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Literature study / State-of-the-art

Mould and moisture safety in constructions

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Report TVBH-3053 Lund 2012
Building Physics, LTH

Lund University

Literature study / State-of-the-art

Mould and moisture safety in constructions

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General regulations, documents and knowledge with reference to underlying factors affecting mould growth; strategies to avoid mould and moisture damages; required boundary conditions and material data; mould models and calculation tools for predicting mould and moisture damages.

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Preface

This literature review is made at the department of Building physics, Lund University, as a part of my doctoral studies and the projects I been working with during my doctoral studies.

My supervisors initiated this literature study and most of it was made during the summer 2011. I would like to thank my supervisor Jesper Arfvidsson and co-supervisors Lars-Erik Harderup and Petter Wallentén that have supported me during the work with this study and for reviewing the report.

Lund 2012-09-17

S. Olof Mundt-Petersen

Summary

This report intends to summarize current knowledge and regulations in the areas of moisture and moisture safety in building constructions. The report includes and summarizes books, articles, reports and other document at different levels. Each studied document is given by full references and includes a short description of its content.

Besides a presentation of studied documents the literature review also includes a description of literature search method that has been used. In the end of the study is the main knowledge and conclusion that could be established in the literature presented.

Contents

1 Introduction

1.1 Aim

The aim of this literature study is to present an overview of current knowledge in the area of moisture and moisture safety in building constructions. Besides reviewing general regulations, documents and knowledge of moisture issues, the purpose of the study is to present new insights into underlying factors, strategies to avoid mould and moisture damages, and the required boundary and material data as well as to discuss mould models and calculation tools that can be used to predict mould and moisture damages in wooden constructions.

Current research projects connected to the literature study are carried out in the field of applied building research. Additional steps have therefore been taken to find literature that is useful and applicable to applied research and possible to use in real building constructions without any further development.

The literature review does not aim to discuss and evaluate basic knowledge. Therefore only a few main basic knowledge documents, books and other documents are presented without any deeper analysis.

The literature study does not include a complete review of all knowledge in the field and it is more a kind of a “state-of-the-art” that overviews and presents the latest knowledge and research published over the last ten years or so.

A specific literature search was made with regards to WUFI, the moisture calculation tool that current research project aims to evaluate. The purpose is to gain deeper knowledge about WUFI and about other studies and research concerning the tool. Furthermore, the study aims to find possible gaps in previous research that need to be filled and thereby demonstrate the need of further research concerning the use and verification of WUFI.

1.2 Literature search method

The literature study consists of studies and research documents at different levels. The fact that the area considers applied in interaction with tools developed from pure research results makes it necessary to include studies at different levels. The connection between and effects of qualitative and quantitative factors also make it necessary to include studies at different levels. Therefore the study includes basic knowledge, basic research, articles and doctoral theses as well as national institute reports, conference articles and master- and bachelor theses.

Initially, test searches in open access data bases in the area were carried out but mostly with poor results. The topic seems to be compact and many articles and papers seem to have been published for local or national use and are not widely spread. Even if the complete title and author are known, it is difficult to find directly hits on articles through normal Swedish library databases such as Lovisa, LibHub ELIN, LUP and other open access data bases. In some cases it is possible to find relevant publications in advanced and specific databases that can be found thought the LibHub system.

The lack of articles in general databases probably depends on the fact that most parts of the research are defined as applied research and there are fewer articles in this area than in pure research. Another factor might be that the construction sector in many cases acts conservatively and in a closed and exclusionary manner. New findings and knowledge are not supposed to be spread to competitors. Furthermore, the construction sector is strongly national. This might have the effect that, although there is a lot of knowledge, it is not made known internationally. In the area of mould and moisture, the local climate has a big influence, and, consequently, only Nordic research is useful in the Nordic area. Another factor might be that the main part of the research is presented at conferences and in licentiate or doctoral theses and not as articles in journals. Conference articles of interest might be unwittingly hidden in a thesis. This makes them harder to find in the library databases. The only open database that gave relevant and reasonable hits was Google Scholar.

Instead of a random literature search on Google Scholar, references and authors in known documents were used as to find new relevant documents.

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

The fact that some research in the area mainly is connected to local or national conditions, or knowledge, has made that a wide perspective of national institute reports and master's and bachelor's theses has been included. In addition, the SP Technical Research Institute of Sweden database was used. This covers the national perspective and also includes applied knowledge and research reports.

WUFI-related articles, from both the institute that developed the calculation tool and other independent institutes, are presented on the WUFI homepage. Here, it is easy to find relevant literature that presents the basic structure of the program. Other relevant literature can also be found on the WUFI homepage. Other references, described above, were also used in the search for relevant literature. A risk with this kind of search is that critical articles may have been excluded.

1.3 Structure of the literature study

The literature review is divided into chapters, each with different sub-sections that are expected to be of interest. In the first part of the study, examples of important documents, including laws, rules and regulations that establish the research are presented. Examples of literature describing basic knowledge in the area are also presented. Since the literature review aims to focus on new knowledge in the area, the literature review in these two initial areas is not complete. Furthermore, literature about a number of different topics that are closely related to the main topic is listed. For example, literature that discusses moisture safety design methods, mould models, water proofing in wet rooms/ bathrooms and airtightness in buildings. Boundary conditions as given in different standards, conditions due to outdoor and indoor climate, material data and air flows in the air gap behind the façade are also among the included topics. The first specific part of the literature review presents documents concerning the function and structure of the WUFI calculation tool. This part includes articles and other documents from the developer of WUFI. The second specific part presents studies from independent universities and institutes where WUFI has been used as a tool. The last part, which also includes literature references, presents examples using different moisture calculation tools and examples of studies connected to these tools.

Each presented article, conference paper, thesis, dissertation and report has been studied and evaluated based on its content. The full title, author and other relevant information is presented together with a short summary of the content.

At the end of the literature study the main and most interesting facts and possible conclusions that could be established from the studied documents are summarized and presented. This intends to focus on the different areas in a wider perspective and focus on possible parts with research gaps that need to be filled more than specific details.

2 Documents that indicate the need for research in the area

This chapter presents example of documents, articles or other studies that in some way show the need of further research in the area. Laws, rules and regulations are presented as well of studies that evaluate level of knowledge in the area and the status and conditions in Swedish buildings.

2.1 Laws, rules and regulations

2.1.1 The Swedish Planning and Building Act (Swedish)

Plan och bygglagen 2010:900, SFS 2010:900, Socialdepartementet, The Swedish Ministry of Health and Social Affairs, effective from 2011-05-02, language – Swedish.

The Planning and Building Act provides general regulations regarding how buildings should be constructed and built. The part concerning energy demands and moisture (Chapter 8, 4§) only says that buildings should be constructed in a manner such that:

- ……
- (3.) there is no risk of hygiene, health and environment problems.
- …..
- (6.) there will be low energy consumption.

This means that both good health conditions and low energy demands must be satisfied in new buildings. Further more specific and detailed regulations are presented in other regulations and ordinances such as “BBR 2008 – Boverkets byggregler 2008” / “BBR 2008 – Swedish Building Regulations 2008” and the “Plan- och byggförordningen” / “The Swedish Planning and Building Ordinance”.

2.1.2 The Swedish Planning and Building Ordinance (Swedish)

Plan- och byggförordningen 2011:338, SFS 2011:338, Socialdepartementet, The Swedish Ministry of Health and Social Affairs, effective from 2011-05-02, language – Swedish.

The Planning and Building Ordinance presents more and further developed regulations based on the “Plan och bygglagen 2010:900”/ “The Swedish Planning and Building Act”. Chapter 3 lists requirements that must be satisfied in new buildings:

- …….
- 9§ in order to satisfy the law concerning hygiene, health and environment the buildings should be designed and constructed in such a manner that no unacceptable risks to occupants, or other users, occur, and particularly not because of:
    - …..
    - (2.) Contamination in the air.
    - ……
    - (6.) moisture in the construction or on the surfaces of the buildings occurring in such a way that might affect the personal health.
    - …..
- …..

- 14§ in order to satisfy the law concerning energy efficiency, a building and its heating system, ventilation system and other installations must be designed in a manner that the energy consumption become low according the surrounding climate.
- 15§ buildings with more than one apartment or office should have exceptionally good energy performance. It should also be possible to make smooth changes between different energy sources, i.e. oil, wood, district heating etc.
- …..

2.1.3 BBR 2008 – Swedish Building Regulations 2008 (Swedish)

BBR 2008 – Boverkets byggregler 2008, ISBN 978-91-86045-03-6, Boverket 2008, language – Swedish.

The regulations have been updated several times since 2008. Changes concerning mould and moisture issues are marginal.

These regulations are part of the Swedish regulations concerning the construction of new buildings. The regulations include mainly detailed requirements that have to be followed in new buildings. Chapter 6:5 considers moisture and mould. The regulations say that the critical moisture levels in materials should be known. It should also be shown that the highest moisture content is below these critical moisture levels in order to avoid mould growth. This means that there is a need of validated moisture calculation tools that can be used during the planning and design process in order to show that the moisture levels are below the critical moisture levels. The regulations also recommend that a moisture safety design process is implemented in each construction phase. Generally, the calculation of moisture conditions is a part of the moisture safety design process.

2.2 National authority investigations and reports

2.2.1 ”Come on guys!” Competition, quality, costs and competence in the Swedish construction industry (Swedish)

”Skärpning gubbar!” Om konkurrensen, kvaliteten, kostnaderna och kompetensen i byggsektorn, SOU 2002:115, Socialdepartementet, The Swedish Ministry of Health and Social Affairs, Byggkommissionen, Building Commission, 2002, language – Swedish.

The report presents the status of the Swedish construction industry concerning competition, quality, costs and competence. The changes in the construction industry during the last 90 years are summarized. Problems concerning building damage, errors, deviations and poor workmanship are discussed. The report show that damage is caused by all parties involved in the industry and there is a lack of incentives to ensure correct and properly performed work. The report suggests that better control functions during the construction period have to be developed, especially in the area concerning mould and moisture. The report also considers problems with high costs and the lack of knowledge among the customers. Problems and solutions of “non-tax pay workers” are discussed.

2.2.2 ”Slow guys?” – A follow-up report to the Building Commission’s report “Come on guys!” (Swedish)

”Sega gubbar?” – En uppföljning av byggkommissionens betänkande ”Skärpning gubbar!”, Stadskontoret, 2009:6, 2008/61-5, language – Swedish.

The report discusses the outcome and changes that have been carried out in the construction industry since the previous report "Skärpning gubbar!"/ "Come on guys!". The report establishes that major problems still exists in the building sector. Lack of knowledge concerning quality responsibility, and responsibilities concerning other questions are still a problem. Furthermore there is a lack of knowledge, especially among the customers. There is a lack of focus on LCC and long-term and financial incentives in order to build energy-efficient buildings. The occurrence of building damage also seems to have increased since 2002.

2.2.3 The standard of our houses – Report on the Swedish government's commissions regarding the technical standard of Swedish buildings (Swedish)

Så mår våra hus – Redovisning av regeringensuppdrag beträffande byggnaders tekniska utformning m.m., 2009, ISBN 978-91-86342-28-9. Boverket 2009, language – Swedish.

The report shows that there is a need to develop validated calculation methods to ensure that buildings do not become damaged by moisture. This is to prevent people being subject to sickness and bad health because of sick buildings, Sick Building Syndrome, SBS. The report says that "Construction techniques in order to achieve robust engineering solutions that are also economical and energy-efficient, with sufficient moisture control to prevent moisture damage, have to be developed". The coupled heat and moisture calculation program, WUFI is mentioned as a possible computer tool. Furthermore, the critical levels of relative humidity are defined as: "Moisture that excess materials critical moisture level might affect the indoor environment". The report presents the goal that less than before the year 2020 five percent of the Swedish buildings should have mould growth that affects the indoor climate.

2.3 Enquires

2.3.1 Moistureproof construction – A survey study of the knowledge in the area (Swedish)

Fuktsäkert byggande – Enkätstudie om kunskapsläget, Jesper Arfvidsson, Eva Sikander. FoU-Väst, 2002, SG idé & tryck AB, ISSN 1402-7410, language – Swedish.

The report presents a study in order to clarify the moisture proofing knowledge in all areas in the construction industry. The study result shows deficiencies handling moisture safety issues in the industry. The different areas and partners in the construction process seem to push the moisture issues on each other. The responsible customer does not have any requirements but are at the same time willing to pay extra for moisture control. The industry sees a potential for improvement and that the knowledge in the moisture area have to be better in the companies. Overall, the study shows that there is a need for further awareness raising measures in the industry.

3 Basic knowledge about moisture, moisture transport and mould growth

The chapter includes examples of books, studies and other articles concerning basic knowledge in the area of moisture, moisture transport and mould growth. Those basics are not aimed to become deeply investigated and are therefore not further revived except included books and studies.

3.1 Moisture and moisture transport

3.1.1 Moisture handbook – practice and theory (Swedish)

Fukthandboken/ Fukt – handboken – praktik och teori, Lars Erik Nevander, Bengt Elmarsson, AB Svensk byggtjänst, Tredje utgåvan, Elanders Infologistics Väst AB, Mönlycke 2007, ISBN 978-91-7333-156-2, language – Swedish.

The moisture handbook describes the basic physical conditions under which humidity and moisture transport occurs. Humidity and moisture transport in both materials and through the air are investigated. Conditions for heat transfer are also described. The initial part of the book considers the practical construction of buildings and how materials are used in buildings. The book also presents basic data for a number of common building materials. The book was first published in 1994 and therefore does not describe any new findings in the field. However, all basic knowledge in the area is discussed.

3.1.2 Moisture in wood during the construction phase – Moisture properties, requirements, handling and measurements (Swedish)

Fukt i trä för byggindustrin – Fuktegenskaper, krav, hantering och mätning, Peter Brander, Björn Esping, Jarl-Gunnar Salin, SP Technical Research Institute of Sweden, SP Trätek 2005, Rapport 2005:24, ISBN 978-91-976310-0-6, language – Swedish.

This book is a manual for measuring moisture in wood with reasonable accuracy. The manual is aimed at the production sector of the construction industry. The book provides guidelines and instructions in order to make it easier to handle moisture issues during the production phase. The book covers the building process from purchase during the full construction phase.

3.2 Mould

3.2.1 Mould growth on building materials under low water activities. Influence of humidity and temperature on fungal growth and secondary metabolism

Mould growth on building materials under low water activities. Influence of humidity and temperature on fungal growth and secondary metabolism, K. F. Nielsen, G. Holm, L. P. Uttrup, P. A. Nielsen. International Biodeterioration & Biodegradation, Volume 54, Issue 4, December 2004, Pages 325-336, 2004, language – English.

The article presents basic knowledge about climate conditions that create mould growth on different building materials. Differences between growth and growth conditions between different mould fungi are discussed. Levels of mould growth on different building materials are presented.

3.2.2 Microbiological growth on building materials – critical moisture levels. State of the art (Swedish)

Kritiskt fukttillstånd för mikrobiell tillväxt på byggnadsmaterial – kunskapssammanfattning, Pernilla Johansson, Ingemar Samuelson, Annika Ekstrand-Tobin, Kristina Mjörnell, Per Ingvar Sandberg, Eva Sikander, SP Technical Research Institute of Sweden, SP Energiteknik, Rapport 2005:11, ISBN 91-85303-442-9, language – Swedish.

The report is a literature review that summarizes the fundamental causes of mould growth on building materials. Critical limits for relative humidity in order to avoid mould growth on different materials are presented. Mould growth is mainly caused by the parameters temperature, relative humidity and duration. The moisture content can also affect the risk of mould growth if the relative humidity is low but the material is wet and the temperature high. Dirt increases the risk of mould growth.

3.2.3 How quickly must gypsum board and ceiling tile be dried to preclude mold growth after a water accident?

How Quickly must gypsum board and ceiling tile be dried to preclude mold growth after a water accident?, Horner, E., Morey, P. R., Lingman, B. K., Younger, B., 2001, ASHRAE Conference IAQ 2001, Moisture, Microbes and Health Effects: Indoor Air Quality and Moisture in Buildings, San Francisco.

The conference article presents drying out time limits for gypsum boards and ceiling tiles in order to avoid mould growth. The study shows that it is not sufficient to have acceptable climate conditions surrounding the material. Wet materials or materials with high relative humidity become affected by mould growth even if the surrounding climate conditions would indicate otherwise.

4 Closely related literature

This chapter presents examples of literature that are important and relevant in the area of mould and moisture safety but not directly connected to the specific topic of WUFI. The literature includes information about factors affecting mould growth and other critical moisture conditions as well as the differences between qualitative and quantitative aspects that are needed to make correct estimations and calculation models.

4.1 Moisture safety design methods

Besides the information presented below, also see the "ASHRAE 160-2009 – Criteria for moisture-control design analysis in buildings" standard under the section "Boundary conditions – standards".

4.1.1 BuildM – method for moisture-proof constructions (Swedish)

ByggaF – metod för fuktsäkert byggande, Kristina Norling Mjörnell, FoU-Väst, 2007, SG Zetterqvist AB, ISSN 1402-7410, language – Swedish.

ByggaF is a method to ensure that moisture damages not will occur during the entire construction process or in finished buildings. The method deals with both qualitative and quantitative approaches. One of the parts of the method maintains that moisture conditions should be calculated before a building is constructed to determine:

- Whether the design will be able to handle the anticipated moisture loads.
- What specific actions should be taken into account during the construction phase to prevent moisture damages.
- The moisture content and moisture conditions in the materials that will be used when constructing the building.

The ByggaF method shows that useful and reliable moisture calculation tools that can take into account local conditions are required.

4.1.2 Moisture safety design using general checklist (Swedish)

Fuktdimensionering med generell checklista, Eva Harderup, Rapport TVBH-3031, Lund 1998, Lund University, ISBN 91-88722-14-7, language – Swedish.

The report presents a moisture safety design method together with a number of general checklists that can be used in the moisture safety design process. The method includes both qualitative and quantitative approaches. The report forms the basis for the above mentioned ByggaF method.

4.1.3 Moisture safety design – Example of a single family houses, drawings and descriptions of materials, facades and rooms (Swedish)

Fuktdimensionering – Demonstrationsexempel på bostadshus, ritningar, material-, fasad- och typrumsbeskrivning, Eva Harderup, Rapport TVBH-3032, Lund 1998, Lund University, ISBN 91-88722-16-3, language – Swedish.

The report presents an example of a moisture safety design process on a single family house. Several of the checklists for different parts of the building are included. The material can be used as an example of how to use some parts of the ByggaF method.

4.1.4 Moisture safety design process provides moisture-proof buildings (Swedish)

Fuktdimensionering ger fuktsäkrare byggnader, Kenneth Sandin, Fuktsäkerhet i byggnader, Byggforskningsrådet, Boverket, 1998, Ljunglöfs offset, ISBN 91-540-5823-6, language – Swedish.

The material presents a moisture safety design method. Examples of the moisture safety design process and suitable ways of documentation are shown.

4.1.5 Quality of timber construction – Guidance for buildings and load bearing structures (Finnish)

Puurakenteiden laadunvarmistus, English translation, Tomi Toratti, Report RIL240-2006, RIL, Finnish Association of Civil Engineers, ISBN 951-758-468-7, ISSN 0356-9403, language – Finnish.

The report presents guidelines for the whole building process in order to achieve high quality timber buildings. Relevant responsibility areas for different professional groups are presented. The report includes an appendix with check lists. Moisture related questions are briefly discussed.

4.1.6 Guidelines to avoid mould growth in buildings

Guidelines to avoid mould growth in buildings, Hector Altamirano-Medina, Mike Davies, Ian Ridley, Dejan Mumovic, Tadj Oreszczyn, Advances in Building Energy Research, Volume 3, Number 1, 2009, pp 221-236, ISSN 1756-2201, language – English.

The article presents guidelines for maximum relative humidity with respect to duration limits to avoid mould growth in buildings. The presented limits relate to previous studies for mould growth. No specific method or control processes are discussed. The presented limits are applicable to English and Wales climate conditions.

4.1.7 Moisture safety design of timber constructions (Swedish)

Fuktsäkerhetsdimensionering av träkonstruktioner, Lars Erik Nevander, Bengt Elmarsson, Rapport R38:1991, Lund University, Byggforskningsrådet, ISBN 91-540-5350-1, language – Swedish.

The report presents an early version of a moisture safety design method based on statistical models. The risk of mould growth is calculated by using the Monte Carlo method where used parameters in order to resist moisture are connected to a safety margin. The calculations show that the risk of moisture damage increases with increased insulation. The report also includes an early version of the isopleth charts now in current use.

4.1.8 Empowerment of decision-makers in mould remediation

Empowerment of decision-makers in mould remediation, Hyeun Jun Moon, Godfried Augenbroe, Building Research and Information, 36 (5) p 486-698, 2008, ISSN 1466-4321, language – English.

The article says that a more sophisticated approach is necessary in order to handle and avoid much of the moisture damage that is seen today. Therefore a new probabilistic mould risk method, MRI, has been developed. The MRI risk method uses the Monte Carlo statistic method to give a probability distribution on mould growth risk based on three factors: temperature, relative humidity and duration. The report also presents a case study using the MRI risk method. The main conclusion is that uncertainty has to be taken into account in mould risk evaluations.

4.1.9 Moisture-induced stress perpendicular to grain in timber constructions

Moisture induced stress perpendicular to grain in timber constructions, Martin Hägglund, Report TVBK-1036, Lund 2009, Doctoral thesis, Lund University, ISSN 0349-4969, language – English.

The thesis describes moisture and variation in moisture conditions with respect to load bearing capacity. It is shown that varied moisture conditions significantly reduce the load bearing capacity. The study therefore proposes that a variation in moisture conditions should be taken into account with other ordinary loads during the static load dimensioning process. Regardless of the quality of the thesis, the topic is not seen as specifically relevant to this study.

4.1.10 Stabilization of wooden single family houses – horizontal stabilization control (Swedish)

Stabilisering av småhus – Kontroll av horisontalstabilitet, Moustafa Charif, ISRN LUTHBG/THID-06/5054-SE, Helsingborg 2006, Bachelor thesis, Lund University, ISSN 1651-2197, language – Swedish.

The thesis evaluates the conditions required to make wooden single family houses stable due to wind forces. One part concerns the influence and effects on stabilization using wood or gypsum boards. The influence of windows and lack of total board area are discussed. Effects on the strength on gypsum boards with high moisture loads are unfortunately only briefly discussed. Regardless of the quality of the thesis, the topic is not seen as specifically relevant in this study.

4.1.11 Mould growth on building timber collected from three different small-house factories (Swedish)

Mögeltillväxt på virke från småhusfabrikanter, Pernilla Johansson, Gunilla Bok, SP Technical Research Institute of Sweden, SP Energiteknik, Rapport 2011:51, ISBN 978-91-86622-81-7, language – Swedish.

The report presents the occurrence of mould growth on constructional timber from three detached house manufacturers. The wood was inoculated with mould spores in different ways. The results show the differences in mould growth depending on the quality of the wood in question.

4.2 Mould models

4.2.1 Factors affecting the development of mould and brown rot decay in wooden material and wooden structures. Effect of humidity, temperature and exposure time

Factors affecting the development of mould and brown rot decay in wooden material and wooden structures. Effect of humidity, temperature and exposure time, Hannu Viitanen, Doctoral thesis, Department of Forest Products, Swedish University of Agricultural Sciences, Uppsala, Sweden, 1996, ISBN: 91-576-5115-9, language – English.

This thesis presents basic models for mould growth and brown rot decay in wooden components. The second part, concerning brown rot decay, is of less interest and not further discussed. The thesis presents results that have been used for developing mould growth models. These models have also been further developed by the author and many others into today’s mould growth models, see other reports below.

The minimal critical level for mould growth is shown to be at 80 percent relative humidity, depending on factors such as temperature, duration and the surface quality of wood. In the study, initial and visual mould growth is separated. The influence of varied relative humidity on mould growth is also studied.

The study presents mathematical models which depend on temperature, relative humidity and duration to describe mould growth.

4.2.2 Moisture and biodeterioration risk of building materials and structures

Moisture and biodeterioration risk of building materials and structures, Hannu Viitanen, Juha Vinha, Kati Salminen, Tuomo Ojanen, Ruut Peuhkuri, Leena Paajanen, Kimmo Lähdesmäki. Journal of Building Physics January 2010 vol. 33 no. 3 201-224, 2010, language – English.

The report presents results of mould growth in different materials and wall assemblies. It also presents models to evaluate the risk of mould growth and decay development. The possibilities of using numerical simulations to evaluate the risk and development of mould growth are briefly discussed. The article also mentions the problems associated with varied and unknown parameters, such as initial moisture content, in the design phase. It also mentions the need for an overview for the complete design to avoid damages.

The article is a good follow-up to the previous work concerning mould and models of mould growth by Viitanen. The new part in the articel is the impact of duration on mould growth. A clear comparison between different mould growth models is also made. The figure below is taken from the article and describes this comparison.

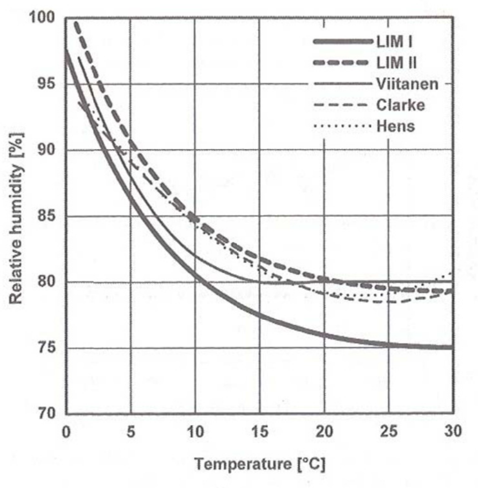

Figure 1. Comparsion of different models for mould growth.

4.2.3 Improved Model to Predict Mold Growth in Building Materials

Improved Model to Predict Mold Growth in Building Materials, Hannu Viitanen, Tuomo Ojanen, Thermal Performance of the Exterior Envelopes of Whole Buildings X – International Conference 2007, language – English.

The aim of the study is to present the risks of mould growth occurring on other building materials. Initial is previous Equations and a mould growth model based on temperature, relative humidity and duration for wood are presented. The materials investigated in the study are: fiberboard, concrete (K30), glass wool, rock wool and expanded polystyrene (EPS).

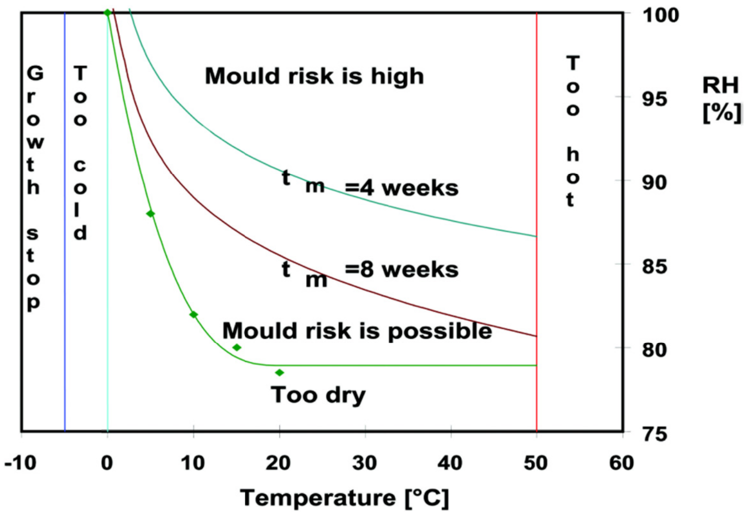

Figure 2. The overall favourable conditions for mould growth on wooden materials as a mathematical model. Previously presented in 1997.

The result shows varying tolerance levels against mould growth for different materials. Wood-based materials showed the lowest tolerance levels for relative humidity compared to mould growth. See the study in order to determine the critical levels for each material.

4.2.4 A mathematical model of mould growth on wooden material

A mathematical model of mould growth on wooden material, A. Haaku, H. A. Viitanen, Wood Science and Technology 33 (1999) 475-485, Springer-Verlag, 1999, language – English.

This study presents a mathematical model for the simulation of mould growth on wooden materials. Previous equations for mould growth are further developed and new equations presented. The model presented in the article consists of equations which consider temperature, relative humidity and durability when calculating the risk of mould growth. Finally, critical levels to avoid mould growth are discussed.

4.2.5 Critical conditions for mould and decay resistance of wood

Critical conditions for mould and decay resistance of wood, Hannu Viitanen, 2009 Wood and Fiber Product Seminar, VTT and USDA joint activity, Espoo, Finland 2009. VTT Symposium, 114-118, 2010, language – English.

The article presents factors that affect mould growth such as temperature, material properties and exposure time. Critical limits to avoid mould growth are also set for wood-based and stone-based materials. In order to prevent mould growth, charts show that a maximum of 77 percent relative humidity can be accepted at 20 degrees Celsius for wood-based materials. At lower temperatures a higher relative humidity can be accepted. Stone-based materials can be subject to higher relative humidity before mould growth starts.

The article also makes it clear that there are limitations in mathematical mould growth models. Modelling can be used as a tool to evaluate risks but it has to be understood that other parameters such as types of wood, modifications, impregnation and surface treatment also affect mould growth.

4.2.6 Service life of wooden materials – mathematical modelling as a tool for evaluating the development of mould and decay

Service life of wooden materials – mathematical modelling as a tool for evaluating the development of mould and decay, Hannu Viitanen, Ruut Peuhkuri, Tuomo Ojanen, Tomi Toratti, Lasse Makkonen, Cost Action E37 Final Conference in Bordeaux, 2008, language – English.

The article presents the state-of- the-art regarding the modelling of mould growth and decay in wooden constructions exposed to different climate conditions. Factors that affect the sustainability of a building are mainly the same as those that create mould growth. These factors are discussed and the most important factors in the risk analysis are defined as: macroclimate (rainfall, temperature, humidity, air pressure conditions etc.), and meso-climate (location of the building, structural details and the materials used). The complications of handling all these factors in one model are investigated. The article also describes a way of connecting results from laboratory and field tests using modelling. Sedlbauer (2001) and Iskasson (2008), who are also presented in this report, are mentioned. Other models for calculating service life are also presented. One part of the article describes the degradation conditions for the façade and a WUFI 4.1 wind-driven rain model is presented.

4.2.7 Development of an improved model for mould growth: Laboratory and field experiments

Development of an improved model for mould growth: Laboratory and field experiments, Kimmo Lähdesmäki, Juha Vinha, Hannu Viitanen, Kati Salminen, Ruut Peuhkuri, Tuomo Ojanen, Leena Paajanen, Hanna Iitti, Tomi Strander, 8th Nordic Symposium on Building Physics, Copenhagen, 2008, language – English.

The article presents results from ongoing mould growth experiments. The materials that are tested are exposed to both laboratory and field conditions. Initially, the test method is described. The results provide information about mould growth on a couple of different but common building materials. The highest mould growth rates are found on pinewood, spruce (glue board) and paper coatings of polyurethane. Mould growth was investigated in different climate conditions, including temperatures below 0 degrees Celsius. The results are discussed further in the article "Development of an improved model for mould growth: Modelling".

4.2.8 Development of an improved model for mould growth: Modelling

Development of an improved model for mould growth: Modelling, Hannu Viitanen, Juha Vinha, Ruut Peuhkuri, Tuomo Ojanen, Kimmo Lähdesmäki, Kati Salminen, 8th Nordic Symposium on Building Physics, Copenhagen, 2008, language – English.

This article presents how the existing VTT model for mould growth (Viitanen 1996) has been improved. It also discusses the problems associated with modelling. The TCCC2D hygrothermal simulation tool using the mould index according to the VTT model is described. An analysis of the improved VTT mould growth model is compared to the WUFI bio-mould growth model. The article also presents a case study example of how to use the mathematical model for expected mould growth.

4.2.9 Prediction of mould fungus formation on the surface of and inside building components

Prediction of mould fungus formation on the surface of and inside building components, Klaus Sedlbauer, Fraunhofer Institute for Building Physics, Doctoral thesis, Universität Stuttgart, 2001, language – English (translation).

The thesis describes the development and validation of a mould growth model by comparing mould growth conditions with hygrothermal conditions in buildings. The model is uses data from the WUFI simulation tool.

The thesis describes current mould growth models. There is a description of how the mould growth results are converted into a mathematical model. The models connection to WUFI is also described. The need of good validation is discussed. The model is based on temperature, relative humidity and duration and does not take into account other factors such as pH values, salt, bacterial intensities and of the presence of oxygen. An isopleth and biohygrothermal model is also described. Different risk factors are presented. Finally, an example of how the model can be used is presented. The model is compared to some other existing models as shown in Figure 3 below. See also Figure 1.

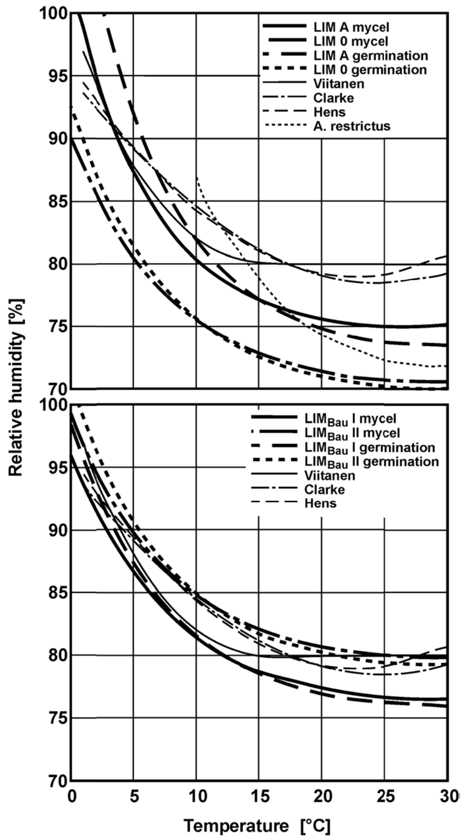

Figure 3. Mould growth model compared to other existing models.

4.2.10 Mould growth prediction with a new biohygrothermal method and its application in practice

Mould growth prediction with a new biohygrothermal method and its application in practice, Klaus Sedlbauer, Martin Krus, K Breuer. IX. Polska Konferencja Naukowo-Techniczna Fizyka Budowli w Teorii i Praktyce "Lódz 2003". Materialy konferencyjne. Czesc 2, pp.594-601, ISBN: 83-88499-09-2 Lódz, 2003, language – English.

The content of the article complies broadly with Sedlbaur's previously presented model. The mould model is a development of this work and employs three different minimum limits to avoid mould growth. The report also discusses the isopleth system and the biohygrothermal system for mould spore growth. Finally, there is an example of how the model can be used.

4.2.11 Critical conditions for onset of mould growth under varying climate conditions

Critical conditions for onset of mould growth under varying climate conditions, Tord Isaksson, Sven Thelandersson, Annika Ekstrand-Tobin, Pernilla Johansson, Building and Environment 45 (2010) 1712–1721, 2010, language – English.

The study presents a mould growth model that handles both favourable and adverse conditions. The mould growth model is presented as a dose-response model which takes into account temperature and relative humidity. A limit for critical conditions is set. If the limit not is passed during mould growth conditions, a revised period with regression of mould starts. If the regression period is long, the initial growth will return to the initial conditions. The time period is calculated in days and there might be a risk to use the method in other units (i.e. hours). The results are checked against previous laboratory measurements from Viitanen.

4.2.12 Modelling reliability of structure with respect to incipient mould growth

Modelling reliability of structure with respect to incipient mould growth, Krystyna Pietrzyk, Ingemar Samuelson, Pernilla Johansson, 9th Nordic Symposium on Building Physics – NSB 2011, 2011, language – English.

The article presents a model that calculates the probability of mould growth in relation to exposure time. The mould resistant properties of materials can also be taken into account. The factors affecting mould growth are calculated by using HAM simulations. The probability of mould growth can be examined with regard to its consequences and risk levels assigned to the associated factors.

4.2.13 m-model: a method to assess the risk for mould growth in wood structures with fluctuating hygrothermal conditions

m-model: a method to assess the risk for mould growth in wood structures with fluctuating hygrothermal conditions, Åse Togerö, Charlotte Svensson Tengberg, Bengt Bengtsson, 9th Nordic Symposium on Building Physics – NSB 2011, 2011, language – English.

The article presents a moisture model developed in conjunction with a moisture safety design strategy. The model makes it possible to compare different building designs with respect to mould growth risk. Critical mould growth levels are taken from literature and laboratory results. The model takes into account temperature, relative humidity and duration. The model presents risk factors for mould growth. Some parts of the model are not in accordance with the Swedish building regulations and need to be developed further. There is a brief discussion about the difficulties of simulating mould growth and the need for limit levels.

4.3 Waterproofing in wet rooms/bathrooms

Besides the studies presented below, see also the report “Tätskikt bakom kakel i våtrumsytterväggar”/ “Sealing layer behind tiles in wet room exterior walls” under the sub-section “Indoor climate” in the chapter “Moisture calculation boundary conditions”.

4.3.1 Double sealing layers in the external walls of wet rooms with internal tile cladding (Swedish)

Dubbla tätskikt i våtrumsytterväggar med keramiska plattor. Anders Jansson. SP Technical Research Institute of Sweden. SP Energiteknik. Rapport 2005:20, ISBN: 91-85303-51-8, language – Swedish.

The report presents calculations of the moisture conditions in an external wall of a wet room with an interior surface of tiles. The studied wall has two vapour-tight membranes at two different depths in the wall. One membrane seals the area behind the tile adhesive to prevent the wall from being directly subject to water and the other membrane is placed a little deeper in the wall to ensure air- and vapour tightness. The results show that there is a considerable risk of moisture damage in the material between these two layers. To avoid damage in this material, the interior sealing has to have an air-tightness of at least 1 500 000 s/m. If only one sealing membrane is used, the weather barrier on the outer part of the wall could be damaged. The calculations were made using the PI 200 PC program developed by SP Technical Research Institute of Sweden.

4.3.2 Water barrier in wet rooms – functional tests of flexible sheeting (Swedish)

Tätskikt i våtrum – funktionsprovning av foliesystem. Anders Jansson, Ingemar Samuelson, SP Technical Research Institute of Sweden. SP Energiteknik. Rapport 2011:01, ISBN: 978-91-86622-25-1, language – Swedish.

The report presents the results of a study of five different flexible sheeting systems. The study mainly deals with detailing errors or unacceptable results due to bad workmanship. The systems are tested for leakages in or close to installations, pipes penetrations or other details penetrating walls or floors. The results show that none of the systems passed the test and only one of the five systems was close to passing. Although none of the systems passed the test, the results do show that it is possible to make all details watertight.

4.3.3 Wet room floors with ceramic tiles on wooden slabs (Swedish)

Våtrumsgolv med keramiska plattor på träbjälklag, Anders Jansson. SP Technical Research Institute of Sweden. SP Energiteknik. Rapport 2010:05, ISBN: 978-91-86319-41-0, language – Swedish.

The report presents the findings from and underlying factors in ten different cases where damage has been caused in wet room floors with tiles set on wooden slabs. All ten of the investigated errors were probably due to bad workmanship. Both “amateur” and “professional” workmanship were investigated. The main cause of damage was poor sealing around or close to the floor drainage point. The study also concludes that a firmly fixed slab is essential to avoid damage. “Amateur” work also appeared to be better than work carried out by professional workers.

4.3.4 Moisture damage in wet areas related to waterproofing behind ceramic tiles (Swedish)

Fuktskador i våtrum relaterat till tätskikt bakom keramiska plattor, Erik Hilmius, Niklas Palmqvist, Bachelor theses, Uppsala University, 2011, language – Swedish.

The report summarizes known knowledge about reasons for moisture and water damage in wet areas, i.e. bathrooms. Product instructions for waterproofing membranes are studied and evaluated. The results indicate that poor product instructions might be one of the main reasons for water damage. The study also shows that waterproofing membranes often leak around floor drains and at the floor/ wall junction.

4.4 Airtightness in buildings

4.4.1 BuildA – method for airtight constructions (Swedish)

ByggaL – Metod för byggande av lufttäta byggnader, Eva Sikander, SP Technical Research Institute of Sweden, SP Energiteknik, Rapport 2010:73, ISBN: 978-91-86622-15-2, 2010, language – Swedish.

BuildA presents a method for building airtight constructions. The report proposes ways in which airtight constructions can be made and the working process required to achieve more airtight constructions. All aspects, from the initial specification of the design requirements to the completion of the construction phase, are covered. A number of checklists that can be used in different parts of the construction process are presented. The report also contains references to studies concerning practical details in airtight construction and air-sealing materials.

4.4.2 Good examples of airtight details (Swedish)

Goda exempel på lufttäta konstruktionslösningar, Paula Wahlgren, SP Technical Research Institute of Sweden. SP Energiteknik, Rapport 2010:09, ISBN: 978-91-863319-45-8, 2010, language – Swedish.

The report describes and evaluates practical solutions for airtight constructions. The report concentrates on different solutions for detail design and construction systems. The report also presents a literature review with references to studies and laboratory tests concerning detailing in airtight constructions and air-sealing materials.

4.4.3 Good airtightness – guidelines for architects, building designers and contractors (Swedish)

God Lufttäthet – En guide för arkitekter, projektörer och entreprenörer, Karin Adalberth, Byggforskningsrådet, Rapport T5:1998, ISBN 91-540-5809-0, 1998, language – Swedish.

The book presents ways in which buildings can achieve proper air-, diffusion-, and windtightness. The basic air-, diffusion-, and windtightness materials are presented. The causes and effects of ventilation and air-, diffusion-, and windtightness in buildings are briefly described. The risk zones for leakages are also described. Methods of sealing joints in membranes and other solutions for better air-, diffusion-, and windtightness are presented in figures and by referring to practical examples.

4.5 Rendered undrained and unventilated façades

Besides the studies presented below, see also the report “Putsade regelväggar”/ “External plaster stud walls” under the section “Independent institute studies using WUFI”.

4.5.1 Moisture damages in rendered, undrained, well-insulated stud walls – state-of-the-art October 2007 (Swedish)

Fuktskador i putsade, odränerade, träregelväggar – lägesrapport oktober 2007, Ingemar Samuelson, Kristina Mjörnell, Anders Jansson, SP Technical Research Institute of Sweden. SP Energiteknik. Rapport 2007:36, ISBN 978-91-85533-97-8, ISSN 0284-5172, language – Swedish.

The report discusses the risk of moisture damages in rendered, undrained, well-insulated stud walls. Factors that cause moisture damages in the construction systems are presented. Furthermore, the report suggests an investigation method to evaluate risks in building design and how measurements in the walls can be performed.

4.5.2 Damage in rendered wooden stud walls (Swedish)

Skador i putsade träregelväggar, Anders Jansson, Ingemar Samuelson, Kristina Mjörnell, Bygg & teknik nr 1/07, ISSN 0281-658X, branch journal, 2007, language – Swedish.

The article was published in a popular science-style trade journal. It describes the causes and consequences of mould damages in rendered, undrained walls with wooden studs.

4.6 Additional closely related literature

4.6.1 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

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. Juha Vinha, Doctoral thesis, Tampere University of technology, publication 658, ISBN 978-952-15-1742-6, ISSN 1459-2045, language – English.

The main aim of the study is to show the need for a vapour retarder close to the internal surface in wooden constructions. Relations between required airtightness and the airtightness of exterior materials are presented. A method to evaluate the hygrothermal performance is also shown. The study includes laboratory experiments, field tests and theoretical calculations.

Besides its main aim, the report is also very comprehensive and discusses a number of useful building physics subjects. . The first part of the report includes a summary of building physics principles. The report discusses important areas concerning airflow in air spaces behind wood and brick claddings. Differences in various calculation methods and calculation programs are described. The impact of some of the deficiencies in WUFI 2D are discussed and evaluated. WUFI 2D calculations are also compared with measured results with good convergence.

4.6.2 Moisture and mould in prefabricated timber framed constructions during production until enclosure of the house

Moisture and mould in prefabricated timber framed constructions during production until enclosure of the house, Lars Olsson, Kristina Mjörnell, Pernilla Johansson, 9th Nordic Symposium on Building Physics – NSB 2011, 2011, language – English.

The study is also presented in a separate report "Kartläggning av fuktförhållanden vid prefabricerat trähusbyggande" Lars Olsson, Kristina Mjörnell, Pernilla Johansson, SP Technical Research Institute of Sweden. SP Energiteknik. Rapport 2010:02, ISBN 978-91-86319-37-3, ISSN 0284-5172, language – Swedish.

The study investigates 24 cases and shows the amount of water that prefabricated timber framed constructions can become exposed to before a watertight seal is achieved is shown. Furthermore, the affects, risks and consequences of exposing wood to water and the treatment of the material used in the studied houses is discussed. The report also describes solutions and how to avoid wetting the wood.

Mould growth and high moisture contents were found in 33 percent of investigated cases. All 24 houses in the study had somehow been exposed to free water during construction. The study also showed that as long as wood not is exposed to free water or moisture for a long time at high temperatures there are no other climate conditions that can create mould growth. The risk of mould growth is highly dependent on the prevailing weather conditions during production until the house is made weathertight.

4.6.3 Wireless in situ measurements of moisture content and temperature in timber constructions

Wireless in situ measurements of moisture content and temperature in timber constructions, Karin Sandberg, Anna Pousette, Simon Dahlquist, 12th International conference on durability of building materials and components, XII DBMC, Porto – Portugal 2011, language – English.

The paper presents experience from a wireless in situ measuring system for temperature, relative humidity and moisture content. The measuring system's structure and components are described. The procedure for collecting measured data and how the measured data is communicated to the researcher are also described. The paper describes problems and other complications that have occurred while taking the measurements. The paper also includes references to companies, product data sheets and other product information about the measuring equipment that was used.

4.6.4 Increased risk of moisture damages in highly insulated houses (Swedish)

Ökar risken för fuktskador i passivhus?, Ingemar Samuelson, Bygg & teknik nr 5/08, ISSN 0281-658X, branch journal, 2008, language – Swedish.

The article was published in a popular science style branch journal. It discusses the risk of moisture-related damage in highly insulated houses. Effects of different insulation thicknesses on the climate conditions in attics and on ventilation systems are presented. The risk of moisture-related damage increases in highly insulated buildings. However, the risk of increased moisture damage is not significantly higher as Swedish houses are already normally well-insulated.

4.6.5 Laboratory investigation of sills and studs exposed to rain (Swedish)

Laboratoriestudie av syllar och reglar som utsatts för regn, Lars Olsson, SP Technical Research Institute of Sweden. SP Energiteknik. Rapport 2011:18, ISBN 978-91-86622-49-7, ISSN 0284-5172, language – Swedish.

The report considers the risk of mould growth on wooden sills and studs exposed to rain. The results show that if sills or studs become exposed to rain during the construction phase they also become damaged by mould growth.

5 Moisture calculation boundary conditions

This chapter presents examples of literature in which the necessary boundary conditions are included so that adequate moisture calculations can be made. Besides material data, standards and preferences depending on in- and outdoor climate conditions, there is a specific subtopic with references to literature in which airflows in the air gap behind the façade air gap are discussed.

5.1 Standards

The standards presented below deal with both indoor and outdoor climate boundary conditions as well as calculation methods and material properties.

5.1.1 SS-EN 15026:2007 – Hygrothermal performance of building components and building elements – Assessment of moisture transfer by numerical simulations

SS-EN 15026:2007 – Hygrothermal performance of building components and building elements – Assessment of moisture transfer by numerical simulations, Swedish Standard Institute, Ref. No EN 15026:2007: E, SIS Förlag AB, language – English.

This is a standard which defines practical applications of hygrothermal simulations. Guidelines for hygrothermal equations, material properties, boundary conditions and documentation of results are given. The standard applies to one-dimensional transient heat and moisture transfer in multi-layer building envelope components subjected to non-steady state climate conditions on either side. Conditions for latent heat effects, heat and moisture storage in materials, and liquid and convective transport with respect to initial conditions are discussed.

Annex B gives briefly information and guidelines regarding the design of moisture reference years (MRY).

Annex C provides a model for indoor climate conditions in which the indoor temperature varies as a function of the outdoor temperature. The indoor relative humidity is based on the outdoor climate conditions.

5.1.2 SS-EN 13788:2001 – Hygrothermal performance of building components and elements – Internal surface temperature to avoid critical surface humidity and interstitial condensation – Calculation methods

SS-EN 13788:2001 – Hygrothermal performance of building components and elements – Internal surface temperature to avoid critical surface humidity and interstitial condensation – Calculation methods, Swedish Standards Institute, Ref. No EN 13788:2001, SIS Förlag AB, language – English.

The standard includes practical calculations using the Glaser method to avoid condensation or critical levels of relative humidity in the frame of a building. Furthermore, indoor relative humidity levels are determined by using four different moisture loads, which are a function of temperature. The indoor moisture load function decreases with increasing outdoor temperature. The standard gives free opportunity to set own indoor temperature.

5.1.3 ASHRAE 160-2009 – Criteria for moisture-control design analysis in buildings

ASHRAE 160-2009 – Criteria for moisture-control design analysis in buildings, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, US, ISSN 1041-2336, language – English.

The aim of the standard is to provide guidelines for designing buildings with adequate moisture control. The standard formulates assumptions for moisture criteria for acceptable performance. Indoor climate conditions are based on engineering principles. The desired indoor temperature requires climate installations with heating or air conditioning, with or without dehumidification. The relative humidity is based on the air change rate in combination with the number of bedrooms or a defined moisture load. Outdoor climate conditions determine the design rain loads on walls. The standard assumes that 1 % of the rain that hits the surface of the wall penetrates the first exterior layer of the frame. Moisture performance criteria in order to avoid mould growth and criteria for selecting analytical procedures are also presented.

5.2 Outdoor climate

Besides the information presented below, see also the following reports:

- ”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.” under the sub-section ”Additional closely related literature” in the chapter “Closely related literature” “Byggnadsdelars fuktbalans i naturligt klimat”/ ”Moisture balance in building elements exposed to natural climate conditions” under the sub-section “PI 200 PC” in the chapter “Moisture calculation programs”.
- The standards presented under the sub-section “Standards” in the chapter “Moisture calculation boundary conditions”.

5.2.1 SMHI – Swedish Meteorological and Hydrological Institute

SMHI – Swedish Meteorological and Hydrological Institute, www.smhi.se, Meteorological measurements, http://www.smhi.se/kunskapsbanken/meteorologi/meteorologiska-matningar-1.5208, 2011-09-02, language – Swedish and English.

The webpage describes how climate data is measured and collected. The conditions under which the measured data concerning air temperature, air humidity, flash intensity, air pressure, cloud index, rain, wind direction, wind speed, sun intensity, and long- and short wave radiation were collected are described. Measuring methods and sources of errors concerning collecting and measuring are presented. The lack of data for long-wave radiation is, however, a problem.

5.2.2 Meteonorm software

Meteonorm software, www.meteonorm.com, 2011-09-02, language – English and German.

Meteonorm software is a climate tool that creates meteorological data. By using known climate data from existing climate stations, Meteonorm interpolates new climate data for positions between the climate stations. Hourly and per-minute climate parameter values are calculated from monthly values using a stochastic model. Meteonorm software can be used as a tool to create climate data for simulations or calculations. Both reference year and specific time series are available.

5.2.3 Watertightness of masonry walls: An overview

Watertightness of masonry walls: An overview, Nathan Van Den Bossche, Michael Lacasse, Arnold Janssens, 12th International conference on durability of building materials and components, XII DBMC, Porto – Portugal 2011, language – English.

The article presents an overview of the research on water infiltration through brick masonry walls. Different test methods are discussed and the results from different tests are compared. Based on the results from the literature review, the assumption that 1 % of the driving rain that hits a brick facade penetrates the facade seems to be reasonable. This is also the same value presented in the ASCHRAE 160 standard, see the section “Moisture calculation boundary conditions – Standards”. The article also suggests that further research is required concerning the amount of water that can penetrate facades.

5.3 Indoor climate

Besides the information presented below, see also the standards presented under the section “Moisture calculation boundary conditions – Standards”.

5.3.1 Building performance – Methods for improved prediction and verification of energy use and indoor climate

Building performance – Methods for improved prediction and verification of energy use and indoor climate, Hans Bagge, Doctoral thesis, Lund University, TVBH 11/1019, ISSN 0349-4950, ISBN 978-91-88722-41-6, language – English.

The thesis presents results from measurements and the methods used to predict energy use and indoor climate. The most interesting method is the one that gives input data for hygrothermal indoor conditions and that takes into account both outdoor climate conditions and user behaviour. Hourly values, depending on the season, for temperature, moisture supply and relative humidity, are given.

5.3.2 Sealing layer behind tiles in wet room exterior walls (Swedish)

Tätskikt bakom kakel i våtrumsväggar. Anders Jansson. SP Technical Research Institute of Sweden. SP Energiteknik. Rapport 2006:46, ISBN: 91-85533-34-3, 2006, language – Swedish.

The report presents important information about boundary conditions that should be used in WUFI calculations on the interior surfaces in bathrooms or other wet rooms. If the interior surface is covered using ceramic or clinker tiles, the adhesive material behind the tiles will become totally wet after one shower. The dry-out period is shown to be longer than six months. In practice, that means that the interior surface or material behind the tiles would have a boundary layer with 100 % relative humidity during the whole of the simulated time.

The report also show that the sealing layer behind the tiles also has to have a vapour tightness of at least 1 500 000 s/m. To safely prevent moisture damages, the sealing behind the tiles has to have an vapour tightness above 2 000 000 s/m. Less tightness can be acceptable if the vapour retarder and wind barrier have less vapour tightness than normal.

The report also shows that the tested sealing layers have higher vapour tightness in lower relative humidity and that accented vapour tightness are too low to be used in wet room areas.

Vapour retarder = an air- and vapour tight layer used in all walls in a building

Sealing layer = a vapour- and moisture tight layer used in a bathroom. This layer is installed closer to the interior surface than the vapour retarder.

5.4 Air flow in the air gap in ventilated cladding

Besides the information presented below, see also the following reports:

- ”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.” under the sub-section “Additional closely related literature” in the chapter “Closely related literature”.
- “Byggnadsdelars fuktbalans i natruligt klimat”/ ”Moisture balance in building elements exposed to natural climate conditions” under the sub-section “PI 200 PC” in the chapter “Moisture calculation programs”.

5.4.1 Ventilated cavity behind façade in external walls – air change rate and convective moisture transport (Swedish)

Ventilerad luftspalt i yttervägg – Luftomsättningar och konvektiv fukttransport, Jörgen Falk, Licentiate thesis, Rapport TVBM-3155, Lund University, Lund 2010, ISSN 0348-7911, language – Swedish.

The thesis investigates the air flow rates in ventilated cavities behind the façade. Four different cavity designs are studied: with vertical battens, horizontal battens and two different kinds of perforated battens. The report presents measured air flow rates and how the air flow rates in the ventilated cavities can be calculated. The report also presents calculations for ventilation drying rates with respect to different air flows.

5.4.2 Hygrothermal performance of ventilated wooden cladding

Hygrothermal performance of ventilated wooden cladding, Kristine Nore, Doctoral theses, Report NTNU 2009:31, Tapir Uttrykk, ISBN 978-82-471-1430-8, ISSN 1503-8181, language – English.

The thesis investigates parameters that affect the sustainability of wooden cladding. Besides investigating the outdoor climate factors affecting the cladding, one part of the study focused on the conditions in the air gap behind the façade and how it affects the cladding. Factors affecting the air flow rate and a wind-dependent equation, in order to calculate the air change rate in the air gap behind the façade, are presented. Furthermore, WUFI calculations are carried out for the conditions in the façade. WUFI calculations are compared with both measured results and CFD calculations with good convergence.

5.4.3 Is ventilation of timber facades essential?

Is ventilation of timber facades essential? Daniel Kehl, Severin Hauswirth, Heinz Weber, 9th Nordic Symposium on Building Physics – NSB 2011, 2011, language – English.

The study investigates whether ventilated cavities behind the façade are needed in Swiss climate conditions. Four different types of facades are investigated. In contrast to other studies, this report says that ventilated cavities, with openings at the bottom and/ or top of the facades, are not needed.

The conclusion that open ventilated cavities are not needed as ventilation occurs through joints and cracks in the façade material. The fact that ventilation occurs throughout the facades is shown by using a smoke test.

5.4.4 Heated air gaps – A possibility to dry out dampness from building constructions

Heated air gaps – A possibility to dry out dampness from building constructions, Tord af Klintberg, Licentiate thesis, KTH – The Royal Institute of Technology, ISRN-KTH-BYT/R-08/202-SE, ISBN 91-7178-637-1, ISSN 1651-5536, language – English.

The report presents a design method with an air gap in order to dry out moisture. The drying process is created by using heating cables. The air flows and drying potential in the air gaps are studied. The effects on mould growth due to different air flows and drying potential in the air gaps are also investigated.

5.4.5 Airflow in the ventilation space behind a rain screen wall

Airflow in the ventilation space behind a rain screen wall, Therese K. Stonvall, Achilles Karagiozis, ASHRAE Thermal IX Conference Clearwater Beach, 2004, language – English.

The article presents a CFD model that is used to determine the relationships between weather and wall geometry and the air flow in the air gap behind a brick façade. The flow rates are presented as differences in pressure at different heights on the brick façade. The CFD model is validated by comparison with experimental data.

5.4.6 Air cavities behind claddings – What have we learned?

Air cavities behind claddings – What have we learned? Mikael Salonvarra, Achilles N. Karagiozis, Marcin Pazeram, William Miller, Thermal X conference Clearwater beach, 2007, language – English.

Initially, the need, purpose and function of a ventilation air gap behind the façade are presented. Different air change rates for different façades and air gap conditions are discussed. Furthermore, the article also establishes the impact of a ventilated air gap behind the façade material, and that this is especially important in walls with façade materials with high absorption rates such as bricks and stucco claddings.

5.4.7 Air movements in air gaps behind brick facades (Swedish)

Luftrörelser i skalmursspalter, Lars Wadsö, Examesarbete, Rapport TVBM-5009, Lund University, Lund 1996, language – Swedish.

The thesis is a study about air movement in air gaps behind facades made of bricks. The result shows that the air flow in the air gap behind the brick facade varies between different places in the air gap. The different air flows in different parts of the air gap mainly depend on the closeness to the ventilation holes and the influence of breaks in the air gap. The air movements are not constant from one place to another and appear to be random. It is impossible to establish a constant air flow rate.

5.4.8 Moisture and temperature conditions in brick façades constructions (Swedish)

Skalmurskonstruktionens fukt- och temperaturbetingelser, Kenneth Sandin, Byggforskningsrådet, Rapport R43:1991, ISBN: 91-540-5360-9, 1991, language – Swedish.

The report presents results and conclusions based on measurements in different brick façade constructions. The measurements cover temperature and moisture conditions in the brick façade, the air gap behind the cavity, the wooden studs and the insulation material behind the façade air gap. The report describes, and shows by measurements, the phenomenon of summer condensation due to high relative humidity during the summer period. The need for a wide and well ventilated air gap behind the brick façade, to reduce high levels of relative humidity and avoid moisture damage, is established. A 50-mm-wide air gap behind brick façades is suggested.

5.4.9 Wooden constructions with brick façades – Moisture safety in constructions (Swedish)

Skalmur med träregelstomme – Fuktsäkerhet i byggnader, Kenneth Sandin, Byggforskningsrådet, T10:1993, ISBN: 91-540-5541, 1993, language – Swedish.

The booklet discusses problems concerning frost damage in brick façades and mould damage in wooden buildings with brick façades. The phenomenon of summer condensation is described. Several examples of good building design with good detailing are presented. The booklet establishes that a proper air flow in the air gap, which gives a high air ventilation rate, is needed in order to achieve a moisture-safe building.

5.5 Material data

A few material data references are presented below. They mainly cover all listed material data and, therefore, there is no further presentation of each document.

5.5.1 IEA Annex 24

IEA Annex 24, Heat, air and moisture transport in insulated envelope parts, M. Kummar Kumaran, Final report, Volyme 3, Task 3: Material properties. International Energy Agency, Energy conservation in building community system, ISBN: 90-75741-01-4, 1996, language – English.

5.5.2 Latenite hygrothermal material property database

Latenite hygrothermal material property database, Achilles Karagiozis, Mikael Aslonvaara, Kumar Kumaran, Report T1-CA-94/04, Contribution to the IEA-Annex 24 meeting, 1994, language – English.

5.5.3 Moisture transport and sorption in wood and plywood – theoretical and experimental analysis originating from wood cellular structure

Moisture transport and sorption in wood and plywood – theoretical and experimental analysis originating from wood cellular structure, Ilmari Absetz, Helsinki University of Technology Laboratory of Structural Engineering and Building Physics Publications, TKK-TRT-102, ISBN 951-22-4642-2, 1999, language – English.

5.5.4 Moisture diffusivities in wood by regular regime analysis and model simulations

Moisture diffusivities in wood by regular regime analysis and model simulations, Liu Tong, Department of Building Materials, Royal Institute of Technology, TRITA-BYMA 1990:4, 1990, language – English.

5.5.5 Moisture diffusivities and sorption isotherms of Swedish spruce and pine

Moisture diffusivities and sorption isotherms of Swedish spruce and pine, Liu Tong, Department of Building Materials, Royal Institute of Technology, TRITA-BYMA 1989:8, 1989, language – English.

5.5.6 Moisture diffusivities in wood and wood based materials – Experimental and theoretical studies

Moisture diffusivities in wood and wood based materials – Experimental and theoretical studies, Liu Tong, Department of Building materials, Royal Institute of Technology, TRITA-BYMA 1990:6, 1990, language – English.

5.5.7 Moisture transport in wood using a multiscale approach

Moisture transport in wood using a multiscale approach, J. Carmeliet, D. Derome, Katholieke Universiteit Leuven, ISBN 978-94-6018-073-6, 2009, language – English.

6 Functions and structure of the WUFI calculation tool

This chapter presents the heat- and moisture calculation tool WUFI. Initially is the calculation tool briefly described. In the following subsections articles and other studies which refer to the WUFI model, equations, function and structure are presented. To limit the scope of the literature study the main publications describing the underlying factors and the latest studies using WUFI have been given priority. Full information can be found on the WUFI website literature page, www.wufi.de (2011-08-26). Other articles, mainly in German, can also be found on the same site.

6.1 WUFI calculation tool

6.1.1 The WUFI calculation tool

WUFI, Wärme Und Feuchte Instationär, is a non-steady state coupled heat and moisture calculation tool used to analyse the hygrothermal performance of building envelope designs. The calculation model is based on forward differential equations for heat and mass transfer. The model uses a full moisture retention function from the suction curve and sorption isotherm. Vapour diffusion and liquid transport are considered separately. The driving potentials for moisture movement are relative humidity and temperature, and the potential for energy is temperature. The program can handle issues such as drying times, influence of driving rain, ventilated air gaps and leakages. The tool has been developed in both one- and two-dimensional versions. Moisture and energy calculation applications are also connected to the program. Compared to other programs in this field, the WUFI calculation tool consider to be user-friendly.

6.1.2 WUFI Pro 5 manual

WUFI Pro 5 manual, Daniel Zirkelbach, Thomas Schmidt, Manfred Kehrer, Hartwig M. Künzel

The WUFI Pro 5 manual describes the fundamentals and gives an overview of the features of WUFI.

6.2 Literature related to the development of WUFI

Below are examples of studies that have been used to develop WUFI and examples of how WUFI can be use presented.

6.2.1 Simultaneous heat and moisture transport in building components – One- and two-dimensional calculation using simple parameters

Simultaneous heat and moisture transport in building components – One- and two-dimensional calculation using simple parameters, Hartwig M. Künzel, Doctoral thesis, Fraunhofer Institute of Building Physics, Fraunhofer IRB Verlag, Stuttgart 1995, ISBN 3-8167-4103-7, language – English.

The thesis presents a calculation method based on previously developed calculation models, which were able to handle coupled heat- and moisture transport in multi-layer building components. The model can be used in practice and takes into account natural climate conditions such as rain, driving rain, wind and long and short wave radiation. The contents of the study constitute the basic principles for the WUFI heat- and moisture calculation tool. Basic equations and structures for the WUFI calculation process are presented. None-blind comparisons between measurements and calculations are shown.

6.2.2 Moisture transport and storage coefficients of porous mineral building materials – Theoretical principles and new test methods

Moisture transport and storage coefficients of porous mineral building materials – Theoretical principles and new test methods, Martin Krus, Doctoral thesis, Fraunhofer Institute of Building Physics, Fraunhofer IRB Verlag, Stuttgart 1996, ISBN 3-8167-4535-0, language – English.

The thesis investigates vapour diffusion and liquid transport through capillary conductivity materials. A number of existing test methods are presented and discussed. A new measuring method is developed and presented. The moisture storage functions in building materials are divided into three areas: hygroscopic area, capillary area and capillary saturation area. New moisture storage functions to describe the amount of water content in materials. Even if there are different potentials in the moisture storage functions in different areas, the developed moisture storage functions are described by relative humidity, even in liquid transport. Comparisons between measured and calculated values are made for a number of materials with good convergence. Moisture movements caused by air flow, gravitation, hydraulic pressure and osmotic phenomena are not considered in the study.

6.2.3 Moisture transport through the contact zone between brick materials (German)

Feuchtetransport über materialgrenzen im mauerwerk, Andreas Holm, Martin Krus, Hartwig M. Künzel, Bauinstandsetzen (1996) 2, H. 5, 375-396, 1996, language – German.

The article presents the influence of the resistance depending on the contact zone between two different materials. The water uptake behaviour in materials connected to the moisture storage curves and function, i.e. the pore structures of the materials, is discussed. A calculation model of the water behaviour is presented and compared to measured results with good convergence.

6.2.4 Liquid transport in the super saturation range (German)

Flussigtransport im ubersattigungsbereich, Martin Krus, Hartwig M. Künzel, IBP-Mitteilung 22 (1995), Nr. 270, 1995, language – German.

The article describes liquid transport in the super-saturation range in building materials.

6.2.5 Energy storage concrete – a concrete with integrated latent heat storage material (German)

Energiespeicherbeton, ein Beton mit integriertem Latentwärmespeichermaterial, Jens Holger Dieckmann, Hermann Heinrich, Bauphysik 30, June 2008, Issue 3, 137-142, 2008, language – German.

The article presents the development of a type of concrete with integrated latent heat storage. An example is presented with tables for the specific enthalpy of latent heat storage in the new concrete.

6.2.6 Heat transfer coefficient during natural climate conditions (German)

Wärmeübergangskoeffizient unter natürlichen Klimabedingungen, H. Schaube, H. Werner, IBP-Mitteilung 13 (1986), Nr 109, 1986, language – German.

The study presents the values of the exterior heat transfer resistance coefficient with respect to wind speed.

6.2.7 Review of heat and moisture transfer coefficients in exterior wall corners of residential buildings (German)

Überprüfung der Wärme- und Feuchteübergangskoeffizienten in Außenwandecken von Wohnbauten, H. Erhorn, M Szerman, Gesundheitsingenieur 113 (1992), H. 4, p 177-186, 1992, language – German.

The article presents heat and moisture transfer resistance coefficient values for different parts of interior surfaces in residential buildings.

6.2.8 Vapour convection becomes calculable – Unsteady model for taking into account convective moisture penetration when simulating lightweight constructions (German)

Dampfkonvektion wird berechenbar - Instationäres Modell zur Berücksichtigung von konvektivem Feuchteeintrag bei der Simulation von Leichtbaukonstruktionen, Daniel Zirkelbach, Hartwig M. Künzel, Beate Schafaczek, R. Borsch-Laaks 4th Intern. Symposium on Building and Ductwork Air tightness. October 2009, Berlin, Germany, 2009, language – German.

The article presents a model for non-steady state calculations which quantify moisture penetration caused by convection. The model aims to imitate a small air leakage in the building structure taking into account airtightness and differences in pressure between indoor and outdoor air.

6.2.9 Two-dimensional transient heat and moisture simulations of rising damp with WUFI 2d

Two-dimensional transient heat and moisture simulations of rising damp using WUFI 2d, Andreas Holm, Hartwig M. Künzel, XII International brick/ block masonry conference, 12th IB2MaC, Madrid, Spain, 2000, language – English.

The article presents the results from two-dimensional simulations of capillary suction and how the relative humidity in buildings can be estimated by using WUFI 2D instead of taking measurements.

6.2.10 Hygrothermal properties and behaviour of concrete

Hygrothermal properties and behaviour of concrete, Hartwig M. Künzel, Andreas Holm, Martin Krus, WAT-Almanach 2008, p 161-181, 2008, language – English.

The paper presents investigations of hygrothermal properties and behaviour of concrete using both simulations and field tests. Comparisons with good convergence between simulations and field measurements are presented.

6.2.11 Hygrothermal calculations applied to water-repellent surfaces – Validation and application

Hygrothermal calculations applied to water-repellent surfaces – Validation and application, Martin Krus, Second International Conference on Surface Technology with Water Repellent Agents, p 169-176, Zürich, Switzerland, 1998, language – English.

The article presents a comparison of calculations and measurements in stone materials. The effects of rain-protected surfaces on the exterior surface of stone material walls are shown in simulations.

6.2.12 Frost damage on masonry walls – A hygrothermal analysis by computer simulations

Frost damage on masonry Walls – A hygrothermal analysis by computer simulations, Klaus Sedlbauer, Hartwig M. Künzel, Journal of Thermal Envelope & Building Science, Vol 23, no 3, p 277-281, 2000, language – English.

The article discusses the risk of frost damage due to the influence of wind driven rain on masonry walls. WUFI simulations of the studied wall are presented.

6.2.13 Moisture risk assessment of roof constructions by computer simulations in comparison to the standard Glaser-method

Moisture risk assessment of roof constructions by computer simulations in comparison to the standard Glaser-method, Hartwig M. Künzel, International Building Physics Conference, Eindhoven, Nederland, 2000, language – English.

The article presents differences between steady state calculations and non-steady state simulations of the climate conditions in a wood framed roof. The impact of taking solar radiation and material moisture storage functions into account in hygrothermal calculations is discussed.

6.2.14 Non-isothermal moisture transfer in porous building materials

Non-isothermal moisture transfer in porous building materials, Materialsweek, Munich, Germany, 2000. Language – English.

The article discusses material properties used to calculate moisture transport. Physical principles and different current calculation methods for moisture transport are summarized. Limitations and the need for future development of the methods are discussed.

6.2.15 WUFI-ORNL/IBP – A North American hygrothermal model

WUFI-ORNL/IBP – A North American hygrothermal model, Achilles Karagiozis, Hartwig Künzel, Andreas Holm, Performance of Exterior Envelopes of Whole Buildings VIII, Florida, USA, 2001, language – English.

The article presents an adjusted model of WUFI to suit American conditions. ASHRAE standards for indoor climate conditions and driving rain parameters are added. Material data and outdoor climate files are also supposed to be included. The WUFI interface is also upgraded.

6.2.16 Stochastic building envelope modeling – The influence of material properties

Stochastic building envelope modeling – The influence of material properties, Mikael Salonvaara, Achilles Karagiozis, Andreas Holm, Performance of Exterior Envelopes of Whole Buildings VIII, Florida, USA, 2001, language – English.

The article evaluates the effects of changing material properties in a stucco clad wall by using two different hygrothermal models, WUFI and LATENITE VTT, combined to the Monte Carlo stochastic model.

6.2.17 Exterior surface temperature of different wall constructions – Comparison of numerical simulations and experiments

Exterior surface temperature of different wall constructions – Comparison of numerical simulations and experiments, Hartwig M. Künzel, Thomas Schmidt, Andreas Holm, 11. Symposium for Building Physics, Dresden, Germany, 2002, language – English.

The article presents the specific model in WUFI that estimates the exterior surface temperature. A modification of this model, to take long-wave radiation into account, is also presented.

6.2.18 Predicting indoor temperature and humidity conditions including hygrothermal interactions with the building envelope

Predicting indoor temperature and humidity conditions including hygrothermal interactions with the building envelope, Hartwig M. Künzel, Daniel Zirkelbach, Klaus Sedlbauer, 1st International Conference on Sustainable Energy and Green Architecture, Building Scientific Research Center, BSRC, Bangkok, Thailand, 2003, language – English.

The article presents a combined hygrothermal model that takes into account moisture sources and sinks inside a room, diffusion, input from the envelope due to capillary activities, and vapour absorption and desorption in connection with varying exterior and interior climate conditions. Examples of the model are presented.

6.2.19 Rain protection of stucco facades

Rain protection of stucco facades, Hartwig M. Künzel, Helmut Künzel, Andreas Holm, Performance of the Exterior Envelopes of Whole Buildings IX – International Conference 2004, language – English.

The article discusses the need of moisture related protection against driving rain loads on stucco and painted masonry walls. Standard requirements are verified by WUFI calculations for climate conditions in Germany and USA.

6.2.20 Moisture buffering effects of interior linings made from wood or wood based products

Moisture buffering effects of interior linings made from wood or wood based products, Hartwig M. Künzel, Andreas Holm, Klaus Sedlbauer, F. Antretter, M Ellinger, IBP-Report HTB 04/2004/e, 2004, language – English.

The report presents moisture buffering effects of different interior wooden materials. Differences in interior relative humidity compared to different wooden wall materials are presented.

6.2.21 Influence of temperature and relative humidity on the durability of mineral wool in ETICS

Influence of temperature and relative humidity on the durability of mineral wool in ETICS, Daniel Zirkelbach, 10 International Conference on Durability of Building Materials and Components, X DBMC, Lyon, France, 2005, language – English.

The article presents a parametric study of lightweight constructions with one-step frame protection, so called ETICS constructions, and mineral wool as the insulation layer behind the façade material. Calculations are carried out using WUFI for the same construction under three different climate conditions. Climate conditions in two locations in the construction for each studied climate condition are presented.

6.2.22 Adapted vapour control for durable building enclosures

Adapted vapour control for durable building enclosures, Hartwig M. Künzel, 10 International Conference on Durability of Building Materials and Components, X DBMC, Lyon, France, 2005, language – English.

Initially the paper explains the circumstances and effects of vapour retarders in lightweight constructions. Furthermore,the effects of a moisture dependent vapour retarder are presented. Vapour retarders with lower vapour resistance, an Sd-value less than 3 m, are also discussed.

6.2.23 Flat roofs in cold climates – climatic limits for building flat roofs with a permeable vapour retarder

Flat roofs in cold climates – climatic limits for building flat roofs with a permeable vapour retarder, Christian Bludau, Hartwig M. Künzel, Cold Climate HVAC, Sisimiut, Greenland, 2009, language – English.

The article presents a parametric study that evaluates the effects of different vapour retarders in roofs. Bothvapour retarders, with constant and relative humidity dependent Sd-values, are studied.

6.2.24 Influence of rain water leakage on the hygrothermal performance of exterior insulation systems

Influence of rain water leakage on the hygrothermal performance of exterior insulation systems, Daniel Zirkelbach, Hartwig M. Künzel, Building Physics 2008, 8^{th} Nordic Symposium, p 253-260, language – English.

The article presents a parametric study of lightweight constructions with one-step frame protection, so called ETICS constructions. Calculations are made using WUFI. The same construction under different climate conditions is evaluated. Also, the amount of water leakages penetrating the façade is varied.

6.2.25 Durability assessment of glass fibre insulation in flat roof constructions

Durability assessment of glass fibre insulation in flat roof constructions, Daniel Zirkelbach, Hartwig M. Künzel, Christian Bludau, IBP-Report HTB 12/2007, 2007, language – English.

The report evaluates real climate conditions according to official standards regarding durability for glass fibre insulation in mineral wool at three different locations. Adjustments to the official standard test method are presented. The report also includes comparisons between WUFI calculations and measurements in flat roofs with glass fibre insulation.

6.2.26 Thermal performance degradation of foam insulation in inverted roofs due to moisture accumulation

Thermal performance degradation of foam insulation in inverted roofs due to moisture accumulation, Daniel Zirkelbach, Beate Schafaczek, Hartwig M. Künzel, International Conference on Durability of Building Materials and Components, Porto, Portugal, 2011, language – English.

The article presents comparisons between measurements and WUFI calculations for inverted roofs. Furthermore, different combinations of inverted roofs are evaluated for different climates.

6.2.27 Vapour control design of wooden structures including moisture sources due to air exfiltration

Vapour control design of wooden structures including moisture sources due to air exfiltration, Hartwig M. Künzel , Daniel Zirkelbach, Beate Schafaczek, 9th Nordic Symposium on Building Physics – NSB 2011, 2011, language – English.

The paper presents simulations and expected effects of vapour leakage through the vapour barrier in a flat wooden roof. Possible dry-out effects of using an interior smart vapour retarder to minimize the risk of damage are presented.

6.3 WUFI limitations and possible causes of divergences between reality conditions and calculation results

WUFI is a calculation tool based on models for coupled heat and moisture transport in multi-layer building constructions. As with all calculation tools and models there are also limitations in WUFI. Some of them are briefly discussed below. Note that it is never possible to make a complete calculation of reality conditions in a calculation model such as WUFI that uses climate conditions as boundary conditions. For more detailed information about WUFI limitations and possible sources of divergences between reality conditions and calculations see the following reports:

- ”Simultaneous heat and moisture transport in building components – One- and two-dimensional calculation using simple parameters” under the section “Structure and studies of WUFI”.
- “Feuchtetransport über Materialgrenzen im Mauerwerk” / “Moisture transport through the contact zone between brick materials” under the section “Structure and studies of WUFI”.
- “WUFI´s Performance and Limitations” in the “WUFI Pro 5.0 online help”.

Since different materials and constructions are affected in different ways, and different climate and boundary conditions have different effects on the materials and the constructions, it is not possible to establish general effects of the calculation results compared to reality due to the limitations in the calculation tool.

Besides all the limitations, and other possible causes of divergences, of the calculation tool there is also a need of user knowledge concerning both the functions and structure of the tool as well as knowledge of the subject, in order to evaluate the relevance of the results. Lack of user knowledge is assumed to be the main cause of errors in the calculation results. In this case, the users are expected to read and understand the “WUFI Pro 5.0 online help” including the chapter “WUFI´s Performance and Limitations”.

6.3.1 Examples of general limitations and possible causes of divergences between reality conditions and calculation results

WUFI is based on a main calculation model for coupled heat and moisture transport, as described in the literature above. Furthermore, specific models are coupled to the main model. Both the main and specific models are only models of reality. A model never reproduces an exactly copy of the real conditions. Depending on the specific construction being investigated, different limitations and sources of divergences between reality conditions and calculation results can occur.

Besides limitations and other parameters that affect the results, the specific user always has to have knowledge of the tool. As in other calculation tools this might be a general cause of errors in the calculation results. Knowledge of the model and calculation tool does not only give better results but also provides the opportunity to consider limitations.

The WUFI calculation tool needs reliable and complete boundary conditions. Poor boundary conditions or lack of data for the boundary conditions could case major errors in the calculated conditions. The impossibility of predicting future climate conditions also makes it impossible to predict the exact future conditions in a construction. This is the case in all calculation tools that are affected by the surrounding climate conditions, since it is not possible to know and use future climate conditions.

A more specific limitation of the WUFI calculation tool is that it cannot be used to make three-dimensional models. The fact that one- and two-dimensional calculation tools gives limitations of model complete constructions also affect the quality of the results. The effects of details cannot be completely taken into account. Air- and heat flows through joints and other leakages have to be considered using specific models. On the other hand, three-dimensional models might provide numerical problems that could affect the calculations results negatively.

Numerical problems may also occur in other parts of the calculation process. Some of those problems may be solved by the user through adjustments of the grids or other numerical settings.

Other main limitations and sources that might cause divergences in the calculation due to reality conditions are the lack of effects on the calculation model with respect to heat and moisture transport that depends on air convection through building materials and air flows caused by gravitation, wind and fans. The moisture storage function used in the WUFI material data does not consider hysteresis.

6.3.2 Examples of specific limitations and possible causes of divergences between reality conditions and calculation results

Material data might be impaired by several specific factors that could cause uncertainties and errors in the calculation results:

- Being able to use material boundary condition parameters at different detailed levels and of different quality in the same calculation might cause errors in the calculation results. This is not a calculation tool problem but rather one caused by the used material parameter and or the user.
- The material parameters concerning moisture transport are divided in two different parts in the WUFI calculation model. One part concerns vapour transport and the other liquid transport. Since these two parts not are known or proportioned in the same way in the known material data this might cause errors in the calculation results due to lack of knowledge by the user.

- The sorption isotherm is set as one curve and not divided into absorption and desorption. A consequence of this is that the effects of hysteresis are excluded from the calculation model. Not having two sorption isotherms or taking into account hysteresis effects might cause divergences in the calculation results when compared to reality conditions.
- All material data for each material in the WUFI material data base has to be checked before it is used.
    - Insulation materials with inaccurate data or definitions have been found.
    - Brick materials data can include or exclude the joint material between the bricks.
- There are two different types of air gaps in the WUFI material database. The one that includes moisture capacity might be used in contact with surfaces. The other one might be in the middle. If airflows or other sources are used these should be placed in the one without additional moisture capacity in the middle. Notice that it is not allowed to change the thickness of the air gap layer.

Air flows in air gaps are dependent on the design of the construction. The flow will behave in different ways depending on the design and construction performance. It has to be established that applied air flow in the air gap also will occur in reality. An incorrect airflow will affect the calculation results and can create major errors in the calculation results. To ensure a high airflow the air gap in a wall it has to:

- Be 25-50 mm wide (Sandin, K., 1991), (Falk, J., 2010).
- Be completely or almost completely open at the bottom and at the top. Openings at the bottom of brick facades should have an area corresponding to that of every forth brick. Note that the area does not include the joints between the bricks. (Sandin, K., 1991).
- Have vertical wooden or steal laths/ battens or highly perforated horizontal laths. (Falk, J., 2010).

The interior boundary conditions in bathrooms or other wet rooms should be set at a level of constant 100% relative humidity (Jansson, A., 2010). This might cause calculation or other convergence errors. To reduce these 99% relative humidity could be set instead.

The WUFI calculation model has been shown to have problems when dealing with free water. In some cases the calculation crashes.

Thick insulation materials or other thick material layers with low moisture capacity could be separated into several layers or set with closer grids to limit the risk of calculation or convergence discrepancies. Avoid single insulation layers thicker than 100 mm, i.e. 270 mm of insulation could be divided into three layers of 90 mm, 90+90+90=270.

Rain loads in reality are normally higher than the measured rain loads and the rain loads that are used in climate data in WUFI. This is due to defects and errors in the measuring methods giving a lower measured amount of rain than the real amount of rain (SMHI). According to the ASHRAE standard 160-2009 – Criteria for moisture-control design analysis in buildings, a penetration of 1 % of calculated driving rain should be used. Other studies say that the important thing is that the rain and driving rain are taken into account, not the exact amount of rain, and a penetration of 1% through the façade materials also seems reasonable (Van Den Bossche, N., 2011).

Sd-values for surfaces can be set in two different ways. A specific Sd-value can be set separately and the Sd-value can also be set as a part of the surface material. Do not set double Sd-values. If paint is applied to the surface material or on the surface it has to be remembered that different paints have different Sd-values. The Sd-values of alkyd paint, acrylate paint, silicate paint and oil paint might differ by a factor of approximately 100.

Values in transient sources from external files including heat, air change rates, water or moisture leakages, have to start the same time as the WUFI calculation. WUFI always use the first value in the transient source file as the first value in the calculation, and the following values. This means that a calculation with a transient source that start first of January also have to start first of January. If the calculation starts another time the transient source has to be adjusted to fit the same time in order to avoid defect calculation results.

As mentioned initially, the “WUFI´s performance and Limitations” in the “WUFI Pro 5.0 online help” have to be studied to get complete information about the limitations of WUFI.

7 Independent institute studies using WUFI

A number of studies have been made by independent institutes and universities using WUFI as a calculation tool. Independent institutes and universities means organizations that are not involved in the development of WUFI but do use the calculation tool as an instrument in their research, verification, validation, teaching or other work. These organizations have more freedom to directly or indirectly criticize the development and functions of the WUFI calculation tool.

7.1 Examples of independent studies using WUFI

Examples of studies at independent institutes and universities are presented below. See also the following reports:

- ”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.” under the sub-section “Additional closely related literature” in the chapter “Closely related literature.”
- “Hygrothermal performance of ventilated wooden cladding” under the sub--section “Air flow in the air gap in ventilated cladding” in the chapter “Moisture calculation boundary conditions”.

7.1.1 Hygrothermal Performance of Lime-Hemp Wall Assemblies

Hygrothermal Performance of Lime-Hemp Wall Assemblies, A. Evrard, A. De Herde, Architecture et Climat, Université Catholique de Louvain Place du levant 1, B-1348 Louvain-la-Neuve, Belgium, language – English.

The article presents a study of concrete made of hemp mixed with lime-based binders, so-called LH materials. In the study WUFI is used as a calculation tool for comparisons between the studied material and other constructions made of mineral wool, pure concrete and bricks. The study presents an analysis of the transient hygrothermal performance of LH-materials and its pore structure. The article also presents a method for producing material data.

The results show that LH-materials have higher heat conductivity than mineral wool. Furthermore, the moisture transport and the moisture storage functions are higher than in other materials due to the pore structure of LH-materials.

7.1.2 External plaster stud walls (Swedish)

Putsade regelväggar, Ingemar Samuelson, Anders Jansson, SP Technical Research Institute of Sweden, SP Energiteknik, Rapport 2009:16, ISBN: 978-91-86319-00-7, 2009, language – Swedish.

This study presents an overview of moisture damages in lightweight constructions with external plaster stud walls. The investigated constructions were made using one-step frame protection, the so-called ETICS constructions. Furthermore, the construction is analysed with respect to moisture damages. Moisture-safe repair measures for damaged walls are presented. Design suggestions for moisture-safe constructions are also given.

The report includes many pictures with explanations of detailing errors and poor workmanship. One chapter discusses how simulation programs can be used in moisture safety processes. A number of WUFI calculations are shown to evaluate different constructions and potential moisture problems.

7.1.3 The drying potential and risk for mould growth in compact wood frame roofs with built-in moisture

The drying potential and risk for mould growth in compact wood frame roofs with built-in moisture, Stig Geving, Jonas Holme, Journal of building physics 2010; 33; 249, Published online November 2009, language – English.

The article presents results from an investigation concerning the drying potential in different wood frame roof constructions with built-in moisture. Both field tests and calculations were made. The studied constructions have different solutions for ventilation through the insulation layer in the roof. In the field test four different kinds of roof design with different solutions for ventilation flow were studied. The calculations were made using WUFI 1D and a specific air flow rate in the insulation layer. The results show an increased dry-out potential if there is ventilation through the insulation layers but also an increased risk of moisture damage if moisture is transported into the construction through the ventilation. No comparisons are made between the field tests and the WUFI calculations other than that both have a positive effect on the dry-out potential.

7.1.4 Hygrothermal behavior of ETICS – Numerical and experimental study

Hygrothermal behavior of ETICS – Numerical and experimental study, Eva Bareira, Vasco Peixoto de Freitas, 9th Nordic Symposium on Building Physics – NSB 2011, 2011, language – English.

The aim of the study is to investigate the possibility of predicting microbiological growth on the facades built using External Thermal Insulation Composite Systems, ETICS. Comparisons of measured and WUFI calculations of external façade temperatures are presented. The effects of wind-driven rain and the WUFI wind-driven rain factors are evaluated.

7.1.5 Rehabilitation of basement walls with moisture problems by the use of vapour open exterior thermal insulation

Rehabilitation of basement walls with moisture problems by the use of vapour open exterior thermal insulation, Stig Geving, Marius Kvalvik, Espen Martinsen, 9th Nordic Symposium on Building Physics – NSB 2011, 2011, language – English.

The article presents the effects of vapour permeable exterior insulation used to speed up the drying potential of a rewetted concrete basement wall. The study is divided into a parametric study using WUFI and a case study of a real basement wall.

7.1.6 Assessment of the risk for mold growth in a wall retrofitted with vacuum insulation panels

Assessment of the risk for mold growth in a wall retrofitted with vacuum insulation panels, Pär Johansson, 9th Nordic Symposium on Building Physics – NSB 2011, 2011, language – English.

The article evaluates different design solutions for adding extra thermal vacuum insulation to the exterior walls in old buildings. The evaluation is made as a parametric study based on two-dimensional WUFI calculations.

7.1.7 Considerations to the hygrothermal behavior of exterior walls in timber frame constructions with direct rendering

Considerations to the hygrothermal behavior of exterior walls in timber frame constructions with direct rendering, Britta Rosenau, 9th Nordic Symposium on Building Physics – NSB 2011, 2011, language – English.

The article presents a parametric study and the risk of moisture-related damage in wooden framed walls with different interior lining materials and various vapour retarders.

7.1.8 The problem of insulation in loft ceiling beams in outdoor air ventilated attics (Swedish)

Problematiken isolering i vindsbjälklag i uteluftsventilerade kallvindar, Daniel Hansson, Niclas Lundgren, Bachelor thesis, KTH – The Royal Institute of Technology, 2009, language – Swedish.

The thesis presents a parametric sensitive analysis of slab insulation thickness in outdoor air ventilated attics carried out using WUFI. The results show an increasing risk of mould growth on the wooden roof parts of the attic if the insulation thickness increases. The climate conditions become better if insulation on the exterior roof membrane, outside the wooden roof is applied. The ventilation rate in the attic affects the risk of mould growth.

7.1.9 Moisture safety assessment with WUFI (Swedish)

Fuktsäkerhetsbedömning med WUFI, Eric Fredriksson, Mattias Svensson, Bachelor thesis, Karlstad University, 2009, language – Swedish.

The thesis presents a parametric study of lightweight constructions with one-step frame protection, so-called ETICS constructions, and constructions with a ventilated air gap behind the façade cladding. The results shows that the critical conditions occur if no ventilated air gap is used and if EPS insulation is used instead of mineral wool.

7.1.10 Numerical simulations of exterior condensation on facades: The undercooling phenomenon

Numerical simulations of exterior condensation on facades: The undercooling phenomenon, J.M.P.Q. Delgado, N.M.M. Ramos, V.P. de Freitas, E. Barreira, Thermal Performance of the Exterior Envelopes of Whole Buildings XI – International Conference 2010, language – English.

The article describes the variations in the surface temperature differences on façades by using different numerical models for the exterior boundary conditions. The study was carried out as a case study on a non-ventilated ETICS façade.

7.1.11 A prototype universal building envelope hygrothermal performance standard for successful net-zero energy building design

A prototype universal building envelope hygrothermal performance standard for successful net-zero energy building design, Louise F. Goldberg, Patrick H. Huelman, Stanley D. Gatland, II, Thermal Performance of the Exterior Envelopes of Whole Buildings XI – International Conference 2010, language – English.

The article presents a proposal for a hygrothermal standard for building envelopes. Several requirements are presented. A design study is made using WUFI two-dimensional softwear.

7.1.12 The hygrothermal performance of wood-frame wall system using spray polyurethane foam insulations and a smart vapor retarder in the Pacific Northwest

The hygrothermal performance of wood-frame wall system using spray polyurethane foam insulations and a smart vapor retarder in the Pacific Northwest, Sam Yuan, Achilles N. Karagiozis, Thermal Performance of the Exterior Envelopes of Whole Buildings XI – International Conference 2010, language – English.

The article presents an investigation of a wood-frame wall system in which sprayed polyurethane foam insulation and a smart vapor retarder are used in the Pacific Northwest. The investigated walls did not have any air gaps behind the façade cladding. A hygrothermal calculation model was made using WUFI. Comparisons between the WUFI calculation model results and the ongoing field test results were made. The field tests show a higher relative humidity than the WUFI calculations. The need of an air gap behind the façade cladding is mentioned.

7.1.13 Monitoring of historic structures for whole-building improvements

Monitoring of historic structures for whole-building improvements, Michael Aoki Kramer, Brian Hubbs, Graham Finch, Jason Teetaert, Thermal Performance of the Exterior Envelopes of Whole Buildings XI – International Conference 2010, language – English.

The article shows how WUFI can be used as a tool to evaluate existing conditions and evaluate different opportunities in renovation projects.

7.1.14 Impact of weather on predicting drying characteristics of spray-applied cellulose insulation

Impact of weather on predicting drying characteristics of spray-applied cellulose insulation, Mikael Salonvaara, Marcin Pazera, Achilles Karagiozis, Thermal Performance of the Exterior Envelopes of Whole Buildings XI – International Conference 2010, language – English.

The article investigates the dry out time for cellulose insulation with different moisture content and applied different times of the year. The study includes both laboratory measurements and calculations carried out with WUFI. Comparison with good converges between measured and calculated values are presented.

7.1.15 Hygric performance of shaded and unshaded highly insulated, lightweight low-sloped roofs

Hygric performance of shaded and unshaded highly insulated, lightweight low-sloped roofs, Christoph Buxbaum, Wolfgang Gallent, Simon Paulitsch, Oskar Pankrantz, Thermal Performance of the Exterior Envelopes of Whole Buildings XI – International Conference 2010, language – English.

The article presents a parametric study of low-sloped highly insulated non-ventilated lightweight roofs in central Europe. Hygrothermal differences and consequences of shaded and unshaded roofs and changes in the roof membranes were studied by using WUFI. Measurements taken from the studied roofs are also presented but not compared with the WUFI simulation results.

7.1.16 Residential exterior wall superinsulation retrofit details and analysis

Residential exterior wall superinsulation retrofit details and analysis, Kohta Ueno, Thermal Performance of the Exterior Envelopes of Whole Buildings XI – International Conference 2010, language – English.

The article presents a number of experiences of applying extra wall insulation in residential buildings. Several case-specific solutions, such as air barriers, drainage planes and moisture control are presented. WUFI was used to evaluate some of the specific cases.

7.1.17 Estimation foundation water vapour release using a simple moisture balance and AIM-2: case study of contemporary wood framed house

Estimation foundation water vapour release using a simple moisture balance and AIM-2: case study of contemporary wood framed house, C.R. Boardman, Samuel V. Glass, Charles G. Carll, Thermal Performance of the Exterior Envelopes of Whole Buildings XI – International Conference 2010, language – English.

The article presents a case study of a house with a wooden foundation system. The effects on the foundation moisture due to different interior and exterior relative humidity, temperature and outdoor wind speed are discussed.

7.1.18 High-R walls for the Pacific Northwest – A hygrothermal analysis of various exterior wall systems

High-R walls for the Pacific Northwest – A hygrothermal analysis of various exterior wall systems, Jonathan Smegal, John Straube, Building Science Corporation, ordered from Walsh Construction Company, Mike Steffen Marty Houston, 2010.

The report evaluates 17 wooden wall constructions with respect to thermal conditions, moisture conditions, constructability and costs. WUFI was used to investigate the risk and effects of moisture balance, wintertime condensation, wall dry-out potentials and summer inward vapour movement. The different wall constructions are rated and ranked according to the following individual factors: thermal conditions, moisture conditions, constructability and costs. All the walls are also ranked in a matrix which shows the results of all the four factors acting together.

8 Moisture calculation programs

This chapter presents examples of other relevant moisture calculation programs, in addition to WUFI. There is a brief presentation and description of each program. In connection with each description one or a few studies are presented which explain the program calculation model or how the program can be used. Besides the information presented below, see also the sub-section “WUFI calculation tool” in the chapter “Functions and structure of the WUFI calculation tool”.

8.1 PI 200 PC

Besides the information presented below, see also the report “Dubbla tätskikt I våtrumsytterväggar med keramiska plattor”/ ”Double sealing layers in wet room external walls with internal tile cladding” under the sub-section “Waterproofing in wet rooms/ bathrooms” in the chapter “Closely related literature”.

The program is one-dimensional non-stationary software that calculates coupled heat and moisture transport. Calculations are made by forward differential equations and take into consideration both the heat and moisture capacities of materials used. The program is probably one of the first in the category for calculating coupled heat and moisture transport and was developed and based on knowledge from the report referred to below.

The program was developed in the early 1970s at Lund University and SP Technical Research Institute of Sweden by Per Ingvar Sandberg.

8.1.1 Moisture balance in building elements exposed to natural climate conditions (Swedish)

Byggnadsdelars fuktbalans i naturligt klimat, Per Ingvar Sandberg, Doctoral thesis, Division of Building Technology, Lund Institute of Technology, Lund University, Report 43, Lund 1973, language – Swedish.

Initially the thesis presents the requirements and conditions for moisture safety design. Different moisture calculation methods are described. A new non-stationary calculation method with coupled heat and moisture transport by using forward differential equations is presented. Mainly problems due to lack of computing power are discussed. The influences of boundary conditions with moisture calculations are presented. At the end of the report there are a number of calculation examples for building components with comparisons to measured values in the same components.

8.1.2 Simultaneous water vapour diffusion and air flow through a porous material (Swedish)

Samtidig ångdiffusion och luftströmning genom ett poröst material, Per Ingvar Sandberg, Division of Building Technology, Lund Institute of Technology, Lund University, Report 27, Lund 1971, language – Swedish.

The report examines the effects of combined moisture diffusion and moisture convection. It also discusses how they interact and can be added. The report only provides a basic theory regarding how diffusion and convection can be described. Only one homogeneous material is studied.

8.1.3 Non-stationary moisture transport (Swedish)

Icke stationär fukttransport, Per Ingvar Sandberg, Division of Building Technology, Lund Institute of Technology, Lund University, Report 16, Lund 1970, language – Swedish.

The report presents a computer program that has been developed to calculate non-stationary moisture transport. The method is probably one of the first in this category and may be seen as the start of non-stationary moisture calculations. The lack of knowledge in the area meant that there was a lot of guesswork concerning boundary conditions.

8.2 HAM-tools

HAM-tools, Heat, Air and Moisture, is the collective name for building simulation software developed at Chalmers University of Technology. HAM-tools can be used to simulate heat, air and moisture transport in buildings and building envelopes. The main aim of the software is to create simulations of building physics processes. The program is connected as a specific tool to MATLAB. The program is often used in research but is less common in the construction industry due to its complexity.

The program was developed during the 2000sat Chalmers University of Technology by Angela Sasic Kalagasidis and Carl-Eric Hagentoft.

There are a number of studies presented in which HAM-tools have been used. Only the main report that describes the software is presented below.

8.2.1 HAM-Tools - An Integrated Simulation Tool for Heat, Air and Moisture Transfer Analyses in Building Physics

HAM-Tools - An Integrated Simulation Tool for Heat, Air and Moisture Transfer Analyses in Building Physics, Angela Sasic Kalagasidis, Doctoral thesis, Chalmers University of Technology, Göteborg, 2004, language – English.

The thesis presents the full HAM-tools structure including mathematical and numerical models that the software is based on. Some results of validations are presented. The report also includes examples of how the software can be used and in which applications.

8.3 COMSOL Multiphysics

COMSOL Multiphysics software is a multiphysics simulation tool that can be used in several engineering areas. The software includes a number of predefined physical interfaces for applications such as heat transfer, fluid flow, structural mechanics and electromagnetics. The COMSOL calculations tool is based on the finite element method. In normal cases this generates more complicated heat and moisture calculation models and requires more computer power to make the calculations. A moisture calculation “tool” does not, as yet, exist in COMSOL. The Swedish building industry regards COMSOL as being too complex for practical use. The article presented below is an example of how COMSOL can be used in building physic applications.

The software COMSOL Multiphysics was developed by COMSOL, a company that was founded in 1986 and has since developed and promoted multiphysics software.

8.3.1 The use of COMSOL to solve hygrothermal building physical problems related to insulation hight rise building facades

The use of COMSOL to solve hygro thermal building physical problems related to insulation hight rise building facades, Schellen, H.L., van Schijndel, A.W.M, Neuhaus, E. Eindhoven University of Technology, Department of Building and Architecture, language – English.

The article tries to evaluate various ways of adding extra wall insulation to existing buildings from the 1960s. Two different methods are discussed: extra internal insulation and extra insulation using foam in the air gap behind the façade. The study shows no awareness of the moisture risks related to filling the air gap with insulation. The study only uses stationary calculations. The study does not take driving rain into account. The article confirms the lack of coupled heat and moisture transfer considerations in COMSOL rather than any new findings. Direct errors, for example that WUFI not would be able to handle air flows, can be found.

8.4 TCCC2D

TCCC2D, Transient Coupled Convection and Conduction in 2-Dimensions, is software for hygrothermal calculations for lightweight walls, i.e. wood framed walls. Calculations are shown for heat, air and moisture transport in two dimensions. Transport equations have temperature, pressure and vapour pressure as driving potentials. The mass and energy balances in the calculation model are solved using the finite difference method. The tool was one of the first to combine convection with moisture transport. The TCCC2D was also the first tool in which the VVT mould model was integrated. The original calculation model is heavy to use due to the user interface and therefore seldom applied.

The program was developed in 1989 at the Technical Research Centre of Finland, VTT, by Tuomo Ojanen and Reijo Kohonen.

8.4.1 Moisture control in buildings

Moisture control in buildings, Manual on moisture control in buildings, Heinz R. Trechsler (editor), American society for testing and materials, 1994, ISBN 0-8031-2051-6, language – English.

The book includes the full spectra of moisture and moisture issues in constructions. Initially, the fundamentals are described followed by descriptions of different applications, construction principles and recommendations. Finally, implementations are discussed. The book also lists suitable moisture calculation software. The TCCC2D calculation software is briefly described.

8.4.2 Moisture conditions and biodeterioration risk of building materials and structure

Moisture conditions and biodeterioration risk of building materials and structure. Hannu Viitanen, Anne-Christine Ritschkoff, Tuomo Ojanen, Mikael Salonvaara. Rotterdam (Netherlands), in-house publishing 2003, approx. 6 p, language – English.

This study presents the subject of biodeterioration and the requirements to numerically simulate mould growth and decay development. Analyses of the risks of mould growth in applications with different materials are presented. Possible damages from different organisms and the conditions under which they react are summarized. The specifically interesting part in this article is the one that discusses local moisture load conditions and effects on constructions. Simulations of these can be carried out using the TCCC2D building physics simulation model. The article points out roofs, floors and lower parts of walls as the building components that often suffer mould growth damages.

8.5 MATCH

MATCH, Moisture And Temperature Calculations for constructions of Hygroscopic materials, is a one-dimensional calculation model for transient coupled heat and moisture transport through building constructions. The program is based on the finite element method and is DOS based. Vapour pressure is used as the driving potential for diffusion and suction pressure for liquid flux. Heat transfer is driven by conduction, radiation and latent heat flow. The program is described further in article below.

The program was developed during the 1990s at the Technical University of Denmark by Carsten Rode (previously Carsten Rode Pedersen).

8.5.1 Empirical validation of a transient computer model for combined heat and moisture transfer

Empirical validation of a transient computer model for combined heat and moisture transfer, Carsten Rode, Douglas M. Burch, Thermal envelopes VI, Thermal performance of the exterior envelopes of building VI, 1995, language – English.

The article presents the basic equations and structure used for the MATCH heat and moisture calculation tool. Comparisons between measured and calculated values are made for a couple of walls. A sensitivity analysis of the calculated values is presented.

8.5.2 Combined heat and moisture transfer in building constructions

Combined heat and moisture transfer in building constructions, Carsten Rode Pedersen, Doctoral theses, Technical University of Denmark, Thermal Insulation Laboratory, 1990, language – English.

Some parts of this doctoral thesis present facts and results on which the MATCH, calculation program were based.

8.6 MOIST

MOIST is a one-dimensional heat and moisture calculation tool. The program calculates the moisture content or relative humidity and temperature as a function of time of year. The program does not take driving rain, rain and heat, or moisture movements by air into account. The basic transport equations are the same as those presented in "Combined heat and moisture transfer in building constructions" under the section "Moisture calculation programs – MATCH".

The program was developed in the 1990s at the National Institute of Standards and Technology, NIST, in USA by Douglas M. Burch and Thomas. Basic calculation algorithms are based on previous results gained by Carsten Rode Pedersen.

8.7 DELPHIN

DELPHIN is software for non-steady state coupled heat and moisture calculations. The numerical model solution is based on three coupled parabolic differential equations which describe heat, air and moisture transport.

The program was developed in the 1990s at University of Dresden by J. Grunewald.

The program is described further in the articles presented below.

8.7.1 Coupled heat, air and moisture transfer in building structures

Coupled heat, air and moisture transfer in building structures, P. Häupl, J. Grunewald, H. Fechner, H. Stopp, International Journal of Heat and Mass Transfer, volume 40, issue 7, May 1997, p 1633-1642, ISSN 00179310, language – English.

The article describes the basic equations and numerical structure of the DELPHIN coupled heat and moisture simulation software. Besides the presentation of the numerical solutions, results from a case study of the simulations tool are also presented.

8.7.2 The thermohygric performance of insulated building structures under conditions of use

The thermohygric performance of insulated building structures under conditions of use, P. Häupl, J. Grunewald, H. Fechner, H. Stopp, ASTM special technical publications, Volume 1320, p 426-442, ISSN 10403094, language – English.

The article presents a system and computer code of non-linear equations to handle temperature, moisture, ice, vapour pressure, air pressure, vapour, water and air flows in porous building materials. The computer code has been further used in DELPHIN, the heat and moisture simulation tool.

8.7.3 Comparison of calculation and measured values of wall assembly test using Delphin 5

Comparison of calculation and measured values of wall assembly test using Delphin 5, Anssi Laujjarinen, Juha Vinha, 9th Nordic Symposium on Building Physics – NSB 2011, 2011, language – English.

The paper presents a study of comparisons of calculated and measured relative humidity with divergent compliance in timber-framed constructions. The calculations were carried out using the Delphin 5 moisture calculation tool.

8.8 LATENITE

LATENITE is a two-dimensional hygrothermal heat and moisture transport model. The model uses a complete moisture storage function including both the sorption isotherm and the suction curve. Vapor and liquid transport are treated separately and their driving potentials are vapour pressure and suction. The model can take airflow, rain, driving rain and leakages into account. The model has been further developed in the hygIRC calculation tool.

LATENITE is a non-commercial program developed in 1994 at the VTT Technical Research Centre of Finland, and National Research Council Canada by Mikael Salonvaara and Achilles Karagiozis.

Below is an example of a study with LATENITE in which a comparison with measured values is presented.

8.8.1 Measurements and two-dimensional computer simulations of the hygrothermal performance of a wood framed wall

Measurements and two-dimensional computer simulations of the hygrothermal performance of a wood framed wall, Stig Geving, Achilles Karagiozis, Mikael Salonvaara, Journal of Thermal Insulation and Building Envelopes, 20, April 1997, p 301-319, language – English.

The article presents a comparison between laboratory measurements made on a wood framed wall and calculations made by the LATENITE method. The calculations are made for temperature and moisture content in two dimensions. The results tend to indicate the possibility of using hygrothermal calculation models rather than showing the convergence between measured and calculated values.

8.9 hygIRC

hygIRC is a calculations software tool for heat and moisture transport. The first versions were one-dimensional, but now the tool can also handle two- and three-dimensional calculations. hygIRC is an enhanced version of the LATENITE model. The calculation model is based on solving balance equations for energy and mass, and water and air. The moisture driving potential is moisture content and vapour pressure. The energy driving potential is created by temperature differences?. Together with WUFI, hygIRC is the only calculation tool that seems to be able to handle rain penetration and driving rain.

The program was developed in the 2000s at NRC, the National Research Council of Canada, by Wahid Maref, Steve Cornic, Khaled Abdulghani and David van Reenen.

The program is described further in the articles presented below.

8.9.1 1-D hygIRC: a simulation tool for modeling heat air and moisture movement in exterior walls

1-D hygIRC: a simulation tool for modeling heat air and moisture movement in exterior walls, Wahid Maref, Steve Cornic, Khaled Abdulghani, David van Reenen, NRC – CNRC, IRC - Building science insight 2003 seminars series, October 2003, p 1-10. 2003, language – English.

The article presents the basic structure and function of the 1-D hygIRC heat and moisture simulation tool. The model used for the building envelope, climate database, material database and models of the interior conditions are briefly described. The calculations process and solver are presented.

8.9.2 Benchmarking of the advanced hygrothermal model-hygIRC with mid scale experiments

Benchmarking of the advanced hygrothermal model-hygIRC with mid scale experiments, Wahid Maref, M. Lacasses, M.K. Kumaran, M.C. Swinton, eSim 2002, Proceedings, Montreal, September 2002, p 171-176, language – English.

The article presents the 1-D hygIRC basic equations for moisture and energy balance. Results from dry-out tests on OSB in the laboratory are compared to 1-D hygIRC calculations for the same conditions. The comparisons show good convergence but were not carried out blind.

8.9.3 Benchmarking of hygrothermal model against measurements of drying of full-scale wall assemblies

Benchmarking of hygrothermal model against measurements of drying of full-scale wall assemblies, H.H. Saber, W. Maref, M.A. Lacasse, M.C. Swinton, M.K. Kumuran, ICBEST 2010 – International Conference on Building Envelope Systems and Technologies, Vancover B.C. June 2010 p 369-377.

The paper presents the results from a comparison between hygIRC two-dimensional and a new three-dimensional version of the calculation tool. The heat, air and moisture transport equations are presented. The new three-dimensional version uses COMSOL as a solver. The comparisons between hygIRC two-dimensional calculations, the new three-dimensional calculations and laboratory measurements show good convergence. The comparisons were not carried out blind.

8.10 MOISTURE-EXPERT

The MOISTURE-EXPERT model is a one- and two-dimensional heat, air and moisture transport model. It was invented for research applications. Vapour and liquid transport are treated separately. The moisture transport potentials are relative humidity and vapour pressure. Temperature is the transport potential for energy. The model has a temperature dependent sorption isotherm. Liquid transport is a function of the drying or wetting processes.

MOISTURE EXPERT is a non-commercial program developed in 2001 at the Oak Ridge National Laboratory, ORNL, in USA, by Achilles Karagiozis.

9 Summary and conclusions of the literature study

Based on the studied articles, dissertations, theses, standards, books and other documents in the literature study, a number of facts could be summarized and several of conclusions could be established. The summary and conclusions are meant to point out examples of relevant knowledge and to give examples of gaps where there is a lack of knowledge and suggest further research. Summarized facts and conclusions are based on the contents of several documents seen as a group. It is therefore not possible to give specific references for each paragraph below. All documents and references are specified and described above.

The main documents that establish the need for research in the area show that moisture-related damage is common and has a great effect on both financial and health issues. New regulations in order to predict and avoid moisture damage also show that there is a need for user-friendly and reliable moisture calculation tools. The WUFI calculation tool is specifically mentioned in investigations carried out by public authorities.

Basic knowledge exists in the area of heat, moisture, moisture transport and mould models. However, this needs to be developed and further research is needed, especially in the area of moisture transport in materials, and mould growth and the mould growth influence on health. The construction industry needs to carry out further work with regard to moisture protection in existing construction systems. The building material industry needs to give complete material data for new materials. In many cases there are a number of material parameters but not all. New materials also need to be further developed, especially waterproofing membranes for bathrooms.

In the case with waterproofing membranes in bathrooms, there is a need to ensure the vapour tightness when the membranes are in contact with high RHs. The membranes also need to be even more vapour tight in high RH conditions. Membrane systems also need to be developed in order to make joints and pipe penetrations completely vapour-tight.

Different countries, universities and institutes have developed different moisture safety design processes and structures to avoid moisture related damages. Some of the methods concern qualitative methods, some quantitative methods and some both qualitative and quantitative methods. The further work concerning moisture safety design processes needs to be international compiled. Differences between qualitative and quantitative methods should be clarified. Even if there are good methods, good construction systems and good examples of how to achieve airtight buildings, a discussion about whether this should be a part of the moisture safety design process or seen as a separated issue is needed.

There is broad agreement about the fact that temperature, moisture and duration are the main factors affecting the risk of mould growth. However, there are a number of different theories and models about reducing, if this is at all possible, the amount of mould growth during non-favourable mould growth climate conditions. Different critical levels with regard to the effects of duration have also been presented. Furthermore, the effects of short-time variations between critical and non-critical conditions have not been studied. The possibility of reducing mould growth and the influence of time need to be further investigated.

The availability of outdoor climate data in Sweden varies. The data exists but is only freely available to research and not to the industry. There is also a lack of long wave radiation data and climate data for long periods. Standards concerning indoor climate are available and their requirements seem to be reasonable in relation to recent research.

There are a lot of information sources and study reports concerning the structure and function of the WUFI calculation tool. There are also a number of comparisons showing good correlation between calculations and laboratory measurements. In some cases calculations are compared to field measurements and the same behaviour could be noticed. In these cases it might be defects in chosen calculation boundary conditions. There are also a few comparisons with acceptable convergence between calculated and field measured values. However, there is a lack of comparisons between calculations and measurements in Swedish climate conditions. A few studies exist with Norwegian and Finish climates. Furthermore, no blind comparisons between field measurements and calculations exist at all. In some cases it would be a reasonable guess that a blind comparison was supposed to have been carried out but the degree of mismatch between measured and calculated values made it impossible.

Besides comparisons between calculations and measurements there are a number of parameter studies conducted using WUFI. Unfortunately, the quality is varied. The main errors can often be connected to lack of knowledge and shortcomings on the part of the user. It seems as though the user-friendly WUFI structure and interface might be the problem because it invites users without complete knowledge in the field to use the tool.

There are also a number of other moisture calculation tools. Some of them use the same engine and structure as WUFI but are designed as research tools. Some moisture calculation tools also seem to be unsuitable for performing moisture calculations. WUFI seems to be the only highly developed and, at the same, time user-friendly moisture calculation tool.