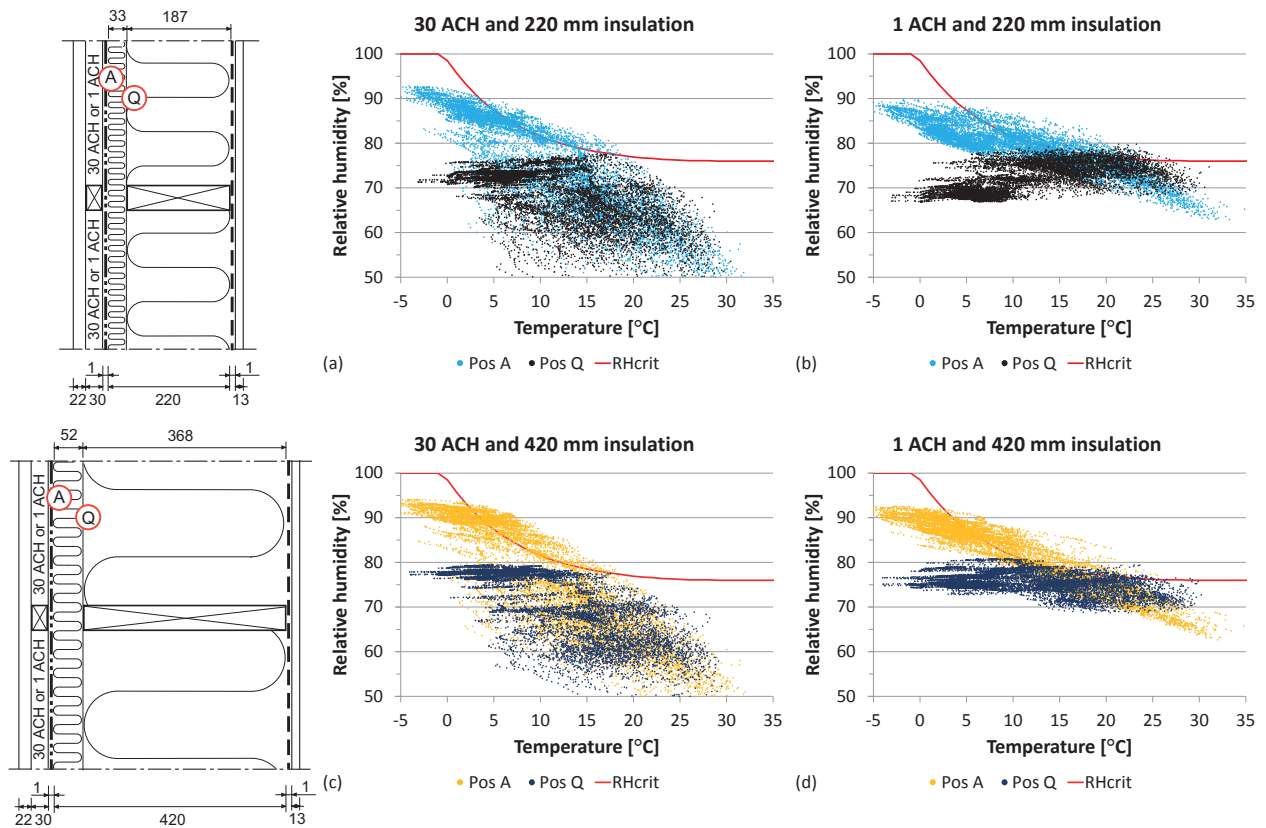


Figure 15. RH in positions A and Q compared to RH_{crit} (red) for two different insulation thicknesses and two different air change rates in the air gap behind the cladding, as shown in the cross-sectional drawings. (a) RH 220 mm insulation and 30 ACH, position A (turquoise) and position Q (black). (b) RH 220 mm insulation and 1 ACH, position A (turquoise) and position Q (black). (c) RH 420 mm insulation and 30 ACH, position A (yellow) and position Q (dark blue). (d) RH 420 mm insulation and 1 ACH, position A (yellow) and position Q (dark blue).

As shown in Figure 14, comparing the cases with 1 and 30 ACH in the 220 mm insulated wall, a low air flow in the air gap behind the cladding had a negative influence on the critical conditions in position A. The results in Figure 15 show that the low air flow of 1 ACH also has a negative influence in position Q. The isopleth charts show that the occurrence of critical conditions in position A and Q increased with thicker insulation. However, comparing positions A and Q at 1 and 30 ACH in the 220 mm and the 420 mm insulated wall showed that there was a higher negative influence on the critical conditions in the wall with 420 mm insulation. I.e. a low air flow in the air gap had a higher negative influence when the walls were well-insulated. Results in position Q also showed that the critical conditions in the wall could be handled by a high air change rate in the air gap and an exterior vapor-permeable moisture-resistant insulation board.

Besides the fact that different outdoor climate conditions during different years affect the risk of damage, different orientations of the facade influence the risk of moisture-related damage, as shown in Paper XII and Technical Report G. South-oriented facades have a higher drying out potential thanks to solar radiation. However, the influence of driving rain has a significantly higher influence compared to the possible positive influence caused by solar radiation. According to the results in Paper XII and Technical Report G, a high air flow in the air gap behind the facade cladding in walls limits the possible negative influence and reduces the risk of damage caused by driving rain. Furthermore, different facade materials influence the risk of damage. Again, in order to reduce the

possible negative influence of different facade materials, a high air flow in the air gap is required (Paper XII; Technical Report G).

Results in Paper XII, as well as the appended Papers III, IV, V, VI and VII focusing on the validation of the studied hygrothermal calculation tool, and in accordance with previous findings (Paper IV), indicate that a well-ventilated air gap behind the cladding is the most important factor in order to limit the risk of moisture-related damage in walls.

3.4.6 Ventilation rates in the air gap and cold attics in roofs

Different ventilation rates in air gaps in roofs and cold attics also influence the risk of damage, as discussed in Paper XIII. Referring to Paper XIII, the influence on the critical conditions in roofs in position A and B was investigated with different air flows in the air gap of 3, 30 and 300 ACH, as shown in Figures 16 and 17.

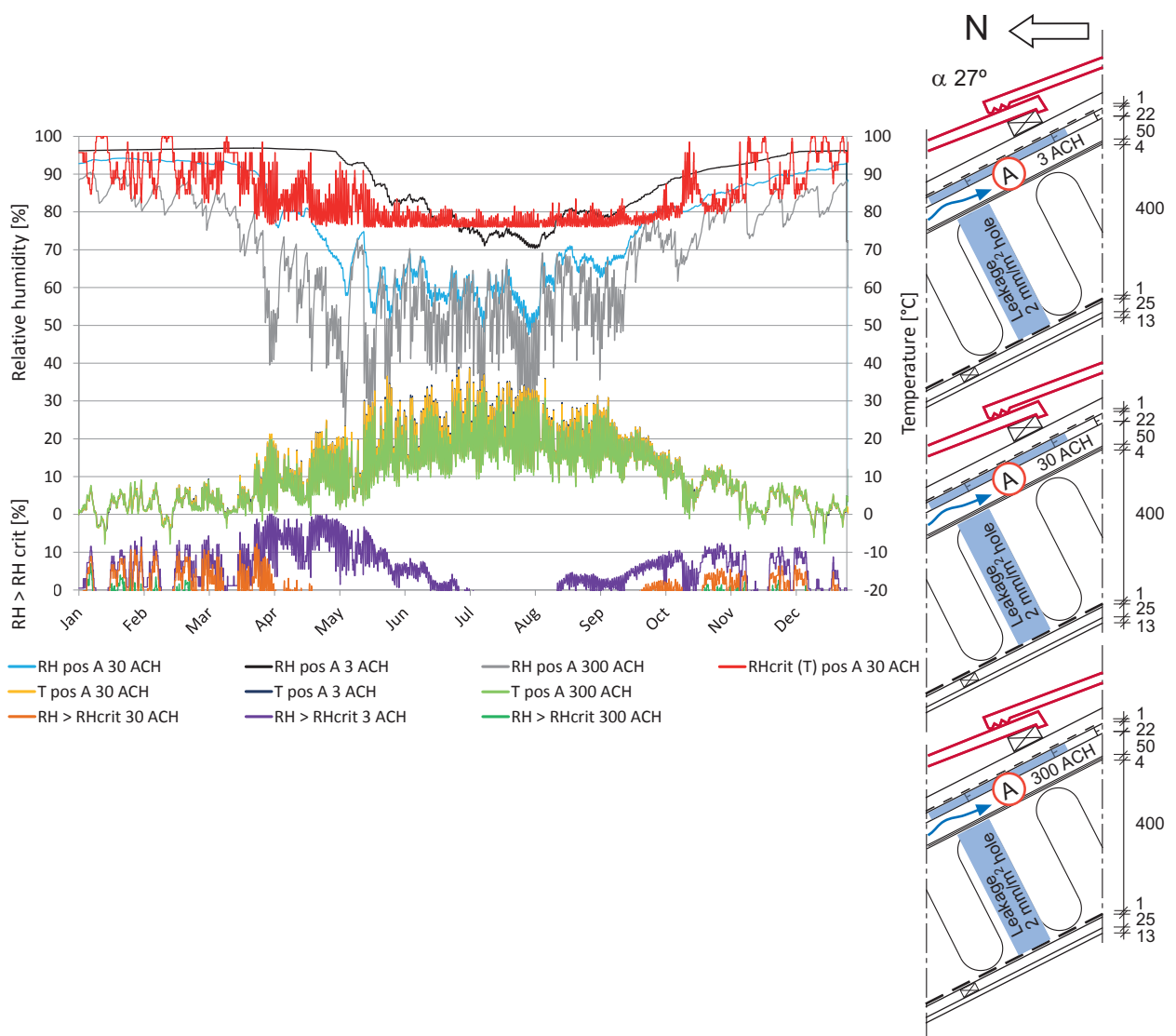


Figure 16. Comparing the climate conditions in position A with three different ventilation rates in the air gap. RH in position A with 3 ACH (black), 30 ACH (turquoise) and 300 ACH (grey). T with 3 ACH (dark blue), 30 ACH (yellow) and 300 ACH (light green). RH_{crit} dependent on T with 30 ACH (red), $RH > RH_{crit}$ for 3 ACH (purple), 30 ACH (light brown) and 300 ACH (dark green).

A low air flow of 3 ACH in the air gap results in extensive critical conditions when mold growth is possible in position A, as shown in Figure 16. High relative humidity conditions occur since the low ventilation rate does not manage to remove all the moisture penetrating into the roof construction. The case of 3 ACH was not investigated further since it had already failed in position A.

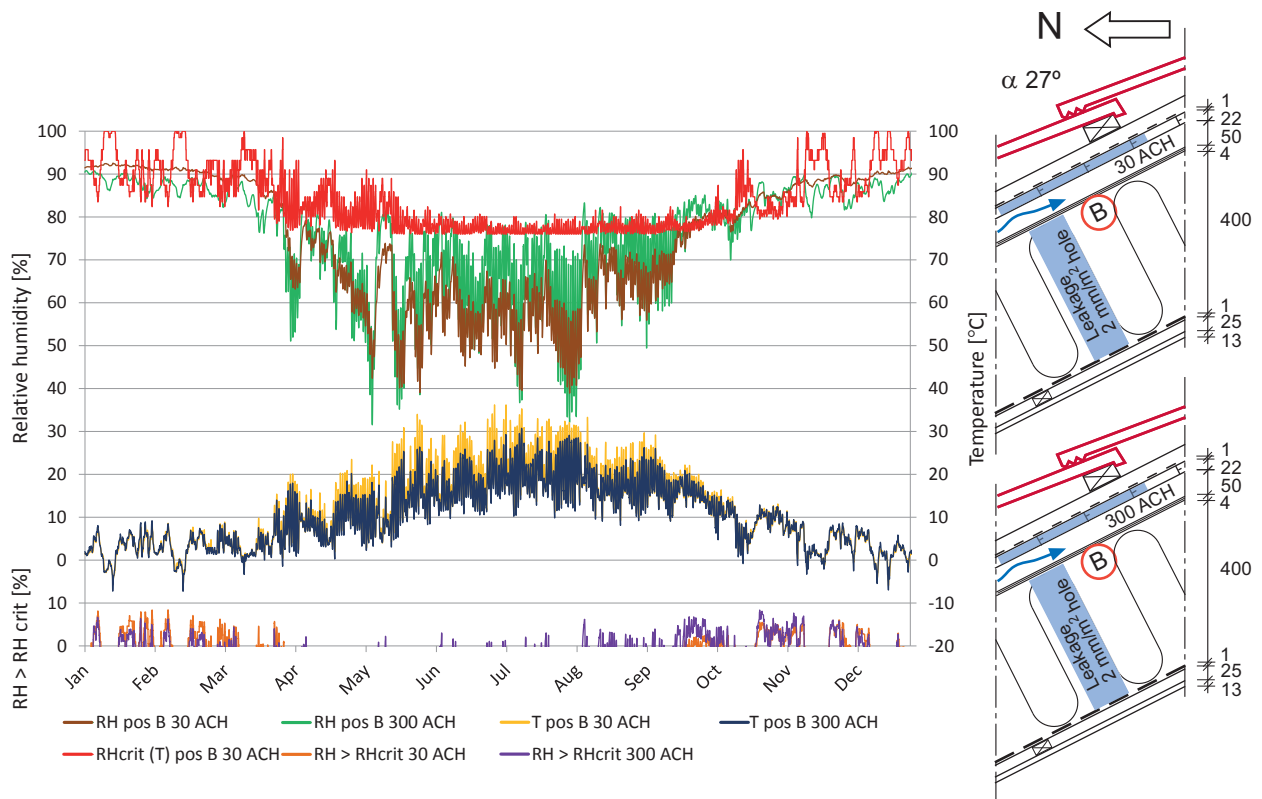


Figure 17. Comparing the climate conditions in position B with 30 and 300 ACH in the air gap. RH in position B 30 ACH (brown) and 300 ACH (green), T for 30 ACH (yellow) and 300 ACH (dark blue). RH_{crit} dependent on T with 30 ACH (red), $RH > RH_{crit}$ for 30 ACH (light brown) and for 300 ACH (purple).

A high ventilation rate in the air gap behind the tongued and grooved roof boarding reduced high moisture levels caused by leakages and initial construction moisture, in position A, as shown in Figure 16. However, high ventilation rates decrease the temperature and increase the relative humidity. A lower temperature at 300 ACH was noticed in both positions A and B, as shown in Figures 16 and 17. The lower temperatures do not generally have a negative influence in position A, as shown in Figure 16, but increase the critical conditions in September in position B, as shown in Figure 17. In the northern, i.e. colder, part of Scandinavia a high ventilation rate may have a significant negative influence on possible critical conditions in position B. To summarize, the ventilation rate should be high enough to remove the moisture penetrating the roof but at the same time as low as possible in order to maintain as high temperatures as possible, which decrease the relative humidity. Bad detailing and poor workmanship can therefore not be solved by increased ventilation. However, initial high air flows in the air gap are required in order to dry out construction moisture.

3.4.7 Drying out potential after leakages and initial construction moisture in walls

According to the unexpected findings in the case studies, to verify and evaluate the hygrothermal calculation tool, significant leakages penetrating deep into the walls were observed, as shown in

Figures 7 and 8. The possible drying out potential for the different designs was therefore studied, as presented in Paper XII. The influence of a leakage of 1% of the driving rain (ASHRAE 2009) located 152 mm from the inside of the air gap, was studied in four different designs, as shown in Figure 18. Four designs were compared in isopleth charts for positions A and Q: Two of the designs had insulation thicknesses of 220 and 420 mm insulation respectively. Two designs had an exterior mold-resistant insulation board of vapor-permeable mineral wool with a thermal conductivity $\lambda = 0.037$ W/mK and $S_d = 0,0013$ m. The other two designs had exterior mold-resistant insulation of a rather vapor-tight expanded polystyrene, EPS, insulation board with a thermal conductivity of 0.037 W/mK, $S_d = 0,05$ m and a density of 30 kg/m^3 (WUFI 2012b; Achziger and Cammerer 1984).

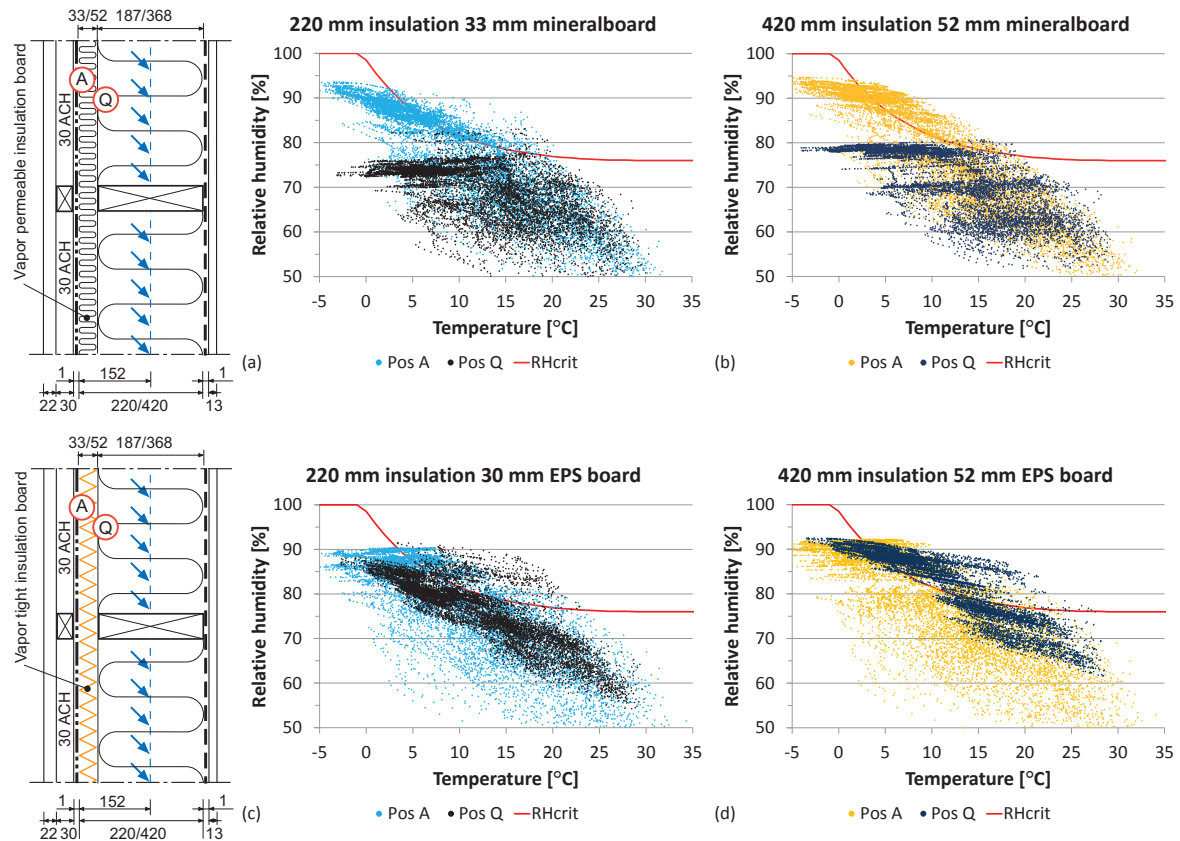


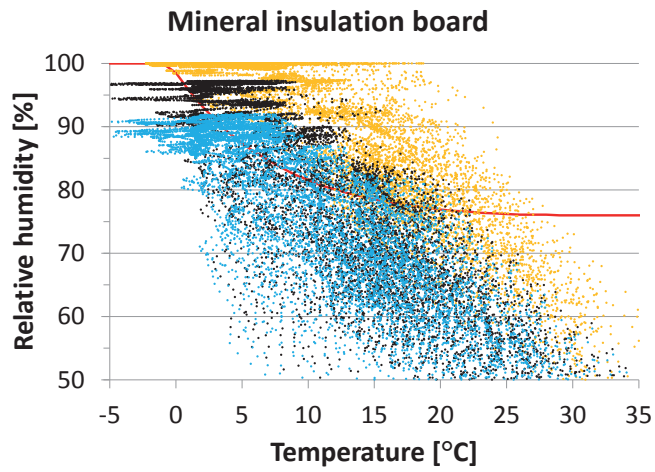
Figure 18. RH in positions A and Q compared to RH_{crit} (red) for walls subjected to a leakage, with two different materials used for the exterior insulation board and two different insulation thicknesses, as shown in the cross sectional top view drawings. (a) RH 220 mm – 33 mm mineral insulation board, 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).

All cases with leakages in Figure 18 showed a higher RH in positions A and Q compared to situations without leakages, as shown in Figures 15 (a) and (c). However, there is a significant difference in high RH in position Q between the cases with vapor-permeable mineral wool and an EPS vapor-tight exterior insulation board. In the case with a total thicker insulation of 420 mm there is also a significantly higher RH in position Q compared to the case with thinner insulation of 220 mm. To handle initial construction moisture and possible leakages, the exterior mold-resistant board must be vapor-permeable.

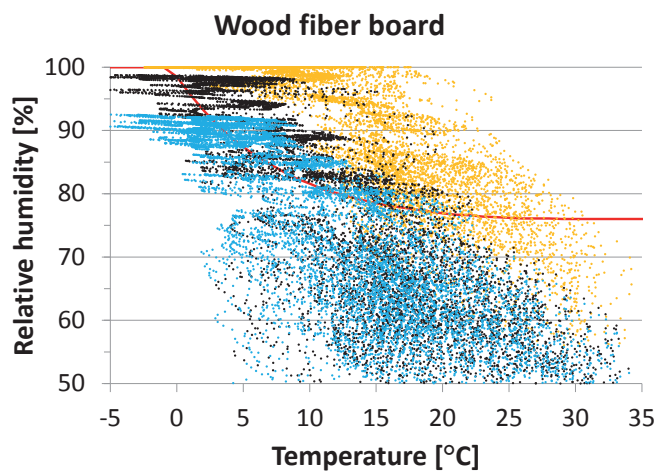
3.4.8 Sensitivity to leakages in roofs

Even if no leakages in roof designs were observed in the case study, the influences of possible leakages were studied, as presented in Paper XIII. Leakages may occur from both outdoor rain and interior humid air penetrating cracks in the interior vapor membrane. Observations in previous studies (Ingelsson and Olsson 2013) as well as the results in Paper XIII indicate that leakages through the exterior roofing felt have a high negative influence on the climate conditions and cause a significantly increased risk of moisture-related damage.

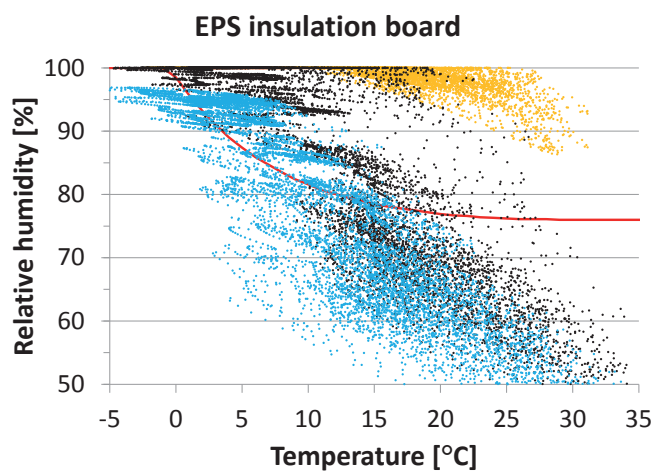
Leakages may also occur from humid indoor air penetrating through cracks and bad joints in the interior vapor membrane. The influence of holes in the interior vapor membrane causing leakages from indoor humid air was studied by Georgsdottir and Sawirs (2012). The consequences of wider holes, i.e. increased leakage from indoor humid air, in combination with different material on the board on the inside of the ventilated air gap, as shown in Figure 19, was studied in Paper XIII. Besides the reference case with holes of 2 mm/m² in diameter, two cases with holes of 5 mm/m² and 12 mm/m² in diameter in the interior vapor membrane were studied. The different amount of leakages were studied in combination with a wood fiber board with $S_d = 0,00625$ m as in the reference case, a vapor-tight EPS insulation board, with $S_d = 0,05$ m (WUFI 2012b; Achziger and Cammerer 1984), and a vapor-permeable mineral insulation board with $S_d = 0,0013$ m (WUFI 2012b), as shown in Figure 19. Since leakages through a damaged interior vapor membrane primarily affect the design on the inside of the board, this part focuses on this location, i.e. position B.



(a) • 2 mm hole • 5 mm hole • 12 mm hole — RHcrit



(b) • 2 mm hole • 5 mm hole • 12 mm hole — RHcrit



(c) • 2 mm hole • 5 mm hole • 12 mm hole — RHcrit

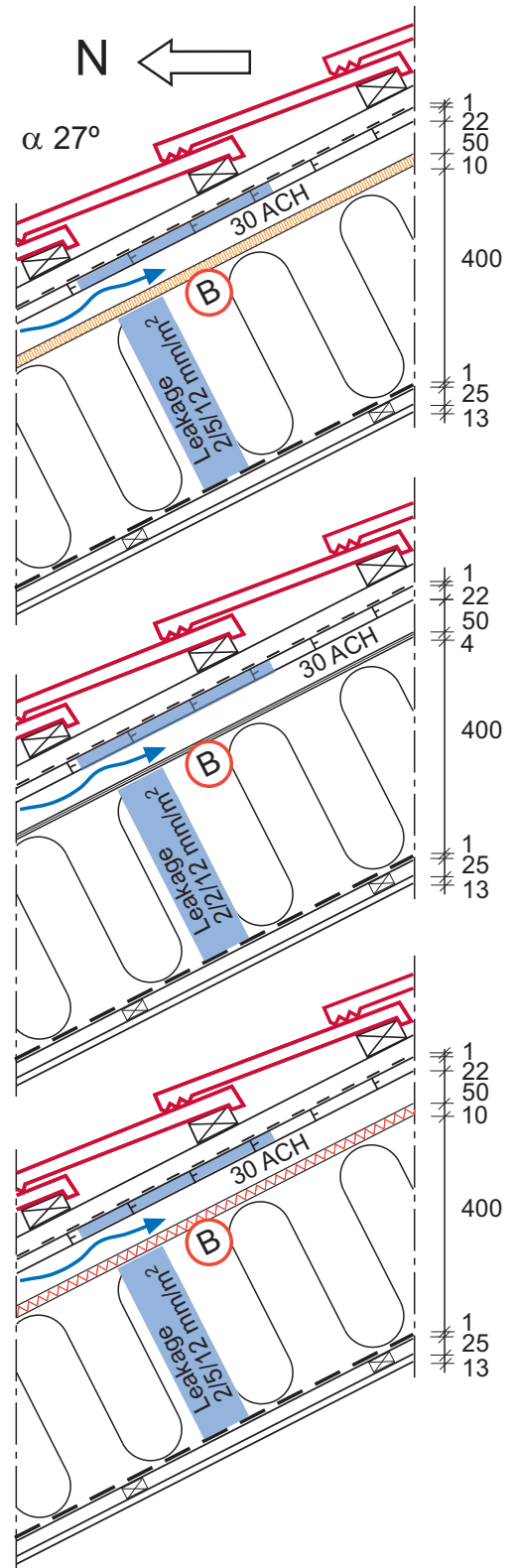


Figure 19. RH in position B compared to RH_{crit} (red) for roofs subjected to three different amounts of leakages and three different insulation retaining board materials outside position B (a) Vapor-permeable mineral wool with $2\text{ mm}^2/\text{m}^2$ hole reference case (turquoise), $5\text{ mm}^2/\text{m}^2$ hole (black) and $12\text{ mm}^2/\text{m}^2$ hole (yellow). (b) Wood fibre board with $2\text{ mm}^2/\text{m}^2$ hole (turquoise), $5\text{ mm}^2/\text{m}^2$ hole (black) and $12\text{ mm}^2/\text{m}^2$ hole (yellow). (c) Vapor tight EPS insulation board with $2\text{ mm}^2/\text{m}^2$ hole (turquoise), $5\text{ mm}^2/\text{m}^2$ hole (black) and $12\text{ mm}^2/\text{m}^2$ hole (yellow).

Wider holes, which increase leakage of humid indoor air, create a major increase in relative humidity and have a significant negative effect on the critical conditions in position B, as shown in Figure 19 and Paper XIII. In agreement with Harderup and Arfvidsson (2008) and Ingelsson and Olsson (2013) the results in Figure 19 clearly indicate that even minor holes can create leakages with significant effects on the moisture safety. Different materials used for the boards in between position B and the air gap show that vapor-tight materials, such as EPS, create a moisture trap in position B, as shown in Figure 19c. A board with higher permeability decreases the relative humidity and reduces the occurrence of critical conditions, as shown in Figure 19a, since moisture can dry out to the air gap and then be removed by ventilation.

The major influence on the relative humidity and the increased risk of damage indicate without any doubt that no leakage at all can be accepted. Vapor-tight materials show the same behavior and consequences as presented in Figure 18, where a moisture trap emerged and increased relative humidity occurred in positions where mold growth was possible. The board between position B and the air gap should, therefore, be made of a vapor-permeable material to allow moisture to dry out towards the air gap. It must be stated that a higher ventilation rate cannot be used to solve problems caused by an increased amount of leakage.

4 Discussion

This section discusses the major results and findings in a general manner. Observations and reflections which were noticed but not possible to investigate completely within the framework of this project are discussed. Possible further research is highlighted.

However, a complete analysis of all possible sources of error and their effects on the results has not been carried out since it would require extensive work

4.1 Reflections on the literature review

Although there are standards concerning numerical simulations using hygrothermal calculation tools, such as SS-EN 15026 (2007) and ASHRAE 160P (2009), there is a lack of information regarding how to use the calculations tools. User manuals in general focus on how the tool works, not how to use the tool in practice. Several hygrothermal calculation tools do not present examples of common models, how to build your models, nor reliable boundary conditions for important factors which highly influence the results, such as reliable air flows in air gaps for different kinds of air gap designs (Paper V).

Although it was not a specific issue in this project, no studies investigating the influence of the results on the usability of the calculation tools were found, besides Fröderberg (2014) and parts of a report by Samuelson and Jansson (2009). This is alarming, since most of the poor calculation results seem to have been created by the users (Samuelson and Jansson 2009; Paper V) rather than the equations.

When looking back at the content of the literature review and experience gained during the research projects some further points were noticed. There is ongoing work to fill up gaps due to a lack of knowledge; today there are mold models and further knowledge regarding air flows and air movements in the air gap. During the studies, it was seen that the literature reviewed in Paper IV consistently lacked papers dealing with roofs and attics. The reason is that the literature reviews in Paper IV and Technical Report A primarily focused on walls. There was plenty of knowledge about air flows in ventilated air gaps but it was difficult to find information about air movements and air change rates in cold roofs with ventilated air gaps or ventilated cold attics.

4.2 Reflections on the blind validation and evaluation of WUFI

4.2.1 General error analysis

The material and test method do not allow a numerical error analysis to be carried out since the calculation models and settings were made individually. I.e., it is possible to estimate the quality in the comparisons between measured and calculated values but the calculation results will vary depending on different users. However, the most important observations are summarized below:

1. The correlation between measured and blindly calculated values was, over all, deemed to be sufficiently good. When deviations between measured and blindly calculated values were observed, the underlying factors creating the deviations were, in general, possible to identify.
2. The indoor and outdoor climate boundary conditions have the greatest influence on the correlation between measured and blindly calculated values. In practice, this means that it is of major importance to consider the variations between different years the outdoor climate,

both in order to reach correlation and for moisture safety purposes. Furthermore, factors affecting the indoor climate conditions, such as user behavior, are also of major importance with regard to correlation and moisture safety.

3. It seems that perfect material data parameters, in general, are of minor importance in the studied calculation models.
4. The recalibration of 16 sensors showed a mean value of 3.3 % lower measured relative humidity compared to the real relative humidity at high relative humidity conditions, i.e. 85.1 % relative humidity. A lower measured relative humidity compared to blindly calculated values was noticed, which meant that if the relative humidity was high, it would indicate that a better correlation would be found using recalibrated measured values.

4.2.2 The independent and blind validation method

Validation of hygrothermal calculation tools seems to focus on presenting results with as good correlation as possible with regard to measurements, without clarifying how good correlations were reached, i.e. what parameters were applied as boundary conditions and what sensitivity tests of the applied parameters were carried out. An example of this was how the air flows in air gaps depend on different air gap designs (Paper V). The air flow is of major importance for the user in order to apply the tool in practice. Furthermore, the tools were not tested and validated by independent researchers. This means that there might be hidden interests in order to obtain good results, or bad results in the case of a competitor (Paper I).

Besides the lack of blind and independent validations, as shown in Paper I, hygrothermal calculation tools were generally not validated in their appropriate environments. This raises several important issues regarding, for example:

1. The testers themselves, who are researchers rather than possible users.
2. The validation objects which, in general, do not consist of real objects.
3. The surrounding environments, where possible influences from external parameters, such as variations in climate conditions and unexpected occupant behavior, are neglected.

This is alarming, since the overall results of the study point out these as the most important factors for reaching reliable results. Focus should be redirected from developing more detailed equations to how to apply the tools in their appropriate environments and what external factors influence the results in order to reach reliable results. Again, it may be questionable whether today's methods for validation fulfill the requirements of a proper validation according to GLP and in accordance with EU directives (Paper I).

Blind validations are reliable since intentional or unintentional adjustments in calculated results, to obtain better correlations to the measured values, are impossible. There are also other positive effects since the blind calculations are in a context similar to the situation that the designer has to deal with before a house is built. This provides important information about how the user perceives and applies the tool in practice.

4.2.3 Factors affecting the correlation between measured and calculated values

During the validation process (Papers V to X and Technical Reports B to F) a need to determine factors which highly affect the correlation between measured and blind calculated values was

noticed. These were factors that do not concern a specific calculation tool and its equations but how to apply the calculation tool in practice. This is of future interest in order to establish parameters which highly affect the results and, furthermore, how to make better calculation models with even more reliable results. Several of such possible factors and parameters were observed during the validation process and are mentioned in Section 2.7 and discussed by Mundt-Petersen (2013). There is broad and extensively summarized measurement data in well-defined measurement positions available to establish such factors and parameters in the Technical Reports B to F. Examples of parameters and factors needed to reach a better, or maybe a perfect, correlation between measured and calculated values, as well as parameters which highly influence the correlation between measured and calculated values, are listed below:

1. The possible measures in order to adjust the calculation models using the relationship between relative humidity, temperature and vapor content, as presented in Equation 1. I.e., the possible measures that influence the temperature or the vapor content in the calculation model in order to reach better correlations should be investigated. For example:
 - a. By moving the chosen studied position in the insulation materials in the calculation models. This changes the temperature which may result in better agreement between measured and calculated values.
 - b. By adjusting the air flow in the air gap. The vapor content may change, which, perhaps, results in a better agreement between measured and calculated values.
 - c. By including tiles on the roofs in the designs. This was excluded in the calculation models in the case study. Comparing the results in Paper IX and XIII it was found that this influence the results.
 - d. By adding the heat resistance of the snow lying on top of the roofs in the calculation models during periods with temperatures below 0 °C.
 - e. By adjusting the vapor permeability and heat- and moisture-capacity in the material boundary conditions in the calculation model.
2. The influence of the leakages in walls caused by driving rain, which was noticed in three positions in the case study. This is of primary interest for providing instructions regarding how to make reliable models for dimensioning purposes. A leakage in the calculation model could be applied at the studied position and a correlation between measured and calculated values could be found by interpolation where the amount of leakage was varied. This showed the lowest levels of leakages to be used later on in calculation models for dimensioning purposes.
3. The possible effect on the correlations after a second recalibration, which was impossible since almost all measurement sensors were built in into the building envelope.
 - a. Comparisons between calculated and calibrated measured results of the 16 sensors which were available for a second calibration could be made.
 - b. Comparisons between calculated results for the other 132 positions to adjusted measured values using a mean calibration curve, based on the 16 available recalibrated measurement sensors.

Results from the second calibration, carried out for the 16 available sensors, may explain some of the deviations (Mundt-Petersen 2013), mainly in the exterior part of the

constructions and, in general, indicate that a better correlation may be found between measured and calculated values if recalibrated values are used.

4. Effects of the design of the measurement sensors. Factors such as the measurement sensors being protected by a plastic shell may affect the influence of any air movements and of the wind speed in the air gaps. These influences can be studied by removing the plastic shell and comparing measurements to those from sensors with plastic shells in windy environments (Rahdevi 2014).

It must be made clear that adjustments and investigations into possible factors influencing the correlation between measured and calculated values, in order to reach better agreement, make the comparison non-blind. Investigations of parameters affecting the results could also include sensitivity tests of the influence of the studied parameters on the results, i.e. the importance that a specific parameter has in a specific context to attain a good correlation.

4.2.4 Influence of incomplete material data

Evaluating the results of the comparisons between measured and blindly calculated values presented in Technical Reports B to F and summarized in Papers V to X, the overall assessment was that no significant influence of possible inadequate material parameters in the calculation models, compared to real material data, was found. The rather good correlation between measured and blindly calculated values indicates that the chosen material parameters in the calculation tool, in general, were good enough to fulfill the purpose.

However, two cases in which the material data may have influenced the correlation were noticed. In the case with a shorter drying out period for the moisture in between two vapor-tight membranes when compared to the expected time, as discussed in Paper VIII, the vapor membrane in reality might have been more permeable than estimated in the hygrothermal calculation model. The possible reason why this was only noticed in those specific cases might have been because the two vapor-tight membranes, with similar material properties, were located close to each other without any ventilated area in between. As mentioned earlier, other parameters might also influence the faster drying out in reality when compared to the estimated time.

The other situation where inadequate material properties might influence possible deviations was when analyzing the differences between measured and calculated amplitude in temperature and relative humidity, as seen in Papers VIII and IX and Technical Reports B to F. The calculations indicate a lower amplitude compared to the measured values. The lower amplitude might depend on an overestimated heat and moisture capacity in the materials compared to reality. However, the higher amplitudes in measured values might also depend on the plastic shell surrounding the measurement sensors, keeping them in an air pocket and not in the specific material, which may, falsely, increase the amplitude of the measurements.

The overall rather good correlation between measured and calculated values indicates that the chosen material properties in the calculation models were applicable in their contexts or that exact material properties were of less importance. However, perfect material properties might be of importance in situations where two similar materials, with similar material properties, are modeled close to each other without any ventilated space in between. Based on the results in Papers V to XIII, other factors such as variations in the indoor and outdoor climate conditions, user behavior and poor

input data in the calculation model etc. appear to have a significantly higher influence than having absolutely correct material parameters.

4.2.5 The risk of moisture-related damage and current mold growth models

Current mold growth models must be developed further, evaluated and validated. Besides presenting when mold growth occurs and whether the chosen design is moisture-safe, the models could include parameters indicating what influences unfavorable moisture and how the risk of damage may be reduced, even if a suitable design has already been reached.

Current mold growth models should also be blindly verified in real houses under real climate conditions, preferably in a similar manner to which this study was carried out. The influence of real climate conditions, rather than using standard climates and safety margins to predict the risk of moisture-related damage, needs to be studied more. This might be possible together with validation of the mold growth models. With respect to the discussion of safety margins, it may also be discussed to what extent user behavior, such as repainting the house, changing the exterior facade or roof properties or reducing the indoor temperature in order to save energy during the winter (Paper XII and XIII) should be included.

4.2.6 Further validations

This study only considers a blind validation of the WUFI one-dimensional calculation tool. A validation of the two-dimensional calculation tool, including factors such as the influence of thermal bridges, detailing etc. might also be needed. This might be possible to achieve in combination with the evaluation of moisture safety in two-dimensional designs.

4.3 Reflections on hygrothermal calculation tools in practice

In a broad context the main question to be asked is to what extent moisture safety designs are made during the design phase at all and, furthermore, why there are so many instances without a proper moisture safety design. In a wide perspective, the results in Paper X indicate that it is easy to have hindsight regarding the factors that should have been taken into account. Papers X and XI present examples of how to apply the validated tool in practice and how it may be used in the moisture safety design process. Focus in this situation may be removed from the hygrothermal calculations and the specific contents in the moisture safety design methods to why so many houses are built without a proper moisture safety design. Proper methods have now become established and the regulations clearly point out that a moisture safety design process is supposed to be carried out before a house is built.

Three major reasons have been observed for the lack of a proper moisture safety design. The main reason is a lack of control and knowledge in most of the local authorities granting building permission in Sweden. The local authorities are obliged to check that a proper moisture safety design process is carried out before granting permission to start the construction phase. However, through experience and via contacts in the construction industry, it is apparent that local authorities do not even appear to know what a moisture safety design process is. The second and third reasons were a result of the building regulations, which first of all state that the owner of the building project, and not the contractor, is responsible for the moisture safety design process. The lack of knowledge, or ignorance, regarding the responsibility of many owners of the building project leads to projects without moisture-safe designs. It may be mentioned that the contractor, who is the most important

partner and the only one who can really influence the moisture safety in practice, does not have any legal responsibility at all. The third part is the structure of the building regulations, which only require a facade and plan drawing in order to receive building permission. Based on the accepted architectural drawings, it may not be possible, in some cases, to create a moisture safe design (Paper XI; BBR 2011; Judgment case T99-12; 2013; SFS 2010:900).

4.4 Reflections on important factors affecting the risk of moisture damage

4.4.1 Air flows in the air gap behind the cladding in walls

A well-ventilated air gap behind the cladding in wooden framed walls may be seen as a universal solution in order to limit the risk of moisture damage. The air flow in the air gap dries out moisture penetrating the cladding as well as increasing the drying out potential for leakages and initial construction moisture. The air gap must also be drained to remove free water from the construction. As seen from the results in Paper XII, it may be questionable whether well-insulated walls with non- or poorly-ventilated air gaps will “survive” without experiencing moisture damage. It should be discussed whether wooden framed walls without well-ventilated and drained air gaps should be allowed to be built. This statement has been reported to the Swedish National Board of Housing, Building and Planning. However, the Swedish building regulations stipulate compliance requirements instead of providing detailed solutions (BBR 2011).

4.4.2 Air flows in air gaps in cold roofs and cold attics

Air flows in cold attics and air gaps in cold roofs must be sufficiently high in order to remove all moisture reaching the area by ventilation. At the same time, the ventilation rate must be limited to maintain as high temperature as possible to avoid high relative humidity. In practice, the reasoning may be questionable, since this kind of ventilation balance is difficult to reach in real attics and air gaps. The primary solution is to avoid all leakages. High ventilation rates are not to be used as an excuse to vent out high moisture levels. Methods to find robust solutions for sustainable climate conditions in roofs must be further investigated and developed, such as innovations by Hagentoft and Sasic-Kalagasidis (2010; 2014).

In new or extensively renovated buildings, a high ventilation rate must always be obtained in order to remove the initial construction moisture as fast as possible to limit the risk of damage.

4.4.3 Exterior insulation on the outside of the organic material

Exterior insulation on the outside of the organic materials, both in roofs and walls, increases the temperature, which decreases the relative humidity conditions and the risk of mold damage.

In the walls, the insulation boards should be installed between the studs and the weather resistive barrier and had to be of vapor-permeable and moisture-resistant materials. It may be noted that these measures are of less importance than a well-ventilated air gap behind the cladding but may be seen as a good complement to the well-ventilated air gap. The results in Paper XII show the importance of a vapor permeable board which allows moisture from leakages and initial construction moisture to dry out. However, in practice, the permeable mineral wool boards are less stiff, and therefore more difficult to install, compared to the more vapor-tight polystyrene boards. A stiff vapor-permeable and, if possible, fire resistant, board is therefore sought after by the construction industry.

There are several different design solutions for exterior insulation in roofs which are supposed to be mounted on top of the tongued and grooved wooden roof boarding. The main differences are with regard to the insulation material, mineral wool or EPS insulation, and the location of the exterior roofing felt membrane, on top of or below the extra insulation layer. Mineral wool is preferable from a fire safety perspective while the stiff EPS insulation boards are easier to install. It is more difficult to install a roofing felt membrane on top of the insulation material and avoid poor joints and cracks due to nail holes. On the other hand the insulation material will stay dry. Installing the roofing felt membrane below the exterior insulation material, on top of the tongued and grooved roof boarding, will probably result in a higher standard of the joints and nailing of the roofing felt, but will result in wet insulation material. A solution with battens, fixed without nails penetrating the roofing felt, should be developed. Some design solutions recommend different roofing felt membranes both on top and below the exterior insulation layer. This may solve the problems concerning the risk of wet insulation material and leakages to the tongued and grooved roof boarding. However, the design may create moisture traps in which moisture can be captured in the material between two vapor-tight materials.

4.4.4 Sensitivity to leakages in roofs

The investigated roof designs in the parametric study were very sensitive to leakages. The major reason was that moisture became trapped between two vapor-tight membranes, and the only way to remove the moisture was by ventilation. In the case of a lower outdoor temperature than in the ventilated air gap or the cold attic, the ventilation must, primarily, be reduced as much as possible to avoid lower temperatures in the roof, which would increase the relative humidity. This problem can be solved in walls using an exterior facade insulation board on the outside of the studs, since mold growth is allowed on the inside of the cladding. The same solution is not possible in roofs, since the regulations do not allow mold growth on the tongued and grooved roof boarding on the outside of the ventilated cold attic or ventilated air gap. It may be discussed why mold growth is allowed on the inside of the cladding in walls but not on the inside of the tongued and grooved roof boarding. The fact that it is easier to retrofit the facade cladding compared to the tongued and grooved wood boarding and that cold attics may be used for storage might be a reasonable explanation (BBR 2011).

The parametric study also highlights the importance of vapor-permeable materials to allow drying out of initial construction moisture and moisture from possible leakages into the air gap, and subsequent removal from the construction by ventilation. A possible risk also occurs when changing to “equivalent materials” to reduce costs during the on-site construction, without taking the vapor permeability into account.

5 Conclusions and recommendations

Although there are differences between measured and blindly calculated values, it must be stated that most of the blind comparisons that were studied, as presented in Papers V to X and in Technical Reports B to F show that the WUFI hygrothermal calculation tool could be used to predict the climate conditions in the studied houses. It may, therefore, be concluded that the WUFI hygrothermal calculation program can be used as reliable tools in the moisture safety design process in order to predict the risk of mold growth in wood framed constructions with an interior vapor barrier and a ventilated air gap behind the cladding or a ventilated roof design. Furthermore, Papers X and XI establish that the tool could be used as a tool in the moisture safety design process. However, several parameters were observed, referred to in all the appended papers, that influence the results and that need to be taken into account in order to use the hygrothermal calculation tool in a reliable manner for moisture safety purposes. The most important parameters include:

1. Differences in temperature, which can have a great effect on the relative humidity. In the studied positions the measured temperature was, in general, higher than the calculated values, making the measured relative humidity lower than the calculated values and the calculated values on the “safe side” from a moisture-safety perspective.
2. It is essential that reliable indoor- and outdoor climate boundary conditions are used. This is necessary because indoor and outdoor climates have a great influence on possible moisture-critical parts of wood frame constructions. Mean or standard outdoor climate boundary conditions, without extremes, should not be used for dimensioning purposes.
3. Unexpected occupant behavior, details and buildings services installation equipment may create climate conditions that affect the moisture safety in a significant manner.
4. Leakages occur deeper into the walls than expected and as indicated in current standards. The size of the leakages and how they may be modeled in the hygrothermal calculation tools should be investigated further.
5. Parameters and factors implemented and checked by the user in the calculation model that highly affect the correlation between measured and calculated values should be investigated to create better input data. Accurate boundary conditions and other settings should be recommended in order to obtain reliable results and limit the risk of poor calculation results.
6. One-dimensional models cannot be used in all situations and this fact needs to be considered in the hygrothermal calculations.
7. Influence from heat sources need to be considered in the hygrothermal calculations.
8. The calculated values were affected when exterior parts of the building envelope, such as roof tiles, were not included in the calculation model.
9. An increased risk of moisture damage was noticed in corners and detailing.
10. A correct air flow in the air gap in walls was required in the calculation model in order to obtain correct results. It must therefore be possible to assume these flows in the finished house.
11. The facade oriented towards the direction with the highest amount of driving rain and the coldest, i.e. the north-oriented, facade and roof must be checked for the risk of moisture damage, if the hygrothermal calculation tool is used for dimensioning purposes.

The study and appended papers also assessed a number of important factors that must be taken into account if moisture-safe well-insulation constructions are to be built. The results were based on a great number of hygrothermal calculations (Papers X to XIII) as well as findings in the case studies with the main purpose of validating the hygrothermal calculation tool (Paper V to X). The main conclusion was that there is an increased risk of mold problems in well-insulated wood frame constructions in Northern European climates. The risk can be reduced by implementing suitable designs in which a number of important factors affecting moisture safety are taken into account. The most important factors are listed below:

1. Moisture-critical conditions in wood frame constructions mainly occur in the exterior parts of the construction but may also occur in connection with vapor-proof materials, if moisture traps are created. Vapor-permeable materials, which provide sufficiently high drying out potential for moisture leaking into the construction or initial construction moisture, must be used.
2. The occurrences of moisture-critical conditions increase as the thickness of thermal insulation is increased.
3. There is a need for a well-ventilated air gap behind the cladding in walls in order to build moisture-safe well-insulated walls. The need increases with higher thermal resistance of the wall. Furthermore, it is especially important when there are high amounts of driving rain and especially important when the facade material has a high moisture storage capacity, such as a brick facade.
4. The air flow in the air gap below the tongued and grooved wooden roof boarding must, primarily, be so high that all moisture from leakages is removed and, secondly, as low as possible in order to maintain as high a temperature as possible in the air gap. Boards used to keep the insulation in place and create ventilated air gaps should be vapor-permeable to allow moisture transport from materials closer to the inside and drying out through the ventilated air gap.
5. Studs and other organic materials in the exterior part of wood frame walls could be protected from moisture-critical conditions by using an exterior moisture-resistant thermal insulation board on the outside of the studs. The required thickness of the exterior moisture-resistant thermal insulation board varies depending on the total thermal insulation of the entire wall. Exterior moisture-resistant insulation boards must be vapor permeable to allow initial construction moisture and water from possible leakages to dry out.
6. Exterior insulation on top of the tongued and grooved roof boarding reduces the moisture-critical conditions in the roof construction in a positive manner.
7. The roof construction is very sensitive to leakages. All kinds of moisture leakages have a major negative influence on the climate conditions in the roof construction and must be strictly avoided.

6 Nomenclature

RH = Relative humidity

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

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

T = Temperature

Pos = Position

hrs = Hours

ACH = Air Change rate per Hour

GLP = Good Laboratory Practice

ϕ = Diameter

7 References

- Achtziger, J. and Cammerer, J. 1984. Influence of moisture content on the thermal conductivity of building and insulation materials. Report BI 5-800883-4, Institute for heat protection, München, Germany. In German
- Arfvidsson, J. and Sikander, E. 2002. Moistureproof construction – A survey study of the knowledge in the area. FoU-Väst, SG idé & tryck AB, Sweden. In Swedish.
- ASHRAE. 2009. BSR/ ASHRAE Standard 160P, Criteria for moisture-control design analysis in buildings. American Society of Heating, Air-Conditioning and Refrigeration Engineers, Inc. Atlanta, USA.
- BBR. 2011. Swedish building regulations 2012. The Swedish National Board of Housing, Building and Planning, Karlskrona, Sweden. In Swedish.
- Björk, C., Kallstenius, P. and Reppen, L. 2003. Old house design 1880 – 2000. Edita Ljunglöfs. Stockholm, Sweden. In Swedish.
- Björk, C., Nordling, L. and Reppen, L. 2009. Single family house design – Swedish single family house architecture 1890 – 2010. Fälth & Hässler, Värnamo, Sweden. In Swedish.
- Boverket. 2009. The Swedish National Board of Housing, Building and Planning. The standard of our houses – Report of the Swedish government’s commissions regarding the technical standard of Swedish buildings. Karlskrona, Sweden. In Swedish.
- Brander, P., Esping, B. and Salin, J.-G. 2005. Moisture in wood during the construction phase – Moisture properties, requirements, handling and measurements. Report 2005:24, SP Technical Research Institute of Sweden, Sweden. In Swedish.
- Dodoo, A., Gustavsson, L. and Sathre, R. 2012. Effect of thermal mass on life cycle primary energy balance of a concrete- and wood-frame building. *Journal of Applied Energy* 2012:92:462-472.
- Falk, J. and Sandin, K. 2013. Ventilated rainscreen cladding: Measurements of cavity air velocities, estimation of air change rates and evaluation of driving forces. *Journal of Building and Environment* 2013:59:164-76.
- Forsberg, T. 2011, Moisture rearrangements in exterior walls. Bachelor thesis. Report 2011:14, KTH Royal Institute of Technology, Sweden. In Swedish.
- Fröderberg, M., 2014. The human factor in structural engineering: A source of uncertainty and reduced structural safety. Licentiate thesis. Department of Structural Engineering, Report TVBK-1046, Lund University, Lund, Sweden.
- GE Sensing. 2006. Protimeter HygroTrac – Wireless environmental monitoring. USA. www.veronics.com/products/Relative_humidity-transmitter/Hygrotrac.pdf. 2014-12-06.
- Georgsdottir, T. and Sawirs, E. 2012. Moisture loads in roof constructions with insufficient vapor barriers. Bachelor thesis. LTH School of Engineering, Lund University, Sweden. In Swedish.

- Hagentoft, C.-E. and Sasic-Kalagasidis, A. 2010. Mold growth control in cold attics through adaptive ventilation: Validation by field measurements. Thermal Performance of the Exterior Envelopes of Whole Buildings XI – International Conference 2010. Florida, USA.
- Hagentoft, C.-E. and Sasic-Kalagasidis, A. 2014. Moisture safe cold attics – Assessment based on risk analyses of performance and cost. NSB 2014, 10th Nordic Symposium on Building Physics. Lund, Sweden.
- Hansson, D. and Lundgren, N. 2009. The problem of insulation in loft ceiling beams in outdoor air ventilated attics. Bachelor thesis. Report 2009:06, School of Architecture and the Built Environment, KTH Royal Institute of Technology, Sweden. In Swedish.
- Harderup, L-E. and Arfvidsson, J. 2008. Moisture safety in cold attics. Report TVBH-3050, Department of Building Physics, Lund University, Lund, Sweden. In Swedish.
- Hedenblad, G. 1996. Material data for moisture transport calculations. Report T19:1996, Department of Building Materials, Lund University, SBUF, Swedish National Council for Building Research, Sweden. In Swedish.
- Häupl, P. Grunewald, J., Fechner, H. and Stopp, H. 1997. Coupled heat, air and moisture transfer in building structures. International journal of Heat and Mass Transfer, 1997:40(7):1633-42.
- IBP 1994. IBP-Report 35. Fraunhofer Institute of Building Physics, Germany. In German.
- IEA Annex 24. 1996. IEA Annex 24, Heat, Air and Moisture Transport. Belgium.
- Ingelsson, M. and Olsson, M. 2013. Moisture analysis on climate attics. Bachelor thesis, LTH School of Engineering, Lund University, Sweden. In Swedish.
- Jansson, A. 2005. Double sealing layers in the external walls of wet rooms with internal tile cladding. Report 2005:20, SP Technical Research Institute of Sweden, Sweden. In Swedish.
- Jansson, A. 2010. Wet room floors with ceramic tiles on wooden slabs. Report 2010:05, SP Technical Research Institute of Sweden, Sweden. In Swedish.
- Jansson, A. 2011. Water barrier in wet rooms – functional tests of flexible sheeting. Report 2011:01, SP Technical Research Institute of Sweden, Sweden. In Swedish.
- Johansson, P., Samuelson, I., Ekstrand-Tobin, A., Mjörnell, K., Sandberg, P.I. and Sikander E. 2005. Microbiological growth on building materials – critical moisture levels. State of the art. Report 2005:11, SP Technical Research Institute of Sweden, Sweden. In Swedish.
- Johansson, P. 2014. Determination of the critical moisture level for mould growth on building materials. Doctoral thesis. Report TVBH-1020, Department of Building Physics, Lund University, Lund Sweden.
- Josephson P.E. and Hammarlund Y. 1999. The causes and costs of defects in construction: A study of seven building projects. Journal of Automation in Construction 1999:8(6):681-687.

Judgment case T99-12. 2013. Judgment in case: T99-12, 2013-01-18. Göta Court of Appeal in the city of Jönköping. Div. 3, Section 37, Sweden. In Swedish.

Krus, M. 1996. Moisture transport and storage coefficients of porous mineral building materials – Theoretical principles and new test methods. Doctoral thesis. Fraunhofer Institute of Building Physics, IRB Verlag, Germany. English translation.

Künzel, H. M. 1995. Simultaneous heat and moisture transport in building components – One- and two-dimensional calculation using simple parameters. Doctoral thesis. Fraunhofer Institute of Building Physics, IRB Verlag, Germany. English translation.

Laujjarinen, A. and Vinha, J. 2011. Comparison of calculation and measured values of wall assembly test using Delphin 5. NSB 2011, 9th Nordic Symposium on Building Physics. Tampere. Finland.

Maref, W., Comic, S., Abdulghani, K. and van Reenen, D. 2003. 1-D hygIRC: a simulation tool for modeling heat air and moisture movement in exterior walls. IRC - Building Science Insight 2003 Seminars Series, NRC – CNRC. Canada.

Maref, W., Lacasess, M., Kumaran, M. K. and Swinton M. C. 2002. Benchmarking of the advanced hygrothermal model-hygIRC with mid scale experiments. eSim 2002. Montreal. Canada.

Mjörnell, K., Arfvidsson, J. and Sikander, E. 2012. A method for including moisture safety in the building process. Journal of Indoor and Built Environment 2012:21(4):583-594.

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

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

Nevander, L. E. and Elmarsson, B. 2007. Moisture handbook – Practice and theory. AB Svensk byggtjänst, Elanders info logistics väst AB, Mönlycke, Sweden. In Swedish.

Nielsen, K. F., Holm, G., Uttrup, L. P. and Nielsen P. A. 2004. Mould growth on building materials under low water activities - Influence of humidity and temperature on fungal growth and secondary metabolism. Journal of International Biodeterioration and Biodegradation 2004:54(4):325-336.

Nik, V. M. 2012. Hygrothermal simulations of buildings concerning uncertainties of the future climate. Doctoral thesis. Chalmers University of Technology, Göteborg, Sweden.

Nordtest method. 1998. NT BUILD 340, Relative air humidity: Calibration of electrical instruments.

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

OECD. 1995, OECD Number 10, 'GLP Consensus document – The application of the principles of GLP to computerized systems' environment monograph no. 116, OCDE/GD (95) 115.

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

Olsson, L. 2014. Moisture conditions in exterior wooden walls and timber during production and use. Licentiate thesis. Report 2014:2, Department of Building Physics, Chalmers University of Technology, Göteborg, Sweden.

Paroc. 2002. Product Information – Construction Book. Sweden. In Swedish.

Persson Lindgren, C. 2010. Building moisture-proof roof constructions. Report 12321, SBUF, Swedish Construction Industry's Organisation for Research and Development, Sweden. In Swedish.

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

Robinson, K. 2003. GLPs and the Importance of Standard Operating Procedures. BioPharm International, The Science & Business of Biopharmaceuticals.
www.biopharminternational.com/biopharm/article/articleDetail.jsp?id=73842. 2014-01-30.

Rahdevi, S. 2014. Sustainable heating of churches – for energy efficiency, preservation and comfort. Bachelor thesis. Report TVIT—14/5046, Department of Building Services, Lund University, Lund, Sweden. In Swedish.

Rode, C. and Burch, D. M. 1995. Empirical validation of a transient computer model for combined heat and moisture transfer. Thermal Performance of the Exterior Envelopes of Whole Buildings VI – International Conference 1995. Florida, USA.

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

Samuelson, I. 2008. Increased risk of moisture damages in well-insulated houses. The Swedish branch journal Building and Technology 5 (Bygg & Teknik 5). In Swedish.

Samuelson, I. and Jansson A. 2009. External thermal insulation composite system walls. Report 2009:16, SP Technical Research Institute of Sweden, Sweden. In Swedish.

Sandberg, K., Pousette, A. and Dahlquist, S. 2011. Wireless in-situ measurements of moisture content and temperature in timber constructions. XIII DBMC 2011, International Conference on Durability of Building Materials and Components. Porto, Portugal.

Sandberg, P. I. 1973. Moisture balance in building elements exposed to natural climate conditions. Doctoral thesis. Report 43. Lund University, Lund, Sweden. In Swedish.

Sandin, K. 1991. Moisture and temperature conditions in brick facade constructions. Report R43:1991, Swedish National Council for Building Research, Lund University, Lund, Sweden. In Swedish.

Sandin, K. 1993. Wooden constructions with brick facades – Moisture safety in constructions. Report T10:1993. Swedish National Council for Building Research, Lund University, Lund, Sweden. In Swedish.

Sasic Kalagasidis, A. 2004. HAM-Tools - An integrated simulation tool for heat, air and moisture transfer analyses in building physics. Doctoral thesis. Chalmers University of Technology, Göteborg, Sweden.

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

SFS 2010:900. 2010. Swedish Planning and Building law. Stockholm: Swedish Parliament, Ministry of Social Affairs, 2010-06-01, Sweden. In Swedish

SMHI. 2014. Swedish Meteorological and Hydrological Institute. Services, Open data, Search SMHI's open data, Explorer SMHI's data. <http://opendata-catalog.smhi.se/explore/>. 2014-12-06.

SOU 2002:115. Swedish building commission 2002. Come on guys! – Competition, quality, costs and competence in the Swedish construction industry. The Swedish Ministry of Health and Social Affairs, Stockholm, Sweden. In Swedish.

SP Eti-QD, Annex E2:1, SP Technical Research Institute of Sweden, Sweden. In Swedish.

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

SS-EN. 2007. SS-EN 15026:2007 – Hygrothermal performance of building components and building elements – Assessment of moisture transfer by numerical simulations. SIS, Swedish Standard Institute, SIS Förlag AB, Sweden.

Stadskontoret. 2009. 2008/61-5. The Swedish agency for public management. Slow guys? – A follow-up report to the Building Commission's report "Come on guys!", 2009:6, Stockholm, Sweden. In Swedish.

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

Thelandersson, S. and Isaksson, T. 2013. Mould resistance design (MRD) model for evaluation of risk for microbial growth under varying climate conditions. Journal of Building and Environment 2013:65:18-25.

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

Viitanen, H. 1996. Factors affecting the development of mould and brown rot decay in wooden material and wooden structures. Effect of humidity, temperature and exposure time. Doctoral thesis. Department of Forest Products, Swedish University of Agricultural Sciences, Uppsala, Sweden.

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

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

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

Walker, I.S. and Forest, T.W. 1995. Field measurements of ventilation rates in attics. *Journal of Building and Environment* 1995:30(3):333-47.

WUFI 2012a. WUFI PRO 5.2. Release: 5.2.0.972.DB.24.76. Fraunhofer Institute of Building Physics, Germany.

WUFI 2012b. WUFI PRO 5.2 Material database – Generic materials and Fraunhofer-IBP – Holzkirchen, Germany. Release: 5.2.0.972.DB.24.76. Fraunhofer Institute of Building Physics, Germany.

WUFI 2012c. WUFI PRO 5.2 Climate database, Sweden, Europe. Release: 5.2.0.972.DB.24.76. Fraunhofer Institute of Building Physics, Germany.

8 Appendix I – Boundary conditions, initial settings and material data

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

8.1 Used material parameters and material data in WUFI calculations

In this section the material parameters and material data that were used in the WUFI calculation models are specified. Each material is 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 vapor diffusion resistance factor [-]. No hygrothermal functions are specified, such as: moisture storage function, suction liquid transport coefficients, redistribution liquid transport coefficient, moisture dependent water vapor diffusion resistance factor, moisture dependent thermal conductivity, temperature dependent thermal conductivity and temperature dependent enthalpy. Those functions could be found in the WUFI calculation tool material database (WUFI 2012b).

8.1.1 Facade- and exterior roofing materials

Concrete board – Fibercementskiva

Material Source: LTH Lund University

Bulk density = $1580 \text{ kg}/\text{m}^3$

Porosity = $0.2 \text{ m}^3/\text{m}^3$

Specific heat capacity – dry = $850.0 \text{ J}/\text{kgK}$

Thermal conductivity – dry 10 °C = $0.13 \text{ W}/\text{mK}$ (Paroc 2002)

Water vapor diffusion resistance factor = 83.3

Initial moisture: $95 \text{ kg}/\text{m}^3$

References: WUFI 2012b; Hedenblad 1996

Solid brick masonry (including mortar joints)

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = $1900 \text{ kg}/\text{m}^3$

Porosity = $0.24 \text{ m}^3/\text{m}^3$

Specific heat capacity – dry = $850.0 \text{ J}/\text{kgK}$

Thermal conductivity – dry 10 °C = $0.6 \text{ W}/\text{mK}$

Water vapor diffusion resistance factor = 10

Initial moisture: $100 \text{ kg}/\text{m}^3$

References: WUFI 2012b; IBP 1994

Facade panel – Spruce, radial

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 455 kg/m³

Porosity = 0.73 m³/m³

Specific heat capacity – dry = 1500.0 J/kgK

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

Water vapor diffusion resistance factor = 130

Initial moisture: 80 kg/m³

References: WUFI 2012b; 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/m³

Porosity = 0.73 m³/m³

Specific heat capacity – dry = 1500.0 J/kgK

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

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

Initial moisture: 80 kg/m³

References: WUFI 2012b; Vik 1996; Nevander and Elmarsson 2007

External roofing tiles – Solid Brick, extruded

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 1650 kg/m³

Porosity = 0.41 m³/m³

Specific heat capacity – dry = 850.0 J/kgK

Thermal conductivity – dry 10 °C = 0.6 W/mK

Water vapor diffusion resistance factor = 9.5

Initial moisture: 100 kg/m³

References: WUFI 2012b

8.1.2 Air gaps materials

Air gaps in walls were modeled with three layers in order to make it possible to handle free water and possible moisture capacity. Two thin layers with additional moisture capacity were added on the exterior and interior surfaces in the air gaps. The reason for the three different layers was also to simulate a construction with a ventilated air gap at the same time as the influence from driving rain was taken into account. An air change rate source of ventilation was added in the layer in the middle of the air gap at the same time as a leakage from driving rain was added in the exterior thin layer in the air gap. All three layers have the same initial thickness in the material database. Afterwards the thickness was reduced in such a manner that the total thickness of the three layers became the same as the initial thickness. This simulates the initial assumed thermal conductivity, in the material database, for the entire air gap. 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. Material parameters in air gaps in walls were listed below.

2 mm air gap – Air layer 30 mm

Material Source: Generic materials

Bulk density = 1.3 kg/m³

Porosity = 0.999 m³/m³

Specific heat capacity – dry = 1000.0 J/kgK

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

Water vapor diffusion resistance factor = 0.46

Initial moisture: 0 kg/m³

References: WUFI 2012b

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

Material Source: Generic materials

Bulk density = 1.3 kg/m³

Porosity = 0.001 m³/m³

Specific heat capacity – dry = 1000.0 J/kgK

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

Water vapor diffusion resistance factor = 0.46

Initial moisture: 0 kg/m³

References: WUFI 2012b

In roofs, below the tongued and grooved wooden roof boarding, different total thicknesses of the ventilated air gap were chosen dependent on the size of the ventilated air gap or cold attic. In case of a ventilated cold roof with an air gap, one air gap was modelled in the middle, including a ventilation rate source, between two thin layers. The two thin layers had additional moisture capacity in order to make it possible to handle free water and create a moisture capacity, and were added on the exterior and interior surfaces in the air gaps, in the same manner as for walls. In one case the air gap was also modeled with two air layers with the same thickness, one with and one without additional moisture capacity. A thicker air gap was chosen in case of a ventilated cold attic. The cold attic was always modeled with at least one thick air layer, including a ventilation rate source depending on the cold attic design. Depending on the air gap design, one- or two thick air layers with additional moisture capacity was also added on the exterior- and the interior surfaces in the cold attic, instead of two thin layers. Material parameters in the ventilated cold roofs and attics were listed below:

Air gap alternative 1 and 2 – i.e. 5 or 2 mm ventilated air gap – Air layer 50 mm

Material Source: Generic materials

Bulk density = 1.3 kg/m³

Porosity = 0.999 m³/m³

Specific heat capacity – dry = 1000.0 J/kgK

Thermal conductivity – dry 10 °C = 0.28 W/mK

Water vapor diffusion resistance factor = 0.32

Initial moisture: 0 kg/m³

References: WUFI 2012b

Air gap alternative 1 and 2 – i.e. 40 or 46 mm ventilated air gap – Air layer 50 mm; without additional moisture capacity

Material Source: Generic materials

Bulk density = 1.3 kg/m³

Porosity = 0.999 m³/m³

Specific heat capacity – dry = 1000.0 J/kgK

Thermal conductivity – dry 10 °C = 0.28 W/mK

Water vapor diffusion resistance factor = 0.32

Initial moisture: 0 kg/m³

References: WUFI 2012b

Air gap alternative 3, 20 mm ventilated air gap – Air layer 20 mm

Material Source: Generic materials

Bulk density = 1.3 kg/m³

Porosity = 0.999 m³/m³

Specific heat capacity – dry = 1000.0 J/kgK

Thermal conductivity – dry 10 °C = 0.13 W/mK

Water vapor diffusion resistance factor = 0.56

Initial moisture: 0 kg/m³

References: WUFI 2012b

Air gap alternative 3, 20 mm ventilated air gap – Air layer 20 mm; without additional moisture capacity

Material Source: Generic materials

Bulk density = 1.3 kg/m³

Porosity = 0.001 m³/m³

Specific heat capacity – dry = 1000.0 J/kgK

Thermal conductivity – dry 10 °C = 0.13 W/mK

Water vapor diffusion resistance factor = 0.56

Initial moisture: 0 kg/m³

References: WUFI 2012b

Ventilated cold attic, alternative 1 – Air layer 130 mm

Material Source: Generic materials

Bulk density = 1.3 kg/m³

Porosity = 0.999 m³/m³

Specific heat capacity – dry = 1000.0 J/kgK

Thermal conductivity – dry 10 °C = 0.79 W/mK

Water vapor diffusion resistance factor = 0.1

Initial moisture: 0 kg/m³

References: WUFI 2012b

Ventilated cold attic, alternative 1 – Air layer 130 mm; without additional moisture capacity

Material Source: Generic materials

Bulk density = 1.3 kg/m³

Porosity = 0.001 m³/m³

Specific heat capacity – dry = 1000.0 J/kgK

Thermal conductivity – dry 10 °C = 0.79 W/mK

Water vapor diffusion resistance factor = 0.1

Initial moisture: 0 kg/m³

References: WUFI 2012b

Ventilated cold attic, alternative 2 – Air layer 70 mm

Material Source: Generic materials

Bulk density = 1.3 kg/m³

Porosity = 0.999 m³/m³

Specific heat capacity – dry = 1000.0 J/kgK

Thermal conductivity – dry 10 °C = 0.4 W/mK

Water vapor diffusion resistance factor = 0.23

Initial moisture: 0 kg/m³

References: WUFI 2012b

Ventilated cold attic, alternative 2 – Air layer 50 mm; without additional moisture capacity

Material Source: Generic materials

Bulk density = 1.3 kg/m³

Porosity = 0.001 m³/m³

Specific heat capacity – dry = 1000.0 J/kgK

Thermal conductivity – dry 10 °C = 0.28 W/mK

Water vapor diffusion resistance factor = 0.32

Initial moisture: 0 kg/m³

References: WUFI 2012b

Some studied roof designs also have different unventilated air gaps, close to the inside, which material properties were listed:

20 mm air gap – Air layer 20 mm; without additional moisture capacity

Material Source: Generic materials

Bulk density = 1.3 kg/m³

Porosity = 0.001 m³/m³

Specific heat capacity – dry = 1000.0 J/kgK

Thermal conductivity – dry 10 °C = 0.13 W/mK

Water vapor diffusion resistance factor = 0.56

Initial moisture: 0 kg/m³

References: WUFI 2012b

25 mm air gap – Air layer 25 mm; without additional moisture capacity

Material Source: Generic materials

Bulk density = 1.3 kg/m³

Porosity = 0.999 m³/m³

Specific heat capacity – dry = 1000.0 J/kgK

Thermal conductivity – dry 10 °C = 0.155 W/mK

Water vapor diffusion resistance factor = 0.51

Initial moisture: 0 kg/m³

References: WUFI 2012b

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

Material Source: Generic materials

Bulk density = 1.3 kg/m³

Porosity = 0.001 m³/m³

Specific heat capacity – dry = 1000.0 J/kgK

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

Water vapor diffusion resistance factor = 0.46

Initial moisture: 0 kg/m³

References: WUFI 2012b

130 mm air gap – Air layer 130 mm; without additional moisture capacity

Material Source: Generic materials

Bulk density = 1.3 kg/m³

Porosity = 0.001 m³/m³

Specific heat capacity – dry = 1000.0 J/kgK

Thermal conductivity – dry 10 °C = 0.79 W/mK

Water vapor diffusion resistance factor = 0.1

Initial moisture: 0 kg/m³

References: WUFI 2012b

When using exterior tiles a ventilated air gap below the tiles, on top of the roofing felt, was added, with the material properties as listed:

70 mm air gap – Air layer 70 mm

Material Source: Generic materials

Bulk density = 1.3 kg/m³

Porosity = 0.999 m³/m³

Specific heat capacity – dry = 1000.0 J/kgK

Thermal conductivity – dry 10 °C = 0.4 W/mK

Water vapor diffusion resistance factor = 0.23

Initial moisture: 0 kg/m³

References: WUFI 2012b

8.1.3 Insulation materials

EPS (heat cond.: 0.04 W/mK – density: 30 kg/m³)

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 30 kg/m³

Porosity = 0.95 m³/m³

Specific heat capacity – dry = 1500.0 J/kgK

Thermal conductivity – dry 10 °C = 0.037 or 0.040 W/mK

Water vapor diffusion resistance factor = 50

Initial moisture: 0 kg/m³

References: WUFI 2012b; Achtziger and Cammerer 1984

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

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 70 kg/m³

Porosity = 0.95 m³/m³

Specific heat capacity – dry = 2500.0 J/kgK

Thermal conductivity – dry 10 °C = 0.037 or 0.040 W/mK

Water vapor diffusion resistance factor = 1.5

Initial moisture: 12 kg/m³

References: WUFI 2012b

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

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 28 kg/m³

Porosity = 0.95 m³/m³

Specific heat capacity – dry = 850.0 J/kgK

Thermal conductivity – dry 10 °C = 0.037 or 0.04 W/mK

Water vapor diffusion resistance factor = 1.3

Initial moisture: 0 kg/m³

References: WUFI 2012b; Paroc 2002; IEA Annex 24 1996.

8.1.4 Wood based materials

Massive wood – Spruce, radial

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 455 kg/m³

Porosity = 0.73 m³/m³

Specific heat capacity – dry = 1500.0 J/kgK

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

Water vapor diffusion resistance factor = 130

Initial moisture: 80 kg/m³

References: WUFI 2012b; Vik 1996

Chipboard

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 600 kg/m^3

Porosity = $0.5 \text{ m}^3/\text{m}^3$

Specific heat capacity – dry = 1500.0 J/kgK

Thermal conductivity – dry $10 \text{ }^\circ\text{C}$ = 0.11 W/mK

Water vapor diffusion resistance factor = 70

Initial moisture: 1.5 kg/m^3

References: WUFI 2012b

Wood fibre board – Träfiberskiva, porös

Material Source: LTH Lund University

Bulk density = 270 kg/m^3

Porosity = $0.83 \text{ m}^3/\text{m}^3$

Specific heat capacity – dry = 1700.0 J/kgK

Thermal conductivity – dry $10 \text{ }^\circ\text{C}$ = 0.06 W/mK

Water vapor diffusion resistance factor = 6.25

Initial moisture: 10.0 kg/m^3

References: WUFI 2012b; Hedenblad 1996

8.1.5 Membrane materials

Weather resistive barrier (sd = 0.2 m)

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 130 kg/m^3

Porosity = $0.001 \text{ m}^3/\text{m}^3$

Specific heat capacity – dry = 2300.0 J/kgK

Thermal conductivity – dry $10 \text{ }^\circ\text{C}$ = 2.3 W/mK

Water vapor diffusion resistance factor = 200

Initial moisture: 0 kg/m^3

References: WUFI 2012b

Weather resistive barrier (sd = 0.5 m)

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 130 kg/m^3

Porosity = $0.001 \text{ m}^3/\text{m}^3$

Specific heat capacity – dry = 2300.0 J/kgK

Thermal conductivity – dry $10 \text{ }^\circ\text{C}$ = 2.3 W/mK

Water vapor diffusion resistance factor = 500

Initial moisture: 0 kg/m^3

References: WUFI 2012b

Vapor retarder (sd = 50 m)

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 130 kg/m³

Porosity = 0.001 m³/m³

Specific heat capacity – dry = 2300.0 J/kgK

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

Water vapor diffusion resistance factor = 50000

Initial moisture: 0 kg/m³

References: WUFI 2012b

Vapor retarder (sd = 100 m)

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 130 kg/m³

Porosity = 0.001 m³/m³

Specific heat capacity – dry = 2300.0 J/kgK

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

Water vapor diffusion resistance factor = 100000

Initial moisture: 0 kg/m³

References: WUFI 2012b

Waterproofing membranes – vapor retarder (sd = 100 m)

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 130 kg/m³

Porosity = 0.001 m³/m³

Specific heat capacity – dry = 2300.0 J/kgK

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

Water vapor diffusion resistance factor = 100000

Initial moisture: 0 kg/m³

References: WUFI 2012b

Roofing felt – Roof Membrane V13

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 2400 kg/m³

Porosity = 0.001 m³/m³

Specific heat capacity – dry = 1000.0 J/kgK

Thermal conductivity – dry 10 °C = 0.5 W/mK

Water vapor diffusion resistance factor = 100000

Initial moisture: 0 kg/m³

References: WUFI 2012b

Roofing felt – PVC Roof Membrane

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 1000 kg/m³

Porosity = 0.002 m³/m³

Specific heat capacity – dry = 1500.0 J/kgK

Thermal conductivity – dry 10 °C = 0.16 W/mK

Water vapor diffusion resistance factor = 15000

Initial moisture: 0 kg/m³

References: WUFI 2012b

8.1.6 Interior surface materials

Gypsum board

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 850 kg/m³

Porosity = 0.65 m³/m³

Specific heat capacity – dry = 850.0 J/kgK

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

Water vapor diffusion resistance factor = 8.3

Initial moisture: 8 kg/m³

References: WUFI 2012b; Krus 1996

Cement plaster (stucco)

Material Source: Fraunhofer-IBP – Holzkirchen; Germany

Bulk density = 2000 kg/m³

Porosity = 0.3 m³/m³

Specific heat capacity – dry = 850.0 J/kgK

Thermal conductivity – dry 10 °C = 1.2 W/mK

Water vapor diffusion resistance factor = 25

Initial moisture: 280 kg/m³

References: WUFI 2012b

8.1.7 Moisture and air change sources added in the materials

Moisture and air change sources were used in some calculations in the thesis. A moisture source of 1 % of the driving rain was in general located in a thin air gap, on the inside of the cladding in walls (ASHRAE 2009). In some specific calculations, a leakage was also stimulated by adding 1 % of the driving rain deeper into the specific studied wall.

No leakages were added in the case studies in roofs. In the parametric studies leakages from both the outside and interior humid air were added in the roof construction. A leakage from the outside of 0,2 % of the rain falling on the tiles, was added in the tongued and grooved wooden board layer, on the inside of the roofing felt. A leakage which intends to imitate the results from humid air penetrating a hole of 2 mm diameter/m² was added in the roof insulation material outside the interior vapor membrane.

An air change source was always located in the air gap in walls and ventilated cold roofs or cold attics. The air change rate varies from case to case but was always located in the middle or on the

inside of the air gap. In one specific attic in the case study a heating cable, i.e. a heating source, was added in the unventilated air gap.

8.2 Used initial and boundary conditions in WUFI calculations

Initial and boundary conditions in the WUFI calculations were listed. Further information can also be found in WUFI manual (WUFI 2012a).

- Orientation – Orientation. The facade direction was specified in each specific case.
 - o Studied walls and roofs from the field measurements were facing its real orientation as far as possible in the case studies.
 - o North and the most wind driving rain exposed oriented walls were studied in the parametric studies.
 - o North oriented roofs were in general studied in the parametric studies.
- Orientation
 - o Wall inclination. Walls are 90 degrees i.e. vertical. WUFI default value (WUFI 2012a).
 - o Roof inclination was set to be its real in the case studies and was 27 degrees in the parametric study.
- Orientation – Building Height.
 - o Short building, height up to 10 m, was used for the walls in the parametric studies and in the calculations made for single-family houses in the case studies.
 - o 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 studies.
- Orientation – Driving rain coefficients. Indicate the amount of driving rain that hits the facade. WUFI default values were used (WUFI 2012a).
 - o Driving rain coefficient $R1 = 0$. WUFI default value (WUFI 2012a).
 - o Driving rain coefficient $R2 = 0.7$ s/m for walls and $R2 = 0$ s/m for roofs. WUFI default value (WUFI 2012a).
- Surface transfer coeff. – Exterior surface – Heat resistance.
 - o Exterior walls and roofs.
 - o Wind dependent.
 - o 0.0588 m²K/W or $\alpha_{conv} = 4.5$ m²K/W, $\alpha_{rad} = 6.5$ m²K/W, $f_{windward} = 1.6$ Ws/m²K, $f_{leeward} = 0.33$ Ws/m²K. WUFI default value (WUFI 2012a).
- Surface transfer coeff. – Exterior surface – Sd-value. No Sd-value was set on the exterior surfaces. However, the Sd-value from a layer of paint was set into claddings with wood panel and the roofs have rather vapor tight exterior roofing felt.
- Surface transfer coeff. – Exterior surface – Short-wave radiation absorptivity. Depends on the color of the facade and the roofing felt or tiles.
 - o In the parametric studies all walls and roofs were assumed to be red with at short-wave radiation absorptivity of 0,67 in the reference case.
 - o In the case studies 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 2012a).

- Surface transfer coeff. – Exterior surface – Explicit radiation balance. Turned on using WUFI default values (WUFI 2012a).
 - Ground long-wave emissivity = 0.90. WUFI default value (WUFI 2012a).
 - Ground long-wave reflectivity = 0.1. WUFI default value (WUFI 2012a).
 - Cloud index 0.66. WUFI default value (WUFI 2012a).
- Ground short-wave reflectivity = 0.20. WUFI default value (WUFI 2012a).
- Surface transfer coeff. – Exterior surface – Rain water absorption factor. According to inclination and construction type; 0.7 for walls and 1 for roofs. WUFI default value (WUFI 2012a).
- Surface transfer coeff. – Interior surface – Heat resistance = 0,125 m²K/W. WUFI default value (WUFI 2012a).
- 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.
- Initial conditions – Initial moisture in component.
 - In each layer was used.
 - Typical built-in moisture was assigned.
 - Water content was based on the material properties.
- Initial conditions – Initial temperature in component.
 - Constant across component.
 - Initial temperature in component 17 °C or 20 °C.
- Control – Calculation period / Profiles.
 - The calculations in the parametric studies were generally 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 studies 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 were used.
- Control – Numerics – Numerical parameters.
 - Increased accuracy. Turned on.
 - Adapted convergence. Turned on.
- Control – Numerics – Adaptive time step control.
 - Enable. Turned on.
 - Step = 3.
 - Max stages = 5.
- Control – Numerics – Geometry.
 - Cartesian.

9 Appendix II – Appended papers

Appendix II

The thesis consists of the following papers:

- I. S. Olof Mundt-Petersen, Lars-Erik Harderup. A method for blind validation of hygrothermal calculation tools. XIII DBMC 2014, International Conference on Durability of Building Materials and Components. September 2nd – 5th 2014, Sao Paulo, Brazil.
- II. S. Olof Mundt-Petersen, Petter Wallentén. Methods for compensate lack of climate boundary data. XIII DBMC 2014, International Conference on Durability of Building Materials and Components. September 2nd – 5th 2014, Sao Paulo, Brazil.
- III. 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, 17th International Meeting of Thermophysical Society. October 31th – November 2nd 2012, Podkylava, Slovak Republic.
- IV. S. Olof Mundt-Petersen, Lars-Erik Harderup. Moisture safety in wood frame constructions – What do we know today? – A literature overview. SB 13, Sustainable Building Conference 2013. May 22th – 24th 2013, Oulu, Finland.
- V. S. Olof Hägerstedt, Jesper Arfvidsson. Comparison of field measurements and calculations of relative humidity and temperature in wood framed walls. Thermophysics 2010, 15th International Meeting of Thermophysical Society. November 3th – 5th 2010, Valtice, Czech Republic.
- VI. 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.
- VII. 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. NSB 2011, 9th Nordic Symposium on Building Physics. May 29th – June 2th 2011, Tampere, Finland.
- VIII. S. Olof Mundt-Petersen, Lars-Erik Harderup. Validation of a 1D transient heat and moisture calculation tool under real conditions. Thermal Performance of the Exterior Envelopes of Whole Buildings XII – International Conference 2013. December 1st – 5th 2013, Florida, USA.
- IX. S. Olof Mundt-Petersen, Lars-Erik Harderup. Predicting hygrothermal performance in cold roofs using a 1D transient heat and moisture calculation tool. Submitted to Journal of Building and Environment.

- X. 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 – Conference proceedings. April 12th – 15th 2011, Porto, Portugal.
- XI. S. Olof Mundt-Petersen, Lars-Erik Harderup. Moisture safety in corners and walls in well-insulated wood framed houses. Submitted to Journal of Building and Environment.
- XII. S. Olof Mundt-Petersen, Lars-Erik Harderup, Jesper Arfvidsson. Important factors affecting the risk of mold growth in well-insulated wood frame walls in northern European climates. Thermal Performance of the Exterior Envelopes of Whole Buildings XII – International Conference 2013. December 1st – 5th 2013, Florida, USA.
- XIII. S. Olof Mundt-Petersen, Lars-Erik Harderup. Important factors affecting moisture safety in well-insulated wood framed cold roofs in northern European climates. Submitted to Journal of Building and Environment.