Historic Environment Scotland
Àrainneachd Eachdraidheil Alba

Assessing risks in insulation retrofits using hygrothermal software tools

Heat and moisture transport in internally insulated stone walls

Joseph Little, Calina Ferraro & Beñat Arregi

Building Life Consultancy
THE SCIENCE OF ARCHITECTURE

This Technical Paper is available as web publication for free download from the Historic Environment Scotland website:
www.historic-scotland.gov.uk/technicalpapers

This Technical Paper should be quoted as:
Historic Environment Scotland Technical Paper 15

Second Edition, 2015

ISBN 978-1-84917-210-3

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Acknowledgements

Bruce Induni, Induni Associates, United Kingdom

Caroline Rye, ArchiMetrics, United Kingdom

Christopher Hall, University of Edinburgh, United Kingdom

Chris Sanders, Glasgow Caledonian University, United Kingdom

Ian Ridley, University College London, United Kingdom

Jens Engel, Remmers Baustofftechnik, Löningen, Germany

Lothar Moll of Moll Bauökologische Produkte GmbH, Schwetzingen, Germany

Neil May of Natural Building Technologies, Bucks

Ralf Killian, Fraunhofer Institute for Building Physics, Germany

Robyn Pender, Historic England, London

Steve Shannon, BuildDesk, United Kingdom

Valentina Marincioni, University College London, United Kingdom

And to Joseph Little’s wife Emma Sides

Foreword

by Historic Environment Scotland

Water can cause building fabric deterioration and create unhealthy indoor environments and, therefore, is a major factor to consider in construction design. Water transport is closely linked to heat transfer. Together, these coupled transport phenomena are the subject of hygrothermal physics.

Heat transfer through the building envelope has received increased attention over the past decades. With governmental policies, today, aiming at significantly reducing the greenhouse gas emission associated with the use of buildings, the installations of retrofit measures in existing buildings is promoted heavily to improve their energy performance. Reducing the heat transfer through building envelopes, by improving their thermal resistance and airtightness, is one of the strategies targeted. Insulation retrofits, for example, improve the thermal resistance of a construction, draught-proofing increases its airtightness. However, while these measures improve the envelope's performance thermally, they also alter its moisture performance, due to the couple nature of the transport phenomena involved. Thermal improvements, therefore, can create or increase the risks of moisture-related deterioration. To give examples: in unsuitably designed or operated buildings, condensation can occur, leading potentially to timber decay, due to rot infestation, or to mould growth, a health risk to building occupants. Liquid water in the near-surface layer of a construction can result in surface spalling, due to freeze-thaw action; salts transported by liquid migration to this near surface-layer have a similar effect. To prevent these risks, an understanding the hygrothermal performance of the building envelope is essential. This in-depth knowledge is necessary not only when designing new construction, but also when planning the retrofit of existing building fabric.

Condensation risk assessments are commonplace today in the design of new-build construction. Most of these assessments are based on indoor vapour loads, assume that adequate ventilation is provided and that liquid water only occurs in the form of vapour condensation. These forms of assessment are generally helpful for analysing new-build construction, as today's construction design aims at preventing rain or ground water from penetrating (deeply into) the building fabric, often stopping the liquid by means of damp proof courses, impermeable rain screens and vented cavities. This way, liquid water does not need to be factored into the risk assessment. However, preventing liquid water penetration is often not possible or sensible in older forms of construction, for both conservation and technical reasons. Until about a century ago, many walls in Britain were constructed as solid masonry walls. They were built as one mass, with bricks or stones bedded in earth or lime mortars. Such construction allows greater moisture ingress than today's wall designs, but also enables easy dissipation of moisture from the wall's surfaces. Solid masonry walls generally manage changing levels of moisture content through their ability to buffer and redistribute moisture, properties often not designed into new-build construction today. It is no coincidence that masonry walls in Britain tend to be thicker in regions with wetter weather conditions. Brick walls in the dryer southeast of England are generally thinner than stone walls in, say, Cornwall, Scotland and Wales, which experience significantly more rain fall and higher levels of wind-driven rain. As said, vapour-based condensation risk assessments are a useful tool for some forms of construction, such as lightweight, timber-framed walls in locations not exposed to severe weather conditions. These assessments, however, might not be suitable for an in-depth analysis of older forms of construction, such as heavyweight masonry walls, or of construction exposed to severe weather.

Fortunately, the field of hygrothermal physics has developed significantly over the past decades. About fifty years ago, condensation risk assessments required major simplifications and were performed graphically using the 'Glaser method' which still forms the basis for most assessments today. Over the last three decades, far more complex assessment methods have been developed, helped by the availability of ever better computing power. Now, hygrothermal assessments can be performed using numerical simulation, which requires far fewer simplifications than the Glaser method. The most important difference between the two assessment methodologies is that numerical simulation can account for liquid transport, whereas the Glaser method simply ignores it. There is huge benefit in using numerical simulation for hygrothermal performance assessments of older forms of construction and of construction in locations with severe weather conditions. These assessments can be particularly informative for the retrospective installation of insulation in older buildings.

To help construction professionals and policy makers understand better the impacts of energy-related building retrofits of older buildings, Historic Scotland (now Historic Environment Scotland appointed Building Life Consultancy, in 2010, based in Dublin. Their task was threefold: firstly, to present, in an easily accessible way, the basics of hygrothermal building physics and how they relate to building practice; secondly, to discuss the Glaser method and numerical simulation as the two assessment methodologies currently in use, together with the related technical standards and commonly available software tools; and, lastly, to demonstrate, in a case study, the two methods for assessing insulation retrofits to stone masonry walls.

Scotland experiences often severe weather conditions, and the country's west coast is particularly exposed to high levels of wind-driven rain. This *Historic Scotland Technical Paper* will hopefully foster a better understanding amongst conservation and construction professionals of the hygrothermal transport phenomena occurring in older forms of construction and of the assessment tools available to assess the moisture-related risks associated with insulation retrofits.

About the authors

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Joseph Little is Assistant Head of School (Discipline of Construction) in the Dublin School of Architecture, Dublin Institute of Technology (commenced Jan 2015). He is the Irish co-operation partner of the Fraunhofer Institute for Building Physics in relation to training and development of the WUFI suite of hygrothermal evaluation software. He holds a Bachelor of Architecture and Professional Diploma (Architecture) from University College Dublin, and MSc Architecture - Advanced Environmental and Energy Studies from the Graduate School of the Environment, at Centre for Alternative Technology, Wales.

Joseph Little Architects won the '*Best Residential Green Building'* awards in Ireland in 2013 and 2014: the first for Ireland's first EnerPHit (Passivhaus Institute certified deep retrofit), the second for a deep retrofit extension of a 1929 red brick house. Little closed the practice on entering the Dublin School of Architecture in the Dublin Institute of Technology. Building Life Consultancy (the building science consultancy wing of the practice) continues to carry out thermal bridge and hygrothermal risk evaluation consultancies for clients in several countries.

Little lectures widely and has been published in various magazines (most notably the 'Breaking the Mould' series in Construct Ireland magazine). He is the lead author of '*Built to Last – energy efficiency of pre-1945 historic Dublin Dwellings'* for Dublin City Council (to be published in 2016). He is also lead author in '*Assessing insulation retrofits with hygrothermal simulations – Heat and moisture transfer in insulated solid stone walls*' for Historic Scotland (to be published at this conference).

Little is committed to establishing building science at the centre of low energy, long lasting architecture and construction; eliminating the various gaps between intended and actual building performance; and safeguarding occupant health and historic built culture. Dublin School of Architecture with its growing range of postgraduate programmes in digital analysis and energy retrofit, thermal modelling and now hygrothermal analysis is a fitting home.

Calina Ferraro PE, LEED AP, CxA, CPD

Calina Ferraro is an Associate Principal and mechanical engineer at Randall Lamb Associates, a building services consulting firm in

La Mesa, California. She holds professional engineering licenses in Canada (Ontario), California and Arizona. In addition to playing a leading role in Randall Lamb's mechanical design team, she specializes in building energy modeling and commissioning as part of their Building Science Division. Ferraro's project experience is diverse, including the commercial, science and technology, healthcare and institutional market sectors.

Previously with Building Life Consultancy in Dublin, Ireland, Ferraro carried out hygrothermal performance analysis using WUFI, developed office management systems; and worked collaboratively with Little and Arregi on building pathology, the creation of CPD education for architects and co-authored Historic Scotland Technical Paper 15.

Ferraro is a corresponding member on the ASHRAE technical committee for Moisture Management in Buildings (TC1.12) and continues to collaborate with the team at Building Life Consultancy in their effort to improve standards and understanding of building fabric.

Beñat Arregi BArch

Beñat Arregi holds a degree in Architecture from the University of the Basque Country. He is the lead consultant at Dublin's Building Life Consultancy for thermal modelling (both 2D and 3D) and hygrothermal risk evaluation (both 1D and 2D). Arregi has been a core member of the consultancy since its launch in 2009.

The combination of his architectural and applied building physics knowledge, together with software simulation skills, gives him a unique perspective and ability in evaluating building fabric performance in modern and historic buildings.

Arising out of consultancy and research work Arregi has authored and co-authored articles for publication and papers for various international conferences. Together with Joseph Little, he has created and lectured two courses on energy-efficient retrofit and building fabric design on behalf of the Royal Institute of the Architects of Ireland (RIAI).

Contents

Executive summary

This paper provides an introduction to the basics of hygrothermal building physics, discusses assessment methodologies, including related methods, standards and software tools and illustrates these in a case study. The report was written for construction professionals, wishing to understand more about hygrothermal building physics, assessment methods and possible risks in retrofitting traditional buildings. While focussing on traditional construction and its retrofit, aspects of this report are also relevant for retrofitting non-traditional construction.

Hygrothermal building physics is the coupled heat and moisture transport that occurs within and through building elements, as influenced by their material characteristics and external conditions. Heat transfer and moisture movement occur through different physical transport mechanisms. Heat transfer occurs in the form of thermal conduction, thermal convection and thermal radiation. Moisture movement occurs by vapour convection or vapour diffusion, when the water is in its gaseous state, and by capillary transport or surface diffusion, when the water is in its liquid state. These mechanisms cannot be easily separated, because moisture carries heat with it and temperature differences impact upon the way moisture moves.

Traditional buildings were erected using natural materials, such as stone and timber. Natural materials are generally porous and permeable, which means that they have open-pore pore structures, thereby allowing moisture transport. There is a common misconception that modern construction materials are generally impermeable. Indeed, some such variants are even more vulnerable hygrothermally than older forms of the same building material. The greatest difference between buildings of traditional and non-traditional construction design lies not so much in the building materials used, but in the way they are used to construct the external envelope of a building – in the way they are joined together. One may say that the defining approach of traditional construction is the management of moisture and, in contrast, one can say that modern construction systems generally depend on blocking, not managing moisture.

The deterioration and decay that occurs in buildings almost always involves moisture. Since heat, water vapour and liquid water are all driven by different forces, they can ‘move’ in different directions at different times within the same wall. However, because the forces driving these transport phenomena are coupled, retrofit strategies to address one issue may have unexpected effects on another. Retrofitting building elements to improve thermal performance carries an unestablished level of risk of moisture-related damage occurring, to the detriment of existing and newly installed portions of the building fabric as well as for occupants. Three relevant moisture sources are identified in this report: indoor vapour, rain wa-

ter (including wind driven rain) and ground water. The report further demonstrates that choosing the most appropriate risk assessment method is important to ensure that retrofits are durable, sustainable and create healthy environments.

The report discusses two available methodologies for conducting hygrothermal risk assessments: steady-state condensation risk assessments, using the *Glaser method*, and transient hygrothermal performance analysis, using *numerical simulation*. In Ireland and the UK, construction guidance and practice are still heavily influenced by the *diffusion paradigm*, a reductionist but deeply held view that vapour diffusion is the only relevant moisture transport mechanism in building fabric and the use of a vapour barrier to control it is always best practice. The Glaser method is suited for the comparative hygrothermal assessment of lightweight building fabric with well-vented rain screens in relatively sheltered conditions, but has little place in the evaluation of solid wall traditional buildings, as is clear from the limitations set out in the standards associated with it, *BS EN ISO 13788:2002* and *2012*. The Glaser method's simplified, steady-state approach excludes several hygrothermal transport processes from consideration, such as liquid transport by capillary action or surface diffusion, and short-term weather events such as driving rain and freezing conditions. All of these are of particular importance in the hygrothermal assessment of traditional building construction, particularly when internally retrofitted with insulation.

Unlike the Glaser method, numerical simulation (under *BS EN 15026:2007*) can allow detailed hygrothermal assessment of a wide range of issues, such as rot infestation, mould growth and freeze-thaw deterioration. It allows users to assess not only geographic location, but also the impact of different orientations, exposures, altitudes and even the radiative absorptivity of surface colours and night time radiative heat losses. Crucially, it can be used to assess short-term climatic events, inside or outside the building, with wind-driven rain being a particularly important factor when assessing solid walls. An increasing number of UK universities are researching hygrothermal performance, using physical testing and/or numerical simulation software. An increasing number of construction professionals in Ireland and the UK have been trained in its use and a limited number of colleges are creating formal academic programmes in hygrothermal assessment. While manufacturers of conservation products have been quickest to adopt numerical simulation software, many mainstream manufacturers of construction products now have personnel using numerical simulation to assess new products. Thus, a good basis is being created to allow a shift to occur in how risk assessment of buildings is carried out. However, the accuracy of hygrothermal assessments could be improved significantly if better hygrothermal material data were available. Laboratory measurement of a carefully chosen selection of traditional building materials, commonly used in Scotland, could significantly advance the accuracy of risk assessments. No existing materials from any building in Ireland or the UK have yet been subjected to the full range of hygrothermal testing.

The case study in this report has demonstrated, by comparing Glaser method and numerical simulation assessments (using BuildDesk U and WUFI software respectively), that moisture transport in solid, unrendered stone walls is predominantly in the form of liquid migrating through the materials' capillaries, due to capillary action and surface diffusion. Vapour diffusion plays a lesser role. The moisture absorption characteristic of an external wall surface determines the relative importance of the different transport mechanisms. When liquid transport is stopped within the building fabric, either by reaching a non-capillary active material or any another form of capillary break, the liquid must be able to diffuse and evaporate to the indoor or outdoor environment. Anything impeding this drying of the wall results in moisture accumulation and can lead to moisture-related deterioration and potential health risks to occupants. Interestingly, an increasing number of innovative insulation products are being developed specifically for use with traditional masonry construction. Manufacturers of such specialist products tend to have measured the full range of hygrothermal characteristics of their products, thereby aiding independent numerical calculation by third parties.

Insulation retrofit in Ireland and the UK is gathering pace. The retrofit of new materials or systems within a traditional building often creates new conditions. Nationwide increasing cases of building fabric deterioration are resulting in additional expense and possible health risks to building occupant, unless more field research is carried out and the switch to hygrothermal analysis using numerical simulation speeds up. National retrofit campaigns, such as the UK's *Green Deal* and Ireland's *Better Energy Homes Scheme* aim at achieving significant improvement of the energy efficiency of the existing building stock quickly. These retrofit campaigns have provoked a sense of urgency in many quarters about the need to carry out knowledge gap studies, significant research and a shift to assessment under *BS EN 15026:2007*, but the retrofits themselves are also increasing the complexity of the traditional building stock and due to their lack of focus on the issues raised in this and other similar reports must surely be increasing hygrothermal risks, without giving all the promised energy savings.

One-size-fits-all insulation strategies will not work in national retrofit programs. Energy-related retrofit to traditional, moisture managing construction, carried out without careful and appropriate risk assessment, will be neither durable nor sustainable. Continuing to live within the diffusion paradigm by accepting unsuitable hygrothermal risk assessment methods is not in the national interest and should no longer be acceptable. The stakes are too high.

1 Introduction

1.1 Context

Heat and moisture transport are intrinsically coupled physical phenomena. Hygrothermal building physics describes these coupled transport processes. Because of this coupling, retrofitting building fabric to improve its thermal performance is likely to also impact on its moisture performance, particularly in traditional construction. Therefore to avoid moisture-related deterioration of the building fabric and health risks, retrofit measures need to be assessed not only for their thermal benefits, but for their *hygro*thermal impacts too. This report discusses two available methodologies for conducting hygrothermal risk assessments: steady-state condensation risk assessments, using the *Glaser method*, and transient hygrothermal performance analysis, using *numerical simulation*. The report argues that steady-state assessment of vapour transport in solid walls may be inappropriate and misleading for most traditional constructions, and that (the more recently developed) transient hygrothermal performance analysis is more accurate and allows a far greater range of conditions and climatic events to be interrogated. The report further demonstrates that choosing the most appropriate risk assessment method is important to ensure that retrofits are durable, sustainable and create healthy environments.

Current governmental policies in the United Kingdom (UK) aim at significantly reducing greenhouse gas emissions, a large portion of which is associated with emissions from buildings in the form of carbon dioxide (CO_2). (Palmer and Cooper, 2012, p. 6, side note) In the UK, space heating accounts for 65 % of residential energy use. (ibid., p. 33, graph 5b) The focus on the thermal performance of the building envelope, therefore, has increased greatly over the last decades, with building regulations requiring an ever better thermal resistance of roofs, external walls, windows etc., in order to reduce the required cooling and heating demand and, in turn, associated CO_2 emissions and fuel costs.

> *The Climate Change Act 2008 commits the UK to reduce carbon emissions by 80 per cent by 2050 … Achieving these significant levels of carbon reductions will require a complete transformation of the UK's existing homes to dramatically reduce domestic emissions. 85 per cent of the UK's existing homes will still be standing and in use in 2050, presenting a significant low carbon refurbishment challenge.*
>
> (UK GBC, 2014, p. 5)

Increased thermal performance requirements in building regulations however, only impact on new built construction and on buildings that undergo changes of use (conversion) or major alterations: they do not impact on existing buildings. To achieve the UK emission reduction targets of 34 % for the UK in general and 42 % for Scotland, both by 2020 against a 1990 baseline, (HM Government, 2009, clause 2(1); Scottish Parliament, 2009, clause 2(1)) emissions associated with the existing building stock needs to be significantly reduced also. (Boardman et al., 2005, p. 7, 84) This can be achieved by improving the thermal performance of the building envelope with increased levels of airtightness and thermal resistance. Retrofit measures for each of these include draught stripping of windows and installation of (additional) insulation. In the UK, such retrofit construction work is supported by the governmental Green Deal programme. (UK Parliament, 2011)

Energy-related retrofits aim at improving the thermal performance of the building envelope, by reducing heat transfer. Heat transfer, however, is intrinsically coupled with moisture transport. The hygrothermal performance of building elements is the coupled heat and moisture transport that occurs within and through them, as influenced by their material characteristics and external conditions. The deterioration and decay that occurs in buildings almost always involves water. Moisture accumulation and transport within the building fabric can lead, for example, to structural damage, spalling due to freeze-thaw, decay though rot, salt efflorescence and reduced thermal performance of insulants. Moisture accumulation can also result in mould growth, a health risk for building occupants. Due to the coupled nature of heat and moisture transport, changing the thermal performance of the building envelope is likely to also change its moisture performance.

Retrofitting building elements to improve thermal performance therefore carries an unestablished level of risk of moisture-related damage occurring, to the detriment of existing and newly installed portions of the building fabric as well as for occupants. The execution of a careful condition survey (which may include some simple physical testing) and a hygrothermal performance analysis using numerical simulation are the appropriate responses to this as they enable the specifier of the retrofit works to quantify, control and minimise this risk, as much as is possible. Surely all parties involved with the energy efficient retrofit of buildings of any age can agree that, *as a matter of course*, risks should be established as best possible and minimised?

While many of the buildings to be retrofitted in the UK's existing stock are of recent origin and of non-traditional construction, approximately 20 % of the UK's stock are traditionally built. The proportion in Wales and Scotland is higher than in England. As traditional solid walls manage moisture transport very differently to non-traditional wall constructions specifiers need to be aware that different retrofitting technologies, different materials and different evaluation methods may be required for each.

Most modern construction design aims at preventing moisture penetration either at the surface of the external building envelope or at a specific layer within its fabric. This can either be achieved with membranes, preventing or reducing liquid and/or vapour transport, or with vented cavities, preventing liquid transport. In modern wall construction, cavities are often incorporated to stop rain water migration from the outer to the inner wall leaf. Rain water can run down the cavity face of the outer leaf without transmission to the inner leaf: at least notionally the only moisture the inner leaf has to deal with is vapour (including condensed vapour). This approach to construction design is often referred to as *non-traditional*, though *predominantly moisture blocking* may be a more useful description in hygrothermal terms as there are a growing number of modern, highly insulated solid wall constructions that manage moisture very similarly to *traditional* solid walls.

The term *predominantly moisture managing* may be used to describe traditional solid walls in hygrothermal terms: in this approach moisture migration is not prevented, yet the materials, layering and overall design ensure the structure has good drying capacity and can be long lasting. An example of this is solid masonry wall construction, which allows rain water absorption and water and vapour movement throughout, but also allows evaporation to both sides. Solid masonry construction was commonly in use until the early 20th century. (The terms *predominantly moisture managing* and *predominantly moisture blocking*, *traditional* and *non-traditional* construction will be discussed in detail in the report.)

Today two hygrothermal risk assessment methodologies are in use in the construction industry. The first involves use of a simplified steady-state assessment (carried out by hand in the past but usually performed using proprietary software today), where the output from the calculations is clear and can be reported without additional analysis. The second uses transient numerical simulation software as a powerful tool within the overall hygrothermal performance analysis conducted by a trained and experienced user. Rigorous interrogation and interpretation of inputs and outputs is the key to successful use of the second methodology.

Both methodologies are described in British Standards (BS), and various computer software programmes are validated against them. For steady-state assessments (that is assessments where time is fixed), the so-called *Glaser method* is commonly used. It is described in *BS EN ISO 13788:2012* (BSI, 2013) and can be performed with software such as BuildDesk U. Because this kind of assessment focuses solely on the risk of vapour condensing during transport it has become known as interstitial condensation risk assessment. Transient numerical simulation (that is the use of calculations to simulate conditions that change with every time step), as described in *BS EN 15026:2007* (BSI, 2007a), reflects more closely the full complexity of building physics. The simulation is not limited to vapour transport, but explicitly accounts for the full range of liquid transport. Software based on the European parent standard includes Delphin and WUFI. As hygrothermal performance analysis using these simulation tools has developed more recently than the Glaser method, and its first standard is as recent as 2007, it has yet to be widely adopted.

Moving forward, to support appropriate nationwide energy efficient retrofit of solid wall buildings, the rate of uptake of use of validated numerical simulation tools, and the hygrothermal performance analysis by trained professionals that relies on them, has to greatly increase.

1.2 Report outline

This report will introduce the reader to the basics of hygrothermal building physics, discuss assessment methodologies, including related methods, standards and software tools and illustrate these in a case study. The report was written for construction professionals, wishing to understand more about hygrothermal building physics, assessment methods and possible risks in retrofitting traditional buildings. The report will be useful for architects, engineers, building fabric consultants, building contractors, insulation manufacturers and building conservation practitioners. While focussing on traditional construction and its retrofit, aspects of this report are also relevant for retrofitting non-traditional construction.

This report discusses hygrothermal physics (Section 2) and its application in building practice (Section 3) as well as the assessment methods and simulation tools available for this (Section 4). Thereafter, the report presents a case study, comparing hygrothermal assessments of a variety of internal wall insulation retrofit measures (Section 5), before drawing conclusions (Section 6). Further details on specific topics in the report are set out in the Appendices. An abbreviation list and a glossary are provided, to make use of the report easy.

2 Hygrothermal building physics

2.1 Overview

Hygrothermal building physics is concerned with heat and moisture transport, which are intrinsically coupled. Heat transport is influenced by moisture, and, conversely, moisture transport is influenced by heat.

Heat and moisture transport can easily be experienced: just think of sunshine and rain or, in a building context, of heat and steam from a cooking pot. These forms of heat transfer and moisture movement occur within the air which surrounds us. Air is present in the outdoors and in indoor spaces. It can move within a room, from one room to the next and from within a building to the outdoors and back. In common building contexts, whenever air moves, it will entail heat and moisture transport.

Air and moisture movement also occur within and through many materials. Most materials used in construction are porous solids, such as brick, stone and mortar. These materials contain a microscopically small, interconnected pore structure, allowing air and moisture to enter and move within (to a greater or lesser extent). Heat transfer can also occur in these materials, but, unlike air and moisture movement, heat transfer also occurs in non-porous materials. (And it can even occur in space, i.e. in an environment where there is no matter present.) Heat transfer and moisture movement occur through different physical transport mechanisms. Heat transfer occurs in the form of thermal conduction, thermal convection and thermal radiation. Moisture movement occurs by vapour convection or vapour diffusion, when the water is in its gaseous state, and by capillary transport or surface diffusion, when the water is in its liquid state. Unfortunately, these mechanisms cannot be easily separated, because moisture carries heat with it and temperature differences impact upon the way moisture moves.

The different transport mechanisms are illustrated in a building context in Figure 1, showing a traditional stone wall typical for many older buildings in Scotland, but also in other parts of the UK and Ireland.

The transport mechanisms will be discussed in detail later in this section. However, before discussing heat and moisture and the associated transport mechanisms, it is useful to start this introduction by describing the two media through which, in a building context, heat and moisture transport occur: the air and construction materials (Section 2.3). Then, heat and the transport mechanisms associated with it will be described (Section 2.4), followed by a discussion of moisture and the various ways by which it can be transported (Section 2.5). Finally, the coupling of heat and moisture transport will be discussed (Section 2.6). Before all this, a short note about the use of measurement units will be helpful.

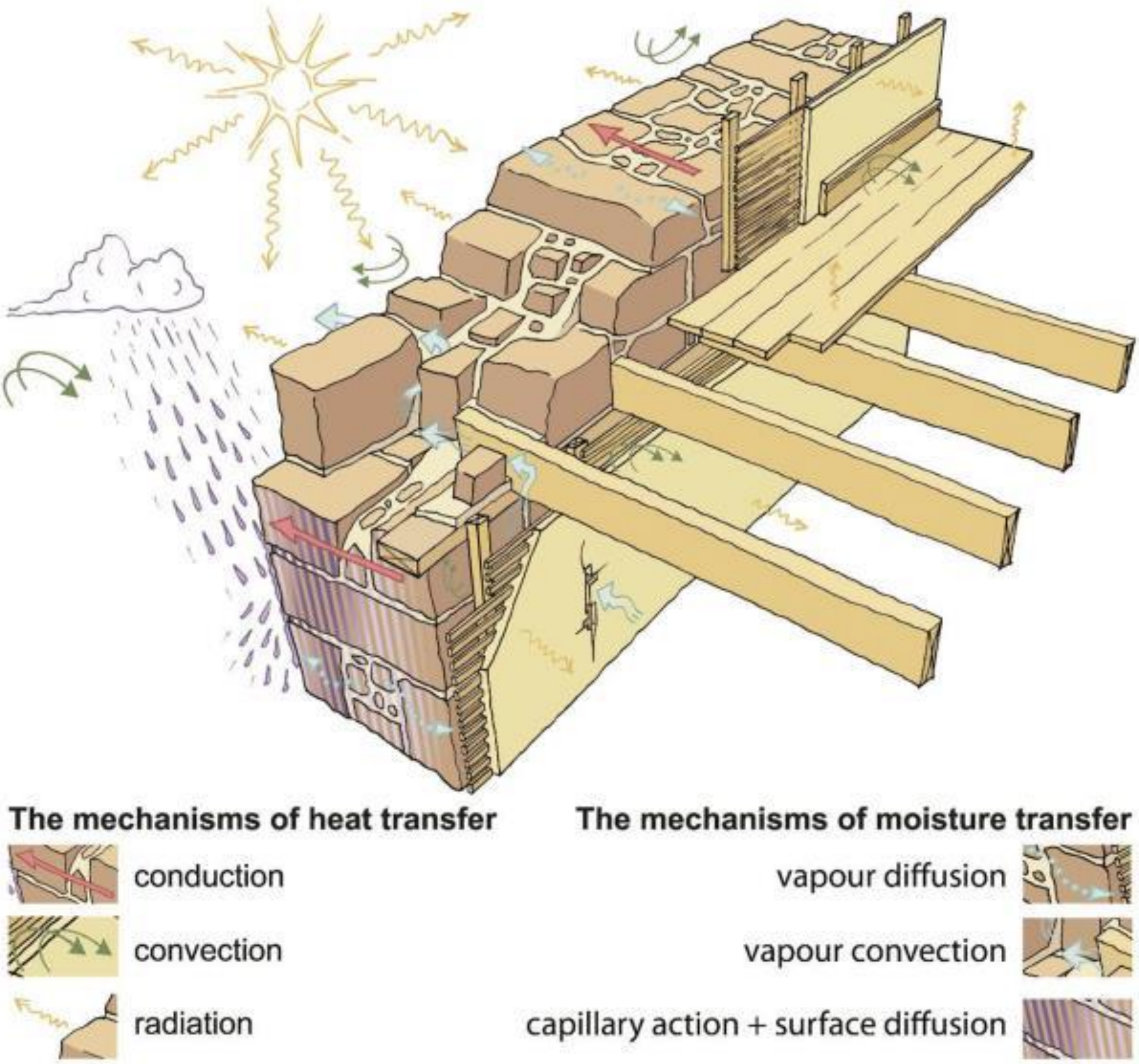


Figure 1 Mechanisms of heat transfer and moisture transport, as they occur in solid stone walls, finished internally with plaster on timber laths: the core of such masonry is made of smaller stones with a large quantity of mortar.

2.2 Units of measurement

The International System of Units (abbreviated to SI based on its French title: Système International d'Unités) are generally used in this report in line with modern European practice and standards, as set out in BS EN ISO 80000-1. Most SI units are decimal: some, most notably time, are not. It is a coherent system of measurement based on seven key units of measurement. For time it uses second (s), for distance metre (m), for mass kilogram (kg). Note that commonly used units like hour and litre are not SI units but are accepted to use with SI. Some non-SI units that are in common usage in the construction and building services sectors such as kWh are used in this document. Having origins in the French Enlightenment, the modern system was first published in 1960, and is considered to still be evolving. It has fully or partially replaced older measurement systems in much of the world. The UK government has adopted a policy termed 'partial metrication' whereby **imperial units**, also known as British imperial, (i.e. inch, yard, stone, etc.) remain widely used in unregulated sectors and common speech. The United States of America (US) is the best example of an economy that still uses a pre-decimal system (which is effectively the UK's imperial system) termed US customary units, despite past efforts by the federal government to move to SI units.

2.3 Media for heat and moisture transport

Heat and moisture transport, in a building context, generally occur within two types of media: the air and the building fabric. Therefore, air and how it moves will be described first (Section 2.3.1), followed by a discussion of building materials, focussing particularly on the porous materials so commonly used in older building construction and describing in detail the pore structures of these materials, as these pores can have a significant impact on heat transfer and moisture movement (Section 2.3.2.1).

2.3.1 Air

Air surrounds us every day and almost everywhere. This dry air is a mix of gases containing approximately 78 % nitrogen (chemical abbreviation: N), 20 % oxygen (O), 0.1 % argon (Ar), 0.04 % carbon dioxide (CO_2) and small amounts of other gases. However, except when under laboratory conditions, air is never completely dry, but contains a variable amount of gaseous water (on average around 1 %). Furthermore, air can also contain liquid and solid water, e.g. rain, snow and steam, and particles, such as small quantities of solid matter, e.g. dust, plant pollen, and ash from fires.

Air exists in the outdoors and within building spaces, and it exists within the pore structure of materials. Because these pores are generally very small, air movement within materials is rather restricted. Outside of materials, air movement is an easily experienced phenomenon: just think of a windy day or of a draught near a slightly opened window. Air is almost always moving; still air is rather an exception.

2.3.1.1 Air movement

Natural air movement occurs generally due to differences in buoyancy and pressure. Differences in temperature and moisture content change the density and therefore the buoyancy of the air, causing warmer, lighter air to rise and cooler, heavier air to sink. Within a building, this is called the **stack effect**: it creates higher pressure in the upper floors, causing the air to push its way out through the building envelope (i.e. the building fabric separating the building from the outdoor environment), and lower pressure in the lower floors, drawing air in from the outside. (Figure 2)

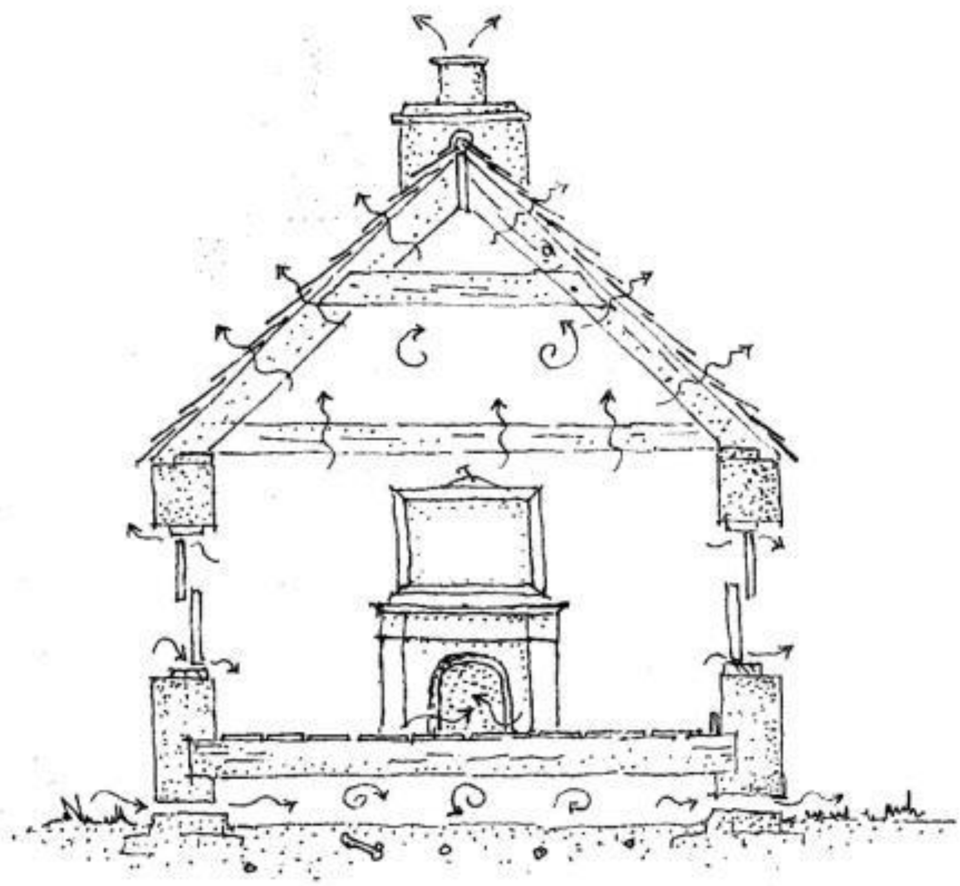


Figure 2 Sketch section illustrating how air moves into, out of and within a building.

Differences in pressure result from forces pushing on a body of air. In building contexts, these can be natural forces, such as wind or buoyant forces, or mechanical forces, such as those created by mechanical fans or combustion appliances. (Figure 3) Regardless of the source of the pressure, it will tend to push air from a location of higher pressure to one of lower pressure. Wind speed, wind exposure and external geometries create varying air pressures outside a building, which can 'press' outdoor air into one side of a building and 'suck' indoor air out of the other side, depending on the relative pressure differences. This can occur through openings in the building envelope, e.g. open doors, windows, vents, or through gaps in the building fabric, e.g. at joints between two window sashes or between window frames and walls.

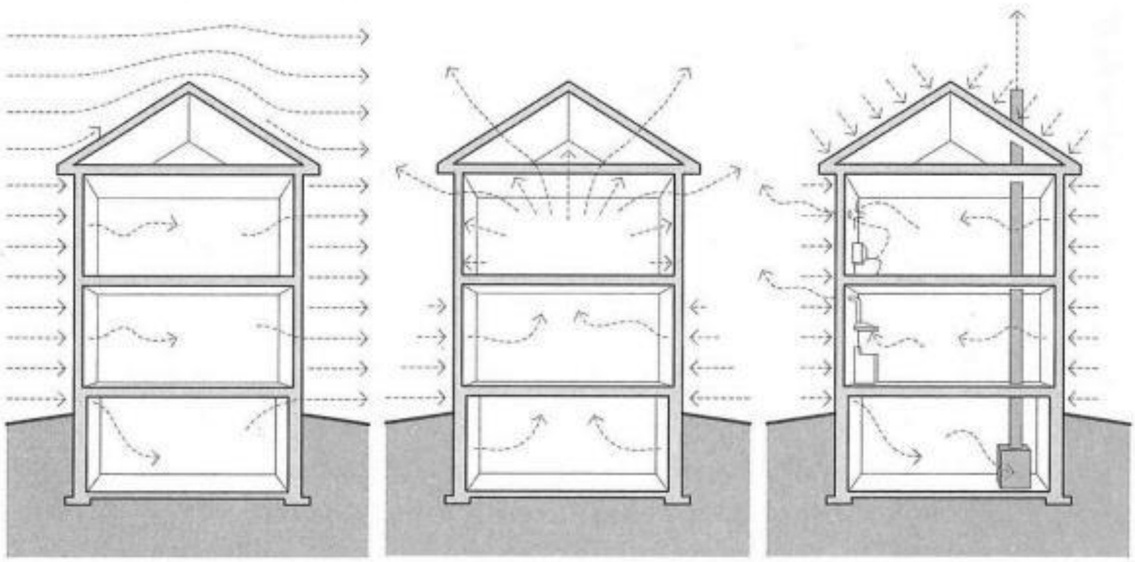


Figure 3 Natural and man-made forces driving air flow through building envelopes. (Straube and Burnett, 2055, p272, fig. 7.2 / Image © Building Science Press)

Within a room, air heated at floor level by a convector heater will rise to the ceiling, where it will cool down and drop down to floor level again, only to be heated again, rise once more and so forth. Convective air currents can result in heat transfer through thermal convection (Section 2.4.2) and moisture movement through vapour convection (Section 2.5.2). Stack effect in tall, heated spaces can also heighten the risk of moisture-related damage within the building envelope, as described in Section 3.2.2, because of its tendency to push or pull air through the building fabric.

The various pathways of air movement are illustrated in Figure 4.

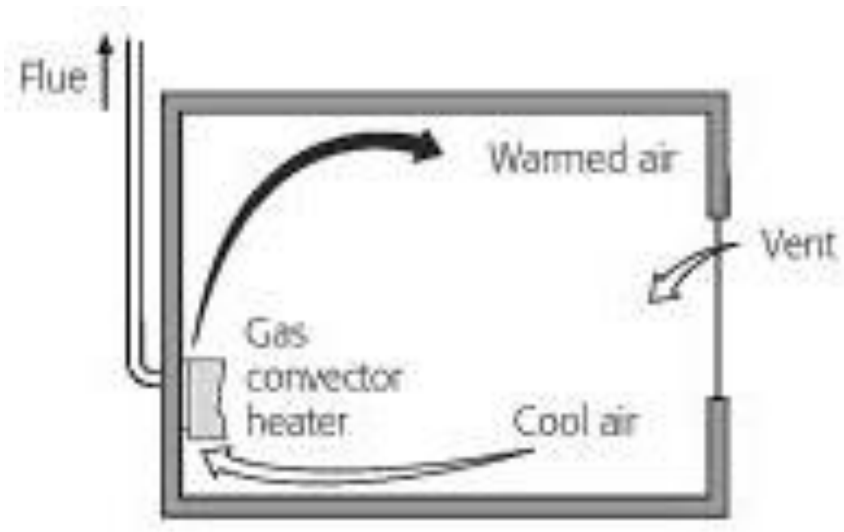


Figure 4 Convection current in a room

2.3.2 Building materials

Air, including the water vapour that it naturally contains, does not only exist in the building spaces surrounding us, but it also exists within most materials used in building construction, because most of these materials are of porous nature. This means that they do not only consist of mass, but also contain a microscopically small pore structure. Depending on the material, this pore structure can vary significantly and will affect how much and how easily air and moisture can move into, out of and through it. Understanding the ratio of mass to pores and the nature of the pore structure of a material is therefore important in assessing its hygrothermal performance.

2.3.2.1 Pore structure

The pore structure of a material consists of differently shaped and sized voids, or interstices. These voids are often interconnected, forming one or more networks. These networks are called the **pore structure**. Figure 5 shows a microscopic photograph of a polished sandstone section, in which the pore structure has been coloured blue, making it more distinguishable from the stone's solid components. Figure 6 shows microscopic photographs of hemp shiv fibres and lime plaster. Figure 7 shows photographs of aerated concrete. Figure 8 shows photographs of mortar. All of the shown materials are porous (Section 2.3.2.3) and vapour permeable (Section 2.3.2.4) but radically different in pore structure. As the photographs are two-dimensional, they can obviously only hint at the volumetric nature and complexity of each porous structure.

The pore structure shown in Figure 7 is extraordinarily complex:

> *These photos show how difficult it must be to find a simple mathematically treatable pore model capable of reproducing even approximately actual pore space geometry vis-à-vis its complex influences on moisture storage and moisture transport.*
>
> (Krus, 1996, pp. 10-11)

Fortunately, the geometrical nature of individual pores is not necessary to understand the moisture behaviour of a pore structure:

> *The behaviour of any individual pore is of theoretical interest only: in general, one speaks rather of macroscopic pore structure parameters – those representing the average behaviour of a sample containing many pores. The most important of these parameters include the porosity, the permeability, and the specific surface area (the interstitial surface area of the pores – per either unit mass or unit volume – which is a measure of the adsorption capacity). Since*

these macroscopic parameters are, together, uniquely determined by the pore structure of the sample, experiments designed to quantify them can serve to characterise the porous nature of the material.

(Dullien, 1992)

Thus, even porous, permeable materials that show great complexity and apparent heterogeneity at a microscopic scale do in fact act in a uniform and measurable manner at a macroscopic scale, which is the scale of interested for hygrothermal assessments.

As can be seen in Figure 5, Figure 6, Figure 7 and Figure 8, pore structures consist of a network of differently shaped and sized voids, or interstices. The larger voids are often referred to simply as pores, or 'large pores', whereas the channels connecting the large pores are called **capillaries**, or capillary pores. (Figure 9) Other terms are also used to describe these different pore sizes. Hall and Hoff (2012) describes pores of different sizes as "voids, cavities, interstices and fissures which make up the total porosity" (ibid., p.7). Borrelli (1999) categorises pores, in the context of stone, into "micropores", "mesopores" and "macropores" (ibid., p.4). And Fraunhofer IBP (2011) refers simply to "small and large capillaries".

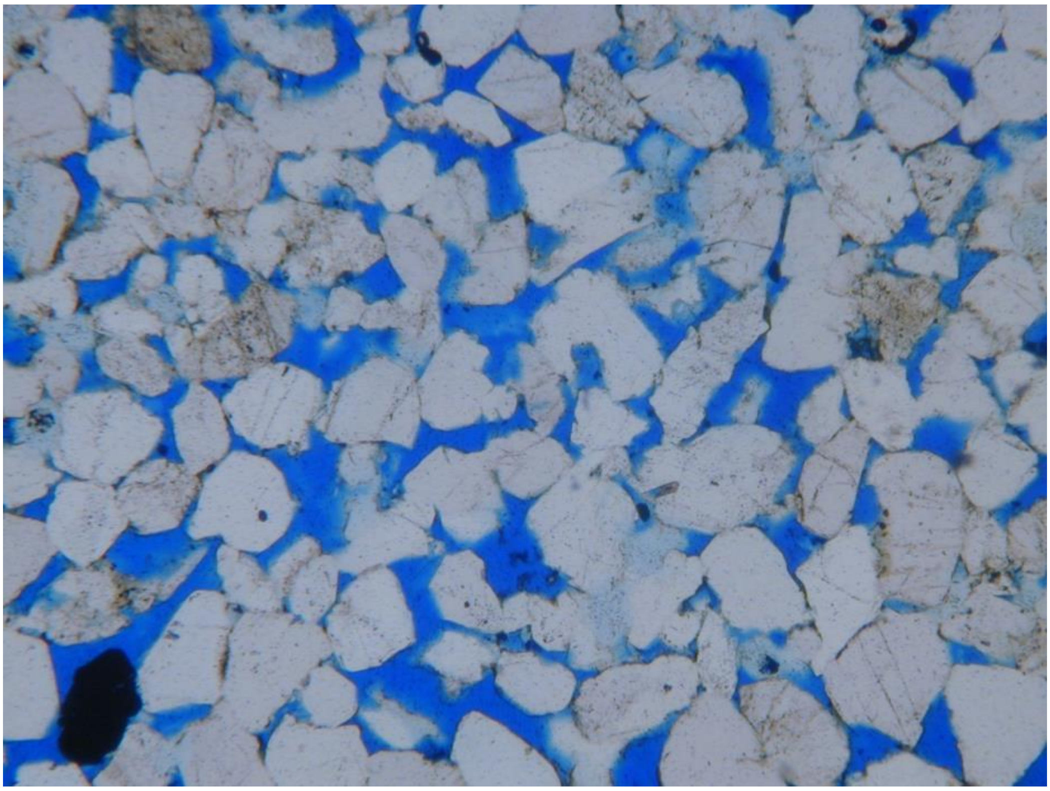


Figure 5 Scanning electron microscope photograph of a sandstone sample, cut, polished and coloured in blue to highlight its pore structure: the photo is of 10 x magnification, with the horizontal view approximately 3 mm wide

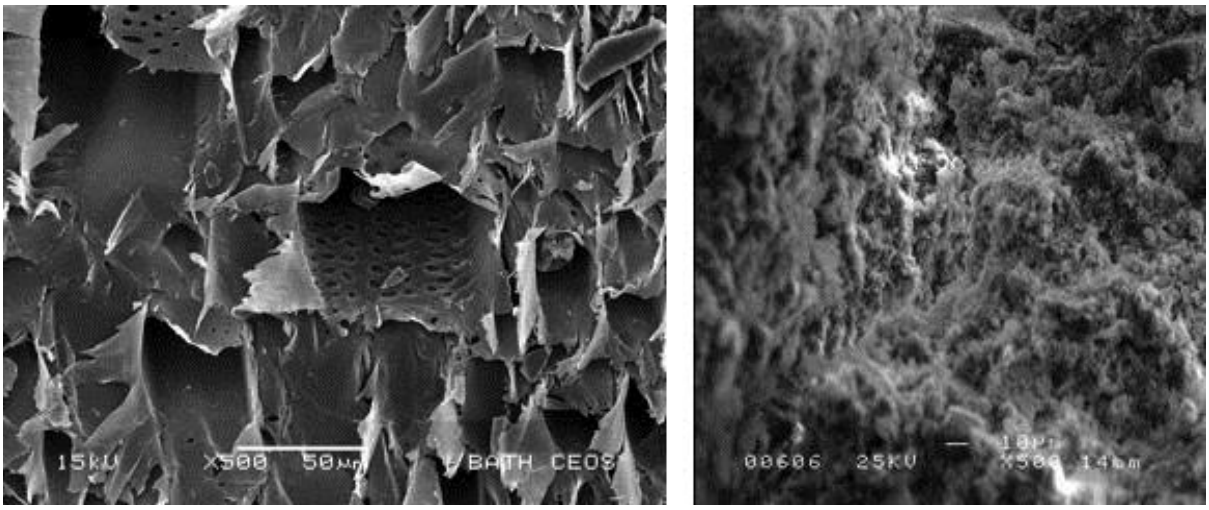


Figure 6 Scanning electron microscope photograph of hemp shiv fibres (left photo) and lime plaster (right photo), both at 250 x magnification. (Image © Mike Lawrence / University of Bath)

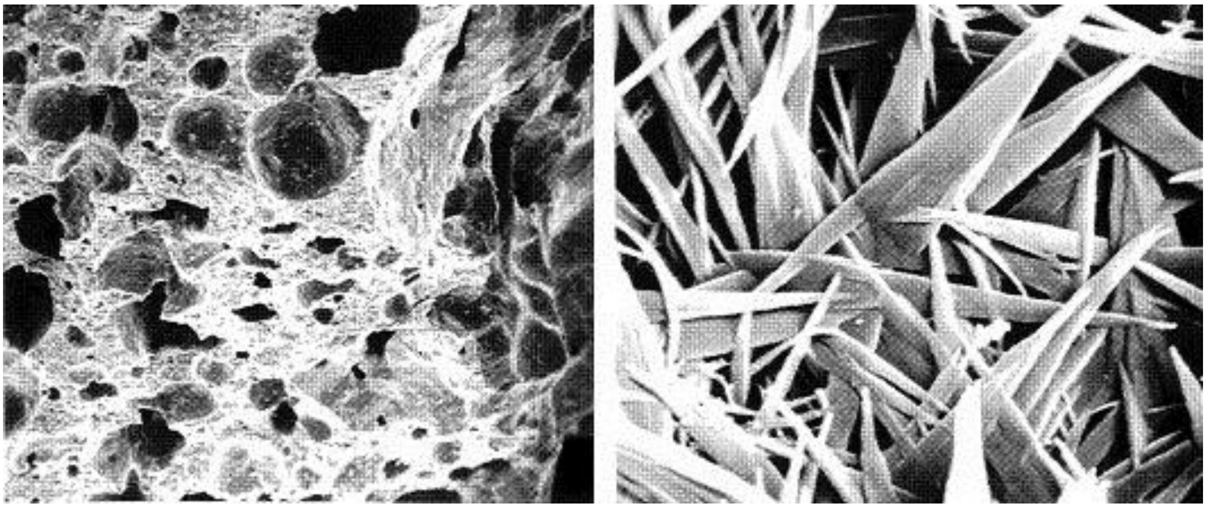


Figure 7 Scanning electron microscope photograph of aerated concrete with 22 x magnification (left) and 11,000 x magnification (right). (Krus, 1996 / Image © Fraunhofer-Gesellschaft)

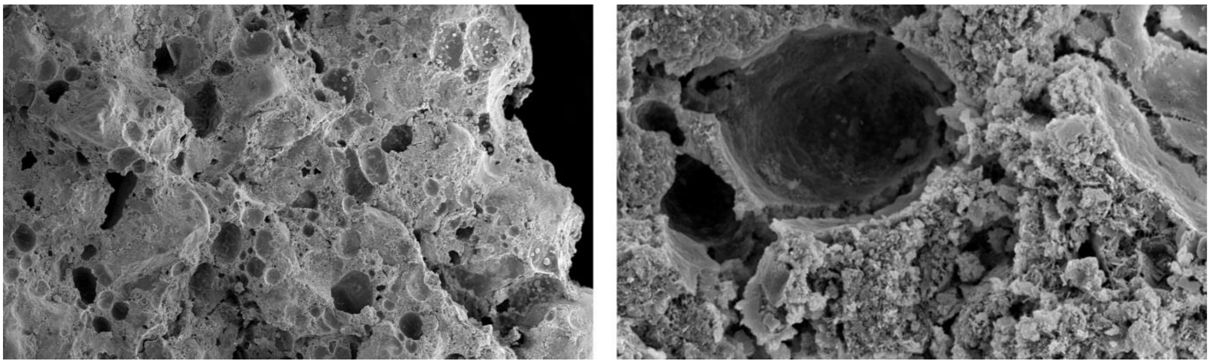


Figure 8 Scanning electron microscope photograph of mortar with 50 x magnification (left) and 2000 x magnification (right)

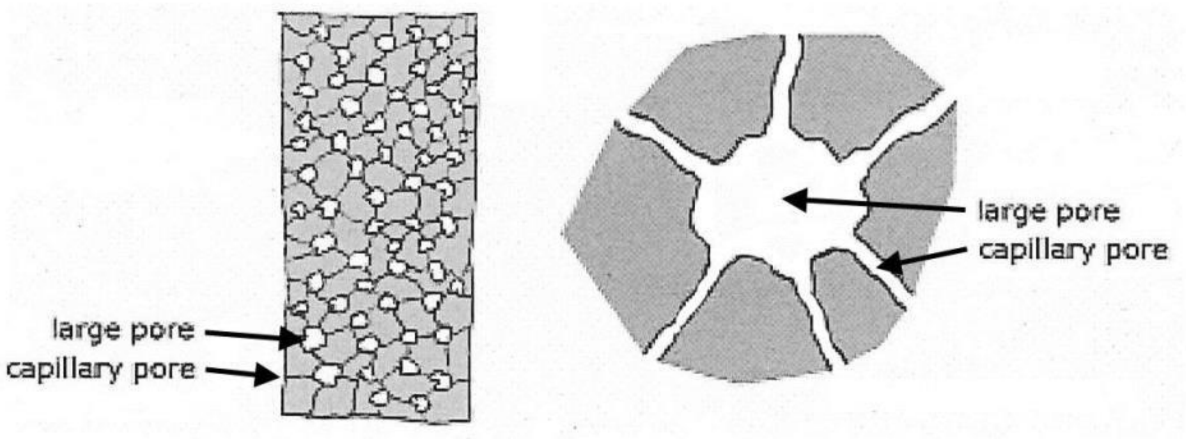


Figure 9 Sketch illustrations of a material's pore structure: the right illustration is a magnification of the left, showing a large pore with connected capillary pores. (Torraca, 2009, p.82, fig. 3.19 / Image © The J. Paul Getty Trust)

To describe a material's ratio of mass to pores and the nature of its pore structure, three physical properties are generally used: density, porosity and permeability.

2.3.2.2 Density

The mass of a material is often discussed using **bulk density (ρ)**, a material property which describes the mass of a material per unit of volume. Density is normally given in units of grams per cubic centimetre [g/cm³] or kilograms per cubic metre [kg/m³], where 1 g/cm³ = 1000 kg/m³. An important distinction must be made between the term **particle density**, describing the microscopic, molecular property of any particular substance, and **bulk density**, which is a macroscopic property that depends on physical geometry. For example, a solid steel block and an equivalent mass of steel wool are made of the same material and have the same particle density. However, because of the physical configuration of steel wool, which includes a large quantity of airspaces between the fibres, the volume of a steel wool sample will be much larger and the steel wool will therefore have a much lower bulk density. Whereas particle density is an intrinsic material property that does not change in common practice, bulk density will change with configuration.

2.3.2.3 Porosity

Whereas density describes the mass of a material, porosity refers to the pores within a material (in relation to its mass). **Porosity (f)** is the percentage of the material's overall volume that is actually pores. Porosity is either described as a unit-less value between 0 and 1 or as a percentage [%]. The values of 0 and 1 (or 0 % and 100 %) are, of course, hypothetical: f=0 describes a material with absolutely no pores, whereas f=1 would mean that there would only be pores and, therefore, no material.

Materials with a relatively large quantity of pores are called **porous**; those with a small quantity or none are called **non-porous**. Most building materials are, in fact, porous, but only few are of such a low porosity that they are called non-porous. The latter include, by example, glass, metals and some plastics. Organic materials are almost always porous, for example timber or thatch, but most inorganic building materials are also porous, for example lime, stone or concrete. However, the degree to which materials are porous can vary.

Given the steel wool example above, bulk density and porosity are obviously related to each other: a material with a large porosity, such as mineral wool, is likely to be non-dense, or of lightweight, whereas a heavy-weight material, e.g. lead, is dense and not very porous.

2.3.2.4 Permeability

Whereas porosity is concerned with the quantity of pores in a material, permeability describes the connectivity of pores with each other and the environment surrounding the material. Parts of a pore structure are open to a material's surface, or boundary, connecting the pore structure to an adjacent material or the greater environment. Thereby, air and moisture from the environment can enter and leave a material via the pore structure.

However, it does not automatically follow that all pores in a material are connected to each other. In fact, some pore connections may be dead ends; others may be small pore structures isolated from the rest, i.e. 'ink bottle' or 'blind' pores. Some pore structures will be connected to the surfaces of the materials and linked in a continuous path.

Pore structures with a large proportion of interconnected networks, are called **open-pore structures**; whereas pore structures with mostly isolated pores or isolated pore networks are referred to as **closed-pore structures**. In an open-pore structure, "a nanoscopic ant could wander throughout the void space and eventually visit all points within it. This means that all pore space is available for flow of gas or liquid and is in communication with the environment in which the material finds itself." (Hall and Hoff, 2012, pp. 6-7) If the ant wanted to wander through the material from one surface to another surface, it might not necessarily be able to take a straight, direct route, but might need to wind its ways through the pore network. "The length of the tortuous path through the pores to get from A to B … may be much longer than the direct distance AB [Figure 10]. This ratio is one measure of the **tortuosity** of the pore system. The tortuosity has nothing to do with the size of the pores but entirely depends on the connectivity of the pores system." (ibid., pp. 23-5, bold formatting added to quotation)

Materials can be very porous, but still have a closed-pore structure that prevents air, vapour, or 'a nanoscopic ant' from navigating through it. Some present-day foamed insulating materials, such as polyisocyanurate (PIR) and polyurethane (PUR) insulation, rely on such a closed-pore structure to trap gases in order to achieve their insulating values.

Even in open-pore structures, however, the tortuosity and the minimum cross section of the passage will significantly impede the ease with which air or moisture can pass through.

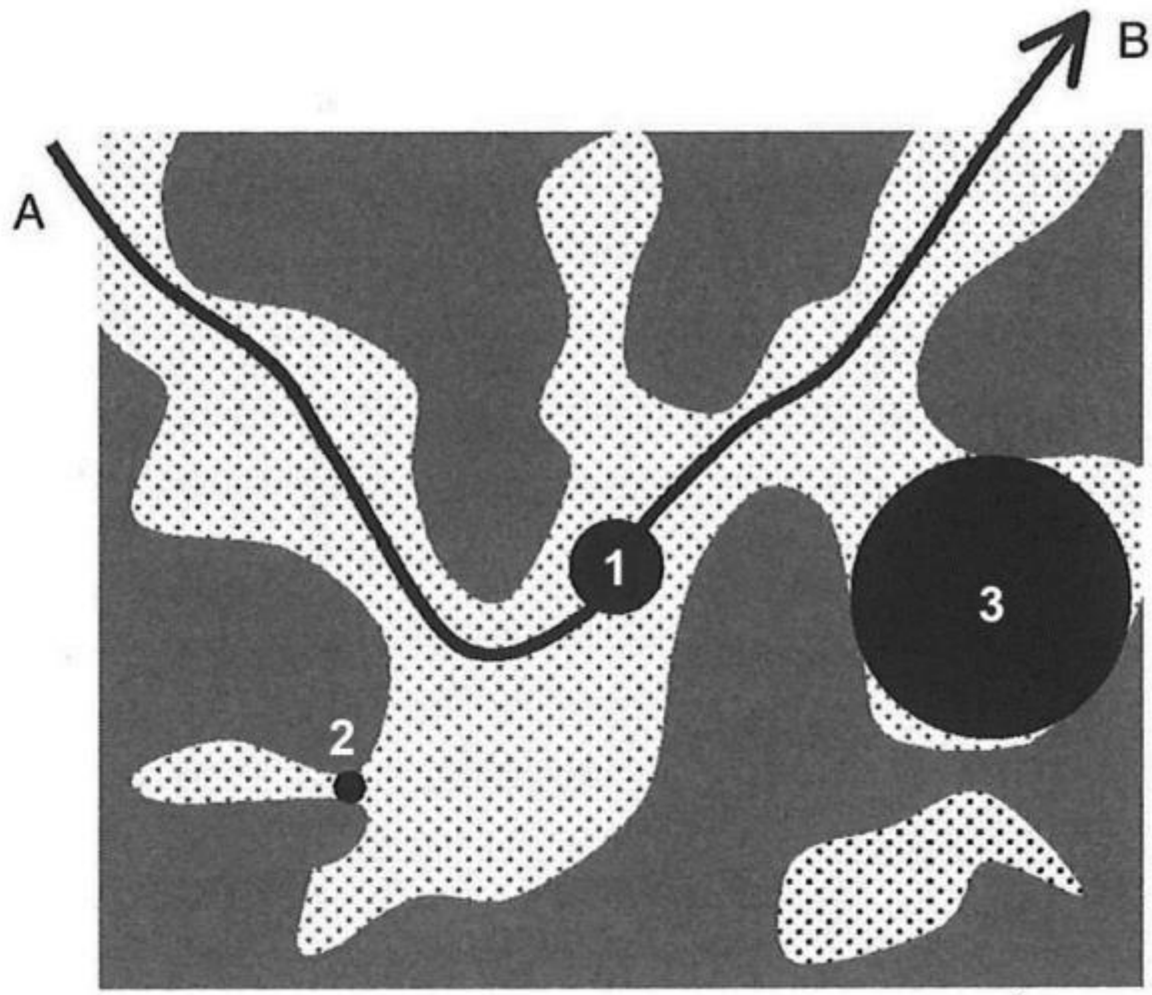


Figure 10 Graphic image of a porous material showing tortuosity of a path AB: the superimposed three black spheres indicate the minimum pore width on path AB (sphere 1) and the minimum and maximum pore widths in the shown pore structure (spheres 2 and 3 respectively). (Hall and Hoff, 2012, p.25, fig. 1.10 / Image © Spon Press)

2.4 Thermal transport of energy

To understand what heat is one must first understand some key concepts and laws of physics in relation to how energy is present and how it transfers. This makes it easier to understand what heat and temperature are, the different mechanisms of heat transport (i.e. conduction, convection and radiation) and energy's conservation.

2.4.1 Thermodynamics, heat and power

All objects above absolute zero, that is zero on the **kelvin** (K) temperature scale, have energy. (0 K is equivalent to -273.15 °C on the relative Celsius scale.) Another way of saying this is that above absolute zero the particles of all fluids and solids (whether molecules, atoms or sub-atomic particles) have internal energy that allows them to vibrate, rotate and move. This can cause the bodies they form part of to move, do work or be changed. The branch of physics concerned with this internal energy is called **thermodynamics**.

Thermodynamic temperature is the measure of the average energy of all of the vibrational, rotational and translational motions of these particles. It is not surprising then that, unlike temperature, thermodynamic temperature is always measured from absolute zero. The full variety of these motions constitutes the **internal energy** of the body (commonly known as its thermal energy). The **First Law of Thermodynamics** states that in a closed system energy cannot be created or destroyed, only changed from one form to another. Phrases like work done or energy used, transferred or converted are therefore more appropriate than energy consumed, expended or lost. The First Law of Thermodynamics is of primary importance in understanding the many changing ways that energy transfer is manifested on Earth, albeit this planet is not a closed system.

While a body is at rest its internal energy at any one time may be measured by a temperature reading. If it is at the same temperature as surrounding bodies no internal (or thermal) energy will be transferred between them, otherwise a transfer will occur: this energy transfer is called **heat**. Incorrectly, it is often thought that heat is a form of energy and that temperature measures heat: this is not so. Heat is defined as the transfer of energy from a hotter to colder body other than by work or transfer of matter. The size of this difference (ΔT) can be thought of as its **driving force**, or driving potential. Heating will continue until **thermal equilibrium** has been reached. As an example an adult human emits about 65 W at rest, more power than a lit 60 W incandescent luminaire, e.g. light bulb. However the portion of its internal energy transferred as heat (as opposed to the portion transferred as light) has a far higher temperature than the person's hand: the resulting heat, i.e. energy transfer, will cause burning if contact is prolonged, long before thermal equilibrium can be reached.

In simple terms **sensible heat** is heat exchanged by a body or thermodynamic system which results in a temperature change, such as with the hand and luminaire above. **Latent heat** is a form of energy transfer that allows a phase change in a body without a temperature change. The phases or states are solid, liquid and gas. (Sometimes plasma is included).

When a body is in motion or at work its speed or how it affects surrounding bodies, or indeed how they affect it, will show that a transfer or use of internal energy is occurring. The amount of energy present or transferred can be measured by **joule** (see definition below). Of course several forms of energy transfer may occur at the same time such as work, heat, light or sound emissions, with a further portion always retained as internal energy. Just think of the sparks and shrieks that might result from the emergency braking of a train's wheels.

The **joule** [J], an SI unit, is the measure of energy used or work done in applying a force of one newton through a distance of one metre. There are equivalent measures: **calorie** [cal], a metric but non-SI unit, is the approximate amount of energy needed to raise the temperature of one gram of water by one degree Celsius. 1 cal = 4.184 J; and **British thermal unit** [Btu], a non-metric, non-SI unit is the amount of energy needed to cool or heat one pound of water by one degree Fahrenheit. 1 Btu = 1.05 kJ (kilojoule). The British thermal unit was used in the UK until the 1980s and is still used in North America and elsewhere.

The image of the braking train evokes a sense of tremendous power. In fact power is defined as the rate of doing work, or to put it another way the rate of energy transfer. It is not surprising then that power's SI unit is joule per second (J/s), though this is better known as watt (W), named for the inventor of the steam engine, James Watt. Unlike the measures of energy used or work done, power and heat are defined by rate – the energy used, or work done over time. These include watt, which is a joule per second [J/s] and Btu/h. In buildings these units are commonly used to describe the power of boilers, fans, luminaires, white goods and air conditioning systems. Because of the focus on energy conservation and comfort watt per kelvin (W/K) is used to describe the rate of energy transfer per degree of temperature through the thermal envelope in buildings. Watt per square metre (W/m^2) is used to describe the energy transfer rate across a surface.

Kilowatt hour is used to describe the amount of energy transferred over a certain period of time. 1 kWh = 3.6 MJ (megajoule). The energy use of a building's space heating system is, for example, normally stated in kilowatt hours. The energy transferred in large generating plants or whole economies might be described in GWh or TWh. Finally $kWh/(m^2 \cdot yr)$ describes the amount of energy transferred over a year per square metre of the thermal envelope: the key unit of measure for building energy rating.

As a body is heated or cooled its internal (or thermal) energy will change and thus its temperature. The thermal inertia of a body is given by its **specific heat capacity (c_p)**, the amount of heat required to change one kilogram of the material by one degree and is given in units of joules per kilogram and per kelvin [J/(kg·K)]. Bodies with high specific heat capacity require more energy to raise their temperature by one degree.

2.4.2 Thermal conduction

Thermal conduction is a direct heat transfer mechanism from molecule to molecule caused by collisions between the molecules. As per 3.2.1 if two bodies are touching the one with stronger molecular movement will be termed the one with greater temperature. Transferring its internal energy, i.e. heating, will increase the agitation of the second body's molecules by chain reaction. Importantly thermal convection cannot occur in a solid and thermal radiation can only occur in a non-opaque solid such as Germanium (which is why this metal is used in the lens of thermographic cameras). However, thermal conduction can occur in fluids, i.e. liquids and gases, because collisions of molecules can occur.

The measure of how quickly thermal energy is transferred by conduction through a material is **thermal conductivity (λ)** (previously termed k-value), given in units of watts per metre and per kelvin of temperature difference [W/(m·K)]. Conductivity is dictated by the molecular and pore structure of a material and is independent of the material's shape or dimensions. The term **thermal conductance** describes the conductivity of a material that *is* dependent on its shape and dimensions and is therefore given in units of watts per square metre per kelvin of temperature difference [W/(m^2·K)]. Thermal conductance should not be confused with thermal transmittance, or U-value, which is a combination of thermal conduction, thermal convection (where air cavities are present) and radiation. (Section 2.4.5)

Compared to liquids and solids, gases are less conductive. Many insulation materials rely on this fact by having a closed pore structure which entraps less conductive air or other gases within the material. Air is a good insulant, particularly when relatively dry, but some other gases have better insulating properties. Gas layers are therefore commonly used in building construction to improve heat retention, and the entrapping of small pockets of gas within the closed pore structure of non-woven quilt or foam materials is the key principle behind a large number of present-day insulants. (Section 3.1.2)

2.4.3 Thermal convection

Thermal convection is a heat transfer mechanism whereby a fluid is brought into motion, either by gravity or another force, transferring thermal energy from one molecule to another and thus from one place to another. Strictly speaking thermal convection is a combination of thermal conduction (Section 3.2.2) and thermal advection. The latter is solely heat transfer by **bulk fluid flow.** Where a fluid meets a solid surface heat is transferred conductively.

An example of thermal convection in water is the circulation of hot water inside the pipes of a non-pumped, water-based heating system. An example of thermal convection in air is heat transferred from such a heating system through the outside surface of its heating pipes or room heating panels (alongside a proportion of heat transfer through radiation). In a room, these convection currents will occur in the form of air movement. (Section 2.3.1.1) Hence, thermal convection will occur within any room that has surfaces or air supply at different temperatures.

Because air is never completely dry, but always carries a certain quantity of water, movement of air generally involves movement of water. In common usage, this movement of water as part of the airflow is referred to as **vapour convection**. (Section 2.5.2) Because water has a relatively high heat capacity, i.e. it stores a lot of heat easily, moisture convection also involves movement of heat.

2.4.4 Thermal radiation

Thermal radiation is the third mechanism by which internal, or thermal, energy can be transferred. All bodies above absolute zero (0 K or -273.15 °C) radiate energy, even if they are at the same or lower temperature than the surrounding fluid or neighbouring bodies.

> *Thermal radiation is emitted by bodies by virtue of their temperature; the atoms, molecules, or electrons are raised to excited states, return spontaneously to lower energy states, and in doing so emit energy in the form of electromagnetic radiation. Because the emission results from changes in electronic, rotational, and vibrational states of atoms and molecules, the emitted radiation is usually distributed over a range of wavelengths.*
>
> (Duffie and Beckman, 2013, p. 138)

The electromagnetic spectrum extends from wavelengths thousands of kilometres long to those that are a fraction of the size of an atom. The term **electromagnetism** arises because a radiating wave has two fields, one electrical and one magnetic. They are always in phase and inseparable.

All radiation is at the speed of light: in a building, it may be thought of as spontaneous, unlike thermal conduction and convection. It can manifest as a wave or a solid particle depending on what it passes through. The medium also determines the nature of absorption and emission of the spectrum. The electromagnetic waves of the sun reach the upper atmosphere of Earth as photon particles: the sun sends radiation over a wide spectrum but concentrated in the wavelengths that transfer thermal energy. The vacuum it passes through is a perfectly efficient transmitter ensuring minimal loss of its original wavelength spectrum.

The electromagnetic spectrum classifies electromagnetic waves by wave length into the following categories, going from short to long wave lengths: gamma ray, x-ray, ultraviolet, visible, infrared, micro- and radio waves. Figure 11 shows the band over which the wavelengths radiate thermal energy. It includes a small part of the infrared band, all of visible light and the large ultraviolet band.

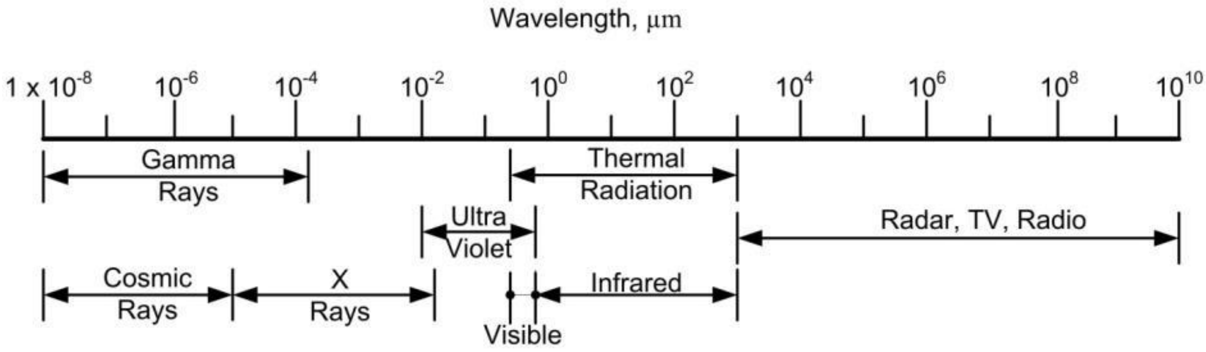


Figure 11 The electromagnetic spectrum is a logarithmical scale

When radiation hits a surface, some of the radiation is absorbed into the body, some is reflected and a portion is transmitted through only if the body is non-opaque (in terms of radiant energy). Thermal radiation hitting an opaque solid body will heat the outer surface with further thermal transfer occurring as thermal conduction, whereas thermal radiation will pass through fluids (such as air or water) heating the fluids *en route*. The heated fluid will then transmit that part of the original thermal energy as thermal convection along with whatever thermal energy it is already transferring.

The ratio in which absorption, reflection and transmission occurs depends on the intensity and wavelength of the radiation and on the material properties. Radiation in the form of visible light (0.4 – 0.7 µm) can, for example, easily pass through an ordinary glass pane, but not through a stone wall, whereas infrared radiation with a wavelength longer than 4.3 µm cannot pass through glass.

Solar radiation can be harnessed to heat buildings – directly or indirectly. As an example direct solar radiation through a patio door will heat the thermally massive internal wall or floor inside. Indirect solar radiation includes the use of solar hot water collectors supplying hot fluids to a water-based heating system. Heating systems based on thermal radiation include the domestic open fire and, through use of piped hot water, under floor heating, radiant wall heating and skirting radiators. What is today generally referred to as 'radiators' are in fact primarily convector heaters, since fins were added to increase the surface area thus making heat transfer to air moving past their large surfaces the dominant heat transfer mechanism.

Infrared radiation can be used in the construction industry to assess the condition and performance of building fabric, by using thermal imaging cameras. The often colourful images of such cameras can be used to investigate heat loss and dampness issues of building fabric.

While an excellent investigation tool, the adjustment needed to obtain a true surface temperature, and interpretation of thermographic images requires suitable expertise, as such images can easily be misinterpreted and their appearance changed. Figure 12 shows two versions of the same thermographic image. The two versions differ with regard to the colour schemes and temperature ranges used. In all cases the temperature scale should be displayed to allow interpretation.

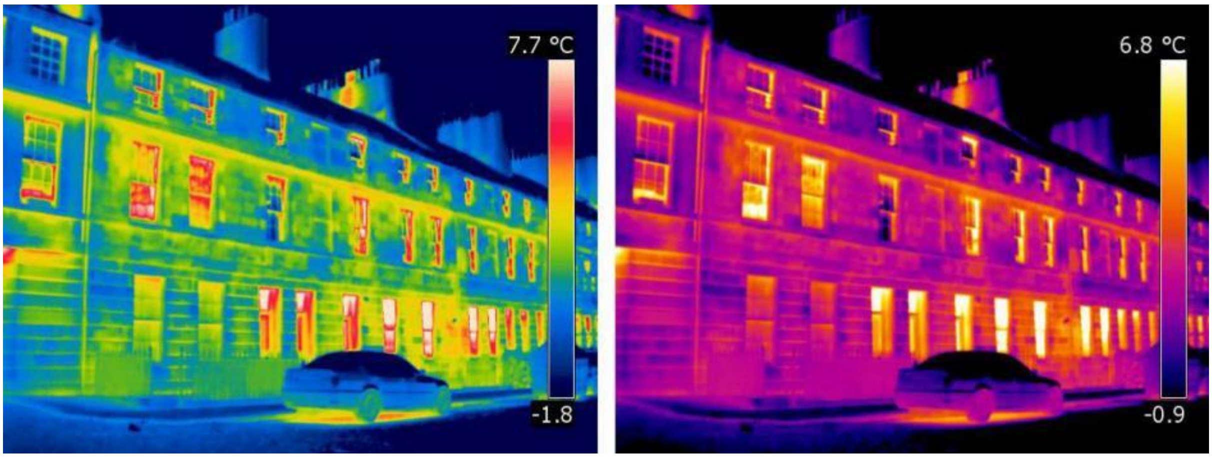


Figure 12 Two versions of a thermogram (infrared image) with different colour schemes and temperature ranges applied

2.4.5 Concurrency of heat transfer mechanisms

The three different mechanisms for heat transfer have been described separately in the sections above. However, in reality, they often occur concurrently and are sometimes difficult to differentiate. To describe this concurrence of the transfer mechanisms for heat flow in materials, the physical property of thermal transmittance is used.

Thermal transmittance, or U-value, describes the rate of heat transfer through one square metre of a structure divided by the difference in temperature across the structure. Thermal transmittance is measured in units of watts per kelvin and per square metre [$W/(m^2 \cdot K)$]. In the USA, it is measured in units of British Thermal Units per degree Fahrenheit and per square foot. Thermal transmittance differs from thermal conduction, in that thermal transmittance is actually a combination of thermal conductions, thermal convection and thermal radiation through the material. (However, radiative or convective properties of material surfaces are not accounted for.) Although thermal conductance is the dominant heat transfer mechanism in solid materials, in loose and porous materials thermal convection and radiation also contribute to their thermal transmittance.

Thermal resistance, or R-value, is the reciprocal of thermal transmittance.

The R-value and U-value are material properties often used in the construction industry to describe the thermal performance of insulating materials. There are established methodologies for calculating U-values: BRE Report 443 is a *Convention for U-values calculations* (Anderson, 2006), and *BS EN ISO 6946* describes a *Calculation methods* for *thermal resistance and thermal transmittance* (BSI, 2007b). However, R-values and U-values relate to heat flow through a plane square metre of material and do not describe heat flow in geometrically more complex situations, such as room corners. How the three-dimensional reality of a building influences heat flow will be discussed in Section 3.1.5.

2.5 Moisture transport

2.5.1 Physical properties of water

Water is practically everywhere on Earth. It covers approximately 75 % of the Earth's surface and is ever-present in the air surrounding us. As with any matter, moisture can exist in different physical states of matter: as a gas, as a liquid and as a solid. However, water "is the only known substance that can naturally exist as a gas, a liquid, and solid within the relatively small range of air temperatures and pressures found at the Earth's surface." (NASA, 2010)

2.5.1.1 States of matter

There are three physical **states of matter**: solid, liquid and gaseous. Matter can change between the different states depending on the environmental conditions, namely pressure and temperature. These changes are called **phase transitions**. Matter can change from being a gas into being a liquid into being a solid; the changes between these states are called condensation and freezing respectively. Conversely, matter can change from a solid into a liquid and then into a gas, with the phase transitions being called melting and vaporisation respectively. (Vaporisation can be in the form of evaporation, which only occurs on surfaces, or in the form of boiling, which can occur below surfaces. This report will refer to this phase transition as only evaporation.) The various states of matter and the terms related to its phase transitions are illustrated in Figure 13. (There is a fourth state of matter, plasma, but, as this is generally of no relevance in a building context, it has been ignored in this report.)

Under everyday conditions, water can exist as a solid, a gas or a liquid. It is then normally referred to as ice when in its solid state, as liquid water when in its liquid state and as water vapour when in its gaseous state. In nature, for example, water occurs as ice or snow (solid water); as rain or river (liquid water); and as a clear gas in the air (water vapour). The above mentioned names for phase transitions – freezing and melting; condensing and evaporating; and depositing and sublimating – do obviously apply to water. The term thawing is sometimes used in lieu of melting.

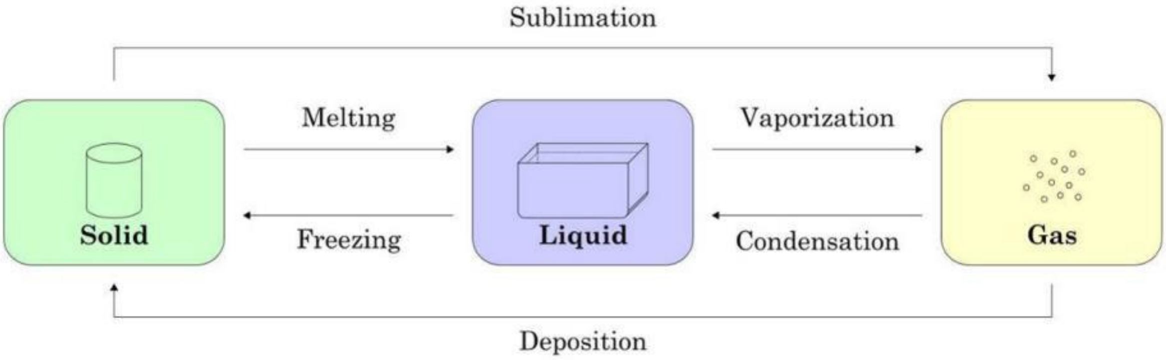


Figure 13 Physical states of matter and terms related to the phase transitions (compare to Figure 15). (ElfQrin, 2011 / Image © ElfQrin CC BY-SA 4.0)

Liquid water can freeze into ice and melt back into liquid water; water vapour can condense – think of the water droplets on bathroom tiling after a shower – and can evaporate, for example when washing is hung up to dry. Examples for water deposition are snow forming in clouds or frost forming on the ground. And the process of water sublimation occurs when wet clothing is hung outside on a winter day under freezing condition, with the water in the cloth first freezing and then sublimating, resulting in the drying of the clothes.

Air always contains water vapour, unless completely dried under laboratory conditions. But air can also contain small quantities of liquid water, e.g. water droplets in the form of clouds, mist or rain; and also small quantities of solid water, e.g. snowflakes or hailstones. Solid water does not often occur in indoor air, i.e. air within a building. Liquid water in indoor air generally results from cooking or showering, e.g. steam rising from a boiling cooking pot, but quickly evaporates into invisible vapour or settles onto a surface.

In addition to indoor air, moisture can also exist within materials or, more strictly speaking, exist within the pore structure of materials. This pore structure is the 'pathway' which allows moisture transport into, within and out of materials, as has been discussed in Section 3.1.4.

In a building context, at least in a climate such as that of Ireland or the UK, it is mostly the processes of condensation and evaporation and the absorption of liquid rain water that are of relevance for assessing the performance of building fabric, and will therefore be discussed in more detail below. Melting and freezing are of relevance when discussing the moisture-related deterioration of exterior building surfaces; this is known as freeze-thaw damage, or freeze-thaw weathering, and will be discussed in Section 3.2.2.3.

2.5.1.2 Density of water

Water has the lowest density when in its gaseous state. In water vapour, the molecules are further apart than in liquid or solid water, and, therefore, requires more space for the same quantity of molecules. In liquid water, the water molecules are closer together than in water vapour; therefore, liquid water has a higher density than water vapour and requires less volume for the same number of molecules. One could now assume that a similar relationship exists with solid water: that the molecules in solid water are closer together, and that it, therefore, requires less volume and is denser. Indeed, this relationship applies to most matter, but not to solid water. Water in its solid state, i.e. when it is ice, is less dense than liquid water at a low temperature. Water expands, if not confined, to occupy 9 % greater volume in this solid state. This is the reason why icebergs can float in the sea. However, it also means that water which freezes expands in volume.

If this phase transition from liquid to solid water occurs in a confined space, the increase in volume results in an increased pressure on the space boundary. This can be experienced when water in a pipe is allowed to freeze, bursting the pipe and resulting in leakage after thawing. This is why, to avoid such damage, outdoor water pipes need to either be drained before the winter or be placed sufficiently deep underground to protect the contained water from freezing. Similarly, moisture within building materials can cause damage if it freezes and thaws, e.g. in the form of surface spalling. The impact of such freeze-thaw damage is describe in more detail in Section 3.2.2.3.

2.5.1.3 Polarity of water

Water molecules consist of one oxygen and two hydrogen atoms, hence its chemical symbol H_2O. Due to the spatially unbalanced way the atoms are positioned relative to each other, water molecules have a slightly positive side near the hydrogen and a slightly negative side near the oxygen. (Figure 14) This phenomenon is called **polarity** and makes the molecules act like tiny magnets, easily connecting with each other, by forming chains and clusters of molecules, and with other matter, e.g. particles in the air or a material's surface.

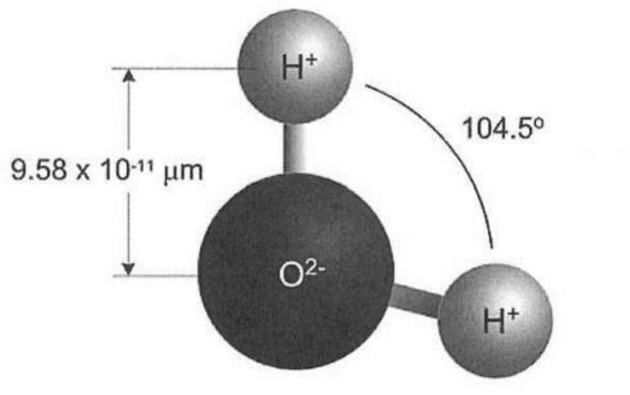


Figure 14 Illustration of a water molecule (H_2O) showing the spatially unbalanced distribution of the two hydrogen molecules to the oxygen molecule. (Straube, 2006a, p. 2, fig. 2 / Image © Building Science Press)

When water is in the form of vapour, it consists mostly of single water molecules moving relatively freely; in its liquid state the water molecules are unconnected, but drawn together into 'clumps'; and when a solid, the molecules connect with each other, forming a solid network. (Figure 15) This means that one gaseous water molecule is smaller than a 'clump' of several molecules forming liquid water, which again is smaller than the molecular networks solid water is made of. The size difference between the single molecules of water vapour and the molecule 'clumps' of liquid water is particularly important for some membranes used in building construction and clothing: these membranes have pores large enough to allow the small water vapour molecules to pass through, but are too small to allow larger 'clumps' of liquid moisture to pass. Examples for such membranes are in clothing 'waterproof-breathable' fabrics, such as Gore-Tex or SympaTex, and in building construction 'breather' membranes, such as DuPont's Tyvek or Glidevale's Protect TF200. (The use of such membranes in the retrofit of traditional buildings will be discussed in more detail in Section 3.1.2.)

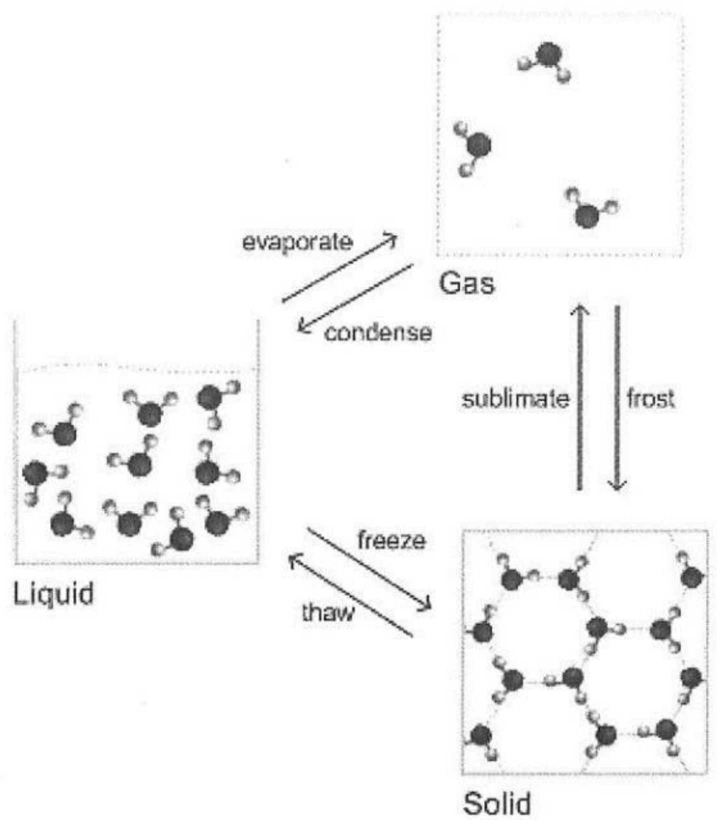


Figure 15 Diagram showing the different physical states of water and the phase transitions processes (compare to Figure 13). (Straube, 2006a, p. 2, fig. 1 / Image © Building Science Press)

2.5.1.4 Sorption and desorption

The polarity of water does not only affect how water molecules bond to each other, but also how easily they bond to the surfaces of solids. The process of adhering to a surface is known as **adsorption** and depends on the chemical composition of the material's mass. The term adsorption should not be confused with **absorption**, which describes moisture being drawn from a material surface into its pore structure. Together the phenomena absorption and adsorption are called **sorption**, sometimes also described as *wetting*. The reverse process to sorption is **desorption**, also described as *drying*, which "occurs most commonly by evaporation." (Hall and Hoff, 2012, p. 1) A measure of the capacity of a material to absorb or desorb liquid (by capillarity) is **sorptivity**. It is measured over time and is generally stated in units of millimetre per minute [mm/min].

2.5.1.5 Hydrophilicity / hydrophobicity and hygroscopicity

How easily water molecules can be adsorbed to a material's surface or absorbed into its pore structure is described with the terms hydrophilicity and hydrophobicity for adsorption and hygroscopicity for absorption.

Hydrophilicity and **hydrophobicity** describe to what degree a material surface attracts or repels water molecules respectively. This is a result of the chemical composition of the material's mass, both on the outer material surface and on the surface of the pore structure. A surface is **hydrophobic** if it tends to repel rather than adsorb water, as can be observed by water 'beading' on a surface. A surface is **hydrophilic** if it tends to adsorb water, as can be seen by water 'sticking' to a surface. (Figure 16) Waxes and resins are, for example, hydrophobic materials; glass and plasters are examples of a hydrophilic material.

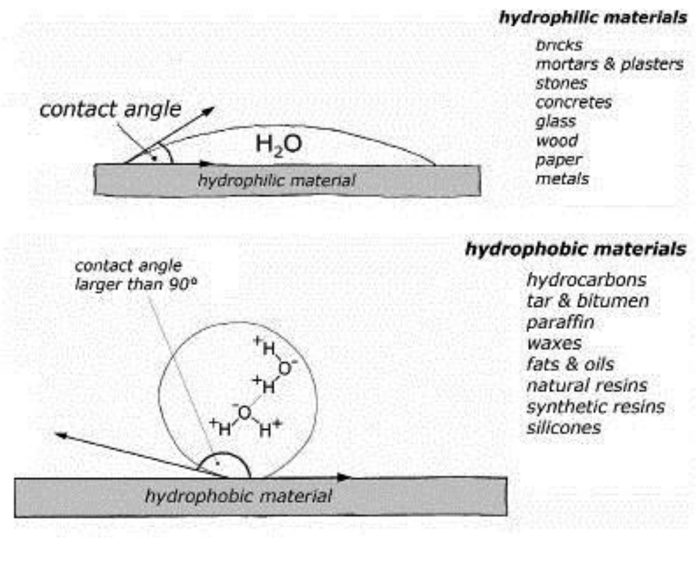


Figure 16 Graphic illustrations of hydrophilic and hydrophobic material surfaces (Torraca, 2009, p. 36, fig. 1.74 and 1.75 / Image © The J. Paul Getty Trust)

Whereas hydrophilicity and hydrophobicity describe water adsorption to surfaces, **hygroscopicity** describes the degree to which moisture is absorbed into a material's pore structure. A hygroscopic material is able to absorb vapour from the air and the water molecules within it into its pore structure without the material appearing to be 'wet'. For example, a starched cotton napkin on a humid day will absorb water vapour from the air: the moisture interacts with the material, e.g. it may not hold its shape as well, but, even with this moisture, the napkin does not feel wet. In comparison, a plastic grocery bag is the same on a dry day as it is on a humid day, because plastic does not absorb vapour. If there is condensation, the plastic bag will get wet as the dew lands on it. The hygroscopic napkin will absorb the vapour out of the air before it condenses into dew and will therefore only become 'wet' with liquid water when the material has absorbed as much vapour as its pore structure can hold. This means that hygroscopic materials are less prone to surface condensation and can help moderate humidity changes in a room by absorbing and desorbing vapour. Often the term hygroscopic is wrongly used to describe permeability, i.e. the ability moisture to enter or pass through a material, Section 2.3.2.4). Strictly speaking, hygroscopicity describes the degree to which the material's mass absorbs and desorbs vapour from the surrounding environment and how that vapour is held within the material's pore structure.

2.5.1.6 Psychrometrics

As already mentioned, air is a gas mix which, under everyday conditions, contains some water vapour. This moisture-laden air exists all around us, but also exists in the pore structures of materials. Moisture is, hence, omnipresent in buildings and in their fabric. Predicting moisture movement is unfortunately very complex. Water can exist in the pores of the same material in all three states of matter simultaneously and can be changing between phases when the environmental conditions change. The branch of science concerned with the physical and thermodynamic properties of 'moist air', i.e. water vapour in a body of air is **psychrometrics**, sometimes also referred to as psychrometry or hygrometry. (It should not be confused with psychometrics, a psychological discipline.) Psychrometrics explains how environmental properties, including temperature, humidity and pressure, impact on gas-vapour mixes. The property of temperature has already been introduced in Section 2.4.1; those of humidity and pressure are introduced below.

Pressure is a force applied to an area. It can be stated in a variety of units, including units of atmosphere [atm], bar [bar], newton per square meter [N/m^2], pascal [Pa] and pounds per square inch [psi], with $1\ Pa = 1\ N/m^2$ and $100\ kPa = 1\ bar \approx 1\ atm \approx 14.7\ psi$. The latter is roughly the pressure of the atmosphere on the Earth at sea level. Variations in atmospheric pressure, even slight ones, can obviously be significant for weather events. Such variations can also have an impact in building physics, as total pressure variations affect vapour transport.

Every gas, including air and water vapour, has a pressure. Air is a mixture of gases, the overall pressure of which is called **air pressure**. However, because air consists of different gases, the pressures of each of these gases can also be considered independently. The relationship between these different pressures is governed, chemically and physically, by Dalton's Law of Partial Pressures. This law states that, when a gas is made of many components, the individual gases will each have their own pressure, their so-called partial pressure. The sum of these partial pressures is the air pressure. However, the individual partial pressures are independent of each other. It is as if all the gases ignore each other, and the partial pressure of each gas depends only on the number of molecules of that particular gas. (Figure 17) Therefore, when discussing water vapour, the partial pressure of the vapour, or the **vapour pressure**, is directly related to the number of vapour molecules present.

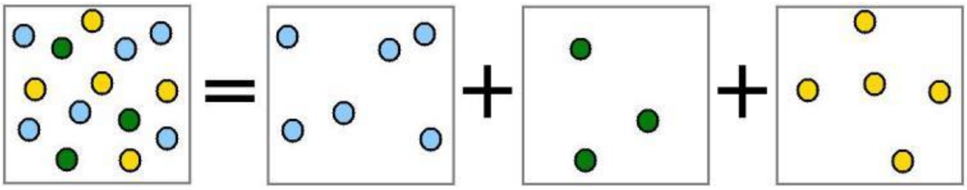


Figure 17 Diagram illustrating the relationship of overall and partial gas pressures: the total gas pressure is the sum of the partial pressures of each particular gas.

Humidity describes the amount of water vapour in the air. There are different ways of quantifying how much vapour is present and, therefore, different terms for discussing humidity. The mass of water vapour in a certain volume of air is normally referred to as **absolute humidity**, generally measured in units of gram per cubic metre [g/m^3]. However, since the volume of air changes with temperature, absolute humidity can also change with temperature, even if the amount of vapour remains constant. To avoid any temperature dependence, the term **humidity ratio** used, which is the mass of water vapour per mass of dry air, generally measured in units of grams of water per kg of dry air [g_w/kg_a]. Absolute humidity and humidity ratio are both distinct from relative humidity, which will be introduced shortly.

Under normal everyday conditions, water can easily change between the liquid and gaseous phase, depending on temperature. For any given temperature, there is a clearly defined maximum amount of water vapour that can exist in the air. Since absolute humidity and vapour pressure directly relate to the number of molecules present, there is for that particular temperature a maximum amount of absolute humidity and a maximum vapour pressure. The latter is also called **saturation vapour pressure**. Because the saturation vapour pressure is dependent on the temperature, it can be illustrated as a graph. (Figure 18) When the saturation vapour pressure is reached within a body of air, the air is said to be **saturated**.

Higher temperatures have higher saturation vapour pressures, as can be seen from the graph in the figure above. This is often thought of as *warmer air can hold more moisture*, which also implies that *cooler air can hold less moisture*. Thus, if moist air is cooled, it loses its ability to 'hold' moisture and will eventually reach a point at which it becomes saturated. If it is cooled beyond this point, **condensation** will occur, which means that (some of the) water vapour will change into liquid state by forming water droplets, called condensate or dew. The temperature at which this occurs is the **dewpoint temperature**, often simply referred to as the dewpoint. In other words, the dewpoint is the temperature at which condensation occurs (regardless of the properties of the surrounding materials). This is the same as saying that it is the point at which the air is saturated or that the saturation vapour pressure has been reached.

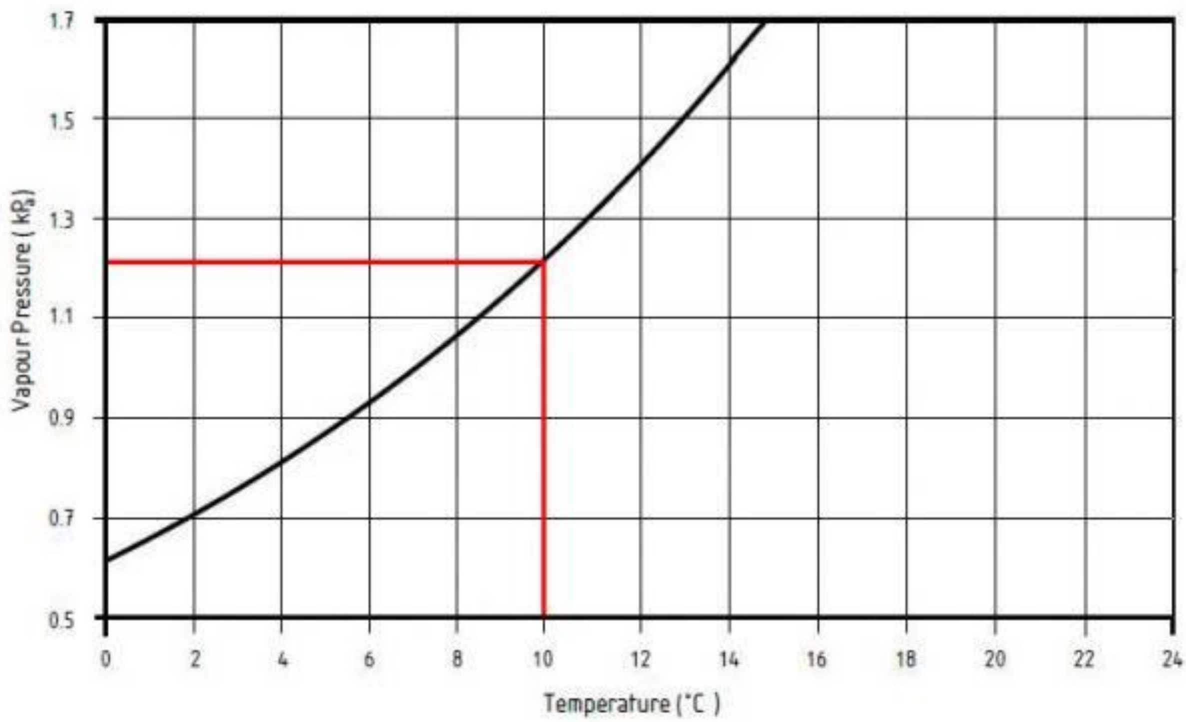


Figure 18 Graph illustrating the saturation vapour pressure (curved line) as a function of temperature and vapour pressure: in this example, the saturation vapour pressure is approx. 1.2 kPa at a temperature of 10 °C. (compare to Figure 19). (BSI, 2011, p. 21, fig. C.1 / Image © The British Standards Institution)

It is useful to know how close a body of air is to reaching this state. This is described by the term **relative humidity (RH)**, which is the ratio between the current vapour pressure and the saturation vapour pressure corresponding to the current temperature. It is measured as a fraction between 0 and 1, or as a percentage. Thus 1.0 or 100 % RH corresponds to the dewpoint.

The relationship between current vapour pressure and saturation vapour pressure is illustrated in Figure 19, which shows a simplified **psychrometric chart**. The 100 % RH curve indicates at which temperature and vapour pressure conditions condensation will occur. The other RH curves are not relevant for condensation, but are important for assessing some forms of moisture-related deterioration and mould growth, which occur at lower relative humidity levels. A psychrometric chart is therefore helpful to understand at which combinations of temperature and vapour pressure critical moisture levels are reached. (Moisture-related deterioration and mould growth are discussed in Section 3.2.2. How to assess the risk of their occurrence is described in more detail in Section 4.5.

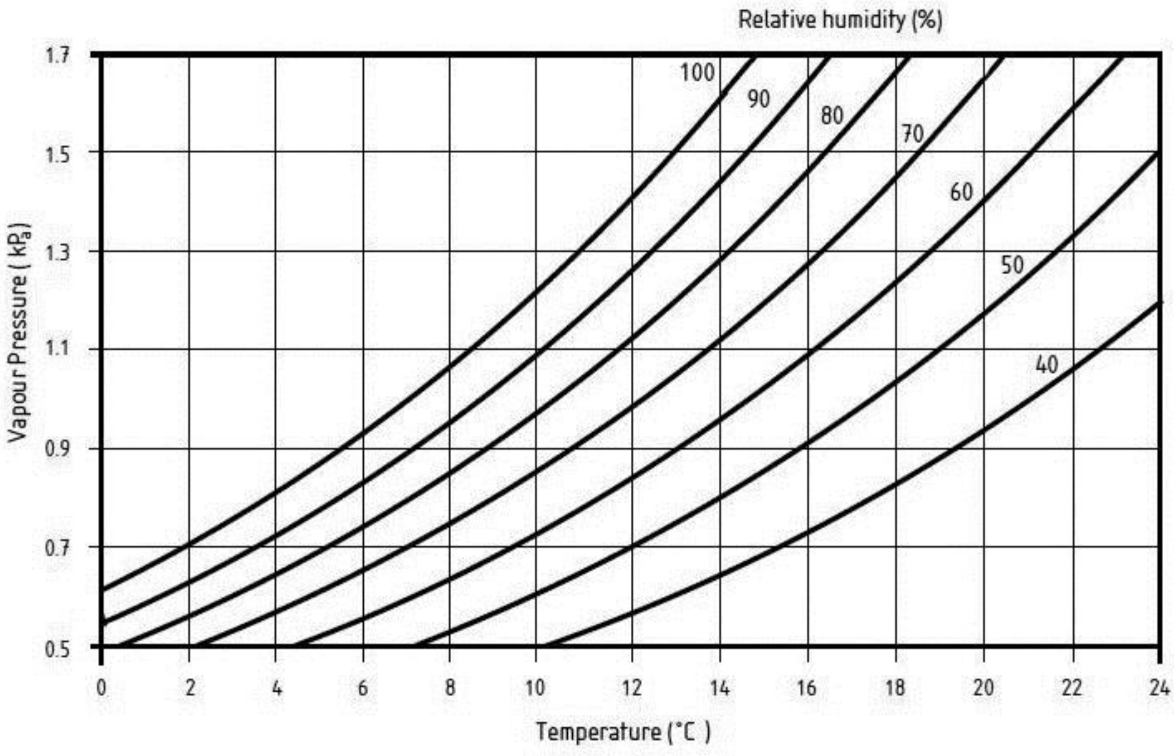


Figure 19 Simplified psychrometric chart showing the relationship between temperature (x-axis), vapour pressure (y-axis) and relative humidity (heavy lines): condensation will occur at 100 % RH, the graph of which indicates saturation vapour pressure and dewpoint temperature. (compare to Figure 18) (BSI, 2011, p. 21, fig. C.1/ Image © The British Standards Institution)

Condensation can, for example, be experienced in a bathroom after having had a shower, which has raised the level of relative humidity to 100%. It can then generally be seen as **surface condensation** on non-porous material surfaces, such as glazed tiles or glass, which cannot absorb moisture. It does not generally occur on surfaces of porous materials, as these can absorb the occurring condensate into their pore structure. However, condensation can not only occur on visible surfaces, but also on the surfaces forming the pore structure of a permeable material and on the surfaces within a building element where two materials abut each other. The condensation is then referred to as **interstitial condensation,** which will be explored further in Section 3.2.1.1.

Because psychrometry is so important for understanding the moisture behaviour in buildings and their fabric, it is worthwhile discussing a good example of a psychrometric chart to understand what information it can provide. The example used here has been taken from *BS 5250:2011*, the British Standard concerned with condensation control in buildings. The example chart in Figure 20 demonstrates the relationship between relative humidity and dewpoint. The curved lines show relative humidity, the 100 % line being saturation (dewpoint).

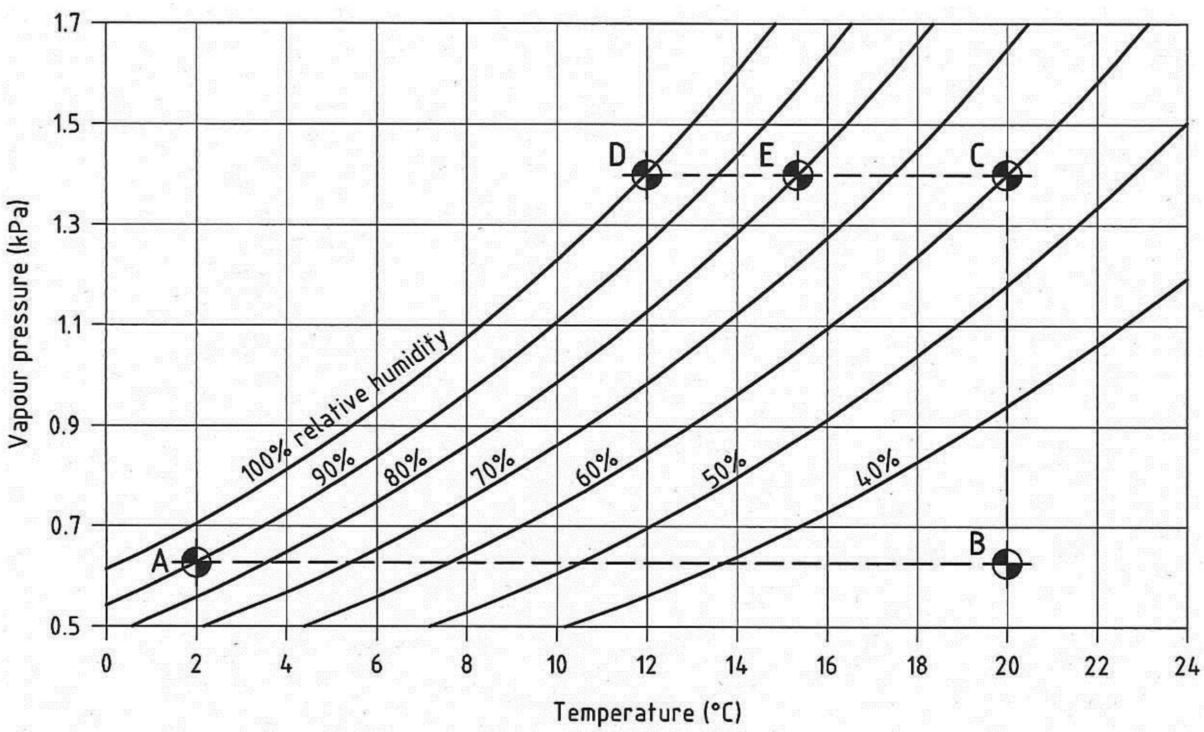


Figure 20 Psychrometric chart with five points (A to E) illustrating exemplarily how to read such charts. (BSI, 2011, p. 21, fig. C.1/ Image © The British Standards Institution)

Point A represents a given volume of air at temperature 2 °C with a vapour pressure of 0.60 kPa: its relative humidity is therefore 90%.

Point B represents that same volume of air, with the same moisture content (and, therefore, the same vapour pressure) but heated to 20 °C; its relative humidity will now be approximately 24%. This illustrates what happens when outside air enters a building and is warmed.

Point C indicates that same volume of air at 20 °C, to which moisture has been added to bring its vapour pressure to about 1.4 kPa. That increase in moisture with no change in temperature means the relative humidity of the air has increased to about 60%. This illustrates what happens when that warmed incoming air absorbs moisture from activities within a building, but is not heated.

Point D illustrates that saturation of that air will occur if it is cooled to its dewpoint temperature of about 11.9 °C; any further reduction in temperature will result in condensation occurring.

Point E on the chart indicates that 80% RH will occur if the temperature of the given volume of air falls to approximately 15 °C. The risk of mould growth occurring when relative humidity at a surface reaches 80 % … This illustrates that designing to avoid surface mould growth is more onerous than designing to avoid condensation.

(BSI, 2011, p. 21)

In the previous sections, the physical properties of water in its different states of matter and its behavioural relationship with air have been described. In the following, four distinct mechanisms of moisture transport will be discussed: vapour convection (Section 2.5.2), vapour diffusion (Section 2.5.3.1), surface diffusion (Section 2.5.3.2) and capillary transport (Section 2.5.4). Thereafter, the combined effects of these transport mechanisms will be described. (Section 2.5.5)

2.5.2 Vapour convection

Because water vapour is a component of air, movement of air will always entail vapour transport. This transport mechanism is called **vapour convection.** It relies on bulk fluid flow, in this case the movement of a body of air. Without air movement to transport the moisture, vapour convection cannot occur. In other words: still air, i.e. still-standing or immobile air, cannot transport moisture by convection. (Air can also transport small quantities of liquid moisture in the form of droplet, such as steam when cooking. So strictly speaking, the term moisture convection should be used to include both transport of gaseous and liquid moisture. However, this report refers to vapour convection, as this is the more commonly used term.)

Bulk fluid flow cannot generally occur in solids, as the pores of the materials are simply too small. Therefore, moisture convection cannot occur within building materials, with exceptions discussed in Section 3.1.6.3. However, it can occur through gaps and within air spaces and cavities in the building envelope.

As vapour convection is moisture transport by air flow, it requires an understanding of air movement. This has already been discussed generally in Section 2.3.1. For example in the context of a room, the air circulation, or convective air current, results in the moisture in the air being circulated around the room, too, following the flow path of the air body. The physical phenomenon by which *warm air can hold more moisture than cold air* has already been described in Section 2.5.1.6. This phenomenon can now applied to the just described example for a convective air current: air will take up (more) moisture in a location where the air is heated up. It will then transport this moisture as part of its body to colder locations, where the air will cool down and can thereby no longer hold the same moisture quantity as before. Due to this, some of the moisture in the air will condense, forming liquid droplets. If, for example, a cold window surface existed in the location where the air cools down, condensation would form on the window glass. This example illustrates how a convective air current can cause moisture transport.

Vapour convection can occur not only in a single room, but throughout a building and into and out of a building. A common example for convection within a building is moisture produced by cooking in a warm kitchen, which is, if doors are left open, then circulated into colder living and bedrooms, where the moisture can condense on cold, non-hygroscopic surfaces, such as single-glazed windows. Whether the air movement by convection transports moisture into the building (or into vented cavities within the building fabric), or it transports the moisture out of the building, depends on indoor and outdoor humidity, pressure and temperature level. On a rainy and windy day, moisture might be transported through convection into a building, particularly if, for example, windows and doors are being left open. On a sunny and dry day, the opposite might occur, with the air movement removing moisture from the building.

To control convective moisture transport independently from indoor and outdoor pressure and temperature differences forced convection is often used. This normally comes in the form of mechanical fan ventilation systems, by which the fan forces air flow in one direction. Mechanical ventilation can be an efficient method of removing larger quantities of moisture quickly from a room to the outdoors and is therefore often used in rooms where larger quantities of moisture are often produced, such as bathrooms, kitchens and utility rooms.

Convection is a complex physical phenomenon transporting air, heat and moisture (and other fluids or particles). Convection transports moisture and heat much faster than diffusion, described in Section 2.5.3. In theory, vapour convection should not occur in most building fabric. In practice, however, air movement and with it moisture transport occur through construction gaps, internal cavities and within air-filled materials. Convection, therefore, cannot be ignored when assessing the hygrothermal performance of building fabric, as will be discussed further in Section 3.1.6.

2.5.3 Diffusion

Diffusion is the movement of molecules due to differences in concentration, driving particles from areas of high concentration to areas of lower concentration. Diffusion differs from convection in that diffusion does not require a current. The simplest example of diffusion is a drop of dye being added to a still glass of water. The colour from the dye will spread out from the high concentration in the initial droplet to the low concentration in the clean water, until eventually it is uniformly distributed. This also occurs within gases, such as water vapour in air; even with no convective air currents, moisture from areas of high humidity, i.e. areas with a high concentration of water vapour, such as a bathroom after a shower, will migrate to the rest of the house, where there is comparatively little vapour. At a much smaller scale, it also occurs within the air filling the pore structure of a solid material. It, therefore, differs from vapour convection also in another way: it can occur within some solid materials, depending on their pore structure.

It was already noted that diffusion occurs in a mix of fluids, when a concentration gradient is present. However, to complicate things further, there is a different form of diffusion that occurs at the surfaces surrounding such a fluid mix. To distinguish between the two, the terms **bulk diffusion** and **surface diffusion** are sometimes used to refer to diffusion in the free fluid and diffusion due to surface impact. Bulk diffusion, in the context of this report, is generally the diffusion of water vapour in air, more simply referred to as water vapour diffusion or just **vapour diffusion**. It will be discussed in the next section, followed by surface diffusion. (Section 2.5.3.2)

2.5.3.1 Vapour diffusion

The difference in vapour pressure is the **driving force** for vapour diffusion. Reversely, it will always act to distribute vapour molecules to equalize vapour pressure. Vapour diffusion and vapour pressure are inextricably linked. However, temperature also plays an important role.

As vapour diffusion is driven by the gradient of vapour pressure, diffusion always goes from regions with high vapour pressure towards regions with low vapour pressure. (Figure 21) But this is not the same as saying that vapour diffusion always goes from areas with greatest to least amount of moisture. In a situation with non-constant temperatures, it can happen that vapour pressure and absolute humidity have opposite gradients. In these cases, diffusion goes from a region with low absolute humidity towards a region with high absolute humidity.

If the temperature is constant across a wall, vapour pressure and relative humidity are proportional to each other. If one of them is constant, the other one is constant, too. If one of them has a gradient, the other one has a gradient in the same direction. However, if temperature is not constant across the wall, the two are no longer proportional. If one of them has a gradient, the other one may have a gradient in the same direction or in the opposite direction, or it may be constant, depending on how temperature varies.

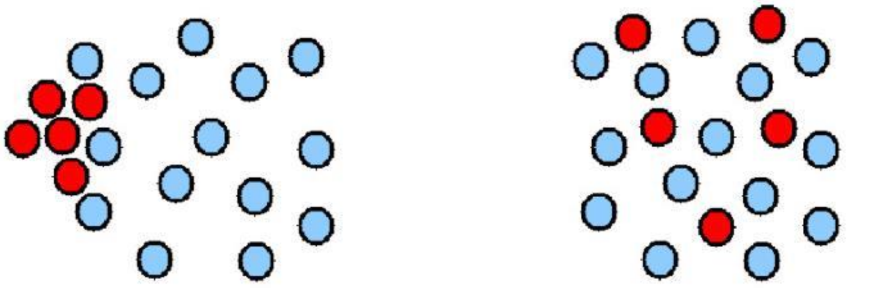


Figure 21 Diagram illustrating equalising pressures and vapour movement

Consider the examples of a house in each of the following climates:

1. In the Sahara, it is hot and dry outside (high external temperature and low relative humidity) → vapour moves from inside to outside

2. In Florida in the summer, it is hot and humid outside (high external temperature and high relative humidity) while air conditioning makes internal conditions cooler and drier → vapour moves from outside to inside

3. In Scotland in the winter, it is cold and damp outside (low external temperature and high relative humidity) → vapour moves from inside to outside

In cases 1 and 2, vapour diffusion moves from high to low relative humidity. In case 3 however, the transport process goes in the opposite direction, with vapour being transported from low to high relative humidity. This is because, at low temperatures, air cannot hold much moisture. Even small amounts of vapour, therefore, result in a high relative humidity. However, as it is only a small amount of vapour and as the temperature gradient thought the walls is from the inside to the outside, the resulting vapour pressure gradient drives diffusion from the inside to the outside also.

Diffusion occurs through still air and, more slowly, through the pores of porous materials. The rate of diffusion through a material is affected by the properties of that material, which are particularly dependent on the form of its pore structure, as has been discussed in Section 0. How difficult it is for vapour to move through a material, compared to still air, is described with the unit-less **water vapour diffusion resistance factor (μ-value)**, sometimes also referred to as vapour resistance factor or diffusion resistance factor. This value reflects the combined impacts of pore size, pore connectivity and tortuosity (Section 2.3.2.4).

There is an abundance of terminology used to describe the ability of vapour to move through porous materials. Like the μ-value, vapour resistivity, measured in units of meganewton seconds per grams and per metres [(MN·s)/(g·m)], describes the inherent characteristic of a material to inhibit moisture diffusion. Vapour permeability is the inverse of vapour resistivity. Similarly, the **equivalent air layer thickness (s_d)** is a measure of the actual resistance of a particular thickness of a material (given as metres of still air). And vapour resistance [MN·s/g] and its inverse, vapour permeance, measure resistance or lack of resistance of a specific width of material. The various terms described above can be converted from one to another. Regardless of the term used, vapour diffusion, like thermal conduction, is governed by the properties of the material.

A material with a low μ-value can be called **vapour-open**, whereas a material with a high μ-value is referred to as **vapour-closed**. By definition, still air has a μ-value of 1. Obviously, the terms *vapour-open* and *vapour-closed* are related to the respective terms *open-pore* and *closed-pore*, when describing a material's pore structure and permeability. Generally, the more open-pore a pore structure, the more permeable and vapour-open it is, and the lower is its water vapour resistance factor; and vice versa.

Table 1 lists μ-values for a selection of materials. Two values are listed for each material, known as dry- and wet-cup μ-values. They are based on measurements where material was placed between a sample 'cup', which has a relative humidity of 3 % for the dry-cup and 93 % for the wet-cup, and the surrounding environment, which is maintained at 50 % RH. Thus, it is the resistance of the material preventing the vapour diffusing from the cup to the room.

Product / material / media	**Water vapour resistance factor μ**	
	Dry	Wet
Air	1	1
Bitumen, pure	50000	50000
Concrete, medium density	100	60
Fibreboard, incl. MDF, ρ=400	10	5
Glass	∞	∞
Granite	10000	10000
Gypsum or lime plasters with sand	10	6
Gypsum plasterboard	10	4
Iron, cast	∞	∞
Limestone, hard	200	150
Mineral wool	1	1
Phenolic foam	50	50
Plywood, ρ=500	200	70
Sandstone	40	30

Timber, ρ=500	50	20
Timber, ρ=700	200	50

Table 1 Values of water vapour resistance factor for selected materials for comparison; values as listed in *BS EN ISO 10456:2007* (BSI, 2010)

The use of the dry-cup and wet-cup method is a generally accepted means of measuring and reporting μ-values. However, there is still debate if this entirely captures the complex phenomena at work.

> *Measurements of μ which are performed at different levels of relative humidity (dry-cup and wet-cup) may result in different values for one and the same material. This is due to surface diffusion which becomes noticeable at higher humidities but is more properly treated as liquid transport. This additional moisture transport is usually not separated out in the analysis of the measurements and, lumped together with vapour diffusion, reduces the apparent diffusion resistance, resulting in a lower μ-value.*
>
> (Fraunhofer, 2009)

This means that the earlier tabled dry-cup and wet-cup μ-values are an over-simplification, causing an additional moisture transport mechanism, surface diffusion, to be masked.

2.5.3.2 Surface diffusion

Vapour diffusion describes the movement of gaseous water molecules in air. If these molecules come into contact with the surface of a hygroscopic material, e.g. within the material's pore structure, the water can condense through adsorption, changing from vapour into a liquid. This condensation by adsorption is slightly different than the condensation described previously in Section 2.5.1.6, because it is not strictly tied to saturation and dewpoint temperature. It is rather that the molecular forces close to the surface are strong enough to pull nearby water molecules out of the vapour into a liquid state on the surface. (Section 2.5.1.4) The higher the relative humidity, the more easily the water molecules condense in this fashion. This only occurs on material surfaces to which water molecules can adhere, namely hydrophilic surfaces. This is illustrated in Figure 22, showing how water molecules can 'cling' to the surfaces of the pores of a material.

Once on the surface, these molecules do not necessarily stay in one place. If sufficient liquid water is available, it will form a water film, which will allow water molecules to move further along the surface to dried locations. This means that the molecules of the water film will move from locations of higher relative humidity to locations of lower relative humidity. This mechanism of liquid transport on solid surfaces is referred to as **surface diffusion**. This transport mechanism is an important and integral part in understanding moisture transport in porous materials, but is often neglected in hygrothermal building fabric assessments. One of the reasons for this may be twofold: vapour transport by diffusion has long been recognised in the commonly used risk assessment methods, and liquid transport by capillary forces, although less commonly considered in risk assessment, is still far easier to observe in practice.

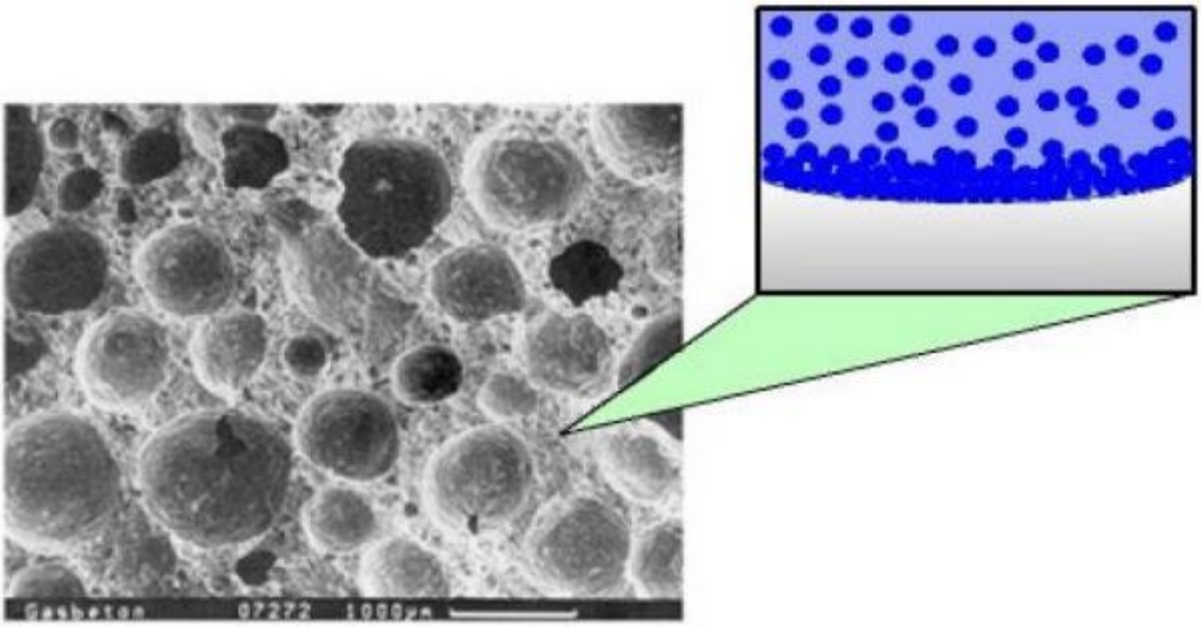


Figure 22 Microscopic photo of a pore structure and graphic illustration showing how the liquid water can adhere / be adsorbed to the surfaces of pores. (Fraunhofer IBP / Image © Fraunhofer-Gesellschaft)

2.5.4 Capillary transport

Capillary transport is the mechanism that draws liquid through a material's pore structure, when completely filling the pore spaces. Capillary transport occurs without the assistance of, and sometimes in opposition to an external force, such as gravity. Capillary attraction, or **capillarity,** describes the ability of water to do this. **Capillary action**, capillary suction and 'wicking' are analogous terms describing the effect, while **capillary active** refers to materials that exhibit a particularly strong wicking action. A good example of a capillary active insulation material is calcium silicate board, which has been specially engineered to have a preponderance of narrow capillaries.

Capillary transport is most obvious when liquid is seen rising up the uniform, narrow tubes used in a laboratory. Other examples of capillary transport are paint being drawn between the fibres of a brush, wax rising up a lit candle wick, a droplet of water being drawn into a paper towel, and rising damp in a stone wall.

Figure 23 illustrates liquid transport by capillary action graphically (left side of figure) and with two photographs showing wicking over time in two porous blocks.

Capillary transport can also occur outside a material's pore structure, in any form of narrow joint or gap, for example, cracks in a mortar joint or gaps between window cills and the surrounding wall construction. Capillary action can thereby be responsible for the transport of liquid water deep into a wall construction that otherwise may display desirable weather-resisting properties.

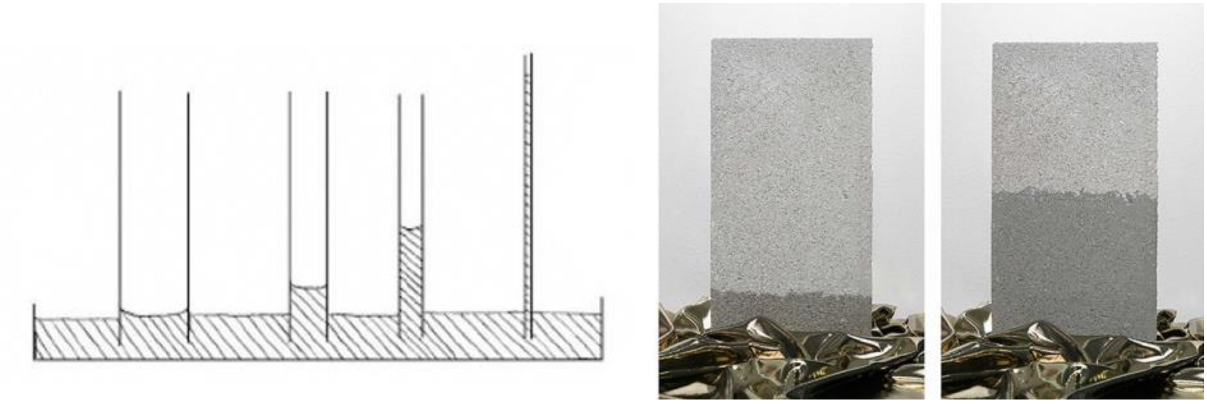


Figure 23 Liquid water risen vertically due capillary transport, illustrated graphically (left) and with two photographs showing rising water transport in a concrete block over time (right). (Left image: Torracca, 2009, fig. 3.17 / Image © The J. Paul Getty Trust) (Right image: Image © APN MJM CC BY-SA 3.0)

"The predominant moisture transport mechanism in capillary porous materials is the capillary liquid transport." (Fraunhofer IBP, 2008) In other words, more water is transported through capillary transport than through surface or vapour diffusion. It is therefore worth examining capillary transport in more detail.

Sorptivity is "the tendency of a material to absorb and transmit water and other liquids by capillarity" (Hall and Hoff, 2012, p. 102) and was already mentioned in Section 2.5.1.4, when discussing the sorption.

The processes by which capillary transport occurs are complex. In simple terms, the forces that attract water molecules to a surrounding surface (adhesion) draw the water in contact along the surface. This forms a curvature at the surface called a meniscus. The forces that bind the water molecules together (cohesion) pull a column of water as the surface is drawn along. In narrow capillaries, there is proportionally more surface area in contact with the water column. Therefore, adhesion forces play here a larger role, compared to those occurring in wider capillaries. Large capillaries can receive more water (at the source), but narrow ones experience a greater suction and draw the water received further. (Figure 24)

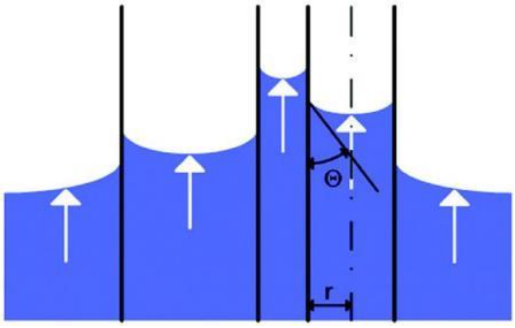


Figure 24 Capillary ascension in ideal material pores due to capillary pressure (Fraunhofer IBP / Image © Fraunhofer-Gesellschaft)

Capillary transport is similar to surface diffusion in that it is liquid transport in the direction from a ‘wetter’ to a ‘drier’ location. However, for capillary transport to occur, sufficient quantities of liquid water need to be available at the ‘wet’ location to fill the pore spaces, rather than just forming a water film on the pore surfaces, as is required for surface diffusion. The difference in the water content between the wetter and drier locations is the driving force for capillary transport.

> *The equilibrium state of the water in an unsaturated porous material is characterized by its capillary pressure function Pc(ϑ). We may therefore regard this as the defining capillary suction property of any porous material. It is of course defined in relation to a stated wetting liquid – which for brick, stone and concrete is invariably water.*
>
> *At first sight this definition is somewhat surprising because it shows that the suction depends not only on the material, but also on the water content ϑ. However this is consistent with everyday experience. When saturated, materials exert no suction. The suction exerted by any and every material is at its greatest when the material is dry and diminishes as the water content rises. When we talk descriptively of a ‘high’ suction material, we mean that the material has a large negative capillary pressure at low water content in the air-dry state. Such a material absorbs water from an external water reservoir, just as water rises into a fine capillary tube. However our definition of suction tells us only about the stress within the water and not about the amount of water that the material can absorb. The suction is an intensive property. The capacity of the material depends of course on the porosity rather on the suction.*
>
> (Hall and Hoff, 2012, p. 46)

The capillary suction and sorptivity depends on several physical properties relating to the material’s pore structure and physical mass. How easily water molecules can adhere to pore surfaces obviously plays a role, i.e. the material's hydrophilicity. However, the properties relating to the pore structure are often more important. Obviously, capillary transport requires an open-pore pore structure to occur. The geometry of the pore spaces is also important, as capillary transport requires capillaries, i.e. pores of sufficiently narrow diameter that water molecules can span from one pore surface to the opposite one.

If the space between pore surfaces is interrupted or becomes much wider, the capillary action can become sufficiently weak for *wicking* to cease. A location in pore structure where this occurs acts as a **capillary break**, preventing moisture transport by capillary action. Examples of capillary breaks commonly used in building construction are the cavities between the inner and outer wall leaves the insertion of a horizontal damp proof courses. However, some highly permeable materials, e.g. a layer of expanded polystyrene bead or mineral wool insulation, can also act as a capillary break within a wall construction.

Whereas the terms *hydrophilicity* and *hydrophobicity* describe how water molecules react to a material's surfaces in capillary active materials, the quantities of water absorbed into and distribution through a material are described by the *moisture diffusivity*. Determining the moisture diffusivity over all possible moisture contents requires complex laboratory equipment, but the *wetting diffusivity* can be estimated from the *water absorption coefficient*. Wider capillaries, when completely filled, allow liquid water to be sucked through them fast (away from the source), as their surface resistance plays a smaller part. In contrast, the surfaces of narrower capillaries exert an adhesion effect over a greater proportion of the water present, but also create more drag. As a result, the water is sucked further, but more slowly. When a wetting event ceases, the wider linked pores begin to act more like capillary breaks, while the narrow pores keep drawing from the reservoir of the larger pores, redistributing the water ever further from the source.

Figure 25 illustrates liquid adsorption and redistribution, as part of capillary transport. The figure portrays a notional uniform material of interconnected capillaries of differing diameters. The graphs in the figure show how, during and after a wetting event, the moisture content can vary not just in distance from the water source, but also in accordance with the material's range and distribution of capillary types, even if equidistant from the source. In building construction, an understanding of the moisture absorption characteristic of the external facing material of the building envelope is particularly important, as these deliver the water the rest of the building fabric has to deal with. What this means in construction practice is discussed in more detail in Section 5.3.4.2.

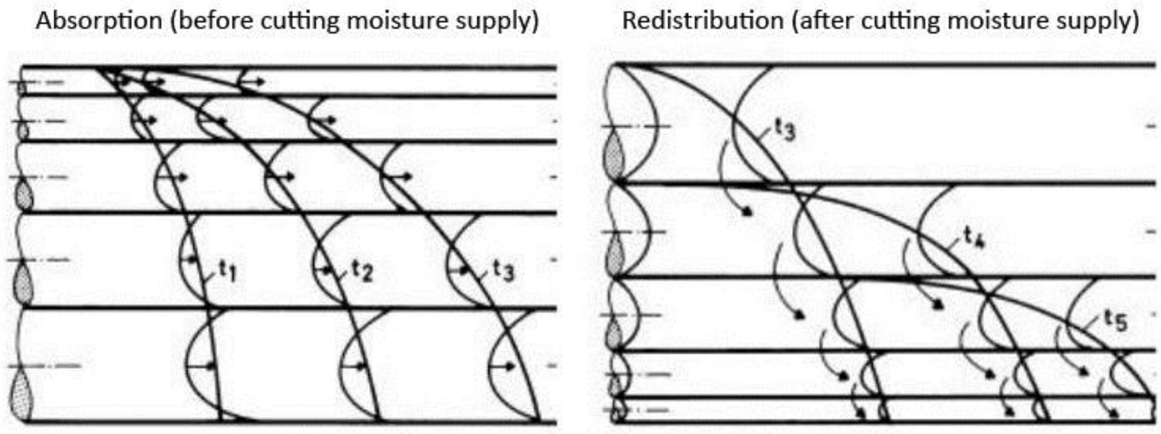


Figure 25 Capillary transport phenomena represented by a model of interconnected cylindrical capillaries of various diameters (Fraunhofer IBP / Image © Fraunhofer-Gesellschaft)

The **water absorption coefficient** describes how fast moisture is absorbed from a material's outer surface into its pore structure. This coefficient is an important value particularly for assessing materials exposed to liquid water, e.g. in the form of rain. Different types of materials obviously have different coefficients. However, they can also vary greatly between materials often considered to be similar: a material with a low water absorption coefficient will absorb less moisture than a material with a high coefficient. Therefore, in the former material, there will be less moisture to migrate through its pore structure, compared to the latter material.

This can be illustrated with a comparison of the water absorption coefficients of two sandstone types: Zeitzer sandstone has an water absorption coefficient of 0.003 kg/(m²·√s), whereas Rüthener sandstone has a coefficient of 0.286 kg/(m²·√s). (Fraunhofer IBP, n.d.1) The difference between these two coefficients is a factor of one hundred, which means that the former stone type absorbs water far slower than the latter. (This does not preclude them having the same amount of water at a particular time).

2.5.5 Concurrency of moisture transport in gas bodies

In the previous sections, moisture transport by convection, diffusion and capillary action were discussed. These transport mechanisms occur often simultaneously. However, a distinction can be made between the moisture transports in large gas bodies, e.g. an air body within a room, and in the microscopically small pore structure of materials.

In gas bodies, moisture transport generally occurs fastest through moisture convection, if sufficient air movement is present to provide the required bulk fluid flow. Moisture transport will also occur through vapour diffusion, as generally some gradient of relative humidity or pressure will be present. However, vapour diffusion is a much slower transport mechanism than moisture convection.

2.5.6 Concurrent moisture transports in the pore structures of materials

Vapour diffusion, surface diffusion and capillary transport can occur simultaneously in the pore structure of hygroscopic, porous building materials. (Convection cannot occur in solid materials, with the exceptions discussed in Section 3.1.6.) Which transport mechanisms are where and when at work in a pore structure depends on how much vapour, liquid water and heat are present and on the geometry and size of the pores. Water vapour will always be present, except when a pore is completely filled with water. The water content in the pore spaces can, however, influence which transport mechanisms are dominant at a certain point in time.

> *With rising relative humidity inside the material pores, more and more moisture is stored at the inner surface of the pores (surface diffusion). Dependent on the pore size, the filling degree can reach from a mono-molecular or multi-molecular moisture film up to a complete fill. As most materials show a wide range of pore sizes, the filling degree inside the pores can be different at the same time. With rising liquid moisture inside the pores, an increasing liquid moisture transport begins along the gradient of relative humidity.*
>
> (Binder, Zirkelbach and Künzel, 2010, p. 2)

During redistribution, capillaries furthest from the wetting source will cease to be completely filled, resulting in liquid water lining the surfaces. Surface diffusion will then join vapour diffusion as the relevant moisture transport mechanisms.

Figure 26 illustrates this concurrence relationship in which capillary transport and surface and vapour diffusion can occur in a pore structure. The transport directions shown in the figure are dominant during wintertime in single leaf masonry walls in northern Europe. Because the cold air outside has less ability to hold moisture, the vapour pressure tends to be higher indoors than outdoors, driving vapour diffusion outward. However, at the same time, surface diffusion tends to transport water inwards, as space heating regimes result in lower relative humidity indoors. If large capillaries are filled with rain water, they will also wick liquid inwards, for redistribution by smaller capillaries thereafter.

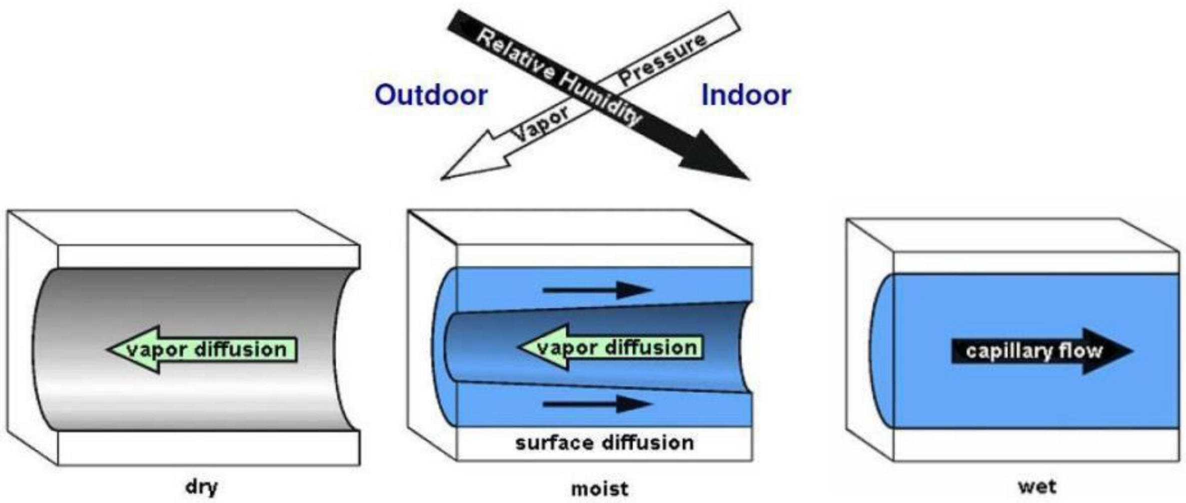


Figure 26 The three different water transport mechanisms possible in a porous, hygroscopic material: vapour diffusion, surface diffusion (of liquid water) and capillary action (also of liquid water). (Fraunhofer IBP / Image © Fraunhofer-Gesellschaft)

2.5.6.1 Moisture storage function

Each porous material has a defined relationship that determines how much moisture is present within the pore at different conditions and, therefore, what moisture transport mechanisms are present. This relationship is described by the **moisture storage function**. Figure 27 shows an example of a moisture storage curve, illustrating that, for every relative humidity value, a specific corresponding moisture content can be obtained, once conditions have reached equilibrium. (Künzel, n.d.; Holm and Künzel, 2000)

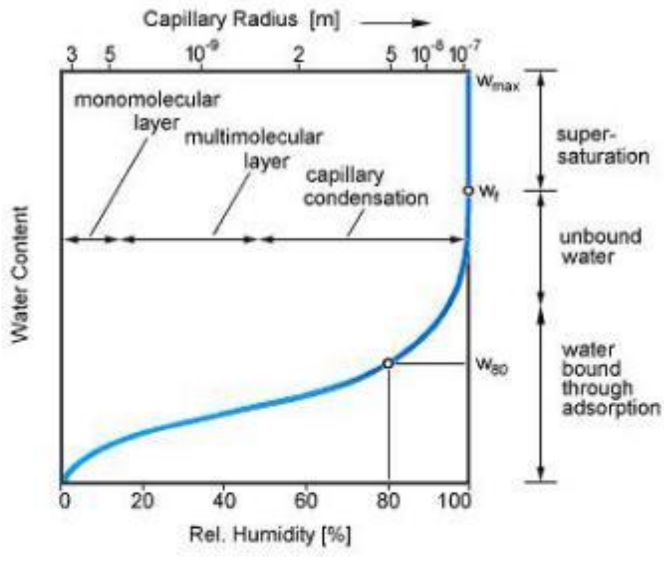


Figure 27 Moisture storage function curve of a material (Fraunhofer IBP / Image © Fraunhofer-Gesellschaft)

The moisture storage function can be used to simulate and thereby predict the moisture conditions under changing environmental conditions. A relative humidity of 80 % is often used as the reference water content (w_{80}), as it is considered the normal equilibrium moisture content of many porous materials. A relative humidity of 100 % is referred to as free saturation (w_f): a capillary-active material will wick water until free saturation is reached. These node points can be seen in Figure 27. Where measurements aren't available for sufficient points to create the moisture storage curve, it can be interpolated by the software using the moisture content at 80 % and 100 % RH.

The moisture storage curve is thereby a function of the relative humidity (seen on the X-axis) and the water content, divided into three *regions*, or phases, (seen on the Y-axis): the sorption moisture region, the capillary moisture region and super-saturated region. The first region is present up to the point that the last vapour molecules in open pores condense into the surrounding liquid. In this large region, liquid water is present first as monomolecular layer and then as multi-molecular layer, adhering to the pore wall. However, the pores themselves are not filled. Vapour diffusion occurs in the central air space of the pore and surface diffusion may occur along the pore walls. The second region, the capillary moisture region, represents the point where linked capillaries are filled (therefore up to 100 % RH) and moisture transport by capillary action replaces vapour and surface diffusion. (Given the shape of the curve it should be noted that at a relative humidity at 95 % RH a porous hygroscopic material can have a moisture content many times less than at 100 % RH. This will be important during the hygrothermal assessments in Section 5.3.) The third region, the super-saturation region, represents a situation where all air pockets in all pores, even dead-end pores or closed pores, are filled with liquid water.

2.5.6.2 Hysteresis

Moisture movement in a porous material has so far been described as if each condition is occurring for the first time. In reality, however, there will generally have been previous wetting and drying events and previous changes in humidity, which will affect the impact of current events. This dependence on past events is called **hysteresis**. For example, when pores have been wetted previously, the way in which they will now dry is slightly different. In other words, the relationship of relative humidity to moisture content in a drying phase is different to that relationship in a wetting phase specifically, because the latter came first. This difference can be graphed and is known as a hysteresis cycle. Figure 28 shows indicative hysteresis cycles for three types of materials.

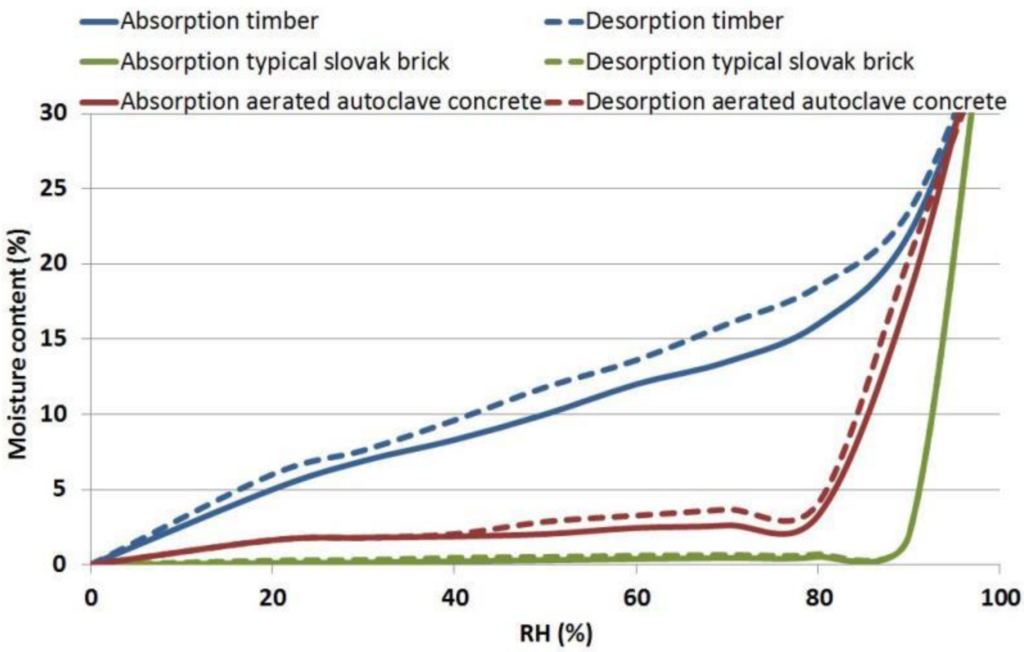


Figure 28 Graphs showing the hysteresis of timber (generalised), of a type of brick and of an aerated autoclave block

> *Hysteresis is to be expected, since for any unsaturated situation there must essentially be an almost infinite number of possible configurations for the water molecules. Whenever the material is totally saturated or totally dry the molecular distribution is in some sense predictable. At all other times it will be the unpredictable result of all the many forces acting on each molecule.*
>
> (Pender, 2004, p. 54)

The impact of hysteresis on moisture transport is generally omitted, when assessing building fabric hygrothermally. Although this appears to be a suitable approach in many situations, there are some construction products, e.g. specifically designed wood fibre boards, which would benefit from taking hysteresis cycles into account. However, a discussion about this is outside the scope of this report.

2.6 Coupled heat and moisture transfer

Predicting and modelling heat and moisture transport is complex, not only because of the multitude of the different transport mechanisms at play, but also because of the fact that they directly impact on each other at any given point in time. Water has a high heat capacity and will absorb or release heat when it evaporates or condenses. Therefore, moisture transport and phase changes from liquid to vapour and vice versa will change temperature gradients, thereby impacting on heat transfer. Conversely, relative humidity is dependent on temperature, as warmer air can hold more vapour than colder air. Therefore, heating or cooling can lead to evaporation or condensation, thus changing the water content and vapour pressure, which drive moisture transport.

Because of this interrelationship, heat transfer and moisture transport are said to be coupled physical processes. This means that they cannot accurately be solved independently, but must be considered together at the same time. In building practice, this means that the impacts of both processes must be taken into account, when designing new buildings and, even more so, when retrofitting existing ones. A retrofit project with the sole focus on improving energy efficiency by reducing heat transfer will also impact upon the moisture behaviour of the building fabric. To avoid any detrimental side effects, coupled heat and moisture assessments, i.e. hygrothermal assessments, are required.

3 Application of building physics

> *The most common single cause of building deterioration is dampness, and it has been estimated that over 1.5 million dwellings in the UK are seriously affected by dampness problems. The principal sources of dampness are rain water penetration through roofs and external walls, rising damp through walls and solid floors, and condensation. Because its causes and prevention are different from those of other sources of dampness, condensation is dealt with separately. Owing to the increased humidity created through modern cooking and heating devices and reductions in natural ventilation, condensation is responsible for a large proportion of dampness and mould growth. The courses of moisture can come from inside or outside the building, and it is essential that proper investigation is undertaken to determine the cause of dampness before any remedial action is taken.*
>
> Gorse & Highfield (2009), Ch.6, Section 6.1, p.122

An introduction to the elements of physics that are relevant to solid wall buildings was provided in Section 2. How this knowledge can be applied to buildings in a practical context is the topic for the following sections. Related assessment methodologies and simulation tools will be discussed thereafter in Section 4. Whereas the previous sections focussed on fundamental physics, such as heat and moisture transfer, the following sections will investigate the more practical aspects encountered in building construction. Buildings are three-dimensional objects with often complex geometries and made from a variety of materials, joined together. All this, obviously, impacts on how heat and moisture is transported through the building fabric.

Section 3 is split into two parts. In the first sections, building materials and construction design will be discussed, by defining the difference between the terms traditional and non-traditional (Section 3.1.1) and applying them to building materials (Section 3.1.2) and to construction design (Section 3.1.3). A nomenclature describing the hygrothermal characteristics of buildings is proposed in Section 3.1.4. Thereafter, the impacts on heat and moisture transport of building geometry and of airtightness and thermal bypass will be described (Section 3.1.5 and Section 3.1.6 respectively). The second part of this section will focus on the impacts of moisture in the building envelope, identifying the relevant moisture sources (Section 0) and describing moisture-related deterioration and health risks (Section 3.2.2).

3.1 Building materials and construction design

3.1.1 Traditional versus non-traditional

The term traditional is sometimes used to refer to older buildings. It generally describes buildings, building materials, construction design and construction techniques which were commonly in use before the 20th century. For walls in Scotland, the predominantly used and therefore traditional form of construction design is the solid wall, generally made from natural stone bedded in mortar. (Other forms of solid wall construction, such as brick masonry and earth construction also exist in Scotland, as does occasional timber framing.) The cut-off point for traditional construction is often set to coincide with the end of the First World War, i.e. 1919, as this is seen as the date when the use of cavity wall construction started to become more common. Cavity walls can therefore be thought of as the first form of non-traditional construction. There are large number of others on an ever expanding list, including concrete post-and-beam construction, timber frame, external wall insulation on masonry, light gauge steel frame etc. The change in construction systems, materials and practice were of course more gradual stretching back into the 19th century and on into the late 1940s. However, 1919 is still a useful marker given the housing boom that then occurred to serve families of returning soldiers.

The change from traditional to non-traditional construction, as a result of moving from solid wall to cavity wall construction, also meant a significant change in the hygrothermal behaviour of these walls. Traditional wall construction is therefore often associated with being more ‘vapour permeable’ than non-traditional construction. This will be described in more detail in section 3.1.3. In the next section, however, traditional and non-traditional building materials will be discussed first.

3.1.2 Traditional and non-traditional building materials

Traditional buildings were erected using many natural materials, such as stone and timber. These materials can therefore be referred to as **natural traditional building materials**. Natural materials are inhomogeneous and of varying quality, their properties and performance often depending on their source. Even where they are of similar type, great variations do exist: sandstone types, e.g., can be of varying degrees of hardness, with *softer* types generally preferred for carving work and *harder* stone types chosen where large structural loads needed to be carried. Natural materials are generally porous and permeable, which means that they have an open-pore pore structures, thereby allowing moisture transport.

In the past, natural building materials were generally processed locally, using physical means, such as stone cutting or timber sawing, and did not receive any (major) chemical treatment. From the middle of the 19th century, manufacturing processes became increasingly centralised and mechanised, leading to changes in the performance of some the building materials, by making them often more uniform in size, more homogeneous and stronger. Other innovations changed the aesthetics or added new hygrothermal benefits, such as the glazing of bricks. These changes happened gradually, resulting in a large variety of material types used in construction. This makes the distinction between traditional and non-traditional often difficult: how does one say which brick is a traditional material and which is non-traditional? Perhaps, one should only talk of age and origin, appearance and performance.

The notion that modern building materials, or present-day variants of natural building materials, are always impermeable or at least more resistant to moisture is a fallacy. Indeed, some such variants are even more vulnerable hygrothermally than older forms of the same building material. For instance, the authors found that the water absorption of some machine-made bricks from the 1950s was twice that of some hand-made bricks from a hundred years earlier. Another example: a typical timber floor made from pine floorboards produced in the 20th century is likely to be more vulnerable to rot than those fitted in Victorian times, as the quality of timber used in construction has generally declined. Each (type and variant of a) material must therefore be assessed on its own merits.

The variety of building materials has increased vastly over the last hundred years, and the chemical and manufacturing processes used today are extraordinarily varied. However, this does not mean that traditional building materials were all natural and therefore healthy. Long before the 20th century, many valuable building materials were chemically processed, such as paint, glass, lead and lime. These could therefore be called **chemically processed traditional building materials**. Some of these processes were noxious, even dangerous. For instance, it was common in Georgian townhouses that the owners would vacate their properties before repainting the interiors, letting them to poorer family until the chemical pong of the fresh paints had dissipated.

Most chemically processed building materials, whether traditional or not, are quite homogeneous. Some are hygroscopic, others have partially or totally closed pore structures. Glass and lead, for example, are essentially impermeable to air and moisture. The pore structures of other materials remain, despite chemical processing, relatively inhomogeneous and open-pore, such as that of lime mortar.

If age and origin are removed as identification criteria, it becomes clear that there is actually much overlap between the characteristics that can be used to define the terms traditional and non-traditional building material. For instance, glass and concrete are two materials that are strongly associated with 20th century construction, though both have their origins long before then. Both materials have changed incrementally over time: for example, the manufacture of glass in Britain went from cylinder glass to crown glass in the 19th century, to drawn glass in the 1920s, to float glass in the 1960s and then to a whole series of laminated and tempered sheet glasses since then. Another example: John Smeaton made a ‘water cement’ using hydraulic lime in 1756; ‘natural’ *Roman* cement was developed by James

Parker in the 1780s; 'artificial' Portland cement was formulated by Joseph Aspdin in 1824; and the idea of reinforced concrete was invented by Joseph Monier in 1849.

Some building materials are obviously non-traditional, be it due to their hydrocarbon-based chemistry (e.g. polyvinyl chloride, expanded polystyrene), their composite nature (e.g. fibre-cement boards, plywood), their shape or size (e.g. membranes, foils) or their unusual chemical structure (e.g. mineral wool, wood fibre insulation boards). Some non-traditional materials are made from natural ingredients, though combined in novel ways (e.g. calcium silicate insulation boards, lime concrete with hemp fibres). Overall, the hygrothermal properties of non-traditional materials are as varied as they are for traditional materials.

Solid wall construction is often considered a key feature of pre-1919 construction and concrete and cavity walls considered as features of later walls, yet, by way of example, within a square kilometre in Dublin, one can find examples of solid wall houses built;

- in the 1890s with rendered walls of a weak, inhomogeneous, pebble-based mass concrete (that may behave hygrothermally in a relatively similar manner to neighbouring, rendered, solid brick walls of the same era)
- in the late 1930s with three-course English bond brick walls
- from the mid-1930s to late 1940s with denser mass concrete, using a graded aggregate which included pebbles and laid in half metre lifts of varying density
- in the 1950s through to 1970s with solid or hollow blocks, made of relatively homogeneous concrete to a modern standard featuring crushed aggregate.

It is likely that one may find equivalent examples in many industrialised British cities. In comparing the four examples listed above, even the usual indicators of a change from solid to cavity wall construction, discussed in the next section, is unavailable to mark the *end* of the use of traditional building materials and the *beginning* of the use of non-traditional materials. One can really only talk of a transition.

3.1.3 Traditional and non-traditional construction design

The greatest difference between buildings of traditional and non-traditional construction design lies not so much in the building materials used, but in the way they are used to construct the external envelope of a building – in the way they are joined together. The traditional form of wall construction in Scotland is the solid wall, normally made with stone bedded in mortar and often up to 600 mm thick (including wall finishes). This form of wall construction is permeable to moisture and does not contain any specific layer(s) stopping moisture migration within the wall. Instead the wall prevents rain water from migrating all the way through it simply due to its substantial thickness. Traditional construction could therefore also be described as construction designed to *manage* moisture migration through the wall, rather than preventing it (Hermann, 2013). Part of this management is that the wall allows vapour to evaporate, generally to both the outside and the room-side.

While examples of cavity wall construction in common usage can be found as early as the mid-19th century for housing in places like Huddersfield in Northern England, its widespread development and adoption, supported by standards and related product innovation, dates to the early 20th century. Cavity wall construction features two masonry leaves, separated from each other by a vertical cavity, often vented. (For structural reasons, the two leaves are connected with metal wire or strap ties.) As cavity walls are often built with permeable materials rain water may penetrate the relatively thin outer leaf of the wall (to a greater extent in unrendered walls): the cavity's primary function is to prevent rain water from migrating across to the inner masonry leaf. Technically it is termed a **capillary break**. It has a secondary value that the unfilled air cavity had in itself some thermal benefit. (In the late 20th century insulation batts, boards or beads were inserted into the cavity to improve its energy performance further, at times reducing the effectiveness of the capillary break.)

The use of a cavity was therefore the central innovation of the new form of construction allowing much less material to be used while still achieving a similar resistance to water penetration through to the inside room surface as would be achieved by a much thicker, traditional solid wall of brick or rubble stone. In Scotland rendered blocks became the most common outer leaf in contrast to the greater use of brick outer leafs in Southern England. This difference is to do with the need for greater protection from driving rain in Scotland, the greater cost of laying brick and possibly also a sense that the brick aesthetic was anti-Scottish. Wall ties, cavity closers and damp proof courses were invented to support this central innovation while movement joints were invented as a response to the reduced ability of walls to absorb thermal expansion forces given the strong but increasingly brittle material they were made of. (The cost imperative of providing dry, warm housing as cheaply and quickly as possible was a major driver in the adoption of this form of construction after 1919. The fact that cement manufacturers could guarantee uniform quality cement while the smaller craft producers of lime could not further hastened the change. It could be said the industrial, mechanistic ethos of 'total war' effected the choices made in the housing boom that followed the Great War's end.) As this approach to moisture management is very different from that used in traditional construction design, cavity walls are referred to as the first significant form of non-traditional construction.

These two very different approaches in wall design, i.e. traditional and non-traditional construction, are illustrated in Figure 29. Although the two design approaches are very different, this is not always apparent when looking at buildings. Particularly during the last decade of the 19th century and the first half of the 20th century, both approaches were used simultaneously and cannot always be easily distinguished. A good example for how mixed this transition from traditional to non-traditional construction has actually been are the houses on the northern part of Skreen Road in Dublin. On this road, terraced houses brick-faced solid walls with three-course English bond face semi-detached houses with stretcher-bonded, brick-faced cavity walls. (Figure 30) Both sides of the road were built between 1936 and 1937. Although of similar aesthetic and built with similar materials, the walls of the buildings either side of the road manage moisture in very different ways. The buildings with solid walls allow rain water penetration and prevent water penetration to the room face by the thickness of the single leaf construction. The buildings with cavity walls stop the water from penetrating though to the room surface by having a cavity that acts as capillary break.

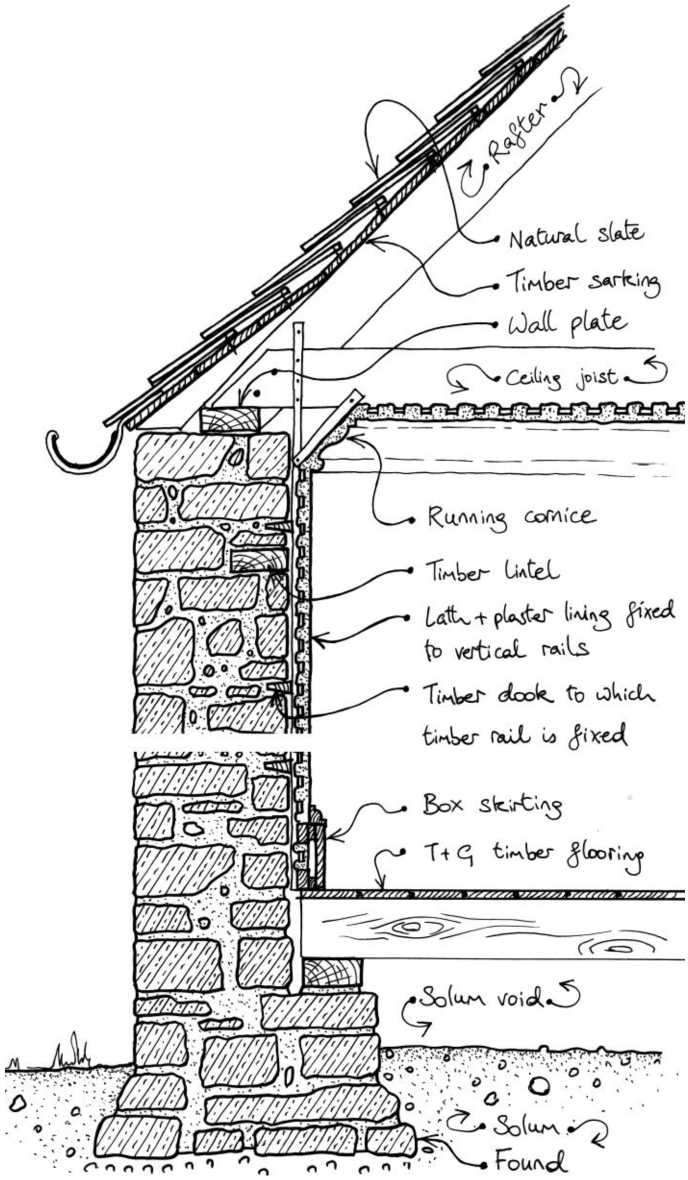


Figure 29 Cross sections through walls of traditional construction (left) and non-traditional construction (right)

Figure 30 Two terraced houses either side of Skreen Road, Dublin, both built between 1936 and 1937: Despite using the same aesthetics and materials, the left building is a solid masonry wall, whereas the right building has a cavity wall.

3.1.4 Proposed nomenclature for the hygrothermal characteristics of buildings

One may say that the defining approach of traditional construction is the management of moisture (predominantly rain water) by a range of strategies to ensure walls, floors and roof structures didn't take on more moisture than their ability to quickly dry out.

In contrast one can say that modern construction systems generally depend on blocking, not managing moisture. The outer leaf of the cavity wall, the render of a rendered solid concrete wall, or the cladding and glazing of more modern constructions are all generally expected to resist the full brunt of driven rain. From the perspective of water management it appears that strategies that used to be well understood and carefully practiced were put aside, much wisdom lost.

It is interesting to note that some key advantages of traditional construction systems have regained popularity in certain circles in the last decade in Britain. For instance, the use of lime mortar, even in modern cavity wall construction, allows re-use of the bricks or blocks after demolition (thereby reducing the waste stream) and can remove the requirement for expansion joints. Other examples are the rediscovery of old biocomposite systems, like cob, and the invention of new, such as Hempcrete (lime concrete with hemp fibres) and strawbale, recover a tradition of crafted thick solid walls, while sequestering CO_2.

In every case, a greater understanding of hygrothermal building physics and boundary conditions would benefit both new buildings, conservation work and energy efficient retrofits rather than a focus on overly general categories such as traditional and non-traditional. The authors therefore propose a novel re-arrangement of terms and categories that may help.

The main terms proposed to define construction approaches are ‘moisture managing’ and ‘moisture blocking’. Tables 2, 3 and 4 below identify two different degrees of ‘moisture managing’ based on the level of vapour permeability and capillarity, while capillary broken, ‘moisture blocking’ strategies are divided into vapour permeable and vapour closed. Furthermore the three tables capture something of the different building cultures that use these construction approaches: ‘*traditional – predominantly moisture managing’*, ‘*modern – predominantly moisture blocking’* and ‘*modern – predominantly moisture managing’*. The reader can locate most common forms of construction in the various cells of these tables.

It is hoped that an adoption of this more nuanced taxonomy may encourage designers and contractors to apply repair and retrofit measures to a building that lie within the same category as it is in, e.g. installing capillary open insulants on capillary open solid walls, using vapour permeable paint on vapour permeable walls, only installing capillary breaks with great care where they are needed, etc. Risk assessment can greatly aid this transition. As an industry and culture we need to move to a building physics and care-centred appraisal and appreciation of our buildings: they are a remarkable inheritance.

Traditional
predominantly moisture managing

		Roofs	Walls	Floors
Moisture managing	high vapour permeability and capillarity	n/a	Stone- and brick-faced solid walls	Flagstone or rammed earth floors
	low vapour permeability and capillarity	Thatched roofs	Rendered brick and stone-faced walls	n/a
Moisture blocking	vapour open with capillary break	Traditional slated pitched roofs	19th century stone and brick-faced cavity walls	Suspended timber floors
	vapour closed with capillary break	n/a	Some rising walls include a slate DPC	n/a

Table 2 Predominantly moisture managing traditional construction systems

Modern

predominantly moisture blocking

		Roofs	Walls	Floors
Moisture managing	high vapour permeability and capillarity	n/a	n/a	n/a
Moisture managing	low vapour permeability and capillarity	n/a	n/a	n/a
Moisture blocking	vapour open with capillary break	Modern flat roofs with ventilated zone below roof membrane or cladding, on breather membrane, vapour open insulation and AVCL	Wet-plastered masonry cavity walls with insulation in cavity or internally, with DPC	n/a
Moisture blocking	vapour closed with capillary break	Modern tiled pitched roofs with AVCL or vapour closed/foil-faced insulants modern unvented flat roofs with foil AVCL, sandwich panels or composite panels	Structurally insulated panels of oriented strand board and rigid foam insulation, with DPC light gauge steel frame with rainscreen, vapour closed/foil-faced insulants and DPC	Reinforced concrete and rigid vapour closed insulation on DPM

Table 3 Predominantly moisture blocking modern construction systems

Modern

predominantly moisture managing

		Roofs	Walls	Floors
Moisture managing	high vapour permeability and capillarity	n/a	n/a	n/a
Moisture managing	low vapour	n/a	Hempcrete, cob or	n/a

	permeability and capillarity		strawbale walls rendered and plastered Wet-plastered 'no-fines' concrete block or autoclaved aerated concrete block walls with external wall insulation	
	vapour open with capillary break	Modern tiled pitched roofs with vapour permeable insulation, and variable diffusion AVCL or no AVCL	Timber frame walls with variable diffusion AVCL, vapour open insulation, rainscreen and DPC	Solid flooring made from lime concrete with lightweight aggregate as capillary break, no DPC
Moisture blocking	vapour closed with capillary break	n/a	n/a	n/a

Table 4 Predominantly moisture managing modern construction systems

3.1.5 Impacts of building form on heat and moisture transport

In Section 3, heat and moisture transport were discussed in relation to plane materials, i.e. materials of a uniform geometric shape. In practice, however, buildings are geometrically complex, a matrix of geometric and construction junctions connecting building elements. Obviously, this greatly influences heat and moisture transport at these locations. In this section, one-dimensional temperature and pressure profiles are first described, following by a discussion of the two-dimensional effects and thermal bridging.

3.1.5.1 One-dimensional temperature and pressure profiles

Heat loss through a plane building component depends on the thermal transmittance, or U-value, of the component and the temperature difference, or temperature differential, across the component. (Section 2.4.5) The temperature differential is the driving force, or driving potential, for the heat flow; the U-value can be thought of as a regulator that controls how quickly the heat will be transferred. The heat flow through a plane building component, which can consist of a number of layers of different building materials, can be illustrated with a temperature profile, a graph plotted over the cross section of a building component. (Figure 31) The different thermal conductivity (λ) of each layer in the component results in an uneven temperature change across the layers. Insulating materials have high temperature difference from one side to the other, while more conductive materials have a much smaller temperature change. The temperature profile of a building component is important for understanding the hygrothermal conditions within those parts which are air and moisture permeable. As air movement normally entails moisture transport, low temperature locations tend to pose the risk of condensation, either on the material surface or interstitially, i.e. within the component.

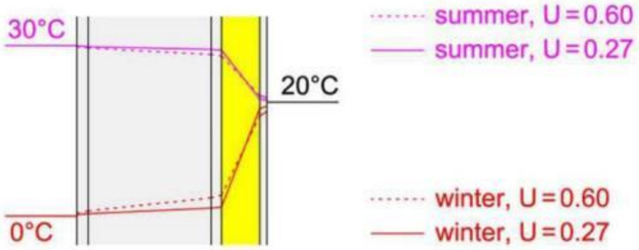


Figure 31 Steady-state temperature profiles for an internally insulated solid wall, with the internal wall insulation shown as yellow layer.

Whereas the temperature differential is the driving potential for heat transfer, the **vapour pressure differential** across the building component is the driving potential for vapour transfer. The **vapour resistance (s_d)** of the component and the **vapour diffusion resistance factor** (μ-value) of each of the component's layers are the regulators. Similar to temperature profiles, it is possible to generate **vapour pressure profiles** through a particular piece of building construction. The driving potential for liquid water transport by capillary action is the difference in water content in the component, i.e. the **liquid water differential**. The difference in relative humidity within the capillaries of the component's materials is the driving potential for liquid water transport by surface diffusion. Finally, the **moisture storage function** of a hygroscopic material describes (among other things) the relationship between relative humidity and the amount of liquid water that will be adsorbed to the pore surfaces and is thereby available for surface diffusion. It is therefore also possible to plot a **water content profile** over the cross section of a building component. (Figure 32)

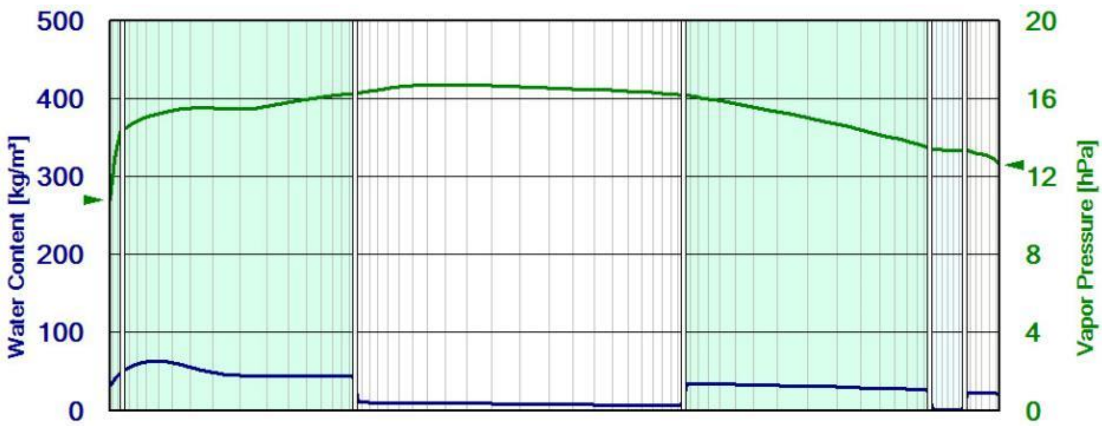


Figure 32 Diagram showing vapour pressure profile (green) and water content profile (blue) across a wall.

Since heat, water vapour and liquid water are all driven by different forces, they can 'move' in different directions at different times within the same wall. However, because the forces driving these transport phenomena are coupled, retrofit strategies to address one issue may have unexpected effects on another. For example, insulating a wall internally reduces the heat transfer through it, but also leads, as a side effect, to higher relative humidity beyond the insulation, especially in winter when external temperatures are almost always colder than inside. The **dewpoint** is the temperature at which vapour will condense, i.e. 100 % RH. The phenomenon of the dewpoint occurring on the cold side of internal insulation is not as common as often thought, and is closely associated with non-hygroscopic materials, e.g. fossil-based insulants, and vapour retarding surfaces, e.g. certain paints, that have little or no ability to adsorb the vapour and in the process locally maintain or reduce the relative humidity. The inverse, hygroscopicity, is discussed in Section 2.5.1.5. The appropriateness of an internal insulation system should therefore not only be judged on its thermal performance, but also on how well the system minimises moisture accumulation and, if condensation or indeed water penetration occur, how well it allows that moisture to disperse (within the building fabric) and eventually evaporate (either to the outdoor environment or back into the rooms).

3.1.5.2 Two-dimensional effects and thermal bridging

The discussion above, relating to U-values and to temperature and moisture profiles of cross sections of building fabric, is based on a uniform, not-bridged building component. In other words, it assumes that all of the layers within a building component are continuous and homogeneous and all heat and moisture transport is one-dimensional and perpendicular to the surface. In building practice, however, this is often not the case: most walls, for example, are not completely uniform but can contain structural framing, windows and doors. Nor are they infinitely long: they join other components.

Building components are often thought of as having a uniform thermal resistance. However, in reality, most construction contains localised areas which are of a higher or lower thermal resistance than the rest of the envelope. Such an area is called a **thermal bridge**. An example of a thermal bridge is the studwork in an insulated timber-framed wall, where the studs have less thermal resistance than the insulated wall areas. Therefore, the studs are, in this case, thermal bridges. Thermal bridges that occur regularly within a component, such as the stud work used in the example above, should be calculated as part of the overall U-value of the building component. However, other irregular thermal bridges should be accounted for separately.

Any linear junction where one building component meets another is potentially a thermal bridge, regardless if it is a geometrical junction, e.g. the corner of a wall, or a construction junction, e.g. a window cill. (Figure 33) Typically, thermal bridges increase heat flow and lower indoor temperatures near the junction. These cooler internal surfaces, in turn, can result in an increased risk of surface condensation and mould growth (Section 3.2.2).

Methods for the evaluation of thermal bridges are discussed in Section 4.6. The impact of thermal bridging is also illustrated in Section 5.4.3 in the case study that forms part of the second part of this report.

3.1.6 Airtightness and thermal bypass

Air movement and its impact on heat and moisture transport were already discussed in Section 3.1.1. In the following, air movement will be discussed in a more practical building context. A common form of air movement in a building is ventilation. All functioning ventilation systems should extract *moist, vitiated* air and supply *fresh, oxygen-rich* air, thereby improving air quality. However, air movement can also occur into, out of, through or within building envelopes. Still standing air is actually a relatively good insulant, but air that is moving in these areas will naturally have a moisture and thermal content. When uncontrolled this air can increase heat loss through the building envelope and result in unacceptable levels of interstitial moisture accumulation. Reducing unintended air circulation, i.e. convective currents, *within* the building envelope reduces the convective portion of heat transfer through it. Reducing unintended air movement *through* the building envelope, i.e. increasing its airtightness, reduces both convective heat and moisture transport.

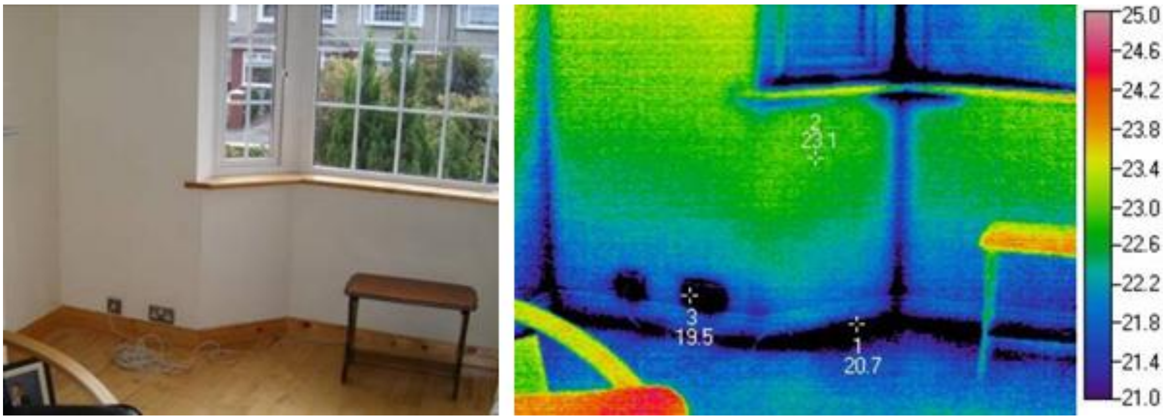


Figure 33 Photograph of an external wall with a room corner, floor junction and a bay window (left) and the corresponding thermal image (right): the thermal image shows the localised areas of lower surface temperature in blue colours. These thermally bridged areas include the outwards facing corner in the window breast, floor-wall and wall-window junctions and area where electrical sockets have been installed into the wall.

In the following, terms such as filtration and ventilation will be defined first, before discussing the impacts of airtightness and thermal bypass (Section 3.1.6.3).

3.1.6.1 Air leakage and ventilation

Intentional air movement through purpose-provided openings is termed **design ventilation.** If design ventilation is provided without constant mechanical supply or extraction it is referred to as **natural ventilation,** i.e. the supply of air without fans or depressurisation through grilles and extraction by intermittent fans or stack effect. Ventilation that requires constant mechanical input, such as provided by fans, is called **mechanical ventilation**. It can be designed to overcome the influences of non-mechanical means, e.g. wind pressure. Air movement transports heat and moisture through convection. The convection is therefore similarly referred to as **forced convection** in situations where mechanical means are used and **natural convection** in situations where mechanical means are absent. Ventilation and infiltration in buildings is examined in detail in the British Standard *BS 5925:1991* (BSI, 1991). (Air movement due to external air pressure or wind is, strictly speaking, a form of forced convection, but in a building context this air movement, even if unwanted, is generally thought of as natural convection because it requires no electrical input.)

Unintentional air movement is referred to as **air leakage**, or air filtration**.** Depending on its direction, air leakage can be either **infiltration**, i.e. air leaking into the building or **exfiltration,** i.e. air leaking out of the building**.** To reduce or prevent air leakage, building envelopes are increasingly designed to achieve higher levels of airtightness.

3.1.6.2 Airtightness

In buildings with low levels of airtightness and with little or no designed ventilation, air infiltration comprises an important, albeit haphazard and uncontrollable portion of the air supplied to the building occupants, but also leads to increased heat loss and lack of comfort. Large rooms with high ceilings (a feature of many, but by no means all, traditional buildings) provide a greater volume to contain water vapour and other gases which can result in better indoor air quality than a similar room with equal air infiltration but a smaller volume.

In buildings with high levels of airtightness (i.e. Q50 value < 5.0 $m^3/m^2.hr$) the required air exchange rates must be achieved by other means than occasional window opening and air leakage, e.g. through suitably designed, commissioned and maintained ventilation systems. Once again this requirement is of greater importance in smaller rooms, and above all small bedrooms (where CO_2 can be released for many hours without occupants modifying conditions by opening windows or internal doors). There is mounting evidence that the greater the level of airtightness achieved the less suitable natural ventilation becomes as the means by which to deliver acceptable air quality (ref: Sharpe, 2014 and Aereco, 2010). The best ventilation systems should provide good air quality at all levels of airtightness without undue heat loss, through modulated supply and extract of air or the use of heat recovery in ventilation systems. When specified and installed well there need be little visual change and no loss in heritage value.

Some forms of present-day construction are prone to air infiltration due to a higher number of poorly controlled junctions. Examples are partial-fill cavity wall and open-panel timber frame construction, when built without a marked focus on airtightness, and, in every case, unsealed blockwork walls, internally finished with mechanically fixed insulated plasterboard. (Doran, 2000; Wingfield et al., 2011) On the other hand, some forms of older construction, e.g. mortar-bedded stone walls with render and plaster finishes, can be inherently airtight. Nowadays it is increasingly usual that continuous airtightness membranes or taped racking boards are used in timber-framed walls to improve the long term airtightness. In traditional wall construction, wet-applied plaster and render finishes perform the same role. Old, unimproved windows and chimney stacks are often the least airtight components of the building envelope of historic buildings. The general aims of reducing air leakage and increasing airtightness raises a host of questions for traditional buildings: How will internal levels of relative humidity change, could there be an impact on interior decoration and objects? What will the new levels mean for the risk of mould growth? How will *vitiated* air be replaced with the *fresh* air needed by building occupants? It is clear that reduced air leakage and increased airtightness impose a greater requirement for well-designed and well-functioning ventilation, particularly in locations where high vapour loads are produced, e.g. bathrooms, kitchens, utility rooms. Yet, insulating retrofit work is all too often installed without even giving the slightest thought to the resulting ventilation requirements.

3.1.6.3 Thermal bypass

The term **thermal bypass** describes the unintended thermal impact of combined impact of natural and forced convection upon thermal performance of building fabric. Siddall (2009) describes thermal bypass, according to Harrje et al. (1986), as

> *heat transfer that bypasses the conductive or conductive-radiative heat transfer between two regions. Defined in this manner, convective loops, which can include both air infiltration and wind washing, constitute a form of thermal bypass. It should be recognised that the term 'thermal bypass' is being applied to largely unfamiliar, and often unregulated, heat transfer. Furthermore it is an acknowledgement that air movement can lead to a significant increase in the heat loss when compared to predicted values … This means that even when the designer thinks that a design has addressed the performance requirement; it is very likely that it has not.*
>
> (Siddall, 2009, p. 1)

Examples of thermal bypass include large-scale air movement through gaps in the building envelope, for example where air barriers have been breached; but also small-scale air cycling between linked voids within the envelope; air movement driven across insulation or through loose fibrous insulation; and wind wash. The latter is air movement, driven by wind pressures, resulting in wind passing through or behind the thermal insulation within building envelopes.

Different forms of thermal bypass are illustrated in Figure 34. In this figure, the examples (a), (c), (d) and (g) show convection through the concerned construction, including convection through the open-pore pore structure of lightweight insulating material, such as mineral wool quilts. The *classic* case of this type of convective heat loss is quilt insulation extending over the timber wall plate at an eaves-wall junction, where no attempt has been made to separate the insulation from the adjoining eaves: air movement, driven by wind or external air pressure differences on either side of the building, is pulled into the eaves, through the perimeter quilt insulation, through the attic void and out the other side, whipping warm air out of the exposed areas of attic insulation in the process. Deseyve and Bednar (2005) estimated fluctuations in the calculated U-value at the eaves as great as 660 % for wind speeds of 7 to 9 m/s for this process. The authors have witnessed a case of air movement drawn downwards from a cold attic through 300 mm of new, carefully laid quilt insulation, woven intumescent hoods and the openings of recessed down-lighters into a bedroom below, to the great discomfort of the occupants.

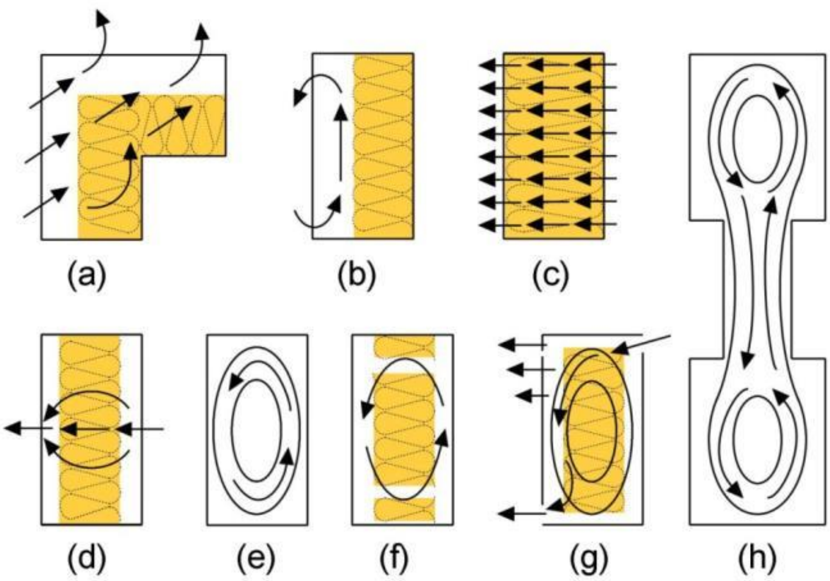


Figure 34 Examples of thermal bypass through or within building envelopes (indoors is on graphic’s right side): The internal air barrier is compromised only in cases c, d and g. In the other cases, even with proper air barriers and good airtightness, air movement occurs within the building fabric, causing convective heat loss. (Siddall, 2009 / Image © AECB)

Rather than passing through lightweight, non-woven materials, however, thermal bypass tends to occur as thermal convection around solid materials, as illustrated in example (f) in Figure 34. The *classic* case here is that of convection loops circulating air around rigid insulation boards within a cavity wall, only partially filled. Lecompte (1990) raised concerns about the actual thermal performance of partially filled cavity walls, by establishing through laboratory tests that any gap on the warm side of insulation could result in a significant reduction in thermal performance: for a 10 mm wide gap between insulation boards, a void as small as 7 mm behind the insulation resulted in an 80 % increase in heat transfer; 15 mm resulted in an increase of 180 %. Because this convective heat transfer occurs within building components, it has the effect of resulting in a higher λ value. In other words: it is an increase of the heat transfer through a 'solid' material, therefore the impact of air movement is recorded as increased conduction.

There are two notable cases of thermal bypass that have led to changes in guidance in the UK. Firstly, Wingfield et al. (2011) found that, at a housing development in Stamford Brook, stack-driven thermal bypass, measured within an uninsulated party wall of cavity wall construction, was so extreme that what had previously been considered negligible had in fact a magnitude equivalent to a U-value of 0.6 $W/(m^2 \cdot K)$. The case is explained further in Figure 35. This particular form of thermal bypass is also illustrated with the examples (e) and (h) in Figure 34. The discovery led to changes in Approved Document L for dwellings. Secondly, Ward and Sanders (2007) found that, in a typical British house, 20 % of the heat loss is into attic spaces, of which circa 80 % is due to air leakage, including vapour. This led Sanders, (2006a) to state, in *BRE IP 5/06,* that hygrothermal numerical evaluation not steady-state interstitial condensation analysis should be used when assessing traditionally insulated lofts.

Importantly while occurrences of thermal bypass are difficult to resolve when found on site, they can be minimised by careful design in the planning process and careful installation of a continuous air barrier.

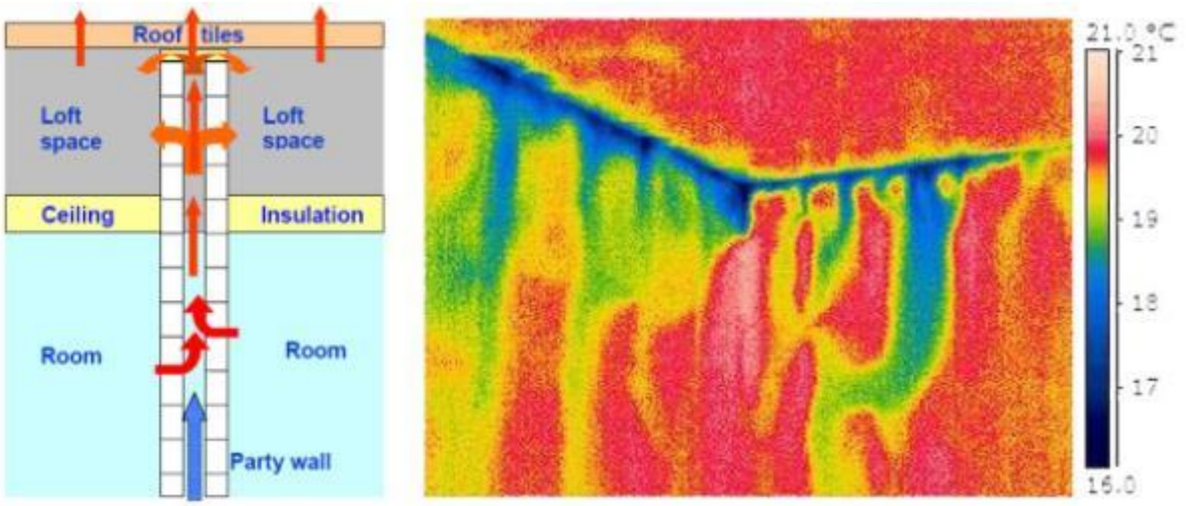


Figure 35 On-site investigations at a housing development in Stamford Brook, London, found that convective heat loss occurred, on one hand, due to heat transfer from rooms either side of a party wall, with a convection current in the wall's cavity causing the air to rise to the colder, uninsulated attic space (left), and, on the other hand, due to air movement behind mechanically fixed plaster-board dry-linings. (Wingfield et al., 2011 / Image © DCLG)

3.2 Moisture in building envelopes

Moisture is one of the main reasons for material decay and contributes to health issues within buildings, such as mould growth. In this section, three relevant moisture sources are identified: indoor vapour (Section 3.2.1.1), rain water (Section 3.2.1.2) and ground water (Section 3.2.1.3). Moisture-related fabric deterioration and health risks will thereafter be discussed in Section 3.2.2, such as wood decay, caused by rot; surface spalling, caused by freeze-thaw action; and mould growth as a health risk.

3.2.1 Moisture sources

3.2.1.1 Indoor vapour

Indoor vapour is gaseous water dispersed in the indoor air and is the form of moisture most often assessed when considering internal insulation retrofits. Vapour transport by convection or diffusion (Section 2.5.2 and Section 2.5.3 respectively) results in the risk that the transported vapour might condense into liquid water if moved to an area with a temperature at or below the dewpoint. The amount of indoor vapour depends on the occupancy and use of a room: the living room of a flat occupied by one person has generally a lower indoor vapour load than a living room occupied by a five-person family. A bathroom used regularly for bathing or showering will generally have a higher vapour load than a living room. Table 5 below lists the vapour loads produced by some typical household activities. The table shows that vapour loads can vary significantly. Due to this, the hygrothermal assessment for a living room is generally not transferable to a bathroom, nor is an assessment for a bathroom in a single-occupancy flat transferable to a bathroom used by a family of five.

Activity	Moisture produced
Cooking (3 meals)	0.9 - 3.0 kg/day
Clothes washing	0.5 - 1.8 kg/day
Clothes drying (indoors)	2.0 - 5.0 kg/day
Baths / showers that means, - for a single person - for five persons	0.2 - 0.5 kg/(day·person) 0.2 - 0.5 kg/day 1.0 - 2.5 kg/day
Perspiration and respiration of building occupants that means, - for a single person for 24 hours - for five persons for 24 hours	0.04 - 0.06 kg/(hour·person) 0.96 - 1.44 kg/day 4.80 - 7.20 kg/day

Table 5 Indoor vapour loads, as typically produced by household activities and, for comparison, by building occupants (Sanders, 2006b, tab. 7.1)

Vapour diffusion in building envelopes

In predominantly cool climates, such as that of the British Isles, interior spaces are maintained at warmer temperatures than the outdoor air for much of the year. This warmer indoor air has the capacity to hold more vapour: the activities described above provide ample quantities of such vapour. The concentration of vapour molecules results in a higher vapour pressure within the building than outside for most of the year, driving vapour outwards through the thermal envelope. (It should be emphasised that most of this vapour is not from the room it was already in the building materials. Most vapour leaves internal volumes through ventilation and the opening and closing of windows and doors.) At the same time even in Spring, but obviously more often in summer, periods occur when the external surface temperature of a wall or roof is far higher than the room temperature due to solar radiation – this temperature differential can reverse the direction vapour is moving through the thermal envelope temporarily. Thus, the combination of the vapour pressure and temperature differentials are the driving force for vapour transport by diffusion through the thermal envelope. (Section 2.5.3.1)

Vapour moves through all materials unless they are truly vapour impermeable: the latter group is surprisingly small. The amount of vapour that permeates into and migrates through a vapour permeable material varies depending on its vapour diffusion resistance factor (Section 2.5.3.1) and thickness. A more vapour-closed material, i.e. one with a high μ-value, ensures less vapour diffusion than a more vapour-open material. The thicker a material, the more difficult it is for vapour to migrate through. Therefore, a material that has a high μ-value and is of great thickness will ensure even less vapour diffusion.

In the context of building envelopes, because there is also a temperature profile through the building envelope which decreases as it gets closer to the cooler outside air, the location where the vapour transport ceases may be at a temperature much lower than that of the room air. At lower temperatures, the relative humidity associated with the vapour is much higher. If the temperature is at or below the dewpoint, the vapour can condense into liquid water within the building envelope.

There are a number of ways to reduce vapour diffusion ingress into the building envelope. First and foremost, adequate ventilation can reduce the interior vapour load, thereby reducing the vapour pressure differential which drives the diffusion. While many homeowners open bathroom windows to expel the high vapour load created by showering they may actually be providing a path for air to enter the dwelling and leave through an opening on a side of the dwelling where the outside air has a lower air pressure. In doing so moist and even mould laden air can get deposited within the dwelling far from the moisture source. Therefore the only reliable way to reduce the interior vapour load in a 'wet' room is through the use of extract ventilation (whether or not a window is open). The best extractors run constantly or are humidity triggered (and will be quiet enough that occupants will use them). Generally fresh air supplied from outside has a lower vapour content and mixes with the indoor air, thereby diluting the vapour to a lower concentration. However, while adequate ventilation can reduce the vapour pressure differential, it is unlikely that the ventilation will eliminate the vapour pressure differential entirely. The vapour load of the room will likely remain higher than that of the surrounding building fabric.

Since vapour diffusion is stopped at the surface of a layer of a material with high μ-value, one approach to avoid a higher vapour content locally, even to the point of interstitial condensation occurring, is to avoid such impermeable layers and allow the vapour to pass completely through (all layers of) the building envelope to the outside. This approach requires careful material selection and some measure of weather proofing against wind and rain (whether that's a good render or rainscreen). Traditionally such a wall featured a wet plastered finish internally that acted as an **air barrier** but not a vapour barrier. An alternative approach is the use of an **air and vapour control layer (AVCL)** to prevent the vapour from reaching cooler location within the building envelope. AVCLs can either be installed as an independent layer, e.g. polythene or polyamide membranes, or be part of a composite construction product, e.g. foil faced phenolic foam panels taped together. In all cases an AVCL must be continuous. However, AVCLs can restrict the evaporation of vapour back into the room. (Binder, Zirkelbach and Künzel, 2010) Because of this, AVCLs on certain masonry walls can create more problems than they solve. These effects are illustrated in the case study of this report. (Section 5) In a situation where interstitial condensation is considered a high risk, construction materials with high capillarity can be used to redistribute the condensate in order to prevent interstitial moisture accumulation over time. This situation occurs in traditional solid wall construction, in which the dewpoint lies somewhere in the middle of the wall thickness.

Vapour diffusion has long been the primary focus of hygrothermal risk assessment of building envelopes. (Section 4.4.3.1) This is partly due to the fact that it is relatively easy to calculate assuming one-dimensional vapour pressure differential and no other hygrothermal effects or short term events. Other moisture sources affecting the building envelope are much more difficult to assess. As will be seen, ignoring other sources, such as rain water and ground water, can often result in an over-simplification that can mask actual hygrothermal risks.

Vapour convection in building envelopes

Vapour convection is vapour transport by convective air currents. (Section 2.5.2) These currents occur within building spaces, but can also occur within the building fabric of some forms of construction. Within building envelopes, these currents are primarily the result of wind pressure, stack effect and/or building pressurization by mechanical ventilation.

The concern surrounding vapour convection is similar to that of diffusion: the interior air with higher vapour content can be transported to a location within the building envelope where the temperature is cooler, causing the relative humidity to increase and potentially condensation. However, air movement transporting vapour by convection occurs much faster than diffusion and can therefore be a much larger source of moisture.

Vapour convection as a moisture source is caused by air movement through gaps and cracks in building construction. This convection is controlled by the airtightness of the structure. Airtightness is concerned with air movement in both directions: infiltration or exfiltration. Since outside air is generally cooler and drier, i.e. contains less vapour, infiltration is of no concern as a moisture source and may actually help to dry building fabric where it occurs. In cool climates, vapour convection is concerned with exfiltration only.

The actual amount of air leakage, however, is not directly related to the risk of moisture accumulation due to convection. In fact, the locations of highest leakage are often not the areas of primary concern, as these locations are generally larger, more direct opening, in which warm indoor air leaks though rapidly. This rapid air movement results in a significant loss of energy, but, because the air does not have time to significantly cool down before it reaches the outside, the surface temperatures at the opening are actually warmed by the air and the dewpoint is often not reached until after the air leaves the building envelope. Instead, it is the smaller, more tortuous cracks in the building envelope that are more susceptible to vapour condensing within them, because the air leaking through spends considerable time in these colder portions of the building envelope. Figure 36 shows a simplified representation of these different types of gaps and the air movement through them.

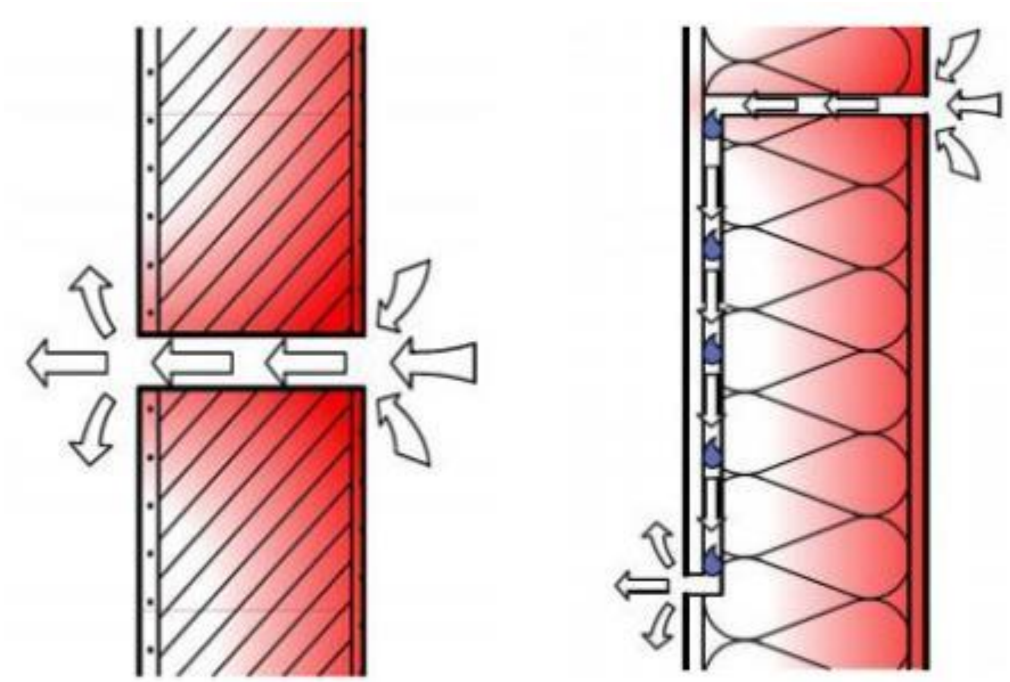


Figure 36 Air leakage through gaps and cracks in the building envelope: whereas through large gaps (left),air escapes rapidly, in small gaps with tortuous air paths, vapour can condense, as it is transported more slowly through the colder parts of the building fabric. (Künzel, 2011 / Image © Fraunhofer-Gesellschaft)

The simplified diagram in this figure represents conditions commonly found in building envelopes. An example for this, in the context of an internal insulation wall retrofit, is the air gap behind rigid insulation boards applied to a wall with mechanical fixings. Any gaps between the boards or poor airtightness seals around openings, such as electrical outlets, could allow air movement into this narrow cavity. If the temperature in these cavities reaches the dewpoint, the vapour condenses, potentially causing moisture-related fabric deterioration. If the vapour in the cavity accumulated above certain threshold levels, mould growth could occur. (Section 3.2.2.1)

Continuing the example above, these rigid insulation boards often incorporate a foil facing as a vapour barrier. However, if vapour convection, which carries more moisture, is able to *bypass* the entire board, this foil layer becomes ineffective as an air barrier.

To prevent all vapour convection into the building envelope would require the elimination of all air leakage through even the smallest gaps and cracks with a perfectly sealed air barrier.

> *While better detailing and workmanship may considerably improve the air-tightness … field observations indicate that it is impossible to achieve a perfect air barrier in building practice.*
>
> (Künzel et al., 2012)

Moisture transport by vapour convection may be reduced by good workmanship and increased attention to airtightness, but it cannot be eliminated completely in practice. Therefore, condensation due to vapour convection must be allowed to dry out to avoid accumulation. In this regard, vapour barriers can sometimes do more harm than good, because they prevent vapour from evaporating to the room by diffusion when outside surface temperatures are higher than the room's ambient temperature. This is common in summer (thus is often called **summer diffusion**) but it can happen due to thermal radiation on sunny days at any time of the year.

This moisture accumulation by vapour convection can be illustrated by comparing the moisture behaviour of three examples of a roof construction. The construction is the same in all examples, except that the AVCLs installed are of different vapour resistance: 100 m, 2 m and variable diffusion. (Figure 37) The AVCL with the highest resistance, s_d = 100 m, leads to moisture accumulation over time, because it prevents summer diffusion. The other two AVCLs allow the drying out of moisture from the construction, albeit at different rates. This example demonstrates the importance of understanding the dominant moisture source in a building component and the need for the use of suitable materials and construction design.

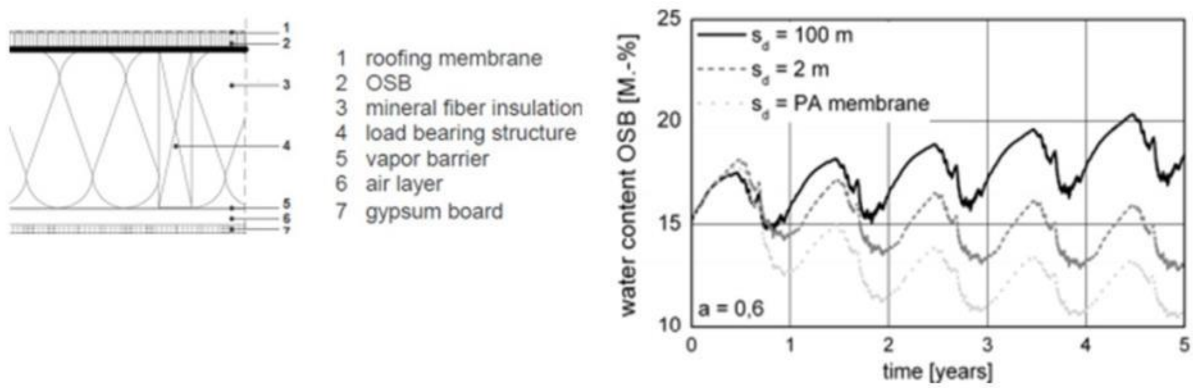


Figure 37 Comparison of three different AVCL options

3.2.1.2 Rain water and wind-driven rain

One of the functions of a building is to provide shelter from rain and wind. Almost every part of a building envelope will come into contact with rain water (or ground water). Construction design generally attempts to reduce the quantities of rain water coming into contact with external wall surfaces, for example by using rain water goods, such as gutters, downpipes and drainage, to directly discharge water from roof areas and/or by sheltering walls with overhanging eaves. These measures offer good protection from rain fall, at least as long as it falls more or less vertically.

However, rain fall often concurs with wind speed, resulting in the rain falling obliquely, rather than vertically. Rain fall which is given a horizontal velocity is called **wind-driven rain**, or *driving rain*. As a result of wind-driven rain, larger quantities of rain water will come into contact with external wall surfaces, resulting in increased moisture penetration. The impact of wind-driven rain are is difficult to predict, because of its dependence on wind speed, building geometry, adjacent landscape etc. To estimate the wind-driven rain load, assumptions are made to conservatively predict the worst case, accounting for the varying influences.

> *Wind-driven rain is the most important moisture source affecting the hygrothermal performance … and durability of buildings facades.*
>
> (Blocken and Carmeliet, 2010, p. 1079)

When rain water comes into contact with a wall, the pores in their external surface become completely filled, and moisture transport by capillary action becomes possible. This transport mechanism is of particular importance for solid walls of permeable construction, especially in climates with significant levels of rain fall and wind speed, like most of the north and west of Ireland and of Scotland.

> *If present, liquid transport may dominate vapour diffusion by some orders of magnitude. Therefore it has to be considered carefully when liquid water has an impact on the building component, e.g. when wind-driven rain hits … a solid stone wall made of natural stone.*
>
> (Künzel and Karagiozis, 2010, p. 50)

That wind-driven rain is of particular significance for at least some parts of British Isles is well established. In the 1950s, the Building Research Station (later Building Research Establishment and now BRE) was at the forefront of researching the impact of wind-driven rain on buildings. (Hens, 2010, p. 2) Publications from as early as the 1950s and 1960s show that wind-driven rain was considered a particular concern (e.g. Lacy, 1966).

Figure 38 shows a map from 1966 of the British Isles with the hatching illustrating three different zones of wind-driven rain intensities: sheltered, moderate and severe. The numbers stated on the map provide an even more detailed picture, with higher numbers indicating a higher 'wind-driven-rain index' and therefore higher levels of wind-driven rain. The map shows that wind-driven rain is of far greater significance in the west of Ireland and of the UK, especially at coastal regions. The middle of the west coast of Scotland is particularly exposed to the impact of wind-driven rain. These areas experience potentially higher levels of wind-driven rain than anywhere else in Europe. (Hermann, 2013)

Understanding the significance of the wind-driven rain and its impact on buildings can be critical for hygrothermal assessment. How to factor wind-driven rain into such assessments is discussed in more detail in Section 5.2.1.2. (It is worth noting at this point that the currently available information about wind-driven rain levels for the UK (e.g. BSI, 1992; Stirling, 2002, fig. 30) is still based on data sets from between the 1950s to 1970s, whereas Met Éireann, Ireland's meteorological service, has recently published an updated wind-driven rain index map, based on more recent climatic data. (Walsh, 2010)

The degree of rain water penetrating into walls, however, does not only depend on the quantities of rain water coming into contact with a wall, but also on the condition of its fabric. Particularly the condition of the exterior wall surface can have a significant impact: where exposed masonry walls are not properly maintained, e.g. lacking re-rendering or re-pointing, they are more likely to allow rain water penetration. During a rain event, the differential of the water content between the sheet of water coating the surface and the comparably dry internal wall core is very large. Therefore, capillary action will quickly draw water into the larger pores of the material. After the rain event, the water will be redistributed within the wall, moving from wetter to drier areas, as water is drawn from the large pores into the smaller pores. In this case, the differential is much smaller, i.e. the differences are more like varying degrees of dampness rather than wet versus dry, and the pores are much smaller, thereby capillary moisture transport is slower.

Moisture transport through capillary action requires water-filled pores. Once the water in the pore structure is redistributed as far as it is possible within the small pores, there will not be enough water left to continue filling the pores further. Moisture transport beyond this point can therefore only occur by vapour diffusion or surface diffusion (though the direction may change). These transport mechanisms are both much slower than liquid transport by capillary action. As a result, it takes much longer for the moisture to work its way out of a wall than it does for the wall to be initially wetted. Indeed, there might be situations where rain water, having penetrated a wall, will never fully evaporate, leading to moisture accumulation in the wall over time and to rain water possibly reaching internal wall faces. Obviously, the more rain water comes into contact with the building envelope and the more moisture permeable its construction is, the more substantial the thickness of the building envelope needs to be to prevent the liquid water from being transported all the way to the interior wall surface. The high levels of driven rain in Scotland is one reason why traditional walls tend to be much thicker (generally approx. 600 mm overall), compared to brick walls in the dryer southeast of England (approx. 300mm thick).

To avoid moisture accumulation, the wall needs to be able to dry over time through evaporation, fed by the relatively slow processes of vapour diffusion and surface diffusion. Since these processes are affected by evaporation and relative humidity, the temperature of the wall is of critical importance. Internal insulation retrofits often change the temperature of the wall drastically by reducing the heat transfer from warmer interior spaces. They also add layers of sometimes impermeable materials that restrict the vapour diffusion and drying toward the interior space. Unless care is taken, the overall drying ability of the wall can be reduced significantly by an internal insulation retrofit. Where walls have a high moisture absorption, the reduced drying can also lead to increased, and potentially damaging, moisture levels. It is particularly in these situations that hygrothermal assessment can provide critical insights for the design of retrofit measures.

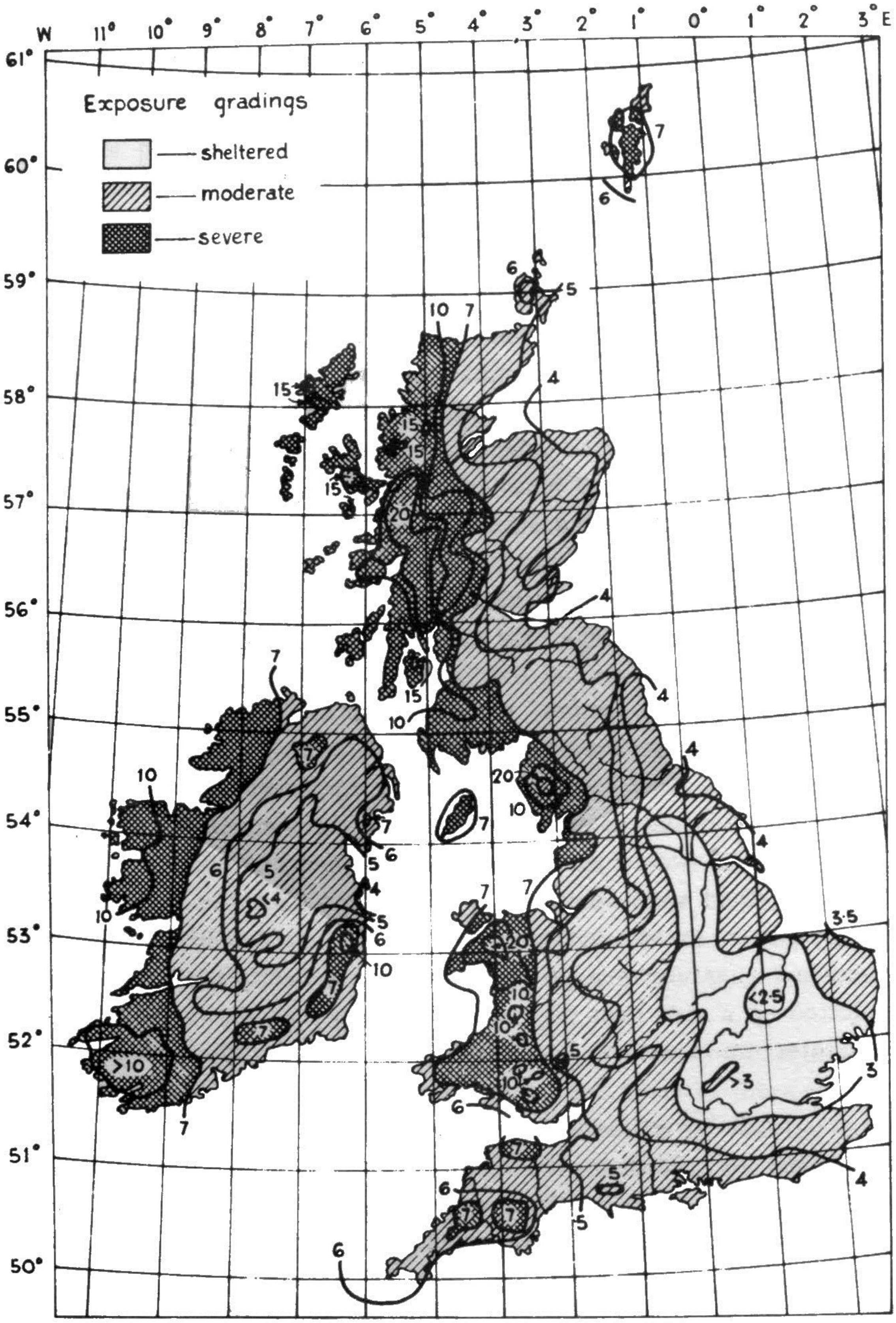


Figure 38 “Driving-rain index map of Great Britain, based on annual mean wind-speed and rainfall ($m^2\ sec^{-1}$)” (Lacy, 1966, p. 22, fig. 19 / Image © Building Research Establishment)

3.2.1.3 Ground water and rising damp

> *Rising damp is the common term for the slow upward movement of moisture in the lower parts of walls and other ground-supported structures. It is an important cause of wetness in buildings. It is a cause of decay and deterioration in standing stones, monuments and at archaeological sites.*
>
> Hall and Hoff (2007), p.1871

Gravity has a weak or negligible effect on how moisture moves within structures that are built of common materials like stone, mortar and brick. Capillary forces are usually dominant, being responsible for (a) most of the uptake from external sources - whether the ground, the atmosphere (driving rain at the wall surface), leaks and so on - and (b) most of the migration of moisture within the structure. (See Section 2.5.4 for more on capillarity.) Eventually moisture leaves the structure through evaporation. All these processes fall within the theory of Unsaturated Flow which has particular importance when assessing the magnitude of rising damp.

Key factors that determine how high rising damp can manifest are the:

- Level of moisture available (under UK conditions moisture is generally available to walls in direct contact with the ground);
- Sorptivity of the wall materials (as this affects how much moisture is wicked);
- Wall's thickness (as this affects how much can be stored);
- Area available for evaporative drying; and
- Immediate micro-climate on either side of the wall (as this effects the drying potential).

The role of evaporation in drawing a continuous flow of water through the structure is termed 'evaporative pumping'. The analogy of a pump is well used. It has been calculated (Hall and Hoff 2007) that one litre of water per day, per metre length of wall, can move through a 150mm wide wall in London (where rising damp has manifested to a height of 610mm above ground level) in this way. This equates to the movement of about 350 litres of water per year: a remarkable effect.

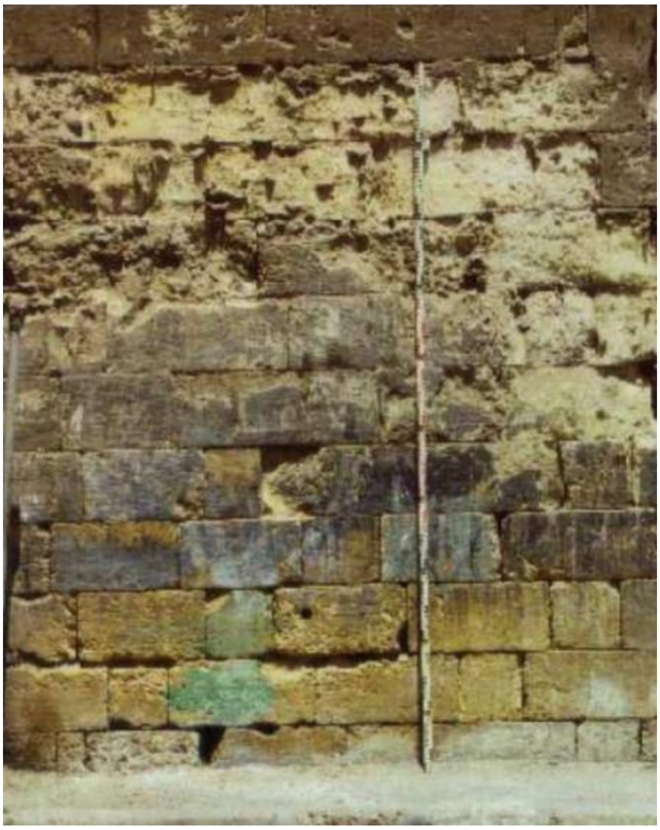


Figure 39 Southeast-facing wall of the El Merdani Mosque in Cairo. The measuring staff is 3m high. (Prof. Berndt Fitzner, Hall et al., 2010, p. 14, fig. 10 / Image © The Royal Society Publishing)

It is often said that 1 - 1.2m is the highest point to which rising damp will rise. This is largely true in the UK simply because few walls tend to be thicker than 600mm (and the London brick wall mentioned above was very much narrower). Rising damp can reach greater heights on thicker walls (for instance a thick castle wall) as their greater moisture storage capacity requires a greater surface area to dry through evaporatively. The wall of the El Merdani Mosque wall in Cairo (see Figure 39) has been extensively studied: it is 1.67m thick and manifests rising damp up to three metres high.

> *Ground water chemical composition is extremely variable, but even relatively clean waters generally have some soluble salts, at the level of 10-100 parts per million. Over many years these accumulate in the wall, since once in the wall, they generally stay there.*
>
> C. Hall, private correspondence with authors, August 2015

According to Hall, these soluable salts are typically sodium chloride, sodium sulfate, potassium sulphate, sodium nitrate; and (somewhat less soluble but also neutral) calcium sulfate (i.e. gypsum). They are relatively neutral in terms of pH. Nonetheless when ground water meets the first mortar joints it experiences what Chris Hall describes as a 'chemical shock' due to the mortar's highly alkaline nature. The water dissolves or leaches lime constituents (calcium hydroxide and calcium carbonate) from the lowest joint. In doing so, the water becomes more alkaline, and has a less 'aggressive' reaction at the next mortar joint. Over time the lower joints are fully leached and the chemical shock passes to successively higher joints, transporting the lime and salts in solution further up the wall.

> *…One can say definitely that the zone where highly-soluble salts (like sulphates, chlorides, nitrates) will appear is in the wet/dry zone, and not lower down where the wall is permanently damp. These salts are deposited as solids when the wet/dry zone dries back in the spring/summer, when the evaporation is more intense for climatic reasons. The water evaporates away but the salts are left in the wall. They may appear as surface efflorescence, but can also be deposited deep below the surface within the pores of the masonry materials. As crystals grow within the pores, they may exert forces on the pore walls which cause mechanical damage. The effect of a multitude of tiny salt crystals all trying to grow within the constraints of the pores adds up to a bursting pressure which may exceed the strength of the material (brick, stone etc.). Hence spalling or powdering. In the autumn/winter when evaporation diminishes, the wet/dry zone is re-wetted, and some of these salts may redissolve, and in addition further dissolved salts move up from lower in the wall. In the following spring/summer, the cycle repeats. It is the cyclic nature of the seasonal wetting and drying that causes the problem.*
>
> Ibid.

The impact of this cyclical nature is significant. The so-called potential evaporation in the UK can be many times greater in July than in December due to micro-climatic conditions that favour evaporation: Hall calculated that it was ten times greater in one case - a considerable difference. Greater evaporation brings greater solid salt accumulation and greater risk of damage to the molecular structure of the masonry. Contrariwise in Winter the forces exerted by salt crystals on some cell walls may lessen as the increasing ground water content dissolves crystals; however the risk of freeze-heave due to high water content in cells 10 - 20mm behind the external surface may increase. Due to higher water content dissolving solid salts, efflorescence (white salty deposits pushing out from the wall surface) may also reduce in extent during Winter, yet whitish stains (of calcium carbonate) may appear in that season that are not evident in Summer, as the micro-climate allows less surface evaporation.

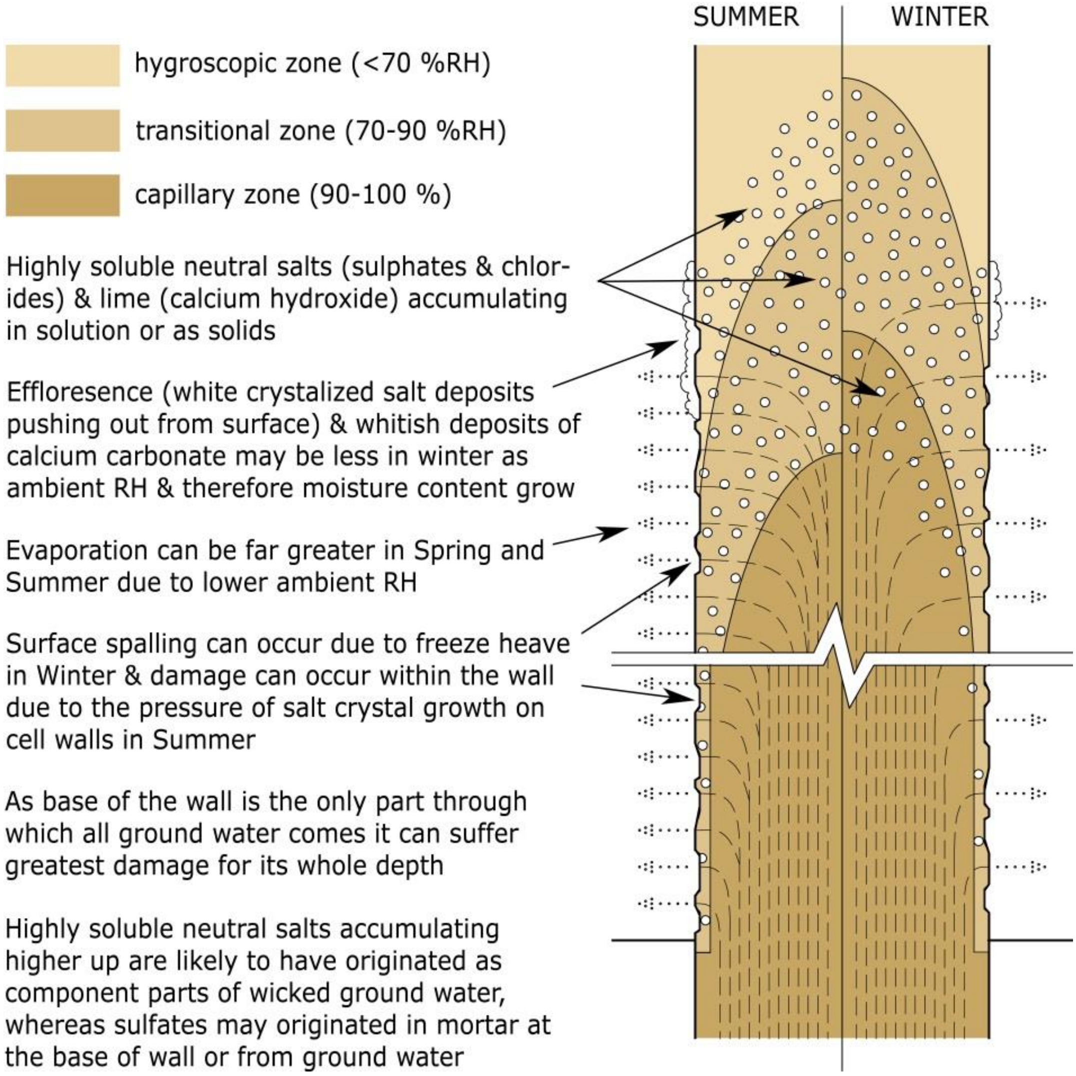


Figure 40 Diagram showing a wall cross-section with cyclical seasonal nature of rising damp and associated salt migration

The drawing in Figure 40 is an attempt to visually represent the cyclical nature of water content, evaporation and visible efflorescence from Summer to Winter. Note that the authors have used colour to emphasize the seasonal variability in relative humidity (which influences whether moisture transport is predominantly through vapour and surface diffusion or through capillary action). Hall's *wet/dry zone* is equivalent to the full area where accumulated salts are shown. The drawing is simplified: (depending on the type of masonry and mortar) salt accumulation would likely occur in mortar joints first, not in the uniform pattern shown there.

The study of rising damp is still developing. Simple mathematical models (such as shown in Hall and Hoff (2007)) can estimate the evaporative pumping effect with reasonable accuracy and Fraunhofer IBP has successfully modelled the effect using Wufi 2D, the two-dimensional numerical simulation tool of the WUFI suite of software (Holm, A., Künzel, H.M. 2000). Overall however Hall is of the view that there have been insufficient systematic field observations and theoretical analysis to be certain of the impact of hygrothermal, chemical and molecular aspects. This is complicated by the fact that each case will be different due to the molecular structure of the various materials in a wall (determining sorptivity etc.), the amounts of salts present (from ground water, mortar, stone or brick) and how acidic the groundwater itself is.

3.2.1.4 Remediating rising damp

> *It is often noted that it is difficult to replicate rising damp in the laboratory. The reasons for this include difficulties in producing a suitable mortar which is sufficiently sorptive. In older walls, it is likely that mortars become more sorptive as a result of the prolonged passage of water through them over long periods of time. Fresh mortars, particularly those containing cements, act as a barrier to rising damp*
>
> Hall and Hoff (2007), p. 1877

The difficulty in replicating rising damp may explain why many walls built without a damp proof course never experience rising damp. It may equally be why it is harder to rid walls of the condition once it has been well established – the material properties of the masonry in the latter walls have been altered, making them more and more effective evaporative pumps over time. Recent research (Rirsch et al. 2011) is establishing the altered characteristics of these mortars to allow better replication.

It is worth remembering that evaporative pumping of ground water of an extent that is considered problematic rising damp is quite uncommon in well-built, traditional buildings in the UK. When faced with an apparent case, the wall and any proposed solution should first be subjected to careful examination to see if another potential cause can be identified first. The cause of dampness may in fact be a broken drain (above or below ground) or perhaps the consequence of a foot path that has risen over time and deposits water directly into the wall. Careful examination and good maintenance can cause many cases of 'rising damp' to abate. Beyond this specialist advice from qualified professionals should be sought.

Be aware of companies that offer advice or free surveys while also selling the technical solution! There are many cases of expensive measures being applied that show little understanding of the hygrothermal and chemical forces in play. Solid walls naturally dry through evaporation through both faces, therefore tanking (i.e. sealing) one side of a wall will (a) reduce overall evaporation thereby increasing the wall's moisture content and (b) force evaporative drying to occur through a greater area on the other side. As moisture content behind the surface of that side rises the likelihood of freeze-heave and mortar decline may also grow (as a direct consequence of this moisture blocking approach). In severe cases the rising damp may also push the tanking off the wall. Equally, sealing both sides of the wall to a certain height will likely cause the rising damp to manifest higher up the wall: inadvertently the tanking creates a large volume of wall that can become saturated (literally a 'tank').

Installing a DPC to prevent capillary rise (a key feature of moisture blocking, non-traditional construction) may be judged a necessary step in severe cases, but it is not the solution to all cases of rising damp and certainly should not be considered a pre-requisite for solid walls that to date have manifested no signs of dampness (whether they are to internally insulated or not). There are physical, injected and electro-osmotic retrofit DPCs. It would appear some retrofit DPCs are unfit for purpose and many are poorly installed. Chapter 6 of 'Understanding Dampness' by Trotman et al. (2004) has good information on rising damp and remediation measures.

A first principles approach would always seek to restore the solid wall and its surrounds to their original moisture managing condition, or at least conditions that act in a hygrothermally equivalent manner. The remedial works could include some, or all, of the following:

- Carry out a maintenance inspection and repairs on rain water goods, roof overhangs and checking underground services and pipes;
- Check if the water table is unusually high or if an underground stream exists;
- Adjust height of footpaths or slopes that may have been changed causing surface water to be channelled to the wall;
- Remove tanking and cement plasters;
- Replace cement mortars and (if possible) altered lime mortars with an appropriate specification of lime mortar;
- Repoint with an appropriate lime mortar;
- Manage the increased salt content by (a) installing a salt extracting compress (that literally leaches the excess build-up of salt) on the area of wall effected, and (b) following this with a restoration lime plaster that blocks salt without reducing vapour permeability (Note, at times step (b) is sufficient.);
- Install vapour permeable finishes.

It is clear all this requires professional guidance, careful specification and skilled workmanship.

3.2.2 Moisture-related deterioration and health risks

Large quantities of moisture within the building fabric are likely to cause material deterioration and health risks, particularly when high moisture levels persist for prolonged periods of time. In this section, mould growth, a risk to occupants' health, will be discussed first (Section 3.2.2.1), followed by two forms of moisture-related fabric deterioration: timber decay due to rot (Section 3.2.2.2) and surface spalling due to freeze-thaw action (Section 3.2.2.3).

All three issues can be of serious concern with regard to the retrofit of internal wall insulation.

3.2.2.1 Mould growth

Mould is a fungus, ubiquitous in nature. Thousands of known mould species exist. Mould reproduces via spores, which are common components of household and workplace dust.

> *Moisture in buildings arises from several sources: if not properly controlled it can lead to mould growth and condensation – problems which affect about 15% of homes in England to some degree.*
>
> (BSI, 2011, p. 5)

Mould growth in buildings occurs generally on the surfaces of building materials. It can often be smelt, frequently identified as ‘a damp smell’, before it is seen. Where surfaces are visible, mould can be perceived due to its colour as surface discolouration, also referred to as ‘ghosting’ or staining, or, in more extreme cases, as fuzzy layer of growth on surface. (Figure 41) Mould growth can also occur interstitially, where it is not as readily noticed.

Excessive mould growth in buildings has multiple consequences. Discoloration due to the onset of mould can lead to higher maintenance costs, to the economic devaluation of buildings where mould is persistent and, in the case of historic buildings, to damage of historically important finishes. At worst, mould growth releases an abundance of spores and volatile organic compounds in the air that can lead to health problems for building occupants, potentially causing allergic reactions and respiratory problems. (WHO Europe, 2009)

However, mould growth can only occur under suitable environmental conditions. Mould growth should therefore be avoided by ensuring that environmental conditions are created that don’t encourage mould growth. These threshold levels and the methods to assess them are discussed in the following. At design stage steps should be taken to design-out the potential for mould to occur.

Figure 41 Severe mould growth on the non-hygroscopic surfaces of a coated window frame (left) and a plasterboarded window reveal (right).

Mould risk evaluation

As living organisms, moulds require certain conditions to grow. In particular, there must be sufficiently high temperature and moisture levels and nutrients available. Moisture does not have to be present in liquid form for mould to grow. If the relative humidity is high enough, it creates environmental conditions sufficient for mould growth.

The British Standard *BS 5250*, concerned with condensation control in buildings, states, regarding the relationship of indoor humidity levels and mould growth:

> *Large numbers of mould spores are always present in the atmosphere. In order to germinate those spores require warmth, a source of nutrition, oxygen and moisture; because they are hygroscopic they do not require liquid water. Many mould spores can germinate if the relative humidity at the surface exceeds 80%. Once established mould spores can continue to grow at a moisture level lower than 80%. …*
>
> *Buildings provide many sources of nutrition, and oxygen is always present, consequently the growth of moulds depends on moisture conditions at internal surfaces. In winter the internal surfaces of the external walls can be colder than the air in the room and the relative humidity at the face of the wall is about 10% greater than that in the room. As a result, if the relative humidity*

of the room stays at 70% for long periods of time the external wall surfaces will be sufficiently humid to support the growth of mould. …

If the relative humidity of the air in a room exceeds 70%, the surface relative humidity of an external element is likely to exceed 80%. If that occurs for more than two or three days, mould is likely to develop on the surface. Surface relative humidity is determined by the internal vapour pressure and the surface temperature of the external element, which depends upon the nature of the construction. The presence of thermal bridges such as those around doors and windows produces lower local temperatures.

(BSI, 2011, pp. 15, 23)

80 % RH is often used as a *rule of thumb* threshold to stay below in order to avoid mould growth on surfaces. (ibid.; DIN, 2001) This threshold level is used to simplify complexity and is based on microbiological studies using isopleths, or contour lines, to describe mould growth.

Isopleth model

As with many rules of thumb, there is value in being able to quickly assess constructions, as long as, firstly, it is clear how much detail is omitted in the process and, secondly, that the assessment rules are abandoned if a better understanding necessitates the use of more accurate thresholds. Advanced simulation software now allows assessment of mould growth that goes far beyond the simplistic 80 % threshold approach.

Since mould growth requires a certain temperature range in addition to moisture, it is possible to establish more accurate tolerances and risk levels that account for both of these parameters. ***Isopleths*** are curves describing mould growth conditions in dependence of temperature and relative humidity levels. (Figure 42)

There are hundreds of thousands of mould species on the planet. Of these, a few hundred have been found in buildings, and their growth patterns studied in detail. (Sedlbauer, 2001) Each mould species is slightly different and, therefore, has slightly different growth conditions. Figure 42 shows the isopleths (dotted curves) for various mould species. Each isopleth describes the threshold level at which growth of the concerned mould species commences, i.e. environmental conditions above the curve support growth. The isopleth models for all mould species under consideration can be combined and an overall isopleth for all species determined (continuous curve in the figure). This overall isopleth is referred to as the ***lowest isopleth for mould (LIM)***. Below the LIM curve, none of the various mould species is able to grow.

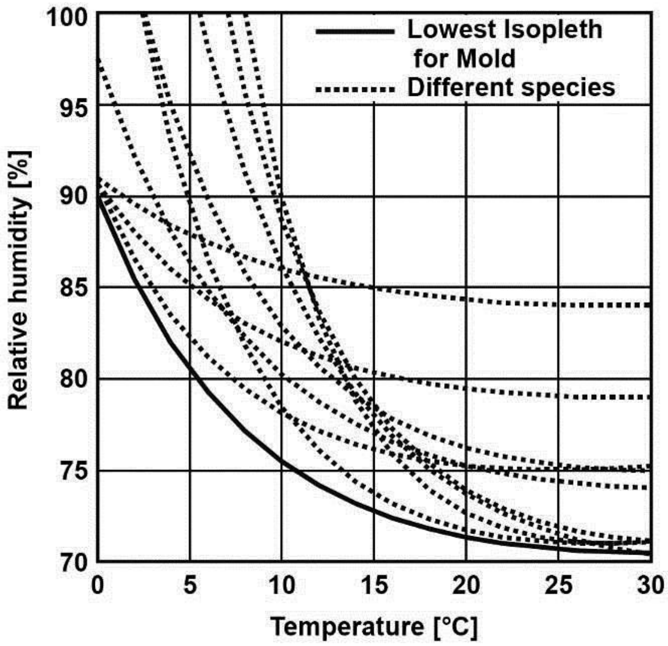


Figure 42 Example of isopleth models: the dotted curves describe the mould growth thresholds for different mould species. The overall threshold is the LIM graph, shown as continuous curve. (Sedlbauer, 2001, fig. 30 / Image © Fraunhofer-Gesellschaft)

To also account for nutrients, the third requirement for mould growth, isopleth models have been developed further to also include different combinations of mould growing on different material substrates. Substrates with fewer nutrients shift the various isopleths curve higher. In other words, higher temperature and humidity levels are required for growth to commence if there is limited nutrients.

Substrate classes

Different materials provide different conditions for mould growth. Building materials are generally grouped into three substrate classes:

- Class I are easily biodegradable materials, such as wall paper and gypsum plasterboard and materials for permanently elastic joints
- Class II are less degradable, porous materials, such as plasters and mineral building materials and some timbers.
- Class III are building materials that can be neither degraded nor contain nutrients non-degradable materials, such as glass, metals, foils and tiles.

Representative LIM curves ($LIM_{Bau}I$, $LIM_{Bau}II$ and $LIM_{Bau}III$) have been developed for mould growing on each of these substrate classes. Figure 43 shows the curves for $LIM_{Bau}I$ and

$LIM_{Bau}II$. In this figure, the curve $LIM_{Bau}II$ describes the threshold levels for materials of *substrate class II*, such as mineral plaster and stone which contain fewer nutrients than, for instance, gypsum plaster or wall paper. The latter material selection would consequently be judged using *substrate class I* and the $LIM_{Bau}I$ curve. Materials grouped into *substrate class III*, such as metal, glass and tiles, do not contain any nutrients and, therefore, do not support mould growth. Hence, no related $LIM_{BAU}III$ curve shown in Figure 43. However, mould can also grow over these surfaces if they become contaminated, e.g. by dust, fingerprints, air pollution or even human perspiration. In fact in cases of significant contamination, materials listed in $LIM_{Bau}III$ and $LIM_{Bau}II$ should be assessed as if they are a material in the $LIM_{Bau}I$ category. (For reference, a LIM 0 curve is also shown in the discussed figure. This isopleth represents an ideal growing substrate for mould with an abundance of nutrients, similar to that used in a laboratory petri dish).

How computer simulation can be used to aid mould growth risk assessments will be discussed in Section 4.5 and further illustrated in the case study in Section 5.4.1 in the second part of this report, where mould risk of stone wall surfaces will be assessed.

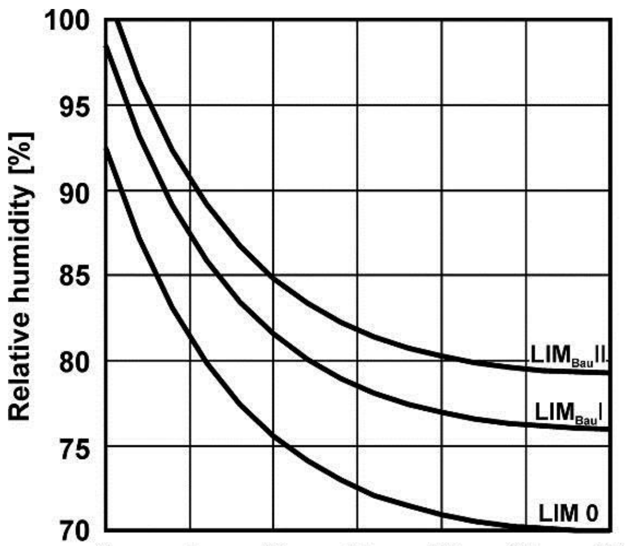


Figure 43 Example of LIM isopleths for different substrate classes for building materials: Curves $LIM_{Bau}I$ and $LIM_{Bau}II$ represents substrate classes I and II respectively; curve LIM 0 represents an ideal growing-substrate. (Fraunhofer IBP / Image © Fraunhofer-Gesellschaft)

Biohygrothermal modelling

Simulation software have been developed to create **biohygrothermal models**, which account for the changing conditions and passage of time in a building component. Using these models, it is possible to predict the length of time that conditions will be suitable for mould growth at a particular location within a building component. For every hour that the temperature and humidity are above the LIM curve, the mould is considered to continue growing. When this changes, it stops, but is considered to restart growing immediately when conditions are right again. This is a conservative approach, because, in reality, growth does not begin immediately and, during the non-growth periods of time, some of the mould is likely to die off. Therefore, hygrothermal models will always conservatively over predict the amount of mould growth.

Because of this overprediction, experimental research and surveys of buildings have determined the growth levels that are acceptable in biohygrothermal models before mould growth issues are expected under real-world conditions. These acceptable thresholds are represented either as the modelled growth rate per year (Sedlbauer, 2001) or as a mould growth index on a scale of 0 to 6 (Viitanen and Ojanen, 2007).

The thresholds within the bio-hygrothermal model that is used in WUFI-Bio, a bio-hygrothermal simulation software (Section 4.5), are as follows (Fraunhofer IBP, 2010):

- Mould growth exceeds 200 mm/year, which corresponds to a mould growth index of approximately 2 → usually not acceptable
- Mould growth is between 50 and 200 mm/year → additional criteria or investigations are needed for assessing acceptability
- Mould growth is below 50 mm/year, which corresponds to a mould growth index of approximately 0.5 → usually acceptable

Biohygrothermal simulation is a field of building science still under development, and more research is needed to refine the accuracy of these models. Because of the interactions affecting mould growth under real-world conditions, these models should only be used to assess the *risk* of mould growth, rather than to predict actual level of growth.

Interstitial mould growth

The three mould growth risk models mentioned above – the 80 % threshold model, the isopleth model and the biohygrothermal model – are all related to internal surfaces of the room. But mould can also grow interstitially, e.g. at the surfaces of cavities within the construction. However, the risk of interstitial growth is reduced due to a lower availability of mould spores, oxygen and nutrients, as a result of lower air flow. Achieving good airtightness levels can therefore help to prevent interstitial mould growth, as well as interstitial condensation.

For internal insulation retrofits, WTA (2009), a Central European association concerned with physics in a building conservation context, recommends that a vapour permeable insulation is continuously adhered to the existing wall to completely avoid any air space at the interface. Where a number of other conditions are also met; including use of (a) renders, rainscreens or impregnations that prevent driving rain ingress, (b) a normal internal moisture load, and (c) certain vapour permeability thresholds; the risk of interstitial mould growth can be disregarded, thereby allowing the critical threshold to be raised to 95 % RH – the relevant level for assessing risk of masonry spalling due to freeze-thaw. (Section 3.2.2.3)

> *"On s'assure de cette manière [éviter une humidité relative dans la paroi supérieure à 95%] qu'aucune condensation n'apparaîtra à l'interface avec le mur ancien, et que, dans les conditions données, aucun dommage lié au gel ne se produira."*
>
> ("This [preventing a relative humidity higher than 95% in the wall] ensures that no condensation will appear at the interface with the original wall, and that no frost damage will occur at the given conditions.")
>
> (WTA, 2009)

However, as many traditional solid wall buildings in the UK and Ireland *are* vulnerable to driving rain (due to having a stone or brick finish) it is not clear if the 95 % RH may be applied when assessing them, *if all other WTA criteria are met*. Certainly greater leeway should be given for bonded insulation systems that are not just vapour permeable but also hygroscopic, capillary active (and ideally biocidic), compared to those that are vapour permeable only. This is clearly an area that needs exploration by British or Irish building physicists.

A short list of insulation assemblies in this category include insulated plasters and fully-adhered insulant board systems. The first group include lime-hemp, lime-cork bead, and lime-aerogel bead composites. The second group includes calcium silicate, cork or wood-fibre board systems used with lime mortar-based adhesives. Some conventional insulation manufacturers wish to widen this group to include mineral wool systems (which are vapour permeable, but neither hygroscopic nor capillary active) once the insulation is pressed up against the wall, but the suitability of this system is less clear and more prone to the vagaries of the wall's flatness and the site worker's care.

For now, it may be best to consider that the traditional 80 % RH threshold still stands but that a fully bonded, hygrothermal, vapour permeable and capillary active insulation assembly should give additional safety benefits. A trained hygrothermal assessor should form judgments in formal risk assessments case-by-case when confronted by such issues.

The use of a biohygrothermal model is illustrated in the case study of this report, where the mould growth risk is assessed for an internally insulated masonry wall. (Section 5.4.1) While, strictly speaking, the model is only directly applicable for internal surfaces, or air spaces on the warm side of the wall with a high airflow, there is value in using the model as a comparative too, particularly if the study using relative humidity and acceptable thresholds has left some ambiguity. To do this one must bear in mind that the absolute risk indicated may be too conservative, if a good airtightness is achieved, and that the model is not applicable to fully bonded insulants where the adhesive or substrate is alkaline, because this inhibits and can kill mould.

3.2.2.2 Timber decay by rot

Rot is a fungus, causing the decay of timber. There are several fungal species which are referred to as rot. Generally, two forms of rot are distinguished: dry rot and wet rot. (Wet rot is also referred to as brown rot.) As with mould, rot requires specific environmental conditions and nutrients to thrive. The main nutrient for rot in buildings is cellulose, hence rot's ability to decompose timber. Timber can be found in various forms in solid masonry walls. Floor joists are set into masonry; ceiling rafters rest on (timber wall-plates placed onto) wall heads; timber lintols are built into walls; architraves, panelling, skirting boards are fixed to walls; so are timber battens to hold timber laths for plaster finishes; etc. Where a wall is drylined, using timber studs, these can also be in contact with the masonry.

An example of an often found rot fungus is *Serpula lacrymans*:

> *The dry rot fungus,* Serpula lacrymans*, is one of the most important wood decay fungi in the built environment …* [*S.lacrymans*] *is particularly common in countries of northern Europe especially where bad maintenance, particularly of old properties, and inappropriate design or alteration may result in water ingress followed by timber decay caused by the fungus. Notably, however, S.lacrymans is rarely found outside the built environment in Europe …*
>
> *The fungus develops in poorly ventilated spaces with elevated moisture levels (>20% moisture content). Though the principle nutrient source for the organism is wood, it very effectively colonises non-woody building materials notably plaster, brick and stone.*
>
> (Palfreyman, 2001, section 1, 2)

Wood is able to hold a certain amount of water within its cells, before the cells are full. The point at which the cells are filled is the ***fibre saturation point.*** Beyond this point, water is held between cells and referred to as ***free water***. This free water is accessible to the dry rot fungi as a water source. Dry rot fungi can exist at lower moisture levels, but will only produce spores and decay wood when the fibre saturation point is exceeded. Rot decay can be halted and the fungi potentially killed through removal of the water source which the fungi depends on. The fungi will be dormant and eventually die once it no longer receives the required water. (McCaig, 2012; Palfreyman et al., 2002; Ridout, 2000)

Moisture thresholds

To avoid rot, it is generally recommended to ensure that moisture content levels are maintained below a threshold of 20 % of the mass of the timber. (The moisture content is a measure of the mass of water per mass of dry wood; it is not a reference to humidity.)

> *Decay generally requires wood moisture content at fiber saturation (usually about 30%) or higher and temperatures between 10 and 40°C. ... Because wood moisture content can vary widely with sample location, a local moisture content of 20% or higher may indicate fiber saturation elsewhere.*
>
> (ASHRAE, 2009, p. 25.15)

A threshold level of 20 % is also recommended in Fraunhofer IBP (2011), whereas Singh (1996) suggests using a lower threshold of 16 to 18 % for subsurface moisture content level. Ridout (2000) describes the different effects that two different water content levels (both greater than 20 % by mass) can have on timbers built into masonry walls. The first may only be relevant at roof leaks and the likes. The latter could well be relevant behind internal insulation installed to certain types of solid masonry walls.

> *If the walls are made of brick or any other porous material and excess water penetration has caused free water to fill the large pores, then the water will travel easily along the end grain of the timber. … the fungi will consume the entire component end as far as the water entering the wall and evaporative loss will allow. This form of decay will continue for some time, even after the supply of water is halted, because until the large pores of the wall are empty of water there is plentiful supply of free water within the wall.*
>
> *However, if the wall is only damp then much of the water it contains will … be held by capillary forces in the small pores, and the amount of water that is available to the fungus is limited. The timber will still wet and rot, but only the bearing within the wall will normally be lost. Decay caused by small leaks is therefore usually restricted, and will cease rapidly when water penetration is halted.*
>
> (Ridout, 2000, pp. 129-130)

To reduce the absorption of moisture from the masonry into the timber, the latter could be isolated from the masonry.

> *Timber should be isolated from damp masonry by air space or damp proof membrane, and free air movement should be allowed around timber in walls, roofs and suspended floors.*
>
> (Singh, 1996)

The purpose of isolating the timber from the masonry is twofold: to avoid moisture transport through capillary action and to increase the potential for evaporative drying. However, isolating timber from the masonry also results in an increased oxygen supply, potentially causing mould growth and thermal bypass.

3.2.2.3 Surface spalling due to freeze-thaw action

Moisture-related deterioration of the exterior surfaces of building envelopes can occur in the form of surface spalling, or *face loss*, due to freeze-thaw action. Freeze-thaw action is the repeated freezing and melting of water within a material. Freezing water increases in volume. (Section 2.5.1.1) When water freezes within the pore structure of a material, the volume increase causes pressure, or stress, on the material's mass, which forms the pore structure. This stress can damage the material structure, if it is not strong enough.

An area particularly susceptible to this form of deterioration is the near surface layer. Where repeated freeze-thaw action occurs in the near surface layer of rather soft materials, such as some bricks and stones, the exterior surface of the material will start spalling, due to the pressure caused by water freezing and thereby expanding in volume. An example of such surface spalling is shown in Figure 44. (The presence of salts in the near surface layer can also cause and/or contribute to surface spalling, but this will not be discussed further in this report for the sake of simplicity.)

Certain materials can resist this stress better than others. Stone can generally withstand greater forces than brick, but the variance between different types of stones, or the same stone laid on a different plane and, even more so, different types of brick is huge. Where freeze-thaw action occurs often the molecular bonds of the materials can progressively weaken, resulting in surface spalling. While a higher content of liquid water may occur deeper into the masonry, the lowest temperatures, the greatest temperature swings and the lowest ability of the masonry to resist increased stress are all likely to be within millimetres of the masonry's external surface. As a freeze-thaw cycle can occur several times in one day during winter time in parts of Ireland and Scotland those maintaining brick and stone-faced buildings should take care.

Figure 44 Surface spalling at a wall made from engineering bricks: It was wetted repeatedly under controlled climatic conditions to simulating freeze-thaw action. (Fraunhofer IBP / image © Fraunhofer-Gesellschaft)

Moisture thresholds

Straube and Schumacher (2006) discuss possible moisture thresholds to prevent surface spalling due to freeze-thaw action:

> *It is well accepted that two factors have the most importance on FT* [freeze-thaw] *damage: the moisture content on freezing and the number of freeze-thaw cycles. We have defined a freeze cycle as occurring when the temperature within the material drops below -5 C (a rather high temperature) and a thaw cycle to occur when the temperature rises above 0 C. This is based on the observation that FT is not a problem at temperatures just below freezing – damage tends to require temperatures much colder than -5 C and most test standards require the material to be cooled below -15 C. …*
>
> *Although the critical moisture content can be found from tests, such tests are rather involved and onerous. The dangerous moisture content is often in the range of 75 to 94% of the free water saturation. Given no other information we often choose to use 90% since it is conservative and one of the more common thresholds for brick. The same threshold can often be used for natural stone.*
>
> (Straube and Schumacher, 2006)

The above assessment of the times that the pores are more than 90 % filled *and* temperatures are lower than 0 °C is a useful guide to risk, but is by no means conclusive. There can be presence of liquid water above a relative humidity of 95 %. Therefore it seems advisable to stay below that threshold as a conservative rule for preventing freeze-thaw deterioration. (WTA, 2009) An example of a freeze-thaw risk assessment for a retrofitted stone wall is included in the case study of this report. (Section 5.4.2)

4 Assessment methods and simulation tools

Full models have as major objective to describe HAM-transport [heat, air and moisture transport] in the closest possible relation to the physics and thermodynamics involved. (Nearly) full modelling is therefore a scientific activity.

Simple calculation tools reflect the other extreme. They build on a typical engineering point of view: calculations should be simple enough to be performed by hand or with the assistance of a pocket calculator. With that objective in mind, physics and boundary conditions are simplified to the ultimate.

Simplified models occupy a position in between. On the one hand, the partial differential equations, these models build on, stay as close as possible to those obtained in (nearly) full modelling. On the other hand, material properties and boundary conditions are simplified to the lowest level possible without unacceptable loss of accuracy

(Hens, 1996)

4.1 Methodological approaches

Risk assessments are carried out when awareness arises that a risk of unknown likelihood and magnitude exists. Those involved with buildings may understand this intuitively or know it through experience or education and, therefore, select a specific assessment method. Alternatively, they may consult guidance documents, which, in turn, may recommend an assessment method. However, every assessment method is a simplification of reality. To use it suitably the assessor must understand the implications that these simplifications have for the applicability of a specific method, and thereby the resulting limitations of the method's scope. In other words, the assessment process must go beyond the use of an assessment tool, putting its use into a specific context. The assessors' judgment and knowledge of construction, building culture and building operation are of crucial importance.

For the hygrothermal assessment of building envelopes, two assessment methods are in common use: *Glaser method* assessments and *numerical simulation* assessments. Both are underpinned by British Standards: *BS EN ISO 13788* and *BS EN 15026* respectively. The methodologies behind these two methods differ significantly. The differences will be outlined in the following. Thereafter, the two assessment methods will be described in more detail and placed in the context of the relevant UK regulatory framework, i.e. building regulations and *codes of practice*, and their use in practice will be critically reviewed. In addition to this, methods and tools for assessing the risk of mould growth and for thermal bridge assessment will also be discussed.

Heat and moisture transport are an intrinsically linked physical phenomena. This coupling makes their assessment complex. Assessing these transport phenomena separately will not lead to the same results as assessing them simultaneously. This makes hygrothermal assessments complex. Methodologically, there are essentially two approaches to dealing with complexity in assessments:

1. to make a number of assumptions to simplify and decouple the equations

2. to solve the equations numerically, using computer simulation

The first approach forms the basis for Glaser method assessments. Its predecessor, the dewpoint method, originated in the US during the 1930s (Rose, 2003), and got further developed in Germany in the late 1950s (Section 4.2.1). The assessment was carried out manually through the graphing of simplified input data based on steady-state conditions: today the latest version of this method is eased and accelerated though the use of computer software.

The second approach, numerical simulation, has only become possible since the late 20th century, due to the availability of more affordable computers and powerful microprocessors. Somehow much of the early work was isolated. In a study from 1990, the International Energy Agency (IEA) found that findings from research were not being implemented in standards and codes of practice:

> *Many laboratories were very active in heat and moisture modelling and testing and applied the knowledge gained on building enclosures. Most national building codes and standards however remained notably silent on HAM-performance or treated the subject in a very elementary way. This situation convinced 14 countries, 12 as full members and 2 as observers, to join forces and to start a common research project named Heat, Air and Moisture Transfer in Highly Insulated Envelope* (HAMTIE) *and was initiated by the Energy Conservation in Buildings and Community Systems Programme Executive Committee as Annex 24.*
>
> (Hens, 2002, p. 1)

Volume 1 of the Final Report was published in 1996 and a Technical Synthesis Report in 2002. (Interestingly certain conclusions of Annex 24 agree closely with the finding of this report – see page 212). This work appears to have created important common ground. Further development and commercialisation followed. Fraunhofer IBP, for instance, solid their first licence of WUFI in 1995. The new powerful software packages could solve the complex, coupled equations required for hygrothermal assessments, using transient-state systems and processing vast quantities of data. As these software packages can make more accurate and realistic predictions of heat and moisture conditions within building fabric than the earlier methods that relied on the decoupling of the equations, their outputs may be termed 'numerical simulations'.

But what is the difference between steady- and transient-state systems? This might be explained best with examples of hygrothermal assessments. When conducting a hygrothermal assessment with a hugely reduced data set, say twelve calculations for the period of a year, daily cycles in weather pattern cannot be considered. The weather data used for such hygrothermal assessments will need to be monthly averages. This means that substantial short-term weather cycles are ignored. Such a simplified assessment, as used for Glaser method assessments, is based on **steady-state system**, which means that numerous input parameters, such as rain fall, pressure or heat flow, are considered in the assessment as unchanging in time. Obviously, for such an assessment, each monthly set of weather data will be unique. Nonetheless, this is considered as being steady-state, compared to the vast data quantities processed in numerical simulation. The substantial number of calculation sets conducted in numerical simulations allows short-term weather cycles to be factored into such simulations. The calculations take account of changes in the system over time, such as hourly oscillations in temperature or humidity. When based on hourly calculations, a yearly simulation would consists of 8760 calculation sets. This assessment approach, used for numerical simulation assessments, allows input parameters to change over time and is therefore referred to as a **transient-state system**.

Table 6 lists the differences between hygrothermal assessment methodologies, based on steady-state and transient-state systems.

Methodological approach	**Steady-state system**	**Transient-state system**
Method design	solve simplified, decoupled equations	Solve complex equations numerically
Assessment type	Glaser method	numerical simulation
Associated standard	*BS EN ISO 13788*	*BS EN 15026*
Assessment basis	twelve monthly calculations for an assessment period of one-year	hourly calculation sets for an assessment period of several years

Table 6 Differences between hygrothermal assessment methodologies, based on steady- and transient-state systems

4.2 Glaser method (*BS EN ISO 13788*)

4.2.1 Scope and limitations

The Glaser method is a procedure to assess the condensation risk in building fabric. The procedure, described in the British Standard *BS EN ISO 13788:2012* (BSI, 2013), consists of "simplified calculation methods, which assume that moisture transport is by vapour diffusion only and use monthly climate data." (ibid., p. v) The method further assumes "one-dimensional, steady-state conditions." (ibid., p. 9)

The original Glaser method, developed by Dr. H. Glaser, a German engineer, was first published in 1959, as an assessment method for diffusion transport processes in the thermal envelopes of cold rooms. (Glaser, 1959) The method was originally developed as a graphical assessment procedure, but is now generally processed using computers. Although the Glaser method, today, is heavily used worldwide, it was only in 2002 that it was first published in a British Standard. (BSI, 2002b) The name *Glaser method* is actually not prominently used in the standard. It is only in a note that the name is acknowledged: "Calculation methods according to this principle [as set out in the standard] are often called 'Glaser methods'." (ibid., p. 10) Strictly speaking, the standard presents a variant of the Glaser method, involving twelve calculations based on monthly mean external environmental conditions and additional criteria for moisture accumulation and evaporation. A revised version of this standard, *BS EN ISO 13788:2012* was published in 2013. (BSI, 2013) This paper refers to the 'Glaser method' as defined in this standard and not to the original method.

In its introduction, *BS EN ISO 13788:2012* outlines its scope, but also hints at its limitations:

> *Moisture transfer is a very complex process and the knowledge of moisture transfer mechanisms, material properties, initial conditions and boundary conditions is often limited. Therefore this … Standard lays down simplified calculation methods, which assume that moisture transport is by vapour diffusion alone and use monthly climate data. The standardization of these calculation methods does not exclude use of more advanced methods. <u>If other sources of moisture, such as rain penetration or convection, are negligible</u>, the calculations normally lead to designs well on the safe side*
>
> (BSI, 2013, p. v, underlining added to quotation)

The standard essentially provides three calculation methods for:

> a) *The internal surface temperature of a building component or building element below which mould growth is likely …*

> b) *The assessment of the risk of interstitial condensation due to water vapour diffusion. …*
>
> c) *The time taken for water … in a layer between two high vapour resistance layers to dry out and the* [associated] *risk of interstitial condensation …*
>
> (ibid., p. 1)

The first two of these methods are of particular interest in the context of this paper.

> *The method used does not take account of a number of important physical phenomena including:*
>
> - *The variation of material properties with moisture content;*
> - *Capillary suction and liquid moisture transport within materials;*
> - *Air movement from within the building into the component through gaps or within air space;*
> - *The hygroscopic moisture capacity of materials.*
>
> *Consequently, the method is applicable only where the effects of these phenomena can be considered to be negligible.*
>
> (ibid., p. 1)

From the above quotations clearly state that the only moisture transport process considered in the standard is vapour diffusion. Liquid transport and vapour convection are not covered, in order to simplify the assessment method. Liquid, in the form of "ground water and ingress of precipitation" (i.e. rising damp and rain water respectively) and its transport by capillary action are ignored. (ibid., p. v) So is airflow and thereby moisture convection, despite being "a major mechanism for moisture transport, which can increase the risk of condensation problems very significantly." (ibid., p. v) In other words:

> *This Standard is not intended to be used for building elements where there is airflow through or within the element or where rain [or ground] water is absorbed.*
>
> (BSI, 2013, p. 10)

Being a simplified calculation procedure, the Glaser method has substantial limitation and is only applicable under specific conditions. It is worth analysing what these limitations and conditions mean in the context of traditional building construction, particularly where traditional stone walls are involved.

Exclusion of precipitation: Traditional masonry walls are air and moisture permeable (Section 3.1.3) with varying susceptibility to rain water penetration. Precipitation is a considerable climatic factor throughout the British Isles. It can have a particularly severe impact on building envelopes when precipitation occurs in the form of wind-driven rain. Although exposure levels of wind-driven rain vary significantly throughout the British Isles, most of their north and west coasts experience regularly severe exposure levels. These also tends to be the areas where traditional walls are constructed in solid stone masonry. It follows that, because of its exclusion of precipitation, the Glaser method is not suitable for assessing traditional stone walls exposed to high levels of wind-driven rain. It is not completely clear, to date, under which conditions rain water penetration of such walls can lead to damaging levels of moisture accumulation (long-term) and how it impacts on condensation issues. (Hermann, 2013; Baker et al., 2014) It is, however, clear that the Glaser method is not suitable to assess walls under such conditions. Considering these uncertainties, it therefore would be prudent to use more advanced assessments methods for such forms of construction.

Exclusion of liquid transport: Traditional masonry walls frequently absorb liquid water in the form of rain water, but occasionally also due to ground water penetration. Moisture content levels will therefore fluctuate hourly, daily and seasonally. As these walls are moisture managing, liquid transport within the wall fabric is a common, naturally occurring phenomenon. But liquid transport is also important where moisture accumulates as a result of driving rain, condensation or where hygroscopic building materials are present. As liquid water accumulates within a porous material's pores, it will migrate away from the wettest point due to transport by capillary action or surface diffusion. Proponents of the Glaser method claim that their calculations are more conservative as they do not allow for this redistribution. While it is true that their calculations may show higher peaks and far more incidence of 100 % RH, they do not reflect the hygrothermal performance of building materials sufficiently well. As shown in Section 5.3, Glaser method assessments of hygroscopic materials can predict failure where none occurs and no risk where risks are actually high.

Exclusion of the hygroscopic moisture capacity of materials: Hygroscopicity is the capacity of a material to react to the moisture content of the air, by absorbing or releasing water vapour. (Section 2.5.1.5) For this process, the water content of the material is of decisive significance (TIS, 2013), including both the amount of liquid and gaseous water. Although the Glaser method considers vapour diffusion as the only occurring form of moisture transport, it excludes, for the sake of simplicity, the hygroscopic properties of material, which can lead, under certain conditions, to distorted diffusion predictions. This can lead to moisture contents higher than that predicted by the Glaser method, which, in turn, can result in mould growth and rot even before condensation occurs. Therefore, in materials subject to such forms of deterioration, e.g. wood-based products, the moisture content is critically important. Ignoring the hygroscopic moisture capacity in an assessment could result in overlooking failure conditions.

From the above discussion, it becomes apparent that liquid transport obviously plays a role –and under certain conditions an important role– in assessing the hygrothermal performance of a traditional stone wall to establish condensation risks. Confusingly, *BS EN ISO 13788:2012* claims, albeit only in a note:

> *Due to the many sources of error, this calculation method is less suitable for certain building components and climate. Neglecting moisture transfer in the liquid phase normally results in an overestimate of the risk of interstitial condensation.*
>
> (BSI, 2013, p. 10)

For which building elements can the standard be used?

> *The limitations on the physical processes covered by this … Standard mean that it can provide a more robust analysis of some structures than others. The results will be more reliable for lightweight, airtight structures that do not contain materials that store large amounts of water. They are less reliable for structures with large thermal and moisture capacity and which are subject to significant air leakage.*
>
> (BSI, 2013, p. v)

This clearly means that the Glaser method is *'less reliable'* –and potentially completely unsuitable– for the condensation risk assessment of traditional stone walls. However, the standard falls short of clear guidance as to when it should not be used.

> *The method is an assessment rather than an accurate prediction tool. It is suitable for comparing different constructions and assessing the effects of modifications. It does not provide an accurate prediction of moisture conditions within the structure under service conditions.*
>
> (BSI, 2013, p. 9)

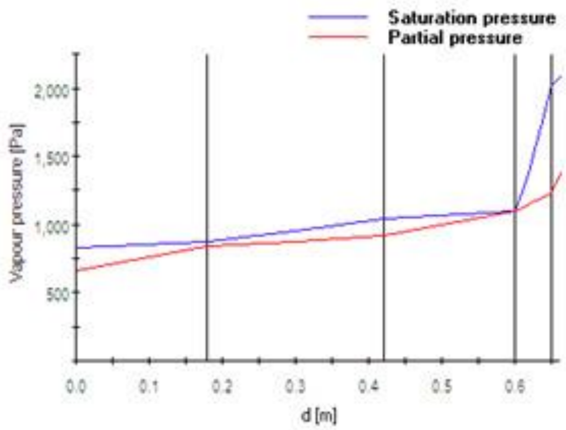
This suggests that the Glaser method should only be used to compare, at the design stage, alternate forms of lightweight, airtight construction, made only with materials with a low water storage capacity. For such construction forms, the Glaser method can be used as a prediction tool. In no case should the Glaser method be used for forms of heavy-weight and potentially less airtight construction, made from hygroscopic materials and subjected to severe weather conditions. Traditional stone walls, particularly in locations with severe wind-driven rain exposure, are thereby specifically excluded from the scope of *BS EN ISO 13788:2012*. The Glaser method should not be used to assess them. Or in the words of related American guidance:

> *Because all moisture transfer mechanisms except for water vapor are excluded* [from the Glaser method]*, results should be considered as approximations and should be used with extreme care. … The dewpoint and Glaser methods … are still used by design professionals and actually form the basis for most codes* [building regulations / building standard] *dealing with moisture control and vapor retarders.*
>
> (ASHRAE, 2009, p. 25.13)

Nonetheless, in practice in Ireland and the UK, the Glaser method is frequently used to assess exactly the condensation risk of building fabric specifically excluded from the scope of *BS EN ISO 13788:2012*. Why the Glaser method continues, to date, to be used as the preferred assessment method for condensation risk, even in situation where it is unsuitable, and what is needed to create greater awareness for more suitable advanced assessment simulations, using numerical simulation, is discussed further in Section 4.4.3.2.

4.2.2 Assessment procedure

The Glaser method calculations are based on decoupling the equations for heat and vapour transport. Therefore, heat transfer and vapour transport (or rather their equivalents according to the Glaser method: saturation vapour pressure and vapour pressure) are each calculated in isolation, and the results of these separate calculations are then overlaid. According to *BS EN ISO 13788*, the calculations at the material interfaces are conducted twelve separate times: once for each month of the year. One-dimensional, steady-state conditions are assumed. For each month, the interior and exterior temperatures and relative humidities are defined, based monthly averages. Essentially, saturation pressure and partial pressure are calculated and plotted over a specific form of a cross section of the construction, resulting in two pressure profiles which can then be analysed. (Figure 45)



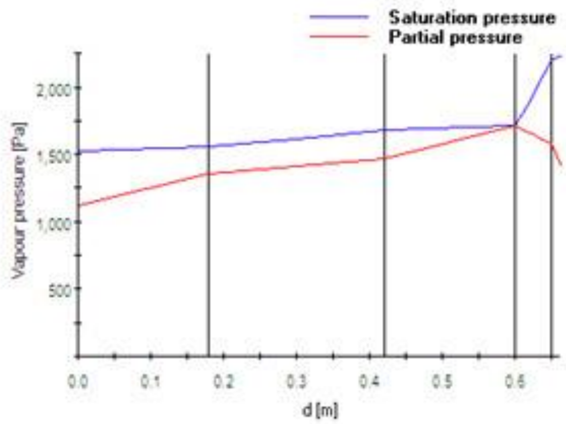


Figure 45 Example of Glaser method diagrams showing partial and saturation pressure profiles across a cross section of building fabric: the left diagram shows profiles for February, indicating interstitial condensation at the location where profile lines meet. The June profiles (right) indicate evaporation.

A Glaser method analysis consists of six steps: firstly, the temperatures at the material surfaces and interfaces are calculated, based on exterior and interior temperatures. Secondly, from the resulting temperatures, the saturation pressures are calculated for the same locations. Thirdly, these pressures are plotted over a cross section of the construction, in which its layers are set out with thicknesses relating to their water vapour resistance, using s_d-values or water vapour diffusion equivalent air layer thicknesses. (Coatings, foils and membranes should be treated as individual layers with their specific thermal and vapour resistance, e.g. foil incorporated into insulation board should be modelled as a separate layer. It is often useful to subdivide layers with high thermal resistance, e.g. insulation, into several layers.) Fourthly, straight lines are drawn to connect the saturation vapour pressures points at each interface. If there was no accumulation in the previous month, the vapour pressure profile is drawn as a straight line from inside to outside. If this profile does not exceed the saturation pressure at each interface, it is judged that condensation does not occur. Lastly, if the vapour pressure profile crosses the saturation pressure profile at any point, the vapour pressure profile is redrawn as a series of lines that touch the saturation pressure profile at as few points as possible. These points are referred to as condensation interfaces. The six-step process is repeated for each month of the year, and the rate of condensation is calculated as the difference between the amount of moisture transported to and from the condensation interface. (The procedure is described in more detail in the standard.)

The standard requires that the interstitial condensation calculations are assessed and reported as follows:

Report the results of the calculations according to a), b) or c) as applicable.

a) No condensation predicted at any interface in any month.

In this case report the structure as being free of interstitial condensation.

b) *Condensation occurs at one or more interfaces but, for each interface concerned, all the condensate is predicted to evaporate during the summer months.*

In this case report the maximum amount of condensation that occurred at each interface, and the month during which the maximum occurred. Also, the risk of water run-off or degradation of building materials and deterioration of thermal performance as a consequence of the calculated maximum amount of moisture shall be considered according to regulatory requirements and other guidance in product standards. …

c) *Condensation at one or more interfaces does not completely evaporate.*

In this case report that the structure has failed the assessment, and state the maximum amount of moisture that occurred at each interface together with the amount of moisture remaining after twelve months at each interface.

(BSI, 2013, p. 16)

Typically, a particular construction assessed using this method is said to *pass* if there is no condensation or if the total amount of condensate at each assessment location is able to evaporate within the same year. Otherwise it is said to *fail*.

It is worth noting that such one-dimensional assessments cannot account for elevated heat losses occurring at construction junctions, which, in turn can lead to lower surface temperatures.

4.2.3 Assessment tools

Glaser method calculations used to be conducted by hand. Nowadays, of course, there are computer programs that will perform the twelve (monthly) calculations to produce the temperature and vapour pressure profiles. Commonly used programs in Britain and Ireland include BuildDesk U. (Figure 46)

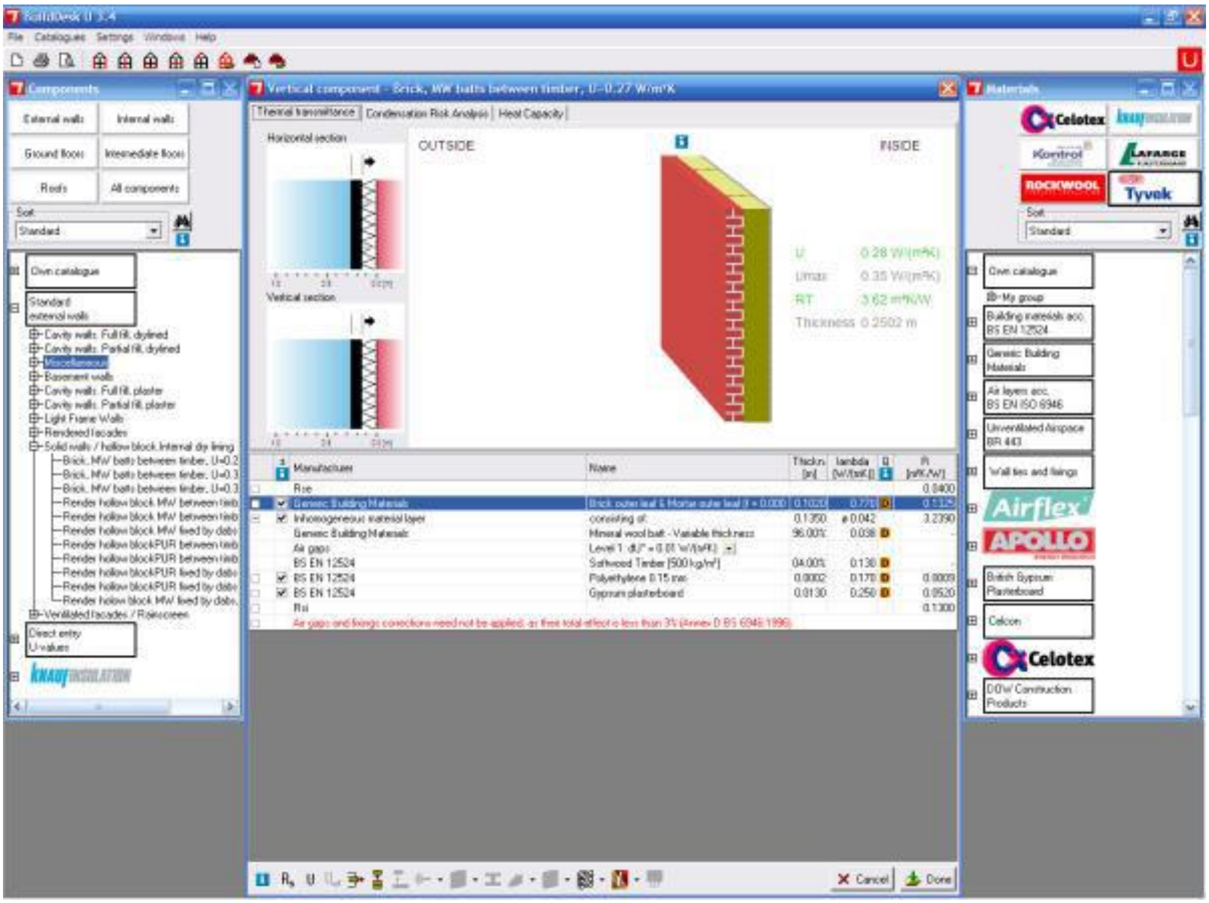


Figure 46 Screenshot of BuildDesk U 3.4: the graphical interface and ease of use make this computer program a popular assessment tool.

These computer programs perform steady-state interstitial condensation risk-assessments, according to *BS EN ISO 13788*. And they do so almost immediately. The ease of use, calculation speed and graphical interface (both for inputs and results) make these programs popular with the construction industry. (Figure 47)

While there are several help features and warnings in BuildDesk U, none of these aids users in ensuring that a building component selected from its database, or assembled by the users, is *within* the defined scope of *BS EN ISO 13788*. (This may, or may not, be true of other software tools used for Glaser-method assessments; the authors have only had access to BuildDesk U.) It is up to the software user to decide whether this assessment method and software tool should be used, based on their own understanding of the underlying standard, its scope and limitations and the form of construction concerned.

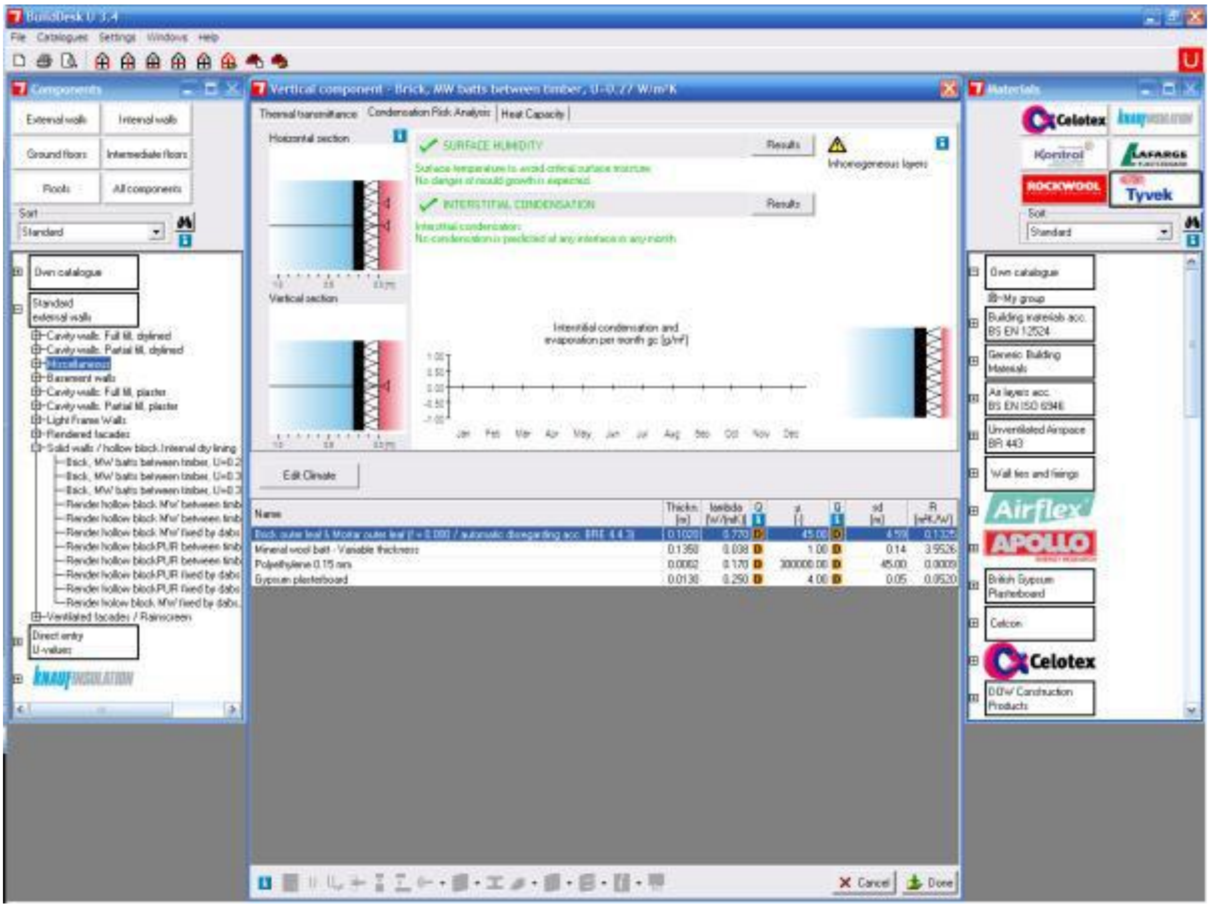


Figure 47 Screenshot of BuildDesk U 3.4: green checkmarks indicate that, according to a Glaser method assessment, no condensation is predicted.

The individual construction layers are based on following five parameters:

- thickness [m]
- bulk density, ρ [kg/m^3]
- specific heat capacity, c_p [J/(kg·K)]
- thermal conductivity , λ [W/(m·K)]
- vapour diffusion resistance factor, µ [-]

Albeit this list of hygrothermal values is limited, the use of the data and the selection procedure in BuildDesk U is robust and clear. The first value, the thickness of a material, can be entered by the user, though manufacturer-defined values are prompted to help reduce input errors. The other four values are material properties. Cleverly, since the launch of version 3.1, BuildDesk has a ranking system for material data, clearly identifying the data provenance and likely accuracy in this ranking system, with user-defined entries given the lowest ranking to reduce the likelihood of errors. Regarding the various forms of measures used for vapour resistance, BuildDesk (n.d.) is a useful guide for their conversions.

4.3 Numerical simulation (*BS EN 15026*)

4.3.1 Scope and limitations

> *In the past, moisture control strategies* [e.g. the Glaser method] *focused on water vapour diffusion. Displacement of water vapour by air movement was treated superficially, and liquid water transport provoked by wind-driven rain or soil moisture* [i.e. 'rising damp'] *was overlooked almost completely. When present, however, these mechanisms can move far greater amounts of moisture than diffusion does. Therefore, air movement and liquid flow should have a higher priority in moisture control.*
>
> (ASHRAE, 2009, p. 25.10)

Whereas the scope for the Glaser method assessments, in accordance with *BS EN ISO 13788*, specifically excludes any forms of construction in which precipitation, hygroscopicity or liquid transport are of importance, the numerical simulation assessments specifically includes these phenomena. Numerical simulation for hygrothermal assessments was developed in the 1990s, and its more general use was made possible through increasingly available computing power. In 2007, the first British Standard on numerical simulation for hygrothermal assessments was published: *BS EN 15026:2007*. (BSI, 2007a)

The standard usefully starts with a describing its scope in comparison to that of *BS EN ISO 13788*:

> *This standard defines the practical application of hygrothermal simulation software used to predict one-dimensional transient heat and moisture transfer in multi-layer building envelope components subjected to non-steady climate conditions on either side. In contrast to the steady-state assessment of interstitial condensation by the Glaser method (as described in EN ISO 13788), transient hygrothermal simulation provides more detailed and accurate information on the risk of moisture problems within building components and on the design of remedial treatment. While the Glaser method considers only steady-state conduction of heat and vapour diffusion, the transient models covered in this standard take account of heat and moisture storage, latent heat effects, and liquid and convective transport under realistic boundary and initial conditions. The application of such models has become widely used in building practice in recent years, resulting in a significant improvement in the accuracy and reproducibility of hygrothermal simulation.*
>
> (BSI, 2007a, p. 4)

The aim of the numerical simulation standard is much wider than the Glaser method standard: whereas the latter was predominantly concerned with the assessment of condensation risk, the numerical simulation standard aims at providing a model for simulating the hygrothermal performance of building fabric over time. This can be used to assess condensation risk, but it can also be used for other purposes. However, this also means that, where the Glaser method standard provide clear *pass / fail* guidance specifically for condensation risk assessments, the numerical simulation standard does not. It only sets out the equations to be used for the simulation model and provides some guidance for the interpretation of results.

The following quotation describes in more detail the scope and limitations of *the numerical simulation standard, BS EN 15026:2007*:

> *This standard specifies the equations to be used in a simulation method for calculating the non-steady transfer of heat and moisture through building structures. …*
>
> *The equations in this standard take account of the following storage and one-dimensional transport phenomena:*
>
> - *heat storage in dry building materials and absorbed water;*
> - *heat transport by moisture-dependent thermal conduction;*
> - *latent heat transfer by vapour diffusion;*
> - *moisture storage by vapour sorption and capillary forces;*
> - *moisture transport by vapour diffusion;*
> - *moisture transport by liquid transport (surface diffusion and capillary flow).*
>
> *The equations described in this standard account for the following climatic variables:*
>
> - *internal and external temperature;*
> - *internal and external humidity;*
> - *solar and longwave radiation;*
> - *precipitation (normal and driving rain);*

- *wind speed and direction.*

The hygrothermal equations described in this standard shall not be applied in cases where:

- *Convection takes place through holes and cracks;*
- *Two-dimensional effects play an important part (e.g. rising damp, conditions around thermal bridges, effect of gravitational forces);*
- *Hydraulic, osmotic, electrophoretic forces are present;*
- *Daily mean temperatures in the component exceed 50 °C.*

(BSI, 2007a, p. 5)

Of the four limitations listed above, the first two are most relevant in the context of this paper: namely, that the standard's procedure should not be used in situations where convection takes place through holes and cracks and where two-dimensional effects play an important part. The other two limitations –hydraulic, osmotic, electrophoretic forces and extreme daily main temperatures– are not generally relevant in a building context in the British Isles.

4.3.2 Assessment procedure

Due to their complexity, hygrothermal assessments by numerical simulation are carried by computer software. The software overlays the building component to be analysed with a computational grid. (Figure 48) Although, in reality, moisture and heat affect each other continuously across the width of a component, in numerical simulation this relationship is only assessed at the centre of a grid cell, or grid element. The grid is variable-sized, with closely spaced grid elements at component surfaces and material interfaces. It is at these locations that the most marked hygrothermal changes occur. Within a component's material layer, more widely spaced elements are used, thereby minimising the number of calculations. A variable-sized grid is used to improve the efficiency of the simulation: too many narrowly spaced grid elements result in an increase in calculation time, but if they are too widely spaced, precision is lost.

In a numerical simulation, coupled, differential equations are solved for heat and moisture transport processes for each grid element and unit of time selected (normally an hour), using as boundary conditions either environmental data from the adjacent grid elements or internal and external climate data. This process is repeated for the duration of the simulation period. For a simulation using a simulation period of ten years and hourly intervals, this will result in 87,600 calculation sets. This iterative process is illustrated in Figure 49 with a flowchart.

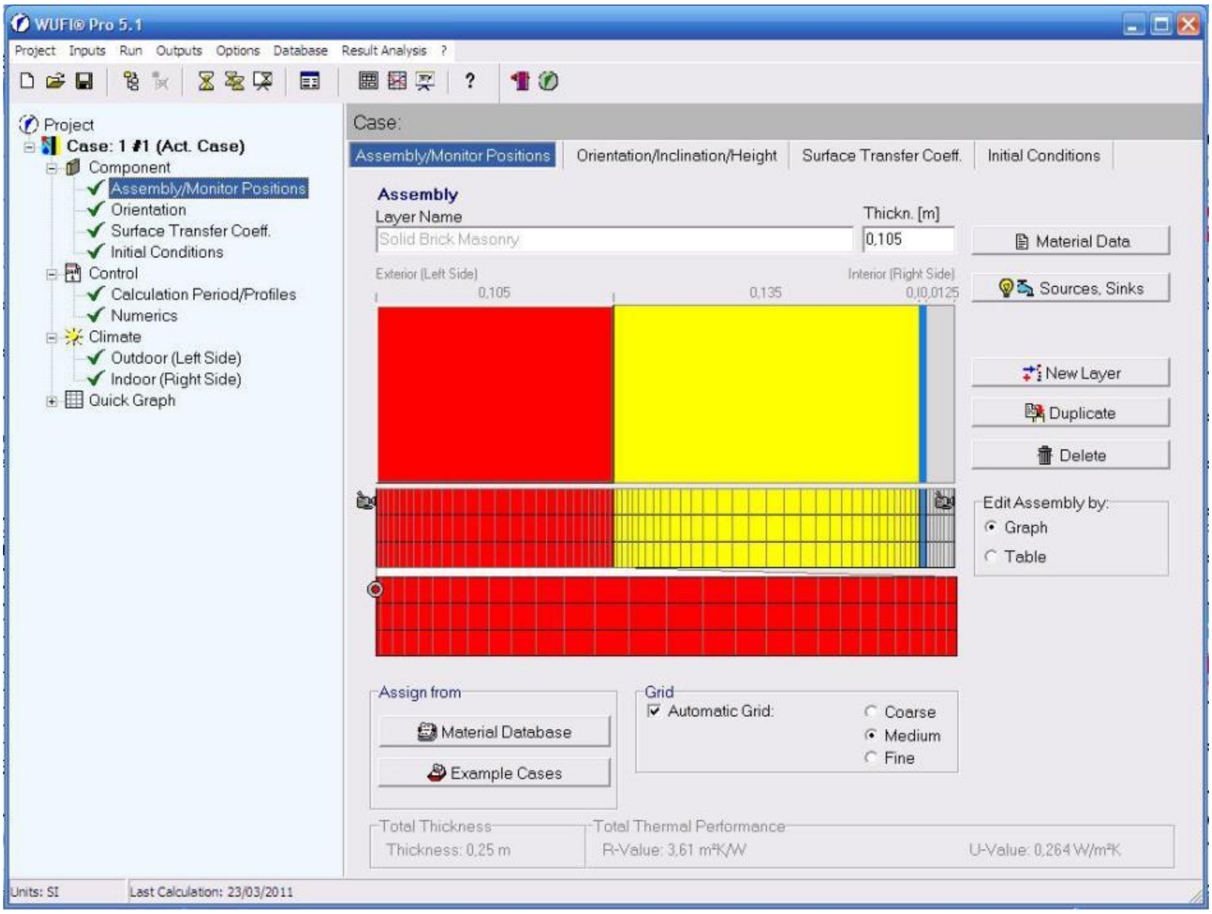


Figure 48 Screenshot of WUFI Pro 5.1: the software uses variable-sized, computational grid elements to assess the cross section of a construction. Denser grid elements are used at the inside and outside surface of the construction and at the material interfaces.

The repetition nature of the simulation over a selected period of time results in a stream of outputs, recording changes in temperature, humidity, water content and vapour pressure. These outputs are based on the material properties and adjacent conditions. The types of outputs can be viewed either together, as a film, or separately, in graph form or as a spreadsheet. This enables the user to interrogate the predicted hygrothermal conditions at any point in the component at any time in the simulation period. This provides a wealth of hygrothermal information that goes far beyond the narrower focus of the Glaser method. It is mostly left to the user to assess if the conditions are acceptable or not. Instead, the numerical simulation standard only provides guidelines for the interpretation of the results.

> *The documentation of the results may be followed by an interpretation of their practical meaning. This may be done by at least one of the following items:*

- *Comparing the resulting hygrothermal conditions with specified limits.*
- *Checking the risk of moisture accumulation by comparing the total moisture content in the construction after one cycle with the initial condition.*
- *Evaluating the moisture tolerance of the construction (drying potential).*
- *Feeding the transient results into a post process model (e.g. for mould or algae growth, rot, corrosion).*

(BSI, 2007a, item 6.4.3)

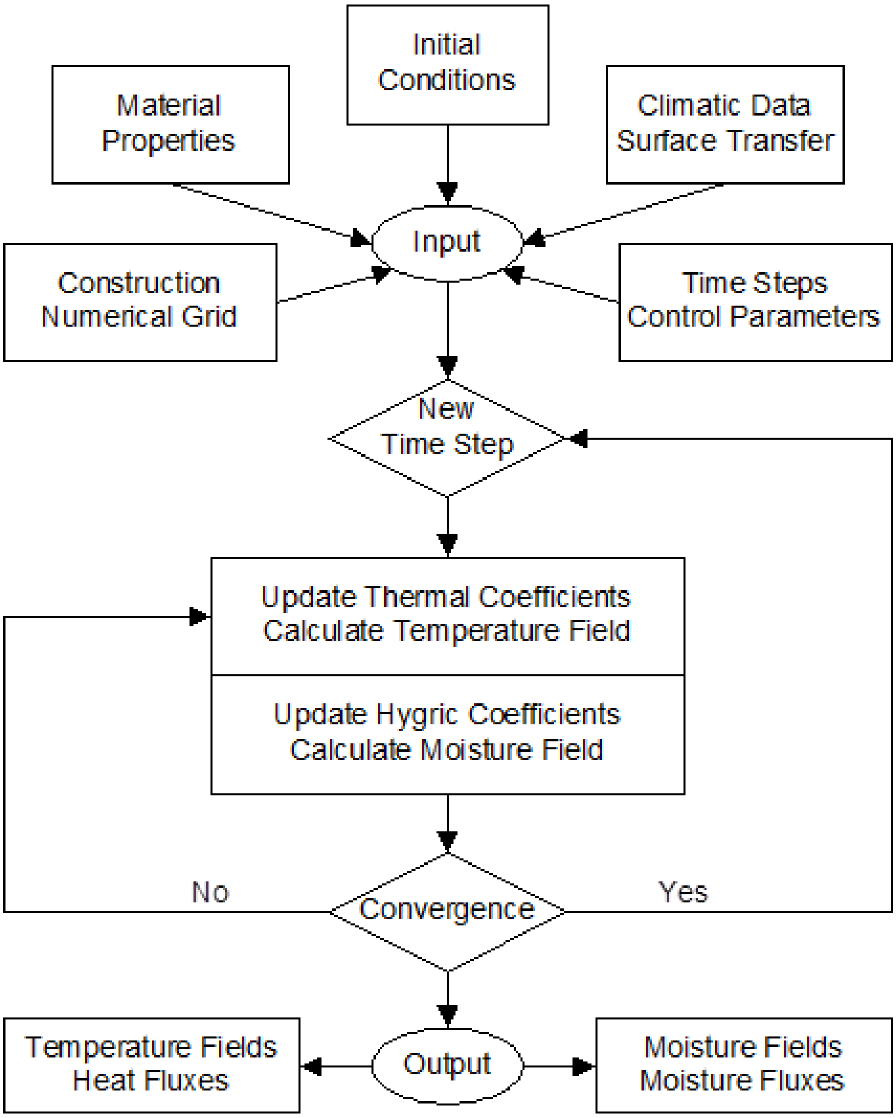


Figure 49 Flowchart illustrating the iterative process behind the numerical simulation method

The related German standard *DIN 4108-3:2001* (DIN, 2002) provides more specific limits, but even these figures can be regarded as somewhat arbitrary. The German standard recommends, as stated in English in WUFI's *Online Help*, that:

- *The amount of condensing moisture in roof or wall constructions must not exceed a total of 1.0 kg/m².*
- *At interfaces between materials that are not capillary-active, no moisture increase exceeding 0.5 kg/m² is permissible. This is meant to avoid moisture running or dripping off, which could accumulate elsewhere and cause damage.*
- *The moisture increase in wood must not exceed 5 mass-per cent; the moisture increase in materials made of processed wood must not exceed 3 mass-per cent.*

(Fraunhofer IBP, 2011)

The first two of these criteria could equally be applied in Glaser method assessments, when calculating the amount for condensation occurring at material interfaces. However, no British Standard places specific limits on the quantity of moisture accumulation *in the way DIN 4108-3* does. The only specific limits noted in *BS 5250:2011* describe the amount of condensate regards to result in visual effect of condensation on impermeable surface, such as mist, droplets, drops and run-off. The British Standard, however, does not specify any limits to remain within when conducting risk assessments. (BSI, 2011, Tab. A.1)

Not surprisingly, numerical simulation software requires more training than software employing the Glaser method. Without question, numerical simulations use more concepts that could be insufficiently understood, inputs that could be entered incorrectly and outputs that could be misinterpreted. Users of numerical simulation should therefore adopt a questioning attitude to outputs and initial interpretation. Numerical simulation is not an *easy* solution for condensation risk assessments. But it is a tool applicable to *every* building type and location in the British Isles.

4.3.3 Assessment tools

Due to their complexity, hygrothermal assessments are conducted using computer software. A variety of programs has developed since the 1990s, including Delphin, HygIRC, MOIST and WUFI. (Hill and McGowan, 2003, Tab. 1) In practice today, WUFI appears to be most widely used, followed by Delphin. (Fraunhofer IBP, n.d.2; TU Dresden, Institute for Building Climatology, n.d.) Both software program have been developed in Germany. They are *readily* available, well supported and capable of being used by non-physicists. More comparable tools will hopefully join them soon.

WUFI is the software used for the case study assessments in part 2 of this report. The software was developed by the Fraunhofer Institute for Building Physics. A whole family of WUFI software is available, including WUFI Pro and WUFI 2D for one- and two-dimensional simulation respectively. (Fraunhofer IBP, 2012) Also available is a free, but functionally limited version (WUFI Light) and a version which imbeds hygrothermal assessment into whole-building simulation (WUFI Plus). The case study assessments for this report were simulated one-dimensionally with WUFI Pro. (Why one-dimensional simulation is suitable in this situation is discussed in Section 5.3.2.3.) WUFI hygrothermal software can also be extended with post-processing programs, including WUFI-Bio, which simulates mould growth. WUFI-Bio will also be briefly demonstrated as part of the case study in this report. (Section 5.4.1)

4.4 Regulatory context and practical application

4.4.1 Regulatory framework

When altering or extending a building, requirements set out in the building regulations need to be met generally. Although different regulations apply to England, Ireland, Northern Ireland, Scotland, and Wales (though England and Wales share most regulations to date), their aims and content are similar. The building regulations are generally supported by governmental documents, providing technical guidance. In the following, only the English and Scottish documents will be discussed. These are, for England, the *Approved Documents* (HM Government and Welsh Government, n.d.) and, for Scotland, the *Technical Handbooks* (Scottish Government, 2013). The focus of the discussion will be on how the regulations and associated technical guidance deal with condensation risk in buildings and, more specifically, how they reference the Glaser method and numerical simulation standards, *BS EN ISO 13788* and *BS EN 15026* respectively. England's regulatory framework will be discussed first.

4.4.1.1 England

The *Building Regulations* for England require that

> *The walls, floors and roof of the building shall adequately protect the building and people who use the building from harmful effects caused by:*
>
> *(a) ground moisture;*
>
> *(b) precipitation including wind-driven spray;*
>
> *(c) interstitial and surface condensation; and*

> (d) *spillage of water from or associated with sanitary fitting or fixed appliances.*
>
> (*Building Regulations 2010*, schedule 1, clause C2)

Regarding condensation risk, the associated technical guidance, *Approved Document C*, states for external walls:

> *An external wall will meet the requirement* [of the building regulations] *if it is designed and constructed in accordance with Clause 8.3 of BS 5250:2002 … and BS EN ISO 13788:2002.*
>
> (HM Government, 2013, clause 5.34)

The English guidance directly references the Glaser method standard, *BS EN ISO 13788*, and makes no mention of *BS EN 15026*, regarding the availability and use of numerical simulations. *Approved Document C* also references another British Standard, *BS 5250:2002*, which sets out a *Code of Practice for Control of Condensation in Buildings*. This standard will need to be examined in more detail, but only after taking a look at how Scotland's regulations and guidance deal with condensation risk. (Although last revised in 2013, *Approved Document C* still references the 2002 versions of *BS 5250* and *BS EN ISO 13788*, despite the publication of revised standards in 2011 and 2012 respectively.)

4.4.1.2 Scotland

The *Building (Scotland) Regulations 2004* deal with moisture-related requirements for building envelopes in three *Building Standards*: 3.4 is concerned with *Moisture from the ground*, 3.10 with *Precipitation*, and 3.15 with *Condensation*. Only the latter shall be discussed here.

Building Standard 3.15 states that

> *Every building must be designed and constructed in such a way that there will not be a threat to the building or the health of the occupants as a result of moisture caused by surface or interstitial condensation.*
>
> (*Building (Scotland) Regulations 2004*, schedule 5, clause 3.15)

Scotland's *Technical Handbooks* complement this by stating that

> *The guidance given in BS 5250:2002 'Code of Practice for the control of condensation in buildings' is helpful in preventing both interstitial and surface condensation. …*
>
> (Scottish Government, 2013, clause 3.15.1)

Walls, roofs and floors should be assessed and/or constructed in accordance with Section 8 and Annex D of BS 5250:2002.

(Scottish Government, 2013, clause 3.15.5)

As England's *Approved Document C*, Scotland's *Technical Handbooks* reference *BS 5250* for condensation risk assessments of building envelopes. However, unlike in the English document, the *Technical Handbooks* refrain from suggesting explicitly that *BS EN ISO 13788* should be used. But they, also, do not mention to *BS EN 15026*. (As in England, the references still refers to the 2002 versions of *BS 5250* and *BS EN ISO 13788*, despite revision of the *Technical Handbooks* in 2013.)

It is apparent from England's and Scotland's technical guidance to their building regulations that *BS 5250* plays a key role for the assessment of condensation risk in buildings. This standard shall therefore be examined in more detail.

4.4.2 Code of Practice (BS 5250)

The principal guidance for Ireland and the UK regarding hygrothermal issues in buildings is the British Standard *BS 5250:2011 Code of Practice for Control of Condensation in Buildings* (BSI, 2011). Originally published in 1975, it was revised in 1989, 2002 and 2011. (BSI, 1975; 1989; 2002a) The standard is extensively referenced, including technical guidance to England's and Scotland's building regulations, although references generally refer to the 2002 versions of the standards.

BS 5250 has a wide scope, describing hygrothermal characteristics, internal and external climatic conditions, moisture production rates, assessment methods, building elements and building components that are intended to be free of interstitial condensation, heating regimes, ventilation systems and guidance for building owners. The assessment methods range from visual surveys and occupant surveys to methodologies set out in internationals standards. *BS 5250* is clearly intended to be a frequently used resource for the construction industry and those involved in building maintenance. *BS 5250:2011* acknowledges that increased levels of thermal insulation result in higher condensation risks and describes how the decisions of building designers, contractors, managers and occupants affect the ability to control condensation. In its foreword, the standard states:

The requirement for more efficient use of energy in the operation and use of buildings has led to increased levels of thermal insulation and airtightness in both new and refurbished buildings; this has led to an increased risk of damage from condensation. ... Bearing in mind that occupants often fail to use buildings in the manner intended, be it by choice, lack of understanding or

> *force of circumstance, designers are advised to err on the side of caution and adopt robust fail-safe solution. … When it is proposed to re-furbish a building or make changes to its use, the risk of condensation has to be re-assessed in the light of the new usage.*
>
> (BSI, 2011, p. iii)

While *BS 5250:2011* provides excellent guidance on many issues, it appears to falls short when dealing specifically with the value of numerical simulation for moisture risk assessment and with issues affecting the retrofit of internal insulation to solid walls. The standard references *BS EN ISO 13788* as the preferred assessment method for condensation risks, but, at least, mentions that “More advanced methods, which are standardized in BS EN 15026, are available”. (ibid., p. 24) The authors of this report find it extremely disappointing that *BS 5250:2011* does not (even attempt to) give equal status to both assessment methods. While *BS EN ISO 13788* is referenced twelve times and its methodologies, inputs and limitations are discussed in several chapters, *BS EN 15026* is referred to in one sentence only. It is regrettable, even perplexing, that *BS 5250:2011* does not give at least equal importance to assessments by numerical simulation or the aspects of building physics which underpin it and are so particularly pertinent for the retrofit of buildings, despite the publication of *BS EN 15026* in 2007.

Although a detailed discussion of *BS 5250:2011* is outside the scope of this report, the following observations can be made:

1) The 2011 revision of *BS 5250* contains expanded guidance on surveying practice, attics and roofs, but little revision with regard to hygrothermal assessment.

2) It is extraordinary that *BS 5250:2011* does not state *BS EN 15026* in the list of relevant normative references, although mentioning the numerical simulation standard in its *normative* annex D. (ibid., section 2 and annex D.3.1)

3) In relation to climatic conditions, *BS 5250:2011* refers to average monthly values, as used in the Glaser method, but when, for example, discussing significant short-term weather events for roof design and radiant heating and cooling, the standard omits to state that one of the best ways to evaluate these risks is using numerical simulation assessment with hourly climatic inputs. (ibid., pp. 7-8)

4) Although there are three driving potentials for moisture transport in building fabric (Section 3.2), only vapour convection through gaps or within air spaces and vapour pressure are discussed in *BS 5250:2011*.

5) Regarding rain water, which can deliver most of the moisture traditional solid walls have to deal with, *BS 5250:2011* only states briefly that the external envelope of a building needs “to provide protection against precipitation, in particular against wind-driven rain, which can be absorbed into masonry, reducing the overall thermal resistance of walling. Careful attention has to be paid to joints and junctions in and between components and elements.” (BSI, 2011, annex A.2, item d) Interestingly, the standard considers the thermal performance at risk, not the moisture content. The only mention in *BS 5250:2011* of liquid transport due to capillary action is as a limitation of the Glaser method. (ibid., annex D.3.5, item c)

With regard to walls, *BS 5250:2011* recommends that the building designer should take account of the following moisture sources: ground moisture, rain water, construction moisture and moisture generated by occupants. (ibid., annex G.1)

The standard specifically covers solid masonry walls when discussing the significance of choosing a heating system appropriate for their thermal mass and the use of external and internal wall insulation. Internal wall insulation is discussed as follows:

> *Solid masonry walls, insulated internally may be used with an intermittent heating regime without incurring a risk of surface condensation.*
>
> *Internally applied thermal insulation isolates the heated interior from the masonry, which will therefore be cold, producing a risk of interstitial condensation behind the thermal insulation; to prevent that, an AVCL should be applied on the warm side of the thermal insulation …*
>
> (BSI, 2011, annex G.3.1.4)

Considering the extraordinary range of traditional wall construction types and internal wall insulation products, this must be considered incomplete and, in some situations, even counterproductive guidance. The influence of different internal wall insulation products and different AVCLs will be illustrated in more detail in the case study of this report. (Section 5)

The above discussion has shown that *BS 5250:2011* focusses, as its title suggests, on the *control of condensation in buildings*. It does so by focussing on the internal climatic conditions and favouring Glaser method assessments. Such an approach appears appropriate for new-built, lightweight, framed construction. For the assessment of traditional wall construction though, this approach severely limits the assessment, by excluding, for example, transient environmental conditions and liquid transport. *BS 5250* briefly notes the limitations of the Glaser method:

> *It assumes one-dimensional, steady-state conditions and does not consider air movement within or through the construction and makes no allowance for the moisture in the material or rain water absorbed during construction. Consequently, while it is useful for comparing the performance of different structures, it does not provide an accurate prediction of moisture conditions within the structure under service conditions. More advanced methods, standardized in BS EN 15026, are available ….*
>
> (BSI, 2011, annex D.3.1)

BS 5250:2011 appears at first to be fully relevant to buildings anywhere on the British Isles, but despite providing valuable guidance on a host of hygrothermal issues, the standard has little relevance to traditional wall construction and their retrofit with internal wall insulation.

4.4.3 Current use of the Glaser method

4.4.3.1 Diffusion paradigm

The Glaser method assessment uses simplification of the involved hygrothermal processes as its basis. This assessment approach has been described as a *diffusion paradigm*:

> *The diffusion paradigm is that version of building physics which explains hygrothermal performance of building envelopes in terms of water vapor diffusion, which uses the steady-state profile method, and which leads to recommendations … for vapor barriers and attic ventilation … the predisposition toward prescriptive guidance inhibited the development of an engineering approach.*
>
> (Rose, 2003, p. 327)

It is 40 years since *BS 5250* first published the Glaser method (BSI, 1975), 70 years since mainstream guidance based on it appeared in the USA and 77 years since it appears to have been invented (Rose, 2003). (Strictly speaking, *BS 5250:1975* described the *dewpoint method*, a predecessor of the Glaser method.) This has allowed generations of building designers to absorb the lessons of the approach described by the diffusion paradigm. The diffusion paradigm has a cultural aspect that goes beyond the clear limitations of the method and explains why the Irish and British construction industries rely so heavily on the Glaser method, including those building designers and contractors who have never heard of it and are not aware that it may influence their thinking.

4.4.3.2 Dominance of the Glaser method

The Glaser method still has a dominant position today: firstly, as basis for guidance documents in almost every field of construction, except maybe in building conservation and surveying; secondly, as basis for a common understanding of *best practice*; and, lastly, as basis for the design of many construction products. Building conservation and surveying are the two fields that deal with building maintenance and failure and, therefore, experience best how building fabric actually performs when in use, compared to predicted performance. While many conservation professionals are rightly suspicious of applying to traditional construction best-practice approaches developed for new-build construction, some of these professionals appear to still be unaware of, or are perhaps reluctant to engage with, numerical simulation as an assessment method which can assist them in conserving and appropriately retrofitting traditional buildings. In mainstream construction, numerical simulation is slowly becoming better known, but is foremost popular in niche markets or by users of niche products.

Despite the publication of *BS EN 15026* in 2007, despite the availability of a wide range of numerical simulation tools over the last two decades and despite the clearly stated limitations of the Glaser method, the Irish and British construction industries have been slow to move from the diffusion paradigm towards a fuller understanding of hygrothermal performance and the adoption of numerical simulation assessments. There are many reasons why the Glaser method is still the preferred assessment tool today, and more efforts are needed to convince the construction industry to replace these simplistic tools with the more accurate and often more appropriate numerical simulation assessments.

The following aspects may be pertinent to the dominance of the Glaser method:

1. The highly simplified understanding of hygrothermal performance that underpins the Glaser method and the *diffusion paradigm* has significantly influenced the development of both building products and technical guidance. Much of its influence is unconscious. Dogmatic advice, such as to *always* place an AVCL on the warm side of internal wall insulation regardless of the wall construction type or where the specification of internal wall insulation does not consider the substrate and external climatic conditions, is influenced consciously or unconsciously by the simplifications of the Glaser method.

2. Understanding of risk is typically based on past experience. Most of the buildings erected over the past fifty years were evaluated using the Glaser methods (or its predecessors).

3. Most external walls in Britain and Ireland are of cavity wall construction and make use of DPCs. Due to the isolation of the inner wall leaf from rain water, liquid moisture is only likely to manifest itself in the form of interstitial condensation or building failure, e.g. rising damp, cracks in the building fabric or failing drainage or rain water goods. Interstitial condensation can be checked roughly, though not predicted, using the Glaser method, due to its focus on vapour diffusion. Other forms of moisture occurrence can clearly be dismissed as a failure not subject to any hygrothermal risk assessment. Thus, the status quo of the diffusion paradigm can appear unchallenged.

4. According to BRE study from 2006, 20 % of air that enters a house leaves via the roof (by which stage it is no doubt heated air) and 80 % of the water vapour found in lofts arrived there by air leakage from below. (Sanders, 2006a, p. 1) Air leakage, particularly through direct paths from inside to outside, will generally remove moisture as much as heat, often removing condensate caused by inappropriate layering of elements in the building fabric. The focus on significantly improving airtightness is relatively new, and the building industry is still learning how to achieve this. Probably because of a lack of reported cases, there is an inadequate focus on moisture accumulation that can occur once air leakage *has* been controlled, due to inappropriate layering of elements in the building fabric. The move to far higher levels of insulation and airtightness greatly increases the risk of material deterioration and building failure.

5. Suppliers of building products may prefer the clear *pass/fail* results generated by the Glaser method. They may also prefer the fact that the method shows that almost any type of wall construction will be judged acceptable if it is used with an AVCL (or a product as vapour tight as an AVCL) on the warm side of the insulation.

6. Suppliers of building products can, in a very short time, train their staff to conduct Glaser method assessments, using software, and offer this service for free. It can then be presented as an added-value service.

7. Within the construction industry, there is a lack of awareness of the limited applicability of the Glaser method and the availability of numerical simulation as an alternative. It may be that too few construction professionals actually read the technical standards they use, and it appears that building designers rarely insist on numerical simulation to assess their designs. The same appears to be true for manufacturers of building products, when obtaining third-party assessments of their products, such as BBA Agréments.

Despite these rationalisations, despite the availability of numerical simulation as a more accurate and sophisticated assessment method and despite software tools based on *BS EN*

15026:2007, it is clear that a significant shift needs to take place in the construction sector. More balanced guidance is required, current guidance needs to be re-evaluated and much of it revised, and efforts must be made to ensure that designers and manufacturers stop using the Glaser method in cases which are clearly outside its scope.

4.4.3.3 Achieving the use of appropriate assessment

The Glaser method is only applicable to specific types of construction and in specific environmental contexts. Nonetheless, it is still used today as the preferred hygrothermal assessment method in Britain and Ireland for all types of construction at any location.

To change this situation, a range of actions should be considered:

1) In general, the value of risk assessments (whether physical surveys or desktop assessment), the stage at which to undertake them and their role (both value and limitations) in proving suitability and compliance should be given greater prominence in the technical guidance documents to building regulations.

2) Technical guidance, such as *BS 5250* and BRE publications, and software tools, such as BuildDesk U, should state more clearly the limitations of the Glaser method and advise unequivocally when other assessment methods should be used.

3) Considering that approximately a fifth of the British building stock is of traditional construction, expanded guidance on the insulation retrofit of traditional walls should be provided in *BS 5250* and elsewhere.

4) More research is needed to fill the knowledge gaps with regard to local climatic conditions, actual indoor environmental conditions, construction materials, the impact of construction workmanship and the performance of building fabric under in-service conditions – let alone how climate change may impact upon buildings.

However, the fact that gaps in guidance and knowledge exist should not delay adoption of better risk assessment methods. Greater caution should be taken through increasing the understanding of the overarching principles. Buildings are hygrothermally complex constructions, particularly where traditional walls are used. Therefore, the most appropriate assessment methods should be used wherever possible, taking into account their benefits but also their limitations:

> *even within the limitations of use laid down in BS EN 15026, there is inevitable uncertainty, as moisture movement, material properties and human behaviour are highly complex and cannot possibly be entirely captured in a model. The dictum 'all models are wrong; some models are useful' applies here. With*

that warning and with acknowledgement of the disadvantages and limitations [of the model] *, it can be said that BS EN 15026:2007 should be adopted wherever possible in the assessment of moisture risk in buildings.*

(Sanders and May, 2014, p. 31)

4.5 Assessment of mould growth risk

The hygrothermal assessment methods, discussed in this report, can indicate when and where in a building component construction moisture levels can rise to a level that could cause deterioration of the building fabric or become a health risk to building occupants through mould growth. The different approaches in use today to assess mould growth have already been discussed. (Section 3.2.2.1) One such approach is biohygrothermal modelling. Computer programs for this are available in the form of postprocessors to numerical simulation software. These postprocessors are essentially software add-ons. For WUFI Pro, the postprocessor is WUFI-Bio. These post processing programs use biohygrothermal models to simulate mould growth, based on transient environmental conditions:

In order to assess the risk of mould growth under transient ambient conditions, a novel biohygrothermal method has been developed which is based on comparing the measured or simulated transient ambient conditions with the growth conditions needed by the fungi usually encountered in buildings. The moisture content of the mould spores is simulated and compared with the critical water content which allows a spore to germinate.

(Fraunhofer IBP, 2010)

Biohygrothermal modelling, as used in WUFI-Bio, has a number of limitations:

Influence factors such as pH value, salt content, light, oxygen content, surface quality and biogenic factors are not considered in the model, instead it is assumed that they do not impede germination and growth. This simplification has the consequence that the predicted spore germination times may be shorter or the growth rates may be higher than they are under real conditions.

Please note that this method only aims to assess the risk of mould growth, it is not a detailed realistic simulation of the growth processes.

(ibid., 2010)

The model used in WUFI-Bio does also not account for mould regression, but assumes that mould, once in existence, is either dormant or grows. (Sedlbauer, 2001) The biohygrothermal simulation, in the end, provides results which need interpretations:

> *As with all similar calculation methods, assessing the result requires some expertise as well as common sense. The calculation result is primarily meant to provide a semi-quantitative criterion for comparing and ranking construction variants. If the spore moisture exceeds the critical water content only by a small amount or for a short period, mould growth should not necessarily be expected in a real building component, since the model contains a few safety factors to make sure that the prediction 'no mould growth' can be relied on.*
>
> (Fraunhofer IBP, 2010)

How an assessment of mould growth risk can look like will be illustrated as part of the case study in this report, using WUFI-Bio 3.0. (Section 5.4.1)

4.6 Assessment of thermal bridging

A thermal bridge is a localised area where the heat flow is different in comparison with adjacent areas. Thermal bridging can occur at junctions of construction, e.g. where construction elements abut. (Section 3.1.5.2) The thermal bridge assessment of a junction determines the additional heat flow associated with that particular junction and its impact on energy use and condensation risk. The assessment of a linear thermal bridge is performed by calculating its linear thermal transmittance (or Ψ-value) and the temperature factor (f_{Rsi}). The Ψ-value of a construction junction is analogous to the U-value: the U-value is the heat loss per unit area of a plane building element, and the Ψ-value is the *additional* heat loss per linear metre of a junction (over and above the U-value of the adjoining plane elements).

An example of thermal bridging is given in Figure 50, using the junction between a window and wall, with a window cill in between. The left diagram in the figure shows the temperature distribution across the cross section of the construction, with arrows indicating uniform and non-uniform heat loss (orange and yellow arrows respectively). The right diagram is a graphic representation of the associated heat flow, with the uniform heat flow of the plane element (as per U-value) shown in yellow and the additional, non-uniform heat flow due to thermal bridging in orange. The figure illustrates that the non-uniform heat flow is greatest at the construction junction, but also occurs, to a lesser degree, at adjacent areas.

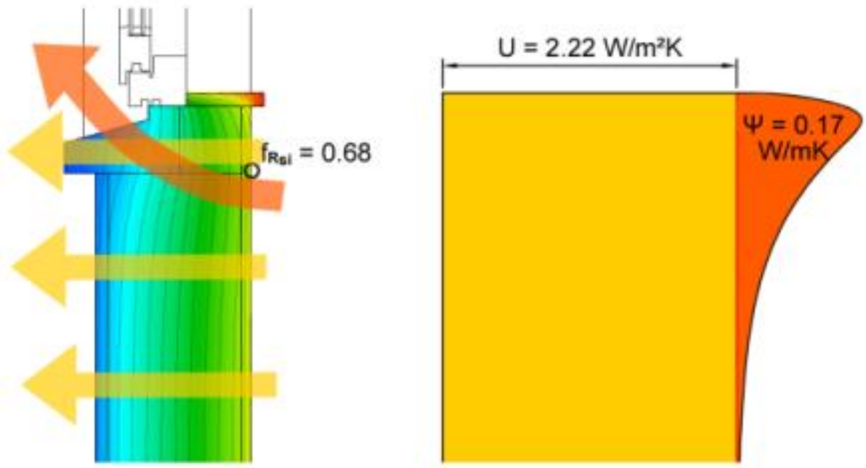


Figure 50 Diagrams illustrating heat flow at a thermal bridge: the junction between a wall and a window, with a cill in between. The left diagram, generated with THERM 5.2, shows the temperature variation across the fabric's cross section, overlaid with arrows for linear and non-linear heat flow (orange and yellow respectively). The right diagram shows the associated heat flow, with linear heat flow in yellow and non-linear heat flow in orange.

Where insulation retrofits are carried out without appropriate consideration of thermal bridging, the desired reduction in uniform heat loss can result in an unexpected increase of non-uniform heat loss. An internal insulation retrofit can thereby result in the heat loss due to thermal bridging increasing manifold, even if the overall heat loss declines. (Little and Arregi, 2011)

The temperature factor is a ratio of the temperatures used to assess the risk of surface condensation or mould growth near a thermal bridge. The factor represents the coldest indoor surface temperature relative to the difference of the indoor and outdoor temperatures. A temperature factor of close to 1.0 indicates a well-insulated structure. The lower the factor, the more severe is the thermal bridging and the higher the risk of mould growth. The example in Figure 50 shows a temperature factor (f_{Rsi}) of 0.68 at the interior wall surface at the height of the cill-wall interface.

Ψ-value and temperature factor are both properties of a thermal bridge, calculated under steady-state conditions and independent of the air temperatures surrounding the assessed construction. This allows for simple, direct comparison between different options of retrofit details with regard to their impact on thermal bridging.

The British standard *BS EN ISO 10211:2007* describes procedures for calculating both the Ψ-value and the temperature factor. (BSI, 2007c) The BRE report *Conventions for Calculating Linear Thermal Transmittance and Temperature Factors* provides additional guidance. (Ward and Sanders, 2007) The critical threshold for the temperature factor depends obviously on the use and the associated indoor moisture load of the building. (Section 3.2.1.1) For residential buildings with normal moisture loads, Ward (2006) recommends that the temperature factor should not fall below a critical threshold of 0.75. Below this threshold, the risk is significantly higher that the localised cold spot created by the thermal bridge will increase the nearby relative humidity to levels that could result in mould growth.

Thermal bridges are inherently two- and three-dimensional. Therefore, they are far too complex to be accurately calculated by hand. A number of computer programs are available to model thermal bridge details. Modelling software in accordance with *BS EN ISO 10211:2007* must successfully calculate results for both temperature and heat flow that agree with stated values for validation examples in that standard. Several software packages meet these requirements, including Psi-Therm, AnTherm, HEAT, THERM and TRISCO. THERM is a Windows-based, freeware program for modelling steady-state, two-dimensional heat transfer. (LBNL, 2014) Originally developed for calculating heat transfer through window frames, it can model and calculate complex geometries, unlike many other programs which are limited to rectangular geometries. Several independent parties, including the authors of this report, have validated THERM 5.2 to *BS EN ISO 10211:2007*.

A thermal bridge assessment has been included in the case study of this report to illustrated the assessment process. The assessment uses the software THERM 5.2. (Section 5.4.3)

5 Case study assessments

5.1 Base wall, insulation products and assessment scenarios

5.1.1 Case study context

In the previous section, different methods and associated modelling tools for hygrothermal assessment were discussed. In the following, the differences of these tools will be illustrated using, as a case study, a traditional stone wall of a Victorian tenement in Glasgow. The wall will be assessed first without retrofit and then with a variety of retrofit options. This will allow comparison of the assessment tools on one hand and of different retrofit options on the other.

To investigate the wall's hygrothermal performance, the following two software tools and assessment methods are used:

- BuildDesk U 3.4, based on Glaser method calculations in accordance with *BS EN ISO 13788:2002*

- WUFI Pro 5.3, based on numerical simulations in accordance with *BS EN 15026:2007*

Assessments were undertaken for four very different insulation products, each achieving two different target U-value: 0.5 and 0.25 W/(m^2·K). In addition to this, the impact of different types of AVCLs and different external material layers will be investigated for some of the insulation products.

Further to these more general hygrothermal assessments, simulations will also be used to explore how three specific risks of specific moisture-related damage can be assessed:

- Risk of mould growth, assessed using WUFI-Bio 3.0, a post-processor for use with WUFI Pro
- Risk of freeze-thaw deterioration, assessed using WUFI Pro 5.3
- Risk of condensation due to thermal bridging, assessed using THERM 5.2 in accordance with *BS EN ISO 10211:2007*

This section provides more details about the base wall and the retrofit options used, concluding with a detailed overview of the assessments to be conducted. The input parameters for the assessments, including climatic and material data, are described in Section 5.2. The hygrothermal assessments and the risk assessments for moisture-related damage are described in Section 5.3 and Section 5.4 respectively.

5.1.2 Base wall

As the case study for this report, a traditionally constructed sandstone wall is used. In its original form, i.e. without any retrofit, the wall will be referred to as the *base wall*. Such a wall has previously been retrofitted by Historic Scotland as part of its *Refurbishment Case Study* series. (Historic Scotland, 2014) The building used for the actual retrofit project was a tenement building in Glasgow, dating from the 1880s. For the case study, the northwest facing rear wall of this building was used. (Figure 51 and Figure 52)

The wall has an overall thickness of about 600 mm, including internal finishes. It is constructed from randomly coursed stonework. The squared sandstones are bedded in lime mortar. The masonry is exposed externally. For the case study, it was assumed that the internal wall finish is lime plaster on timber laths, as would have existed originally. The horizontal laths would have been fixed to vertical timber battens. This arrangement leaves air cavities in between the battens and between the laths and the masonry (this is shown clearly in Figure 29). The air in these cavities is assumed to be still-standing, i.e. without significant air movement.

The Historic Scotland retrofit project trialled a variety of internal insulation options. Although the idea for this case study was based on this actual retrofit project, not all the information required for hygrothermal modelling was readily available, because no invasive investigation of the masonry was undertaken as part of the actual retrofit project. Therefore, the construction details of the wall and the properties of its materials could not exactly be determined. Instead assumptions were made. The case study assessment should therefore be interpreted as an exploratory study, rather than an exact simulation of the retrofit options installed on site.

5.1.3 Insulation products

5.1.3.1 Product selection

Four insulation products are assessed in the case study:

1. Cellulose fibres
2. Aerogel blankets
3. Phenolic foam boards
4. Calcium silicate boards

The first two products were used in Historic Scotland's retrofit project. Phenolic foam boards were assessed as a product used in the mainstream construction industry. And calcium silicate boards were investigated because of their unusual hygrothermal properties, namely their ability to transport liquid by capillary action.

Figure 51 The idea for the case study was based on a real retrofit project by Historic Scotland in a Victorian tenement building in Glasgow.

Figure 52 The case study is based on the rear wall of a Glasgow tenement, constructed as randomly coursed masonry with squared sandstones, bedded in lime mortar.

5.1.3.2 Cellulose fibres

Cellulose fibre insulation is made from new or recycled plant fibres. Some cellulose insulation is produced from recycled paper. In the Historic Scotland project, wet cellulose fibres were sprayed, in between timber battens, against the wall. This installation ensures that there are no air spaces between the cellulose and the masonry. The applied product is permeable, hygroscopic and capillary active. The retrofit was finished with gypsum plasterboard, fixed to the battens. No AVCL was installed in the actual project. (Figure 53)

Figure 53 Cellulose fibre insulation is sprayed against the wall surface, lined with timber battens to receive a plasterboard finish.

5.1.3.3 Aerogel blankets

Aerogel is a solid derived from a gel, in which the solvent component of the gel has been removed with minimal shrinkage or disruption of the material's structure. (Pérez, 2012) The resulting, synthetic material is one of the lightest manufactured solids known, with low density, ultra-small, air-filled pores and a large surface area. These properties give aerogel a remarkably low thermal conductivity. The material is highly hydrophobic and not capillary inactive. It is used as a bead or granulate in a range of applications. As an insulation product for use in building construction, aerogel is currently available as a coating on non-woven polyester fibre mesh. These aerogel blankets are vapour-open and, due to the aerogel coating, also highly hydrophobic and capillary inactive. The product used in the Historic Scotland project was an aerogel blanket bonded to a gypsum plasterboard. This board product did not incorporate an AVCL. The boards were mechanically fixed to metal studs, thereby leaving a space of still air in between the studs and between the boards and masonry. (Figure 54)

Figure 54 Aerogel blanket insulation bonded to plasterboards is fixed to metal studwork, leaving air cavities in between the studs and between insulation and masonry.

5.1.3.4 Phenolic foam boards

Phenolic foam insulation is made from phenolic resin. It has a low thermal conductivity, due to encapsulating microscopically small pockets of gas. The insulation product considered in this case study is a rigid composite board, consisting of phenolic foam, foil and gypsum plasterboard, all bonded together. This board is capillary inactive, impermeable and non-hygroscopic. For the case study, it was assumed that the boards are mechanically fixed to timber battens. This form of installation leaves a space of still air in between the battens and between the boards and the masonry. (Figure 55)

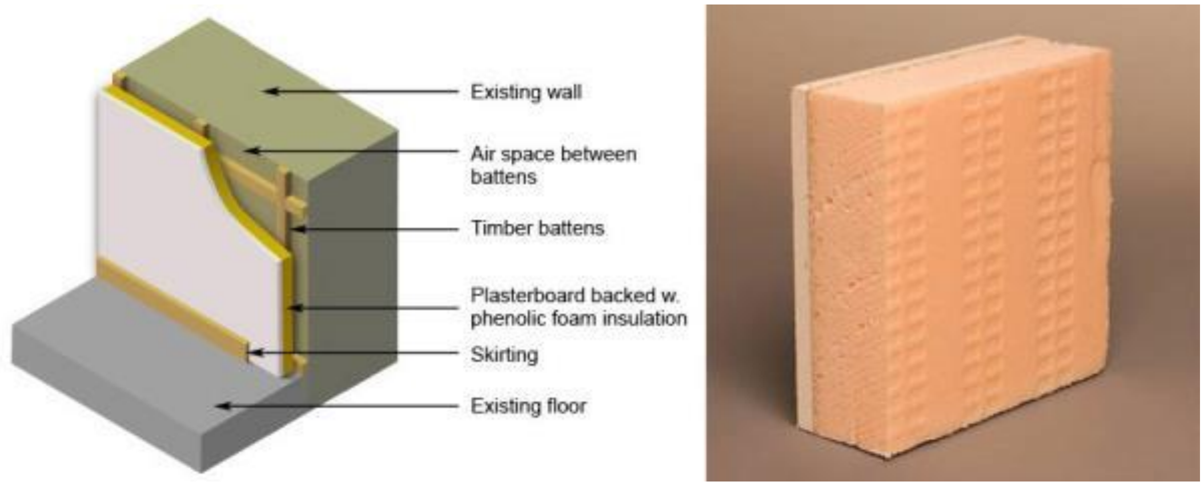


Figure 55 Phenolic foam insulation bonded to foil-backed plasterboard is fixed to timber studwork, leaving air cavities in between the studs and between insulation and masonry.

5.1.3.5 Calcium silicate boards

Calcium silicate foam is a microporous, low-density material, specifically engineered to be highly capillary active. Made from sand, quartz, lime and water, the foamed calcium silicate is supplied to the construction industry as a rigid board insulation. The boards are also hygroscopic, vapour permeable and highly alkaline. They are fully bonded to the wall using a lime mortar-based adhesive (Figure 56). A levelling lime plaster may be necessary where the original wall is out of true. This form of installation ensures that there will be no air gap between the boards and the masonry. A lime based plaster provides the finish.

The resulting assembly manages room moisture as well as moisture from the wall while performing well in terms of acoustics and fire.

Figure 56 Calcium silicate boards are fixed to the masonry with a mortar-based adhesive. For the case study, a plaster finish and a levelling plaster coat was assumed to provide a level surface.

5.1.3.6 Product comparison

To allow easy comparison, Table 7 lists the four insulation products used in this case study, with the various characteristics discussed.

Product ID & name	**1. Cellulose fibres, sprayed**	**2. Aerogel blankets**	**3. Phenolic foam boards**	**4. Calcium silicate boards**
Product overview				
Reason for use in case study	used in Historic Scotland project	used in Historic Scotland project	mainstream construction industry	unusual hygrothermal properties
Description	sprayed cellulose fibres, finished with plasterboard	aerogel-coated polyester mesh, bonded to plasterboard	board made from phenolic resin, foil and plasterboard	calcium silicate boards, finished with lime plaster
Natural or synthetic	natural (plant fibres)	synthetic (aerogel & polyester)	synthetic (phenolic resin)	natural (sand & lime)
λ value ranges[*] [W/(m·K)]	0.035 - 0.046[†] 0.040 - 0.045[§]	0.013 - 0.014[†] 0.015 - 0.021[‡]	0.020 - 0.025[†] 0.029 - 0.041[#]	0.045 - 0.065[‡]
Pore structure				

Pore structure content	air	air	inert gas	air
Vapour resistance	highly permeable	permeable	impermeable	permeable
Absorption behaviour	hygroscopic	hydrophobic	not hygroscopic	hygroscopic
Capillary behaviour	capillary active	capillary inactive	capillary inactive	highly capillary active
AVCL incorpo-rated in product	no	no	yes	no
Installation				
Fixing method	bonded to ma-sonry (no sepa-rate adhesive)	mechanically fixed to battens	Mechanically fixed to battens	bonded to masonry with adhesive
Studs	timber	timber	timber	none
Room finish	plasterboard	plasterboard	plasterboard	wet plastered
Air gap at insula-tion / masonry	no	yes	yes	no

* λ value ranges for insulating materials, not taking into account AVCLs, plasterboards or polyester meshes incorporated into products; sources for value ranges: [†]EST (2010); [‡]Gellert *2010a, p.203, tab.8.7); [§]Gellert (2010b, p.236, tab.9.7); [#]Zeitler (2010p.291, tab.11.3)

Table 7 Qualitative comparison of the insulation products assessed in the case study

5.1.4 Assessment scenarios

5.1.4.1 Scenario selection

The case study demonstrates not only the different assessment tools, but also illustrates the performance differences of different insulation products. The products have therefore been assessed for a range of scenarios:

- use of two different target U-values
- optional use of three AVCLs with different airtightness levels
- impact of different external material layers

5.1.4.2 Target U-values

Because the primary aim of this case study is to illustrate the use of hygrothermal assessment methods, it was decided that all four chosen insulation products should be compared for specific U-values regardless of the typical thicknesses at which they were supplied to the market. In other words, the case study does not compare 100 mm of aerogel insulation with 100 mm cellulose fibre insulation.

Instead, two target U-values were chosen, which can be thought of as representing a *minor retrofit* and a *major retrofit*:

- a *minor retrofit* results in a wall construction with a U-value of 0.5 W/(m^2·K)
- a *major retrofit*, results in a wall construction with a U-value of 0.25 W/(m^2·K)

All four retrofit measures are assessed for both retrofit scenarios, except for the calcium silicate insulation which is only assessed for a *minor retrofit*. This means that eight assessments will be made: for the base wall, four *minor retrofits* and three *major retrofits*.

Table 8 lists these eight assessments, together with the required product thicknesses. While insulation boards are limited to various sizes (determined by the manufacturer) other systems such as sprayed cellulose fibres can be installed in whatever thickness is required. However, because the case study is of theoretical nature, such practical aspects are ignored.

Product ID	**Insulation product**	**Target U-value** [W/K·m^2]	**Required thickness** [mm]	**Scenario ID**
1	cellulose fibres, sprayed	0.50	668	**1.1**
		0.25	754	**1.2**
2	Aerogel blanket with plasterboard	0.50	650	**2.1**
		0.25	677	**2.2**
3	Phenolic foam with plasterboard	0.50	667	**3.1**
		0.25	720	**3.2**
4	Calcium silicate boards, plastered	0.50	708	**4.1**

Table 8 Assessment scenarios as a combination of the chosen retrofit products and target U-values, together with required product thicknesses

5.1.4.3 Use of AVCLs

Installing an AVCL between plasterboard and insulation is often considered *good practice*. (Stirling, 2002, pp. 32-33) However, to be able to critically review this, some assessments are undertaken with and without AVCLs. Three different types of AVCLs are used:

- polyvinyl chloride (PVC) foil (as often incorporated in phenolic foam boards)
- Intello membrane (as a relatively novel, advanced product)
- polythene (PE) membrane (as a product used in mainstream construction industry)

Whereas the PVC foil and PE membrane have fixed diffusion resistances, the more advanced Intello membrane, a proprietary product, has a variable diffusion factor.

All four chosen insulation products are assessed without AVCLs. In addition to this, the cellulose fibre retrofit is assessed with both Intello and PE membranes. Phenolic foam boards generally incorporate a PVC foil between the foam and the plasterboard. However, to illustrate the impact of the foil, the phenolic foam retrofit is assessed with and without a foil.

5.1.4.4 Impact of external material layer

The assessment of the 13 previously described retrofit options will focus mostly on the impacts of indoor vapour loads. To investigate the impact of the external wall surface and therefore the impact of rain fall on the assessments, all 13 retrofit options will be reassessed with three different external material layers. These layers are:

- Outer wall layer is a less absorptive sandstone (Stone A): this stone will be used for the 13 previous assessments and therefore acts as basis for comparison.
- Outer wall layer is a more absorptive sandstone (Stone B): Stone B replaces Stone A, thereby allowing comparison of the impact of these very different stone types.
- Outer wall layer is an external lime render, applied to the stone layer (Stone A): this additional material layer will demonstrate the impact of a render, as a form of an additional, protective outer layer.

The assessments of the external material layers will only be conducted in WUFI, but not in BuildDesk U, as the latter does not take account of liquid transport, such as rain water.

5.1.4.5 Scenario overview

Table 9 summarises the 13 combinations of retrofit products, target U-values and optional AVCLs assessed in the case study. These 13 assessments plus the assessment of the base wall were carried out using both BuildDesk U and WUFI, for Glaser method and numerical simulation assessments respectively. The 13 retrofit options are further assessed, using WUFI only, with three different external wall layers. This results in a total of 16 BuildDesk U assessments (13 retrofit options plus three base walls) and 42 WUFI assessments (13 retrofit options times 3 external material layers, plus the three base walls).

The input parameters for these assessments are described in the next section. The actual assessments are discussed and analysed thereafter. (Section 5.3) Assessments conducted to investigate the risks of moisture-related deterioration are discussed separately. (Section 5.4)

Product ID	**Insulation product**	**Target U-value** [W/(m2·K)]	**AVCL**	**Scenario ID**
1	Cellulose fibres, sprayed	0.50	None	**1.1.1**
			Intello	**1.1.2**

			PE	**1.1.3**
		0.25	None	**1.2.1**
			Intello	**1.2.2**
			PE	**1.2.3**
2	Aerogel blanket with plasterboard	0.50	None	**2.1.1**
		0.25	None	**2.2.1**
3	Phenolic foam with plasterboard	0.50	None	**3.1.1**
			Foil	**3.1.2**
		0.25	None	**3.2.1**
			Foil	**3.2.2**
4	Calcium silicate boards, plastered	0.50	None	**4.1.1**

Table 9 Assessment scenarios as a combination of retrofit products, target U-values and optional use of AVCLs

5.2 Input parameters

5.2.1 External climate data

5.2.1.1 Use in Glaser method

Any time periods can be used for Glaser method assessments, but the associated standard, *BS EN ISO 13788:2002*, specifies the use of twelve monthly mean values for external temperature and relative humidity. BuildDesk U provides external climate data for a range of meteorological stations across the British Isles, with 22 location in Scotland. (Figure 57) The figure also shows the complete climate dataset used in the Glaser method assessment for the location *Glasgow*. The set consists of single monthly values for internal and external temperatures and relative humidities. It is possible for users to input their own data.

Regarding the criteria for the selection of a representative year, the recommendations of *BS 5250:2011* are stricter than those of *BS EN ISO 13788:2002*:

> *For most buildings, a once-in-ten-year climate year will be appropriate. For particularly sensitive constructions or buildings with vulnerable contents, a once-in-twenty or once-in-fifty-year climate year may be considered more appropriate.*
>
> (BSI, 2011, p. 5)

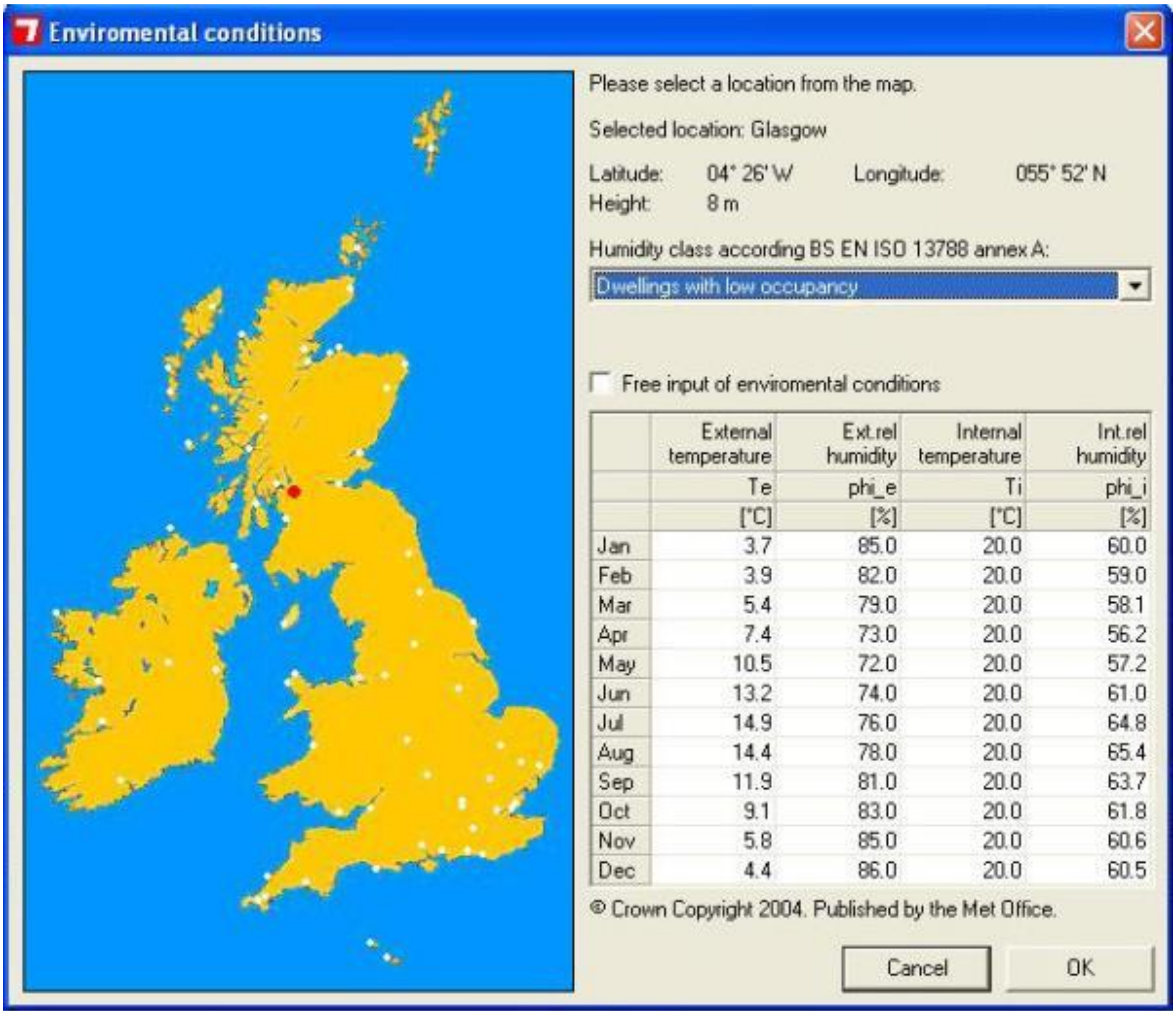


Figure 57 BuildDesk U screenshot showing the meteorological stations available for the British Isles and the environmental conditions available in the software for the location *Glasgow* with a humidity class setting of *Dwelling with low occupancy*.

5.2.1.2 Use in numerical simulation

Data selection

For numerical simulations, hourly values are not only required for temperature and humidity, but also for solar radiation, cloud cover, precipitation, wind direction and wind speed. The latter three are used to describe wind-driven rain.

The standard associated with numerical simulation, *BS EN 15026:2007*, sets out the criteria and preferences for external climate data:

> *The external conditions used shall be representative of the location of the building. Test reference years for energy design are generally available; as these are representative of mean conditions they may not be appropriate for*

moisture design … If the design of a new building is being assessed, at least one year of external conditions appropriate to the most severe likely location of the building shall be used.

(BSI, 2007a, p. 14)

For new buildings, the preferred option is to use ten years of measured data, relevant to the most severe likely location of the building. The second best option is to use a Design Reference Year dataset, “constructed to cause the most severe conditions likely to occur once every ten years”. (BSI, 2007a, p. 14) The least preferred option is to use a Test Reference Year dataset, where an annual temperature shift of ±2 K is applied to the mean of the whole dataset (regardless of its size), keeping the relative humidity unchanged. (The most severe conditions may be judged to be in summer or winter, via summer or winter condensation. The temperature can therefore be either decreased or increased.)

The requirement to use severe conditions seems to be relaxed for existing buildings: “If a problem in an existing building is being investigated, any data measured at the site of the building shall be used, otherwise the data from a similar location.” (BSI, 2007a, p. 14) However, as the case study assesses for an existing building hygrothermal impacts of retrofits which will undoubtedly change the hygrothermal conditions, the more conservative approach, set out for new buildings, was taken in the case study.

Although WUFI Pro provides a range of weather data across Europe, it does currently not contain climate files, covering the British Isles. (Figure 58) As neither measured data was available for the site or a similar location nor access to Test or Design Reference Years for Glasgow from the Met Office, a Design Reference Year dataset was generated, representing severe conditions. The dataset was generated using the climatological database Meteonorm 6, provided by Meteotest.

Meteotest uses proprietary algorithms and triangulation to translate daily climatological data from weather stations into hourly datasets for anywhere worldwide. To generate hourly temperature and global radiation values at a selected location, Meteonorm uses interpolations of measured monthly values from neighbouring locations, coupled with stochastic models.

The stochastic models generate intermediate data having the same statistical properties as the measured data, i.e. average value, variance, and characteristic sequence … The generated data approximates the natural characteristics as far as possible. Recent research shows that data generated in this way can be used satisfactorily in place of long-term measured data.

(Meteonorm, 2014, part 2, p. 41)

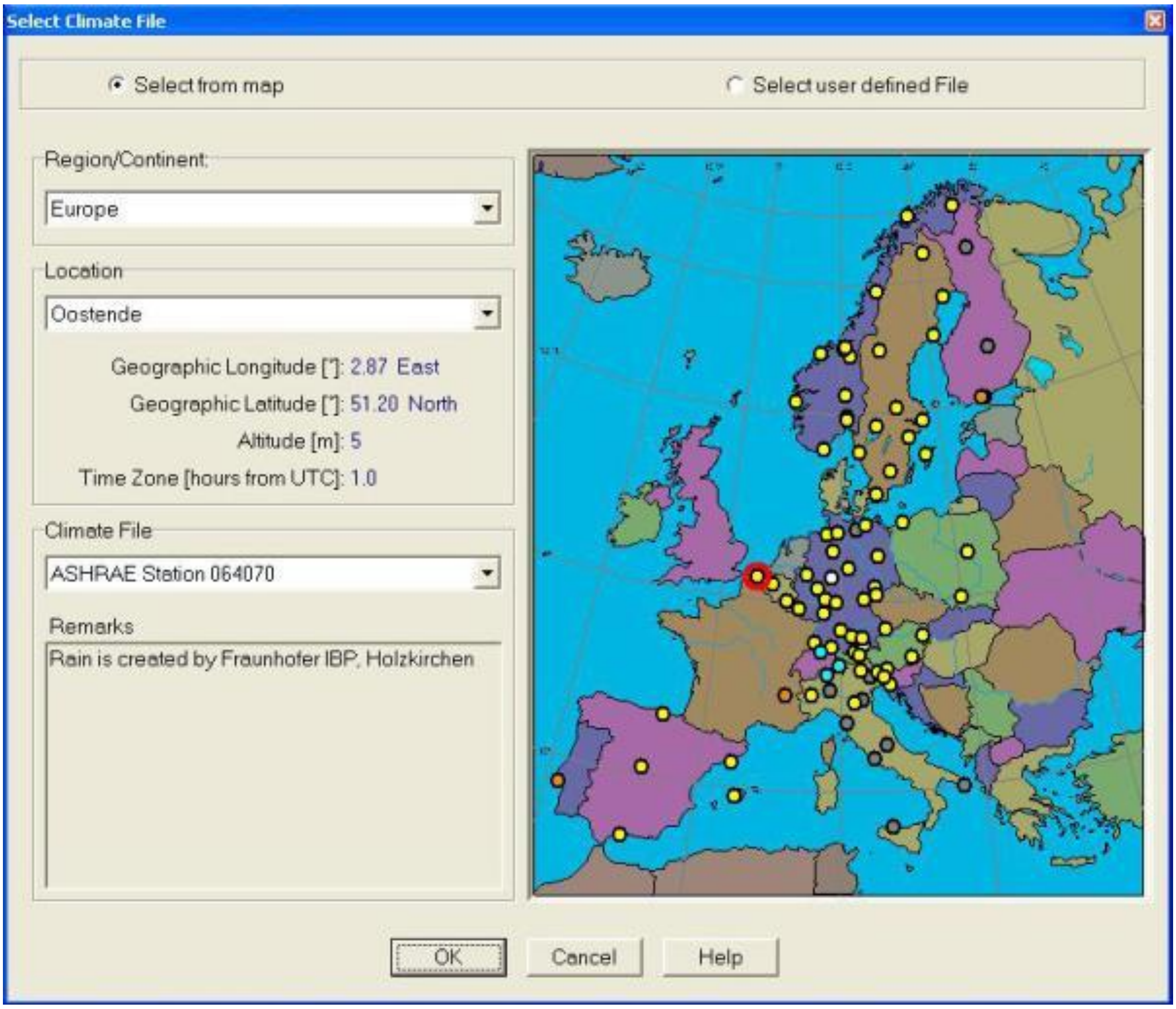


Figure 58 WUFI Pro screenshot showing the meteorological stations of Europe available within the software, with the city of Ostend (Oostende), Belgium, circled in red.

However, it should be noted that "the supplementary parameters are not of the same quality as the main parameters (global radiation and temperature) and were not validated in an equally comprehensive way." (ibid., part 2, p. 74) This leaves the software user wanting to understand whether there are inaccuracies and, if there are, how significant these might be. The dataset, generated for use in the case study, was titled *Glasgowhour_extreme.wac*. It was uploaded in the outdoor climate selection window of WUFI Pro. This is illustrated in Figure 59, showing also the dominant patterns for solar radiation and wind-driven rain.

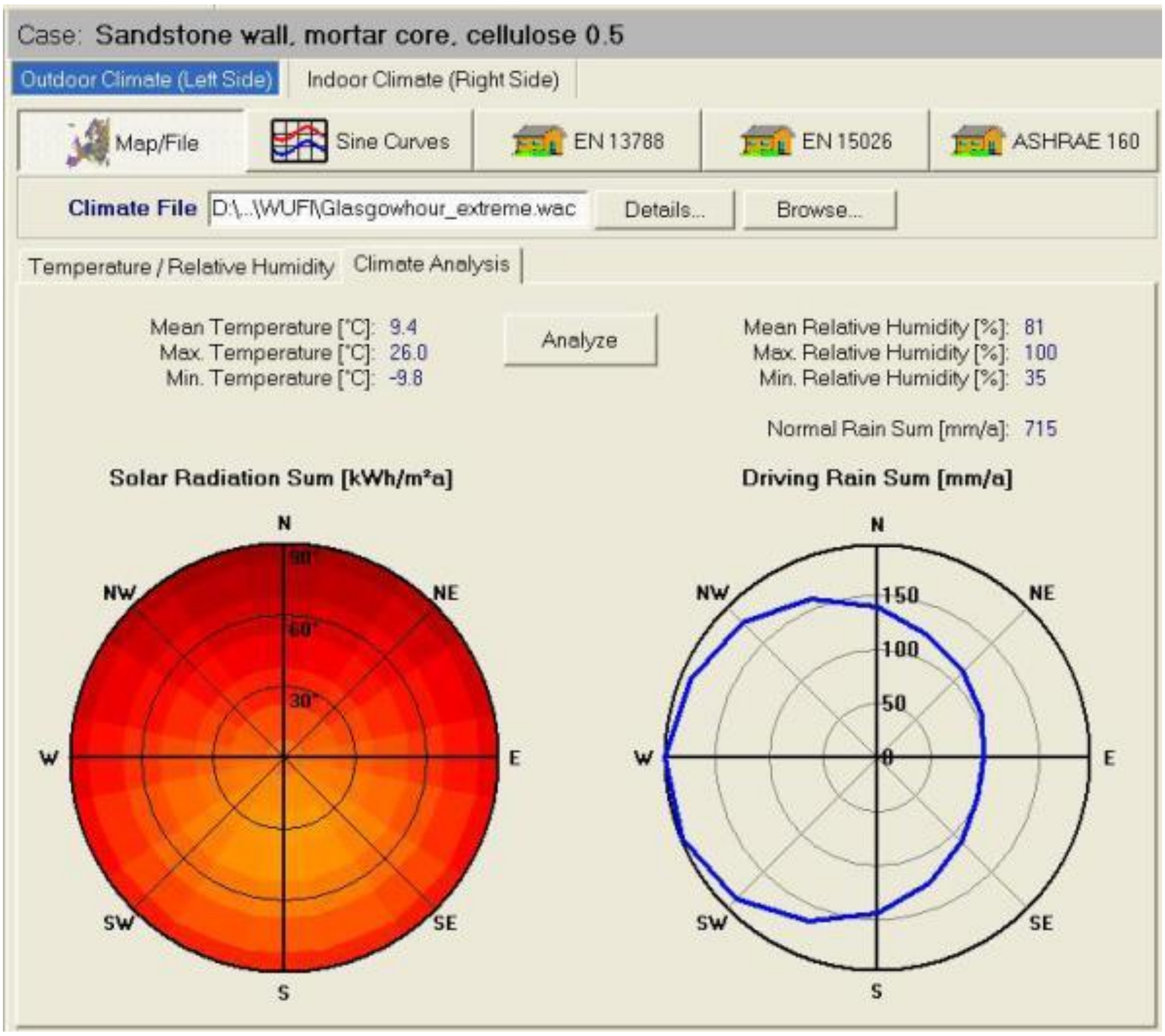


Figure 59 WUFI Pro screenshot showing basic climatic analysis of solar radiation and wind-driven rain for the location Glasgow

The figure shows that significant amounts of wind-driven rain occurs at the case study location. This is not unexpected. Stirling (2002) identifies four different exposure zones for the UK: sheltered, moderate, severe and very severe. (Figure 60) Glasgow is located in the severe exposure zone, (whereas all other Scottish cities are in the sheltered or moderate zones).

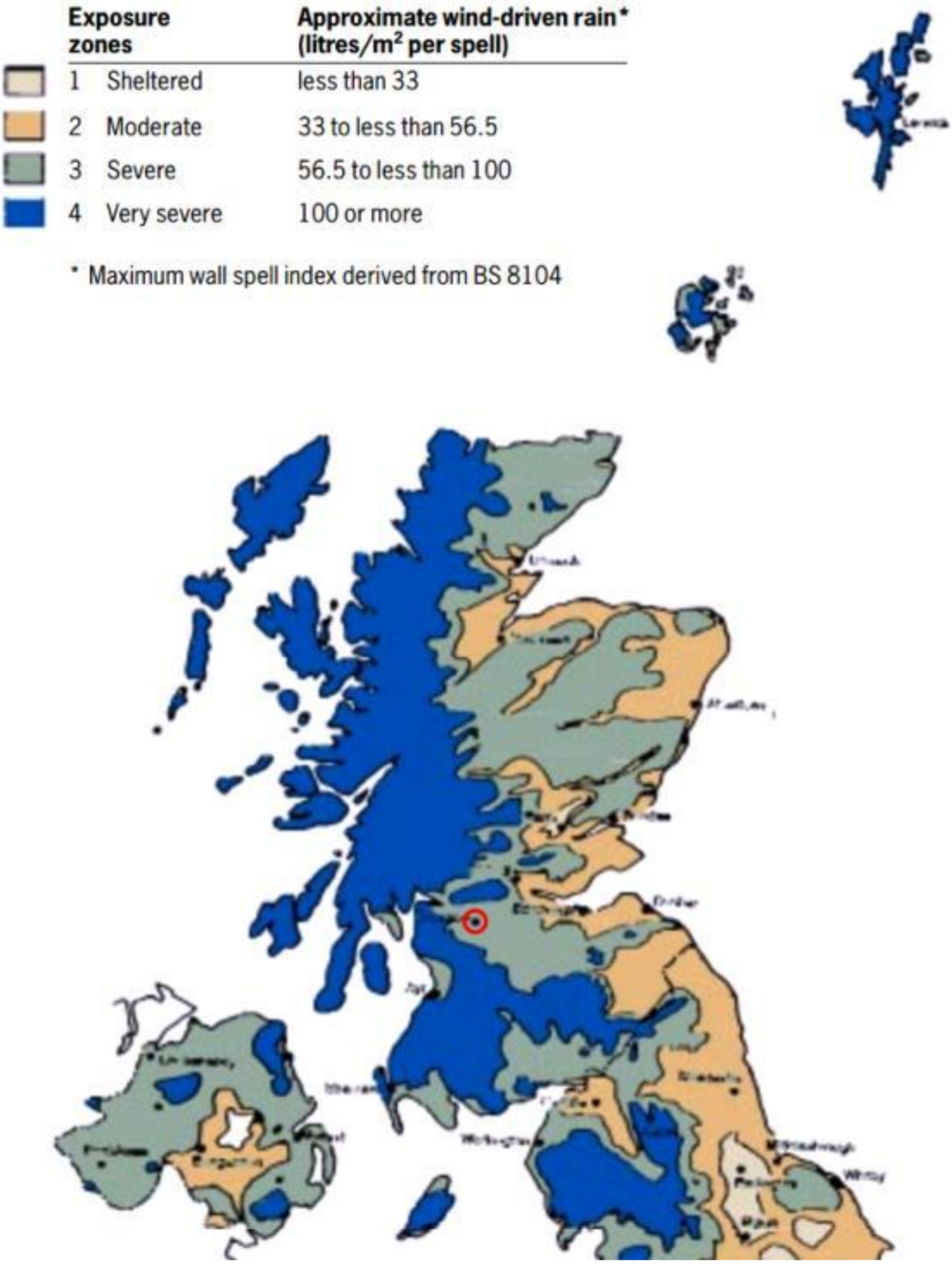


Figure 60 Map of the north of the UK with four exposure zones for wind-driven rain: Glasgow is marked with a red circle. (Image © Building Research Establishment)

Comparing measured and synthetic climate data

Fraunhofer IBP has compared its own climatological data, measured over twenty years at its outdoor facility in Holzkirchen, Germany, with a synthetic Design Reference Year, generated in Meteonorm, finding it to be an acceptably close match. In line with the requirements of *BS EN 15026:2007*, the use of climate datasets generated from site measurement or supplied by meteorological services is, of course, be preferred.

> *We [Fraunhofer IBP] can confirm that Meteonorm data are generally suitable for hygrothermal simulations as long as the emphasis of the investigation is not the assessment of wind driven rain effects. The data for driving rain loads produced by Meteonorm may not always have the required accuracy. Therefore, measured data should be used if wind-driven rain has a great influence on the hygrothermal behaviour of the considered building component. However, using the Glaser method under such circumstances would be completely inadequate. The European "Glaser" Standard EN 13788 explicitly excludes the assessment of building components that may absorb driving rain.*
>
> (Künzel, 2013)

A comparison by the authors of measured and synthetic climate data for Dublin Airport confirms these findings. The diagrams in Figure 61 overlay a Design Reference Year created in Meteonorm (in red) with data measured over eleven years, between 1999 and 2010, by Met Éireann, the Irish meteorological office (in blue). Although monthly mean values for temperature, relative humidity and rain fall show a remarkably good agreement, it appears that Meteonorm's algorithms result in an underestimation of the amount of wind-driven rain. (It would be beneficial to repeat such a comparison for Glasgow to understand if the underestimation for wind-driven rain is similar to that of Dublin. Unfortunately, no Glasgow climate data were freely available during the writing of this report.)

The authors find it highly unsatisfactory that Design Reference Years, derived from data obtained from the meteorological offices of Ireland and the UK, are not yet easily available for users of numerical simulation software, despite guidance in both countries advising its use.

Comparing the climate datasets used in the case study

The two datasets used in the case study for the Glaser method and numerical simulation assessments can be compared with each other. Figure 62 presents the temperature data for both assessments methods, Figure 63 the humidity data. The comparisons show that, in both cases, significant disparities in the used data quantity exist: 8760 reference points per year for numerical simulation assessments versus twelve reference points for the Glaser method assessments. Reassuringly, however, the monthly values appear to track the median of the hourly values reasonably well, despite their different origins.

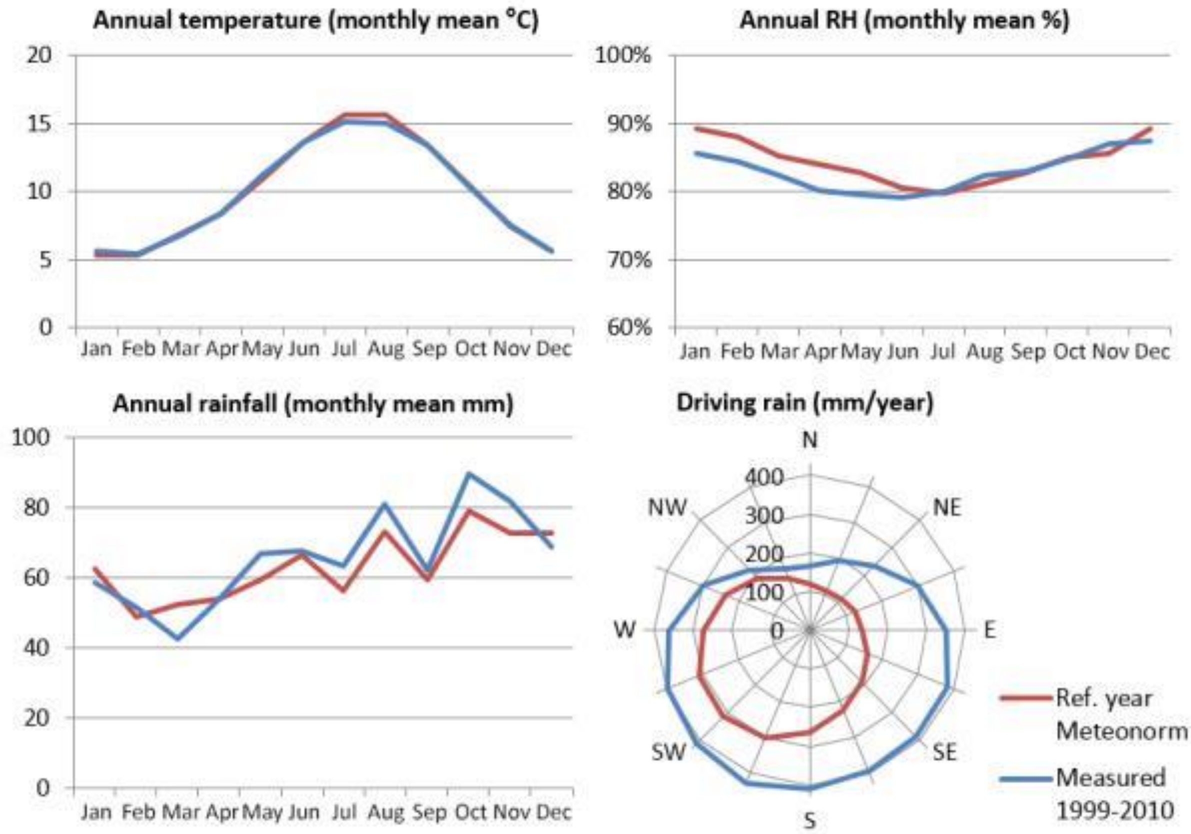


Figure 61 Comparison of synthetic climate data from a reference year in Meteonorm (red) and the related measured data from 1999 to 2010 (blue), both for Dublin Airport. Temperature, relative humidity and rainfall are averaged by month, while wind-driven rain is averaged by year over different directions.

In addition to this quantitative difference, there are two important observations that can be made with regard to the use of monthly mean values:

1. The Glaser method never assesses conditions where rapid temperature changes can occur, such as those causing freeze-thaw deterioration.

2. The Glaser method cannot calculate the impact of the extreme conditions that may exist for short periods of time. (While it could be argued that the slow response of solid masonry walls to changes in external temperature and relative humidity might make use of monthly means acceptable for *normal* conditions, it takes no account of the short-term external climate conditions relevant to buildings, e.g. wind-driven rain.)

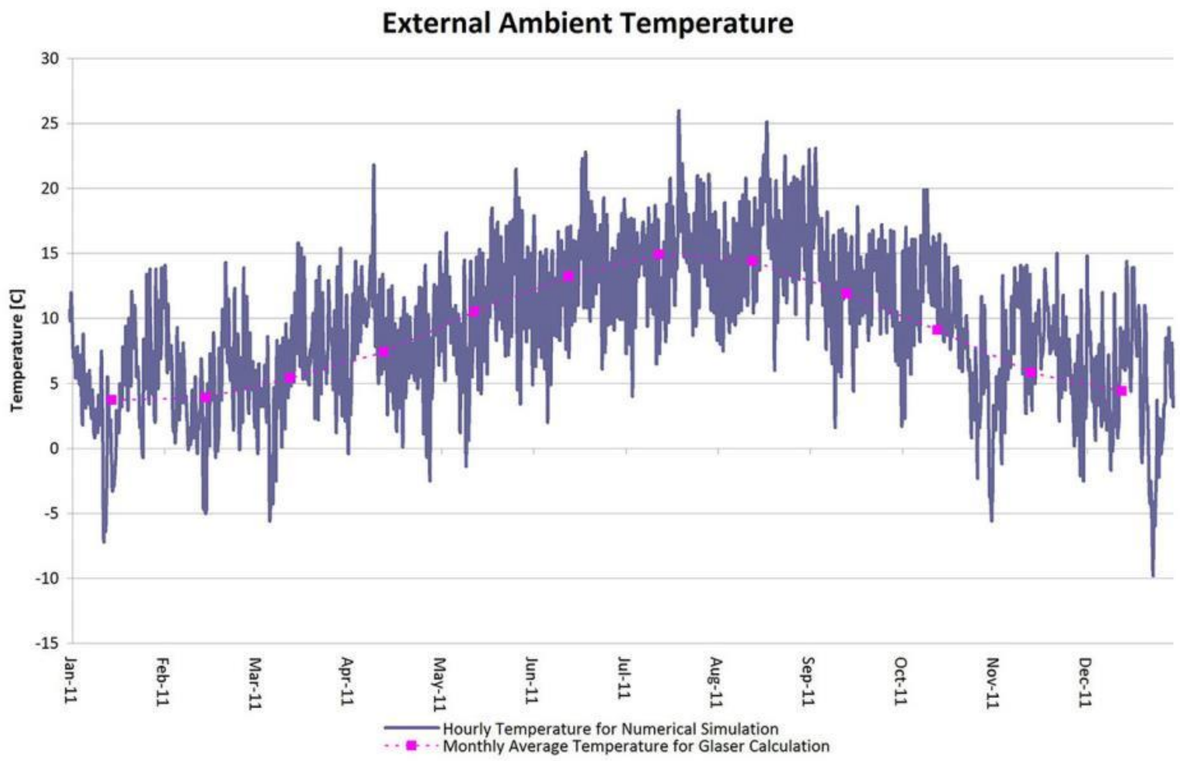


Figure 62 External temperature data used for Glaser method and numerical simulations assessments

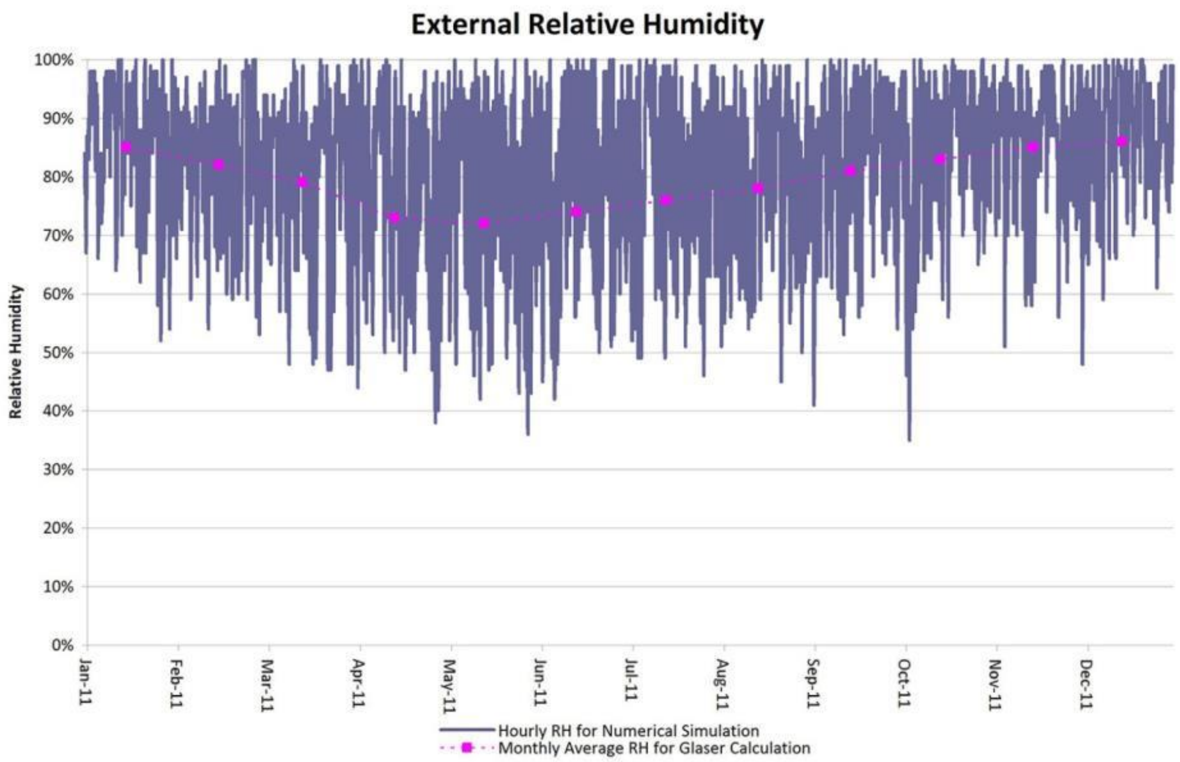


Figure 63 External relative humidity data used for Glaser method and numerical simulations assessments

Building design generally aims to ensure that building elements perform suitably, even under extreme conditions. For example, the sizing of heating systems is based on extreme cold temperatures, and structural wind loading calculations are based on extreme gusts. However, when assessing the building fabric using the Glaser method, *all* short-term and extreme external conditions 'fall off the table' due to the marked averaging and reduction of the climate data used.

Impact of exposure and orientation

Regarding exposure and orientation, *BS EN ISO 13788:2002* recommends for assessments that "*the external conditions used shall be representative of the location of the building, taking account of altitude where appropriate."* (BSI, 2002a, p. 7) A note in the standard states that a drop of 1 K in mean monthly temperature can be assumed for every 200 m increase in altitude. No recommendations are given as to otherwise represent external conditions, and, of course, no short term events are considered. This suggests that the Glaser method may be most accurate when dealing with structures in sheltered locations.

BS EN 15026:2007 recommends for numerical simulations:

> *The external climate file shall include the climate parameters necessary for the analysis to be undertaken. A complete set would contain:*
>
> - *dry bulb temperature;*
> - *vapour pressure, or any other humidity parameter that can be used to calculate vapour pressure;*
> - *global and diffuse solar radiation;*
> - *sky temperature;*
> - *wind speed and direction;*
> - *total atmospheric pressure;*
> - *precipitation (rain, snow, drizzle).*
>
> (BSI, 2007a, p. 14)

One of the strengths of numerical simulation tools is that the underlying standard recognises that important climate parameters are not only those at the weather station, but also the local conditions occurring at the building element to be assessed. In addition to the minimum input requirements of the standard, WUFI Pro also allows inputs for the building's context, such as urban or in a valley, and the height above ground level. A northwest facing wall may experience less wind-driven rain, but may also have a reduced drying ability compared to a southwest facing wall. Equally, wind velocity increases with every few metres above ground level. A sloping wall will therefore experience a different load of wind-driven rain than a vertical wall.

WUFI Pro, therefore, provides two options for establishing the wind-driven rain coefficient. (Figure 64) The default approach is based on advanced, three-dimensional, computational fluid dynamics simulations of droplet flow, based on the inputted data for precipitation, wind direction and wind speed. The alternative approach is based on methods described in the American standard *ANSI/ASHRAE 160-2009*. (ANSI and ASHRAE, 2009) In this case study, the default approach has been chosen.

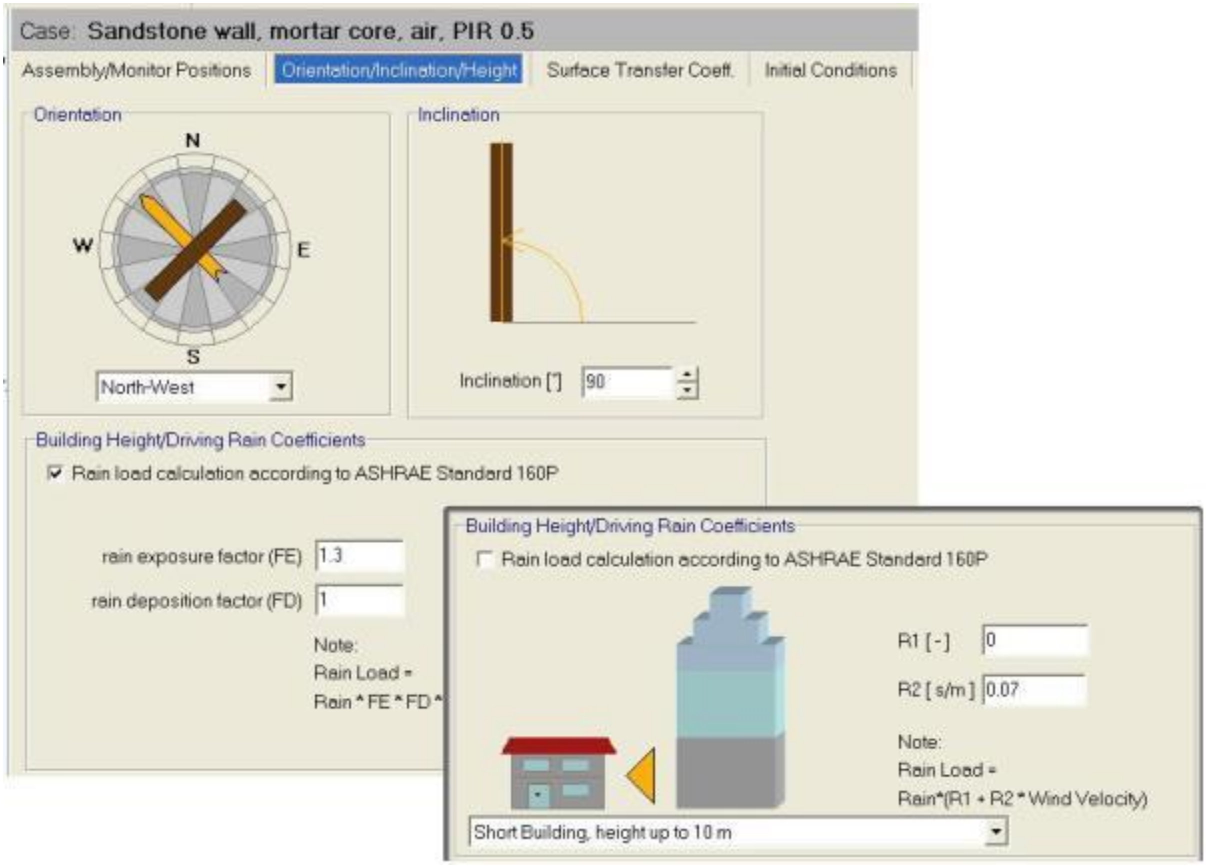


Figure 64 WUFI Pro screenshot showing selections possible to localise selected climate data for a specific building element, including orientation, inclination, height above ground and wind-driven rain coefficient

5.2.2 Internal climate data

The internal climate conditions for the case study assessments were determined according to the relevant standard in each assessment method. For the Glaser method, *BS EN ISO 13788:2002* recommends the use of 20 ˚C as indoor air temperature. Appendix A of the standard provides a correlation for estimating the internal relative humidity, based on the outdoor air temperature.

The internal vapour loads are described using a categorisation system of humidity classes. For the case study, a 'low occupancy' setting was assumed, which relates to humidity class 3 in accordance with *BS EN ISO 13788:2002*. (Table 10 and Figure 65).

It is possible, however, that the kitchen or bathroom might be in humidity class 4, particularly if inadequately ventilated. (The classification of humidity classes has been changed for the 2012 version of *BS EN ISO 13788*. This case study still uses the 2002 version.)

Humidity class	Building
1	Storage areas
2	Offices, shops
3	Dwellings with low occupancy
4	Dwellings with high occupancy, sports halls, kitchens, canteen; buildings heated with un-flued gas heaters
5	Special buildings, e.g. laundry, brewery, swimming pool

Table 10 Internal humidity classes, as described in *BS EN ISO 13788:2002* (BSI, 2002a, p. 21, table A.1)

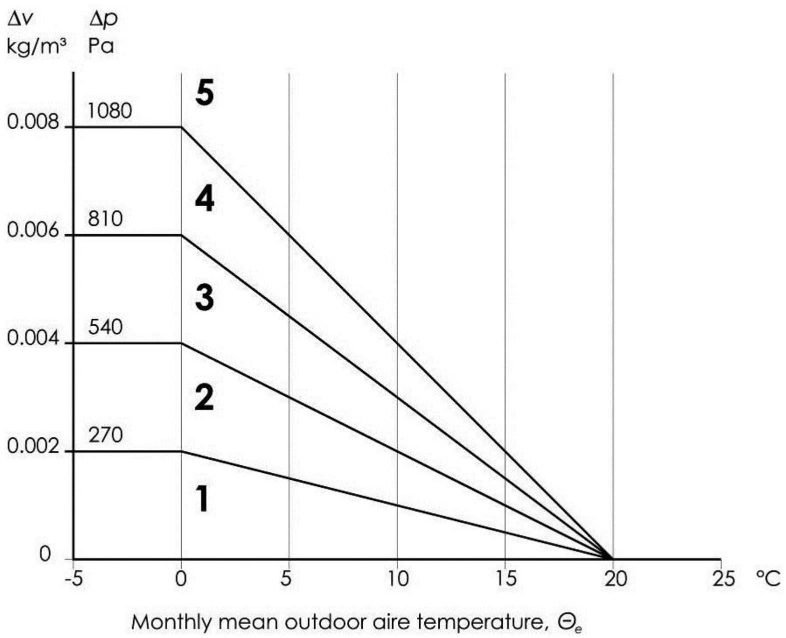


Figure 65 Correlation between indoor vapour load and outdoor air temperature for internal humidity classes, as defined in *BS EN 13788:2002* (Image © Building Standards Institute)

While the Glaser method does not allow for short-term extreme external weather conditions, it does raise internal relative humidity to stress conditions within and on the surfaces of components to compensate for other inaccuracies. This is done in two ways: firstly, by asking assessors to use values at the top of the relevant humidity class band (BSI, 2002a, p. 21) and, secondly, by adding an additional 'safety margin' to the calculated relative humidity. The reasoning given for use of the safety margin is:

> *The calculation method as described in this standard is a steady-state calculation. In reality, however, external air temperature variations, changing solar radiation, hygroscopic inertia and intermittent heating can influence surface humidity conditions. This is especially the case for a thermal bridge area consisting of building materials with high thermal inertia. The factor does not include the behaviour of the occupants, which can have a significant effect on ventilation.*
>
> (BSI, 2002a, p. 9)

This raised internal relative humidity can be clearly seen in comparison with internal conditions as estimated under *BS EN 15026:2007* in Figure . The latter's values, though varying much more, are lower than those estimated in the Glaser method. The existence of this safety margin is often referred to by those promoting the method as the key feature making it both valid and safe for assessing interstitial condensation risk of all types of building elements. Section 4.3.1 makes clear the limited applicability of the standard to certain element types, while Section 5.3.4 illustrates that stressing internal relative humidity does not allow one safely estimate risks of moisture accumulation or mould growth.

BS EN 15026:2007 states that, where possible, measured data should be used for simulation. Fraunhofer IBP has conducted or accessed thousands of measurements of internal residential conditions in different areas. (Künzel, 2013) From this measured data, correlations between outdoor temperature, indoor temperature and indoor humidity have been developed to be demonstrate compliance with *BS EN 15026:2007*. (Figure 66) In this study, a 'normal moisture load' setting was used.

When comparing the internal climate inputs of both assessment methods in the graphs of Figure 67 and Figure 68, the differences are even greater than when comparing the external climates. The reason for this is that the internal conditions are based on different correlations. The steady indoor air temperature of 20 ˚C, recommended for the Glaser method, bears no relation to the varying graph for use with numerical simulation, which is influenced by the outdoor air temperature. The relative humidity values are also dependent on outdoor air temperature, with higher external temperatures resulting in higher indoor relative humidities. As already mentioned, Glaser method values are significantly higher than the median of the 8760 numerical simulation values, showing the influence of the already discussed safety margin. (The 2012 edition of *BS EN ISO 13788* has changed the definition of the humidity classes and eliminated the 'safety factor'.)

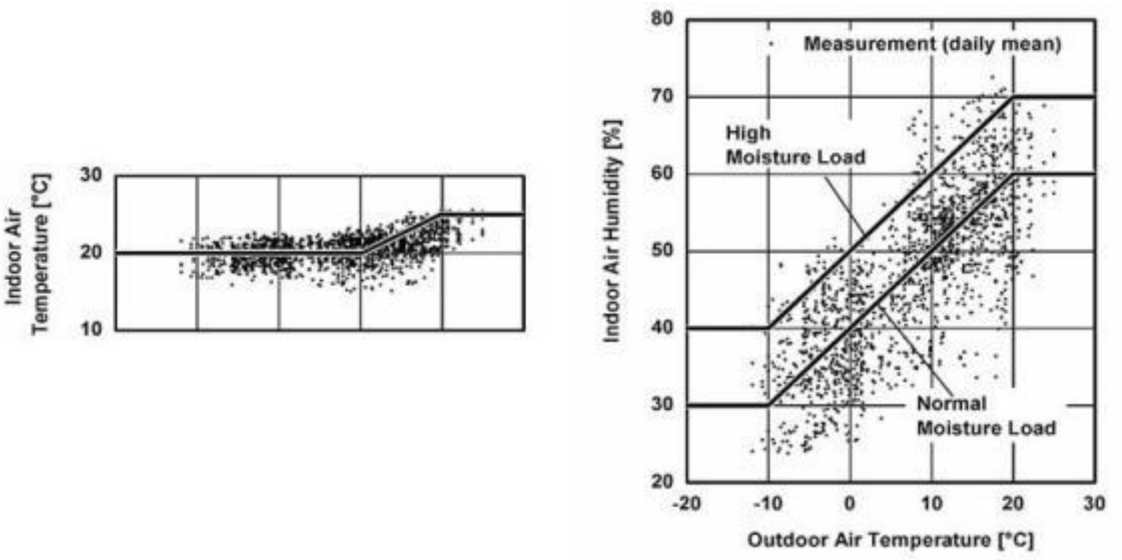


Figure 66 Correlation between indoor humidity and indoor and outdoor temperatures for simulation in accordance with *BS EN 15026:2007*

5.2.3 Geometrical representation and material properties of the base wall

5.2.3.1 Geometrical representation

For the case study, a traditionally constructed masonry wall is used. This form of solid wall construction is of an inhomogeneous nature, with larger stones forming the wall's two surfaces. These stones are often dressed or squared (i.e. they have at least some plane surfaces), and the mortar joints between these stones are therefore relatively thin. The core of such a wall, by comparison, consists of a mix of smaller stones in a large quantity of mortar. The wall core might also include small, air-filled voids.

Baker (2010) investigated the impact of this form of construction on U-value calculations, estimating that the ratio of materials in a traditional stone wall is 60 % stone to 40 % mortar.

Because Baker's research focused on the U-value of the entire wall construction, the location of the mortar relative to the stone had little effect, provided the ratios were correct. Baker could therefore use an extremely simplified geometrical model for calculations, consisting of only a stone layer and a mortar layer. (Figure 69)

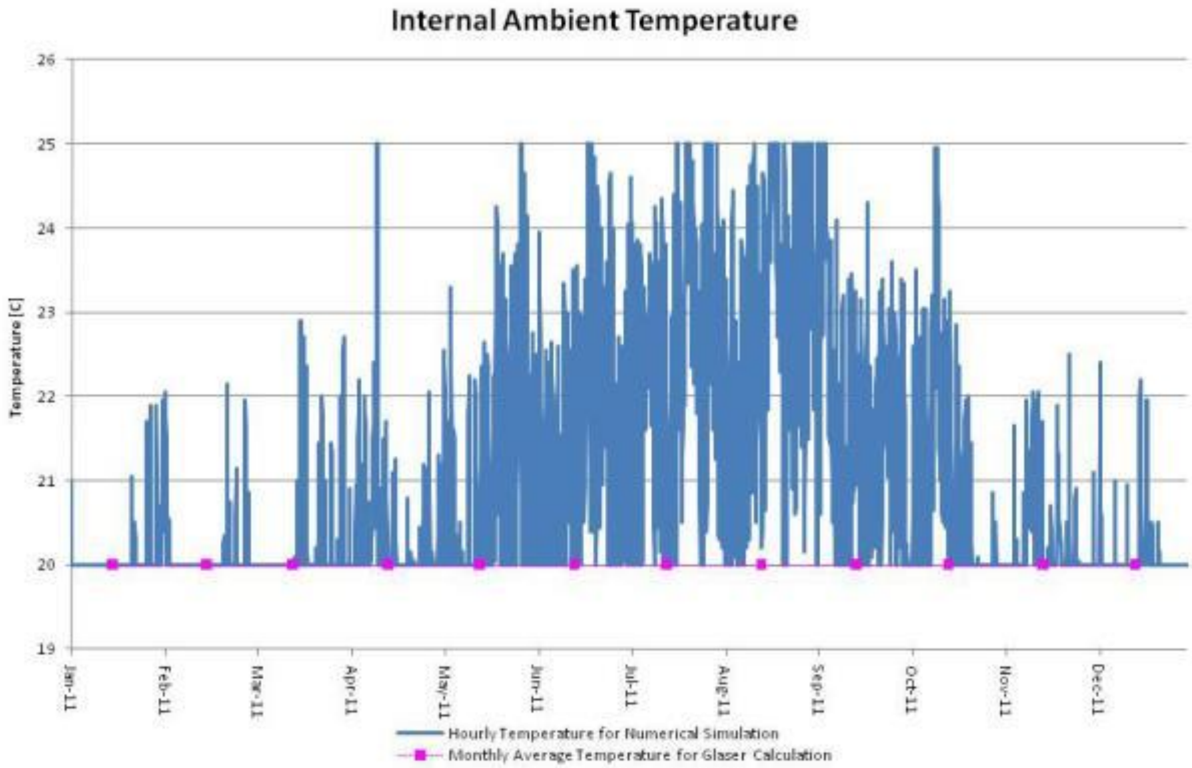


Figure 67 Indoor air temperature data used for Glaser method and numerical simulations assessments

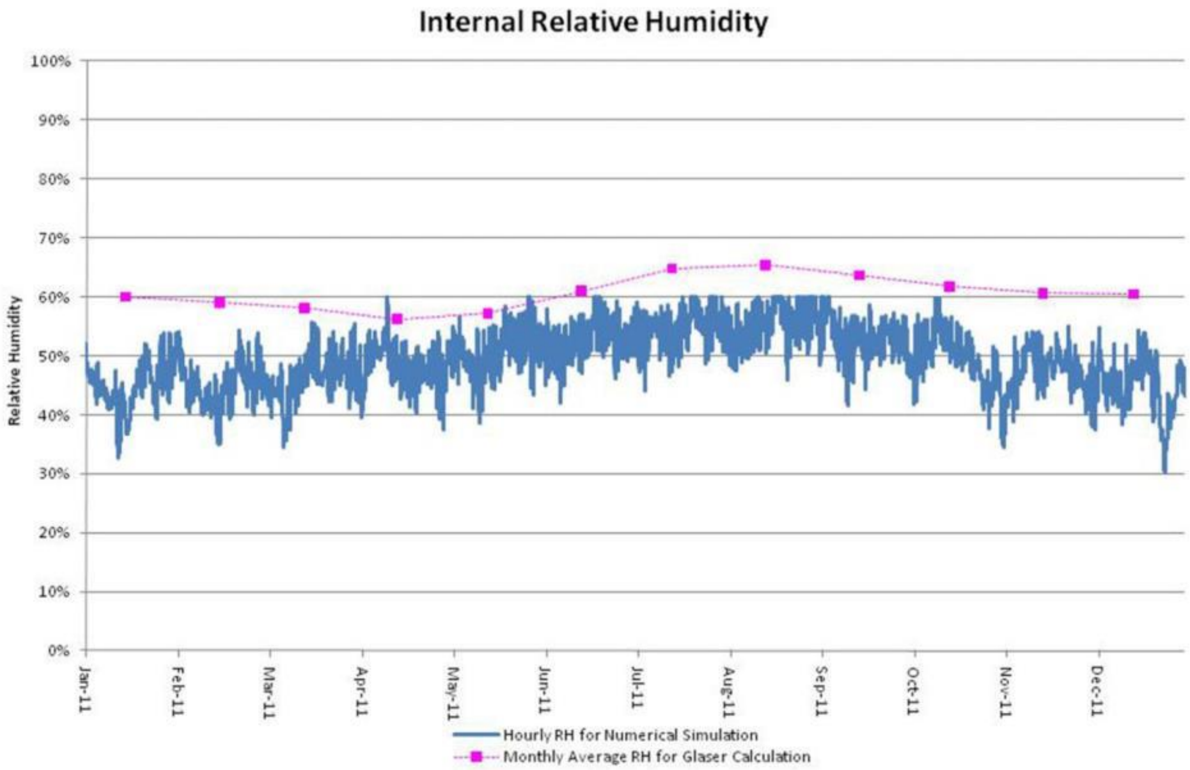


Figure 68 Indoor relative humidity data used for Glaser method and numerical simulations assessments

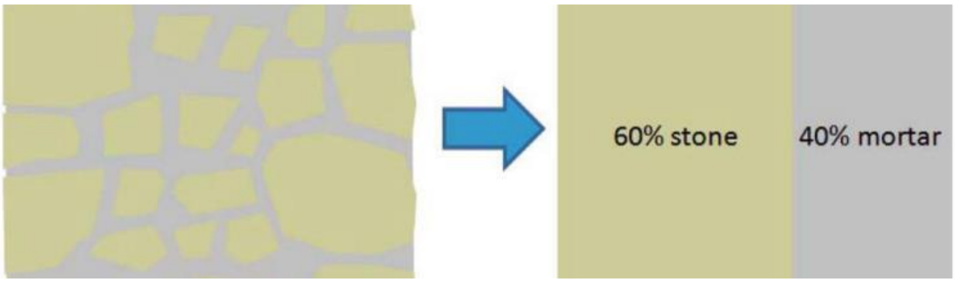


Figure 69 Schematic illustration of a cross section of a solid stone wall (left) and the simplified geometrical model (right) used in Baker (2011) for U-value calculation.

For hygrothermal simulation, however, the location of the material layers can have a significant impact. Therefore, Baker's model was modified for this case study, by using two stone layers with a mortar layer in between. (Figure 70) This model, although still very simple, represents more accurately the higher presence of mortar within the core of traditional stonewall construction. The material in the core is known in Ireland as the 'hearting' of the wall, and trimmings from the facing stones were commonly used for this purpose.

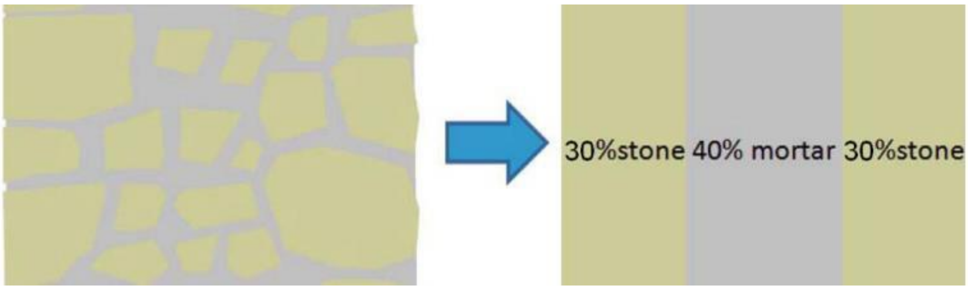


Figure 70 Simplified representation of a solid stone wall construction with a mortar core between two stone layers, as used for the hygrothermal assessments in this case study.

The mortar joints between the stones in the inner and outer portions of the wall will affect its hygrothermal performance also, as can the local presence of 'through stones' (stones that tie both leafs together by spanning the full width of construction). For some WUFI material data for bricks, the effect of the mortar is already factored into the hygrothermal values listed. Obviously, such data could also be created for stone masonry, but this not yet been done. Assessing inhomogeneous constructions, like a traditional stone wall, more accurately would require a two-dimensional numerical simulation, using software such as Delphin or WUFI 2D. While it would not be practical to use two-dimensional simulation in this way for every masonry wall, it is important at this early stage in the development of numerical hygrothermal assessment that the impact of these kinds of choices are tested. For what types of stones or bricks and for what shapes and thickness of joints must two-dimensional simulation be used? And when is the quicker, easier one-dimensional alternative acceptable? In time, guidance could be drawn up to reflect a large-scale sensitivity analysis of these kinds of issues. As part of the case study, one such comparative assessment of different ways of modelling a stone wall has been undertaken. (Section 5.3.2.3)

5.2.3.2 Material properties

Data selection

The wall to be assessed consists of sandstone bedded in lime mortar, with the masonry finished internally with lime plaster on timber laths. (The timber laths, surrounded by plaster on three sides, were ignored in the case study, for the sake of simplicity.)

Where properties for these materials were available in the WUFI material database, this data was used in the case study assessment. For the assessments under the Glaser method, additional data needed was taken from the standard *BS EN ISO 10456:2007 Building Materials and Products – Hygrothermal Properties*. (BSI, 2010) A complete set of the materials properties required hygrothermal simulation which can be difficult to source. The assessor often needs to use data from different sources and of different degrees of reliability.

In the following, the material properties for the base wall have been identified first. Those for the retrofit materials are discussed in Section 5.2.4.2. To allow easy comparison, all material properties used in the case study have also been assembled in one table in Appendix 4 Material properties used in the case study.

Sandstone

For the assessments under the Glaser method, the material properties listed for *Sandstone (silica)* in *BS EN ISO 10456:2007* (and also *in BS 5250:2011*) were used. For hygrothermal numerical simulation, the WUFI database was accessed. It lists nine types of sandstones, eight of which are German and one is Indian. Selected material properties of these stones are listed in Table 11.

As a *bracketing approach* (see Section 5.2.3.2) was considered advisable, two of the German sandstone types were selected that reflect the basic values of *Sandstone (silica)*: Baumberger and Obernkirchner sandstone. They will be referred to in the case study as Stones A and B respectively. Their properties are approximately mid-range in terms of the basic hygrothermal values for the German sandstones listed in the database, but vary significantly from each other in key hygrothermal functions, namely water absorption and moisture storage.

Stone type	**Use in case study**	**Density** [kg/m³]	**Porosity** [m³/m³]	**λ-value** [W/mK]	**µ-value** [-]
Rüthener	not used	1950	0.24	1.7	17
Baumberger	Stone A	1980	0.23	1.7	20
Cottaer	not used	2050	0.22	1.8	15
Ummendorfer	not used	2080	0.227	1.7	14
Sander	not used	2120	0.17	1.6	33
Obernkirchner	Stone B	2150	0.14	2.3	32
Worzeldorfer	not used	2263	0.13	1.8	26
Zeitzer	not used	2300	0.05	2.3	70
Average values		**2112**	**0.18**	**1.86**	**28**

Table 11 Material properties of the eight German sandstones listed in the WUFI database (in order of their density) and averaged values: the two stones used in the case study, Baumberger and Obernkirchner, have been highlighted.

Within the WUFI database, the moisture absorption characteristics of a material are described by its liquid transport coefficient and moisture storage function respectively. These two material functions are described for all eight sandstones in Figure 71, illustrating the wide range of values possible. The liquid transport coefficient for suction (left diagram in the figure) describes *how quickly* water is wicked into the masonry. Of the two stones chosen for the case study (dashed lines in the figure), Obernkirchner sandstone has a mid- to high absorption value, while Baumberger sandstone has a mid- to low absorption value. The moisture storage function (right diagram in the figure) indicates the relationship of water content and relative humidity. Again, the stones' performances vary significantly. At the same relative humidity, Baumberger sandstone stores significantly more water than Obernkirchner sandstone.

Of the two chosen stone types, Baumberger sandstone absorbs water more slowly, but can store larger water quantities. This make Obernkirchner sandstone more vulnerable to moisture-related deterioration if its surface is exposed, because it can become saturated quicker. (The significant impact that this wide range of hygrothermal values can have on modelling results has also been demonstrated by Baker et al. (2014), simulating three of these German sandstone types with WUFI.)

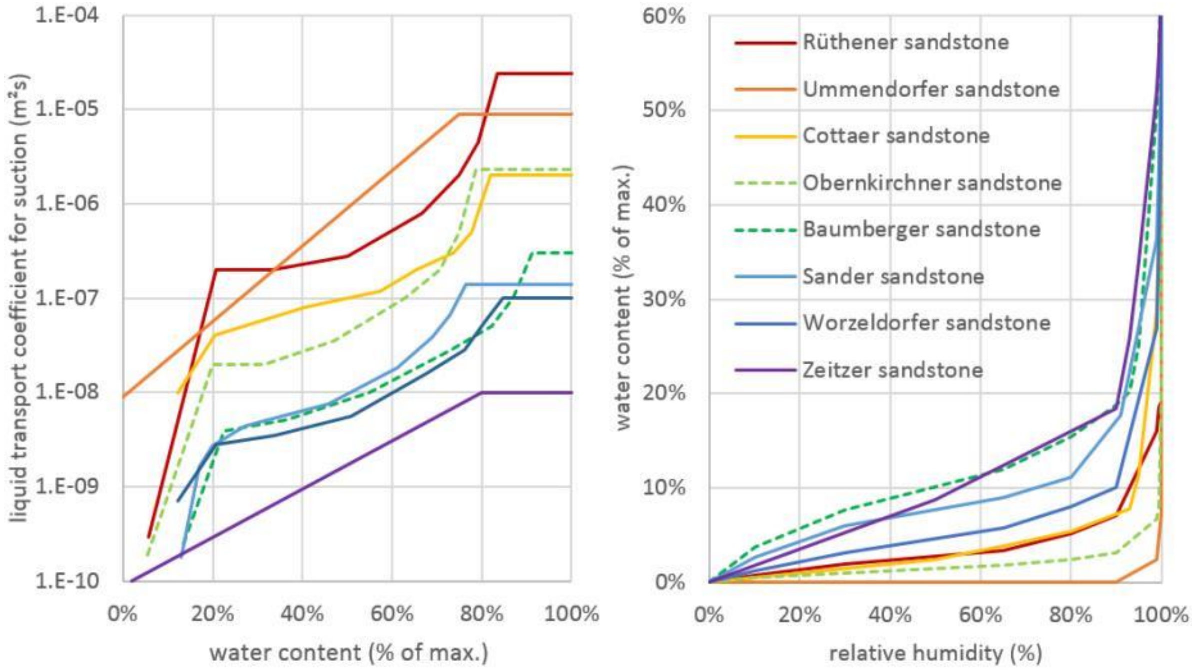


Figure 71 Capillary liquid transport (left) and moisture storage functions (right) of all German sandstones listed in the WUFI database.

In general, Stone A (Baumberger sandstone) has been used for case study assessments. Stone B (Obernkirchner sandstone) has been used in additional assessments to illustrate the impact of the different hygrothermal properties of the stones on the simulation results.

The properties used for the three 'stone types' are listed in Table 12.

Material properties		**Sandstone (silica)**	**Stone A (Baumberger)**	**Stone B (Obernkirchner)**
Bulk density	[kg/m³]	2600 BS	1980 WD	2150 WD
Porosity	[m³/m³]	n/a	0.23 WD	0.14 WD
Specific heat capacity	[J/(kg·K)]	1000 BS	850 WD	850 WD
Thermal conductivity	[W/(m·K)]	2.3 BS	1.7 WD	2.3 WD
Vapour diffusion resistance factor	[-]	30-40 BS	20 WD	32 WD
Free water saturation (100 % RH)	[kg/m³]	n/a	210 WD	110 WD
Liquid transport coefficient	[m²/s]	n/a	3 x 10^{-7} WD	2.3 x 10^{-6} WD

Data provenance: BS: *BS EN 10456* / WD: WUFI data

Table 12 Properties of stone, including data provenance

Mortars and plasters

For the mortar and render, the option *Lime Mortar, Fine* has been selected in the WUFI material database. For the lime plaster, *Lime* Plaster has been chosen. The relevant material properties are listed in Table 13. (In the case study, the plaster is referred to as 'lime plaster (general)' to distinguish it from a product used in the installation of the calcium silicate boards.)

Material properties		**Lime mortar (general)**	**Lime plaster (general)**
Bulk density	[kg/m^3]	1785 WD	1600 WD
Porosity	[m^3/m^3]	0.28 WD	0.3 WD
Specific heat capacity	[J/(kg·K)]	850 WD	850 WD
Thermal conductivity	[W/(m·K)]	0.7 WD	0.7 WD
Vapour diffusion resistance factor	[-]	15 WD	7 WD
Free water saturation (100 % RH)	[kg/m^3]	247.6 WD	250 WD
Liquid transport coefficient for suction at 100% RH	[m^2/s]	1.63 x 10^{-6} WD	1.5 x 10^{-7} WD

Data provenance: BS: *BS EN 10456* / WD: WUFI data

Table 13 Properties of mortar and plaster of base wall, including data provenance

Air cavities

Cavities can result from the creation of traditional plaster and lathe assemblies or from modern insulation and batten assemblies. These cavities are assumed to be air-filled and unvented. The 'material' properties used in the assessments for air are listed in Table 14.

Material properties		**Air**
Bulk density	[kg/m^3]	1.3 WD
Porosity	[m^3/m^3]	0.999 WD
Specific heat capacity	[J/(kg·K)]	1000 WD
Thermal conductivity	[W/(m·K)]	0.155§ WD
Vapour diffusion resistance factor	[-]	0.51 WD
Free water saturation (100 % RH)	[kg/m^3]	0 BS
Liquid transport coefficient	[m^2/s]	0 WD

Data provenance: BS: *BS EN 10456* / WD: WUFI data

§ for air cavities, an equivalent thermal conductivity is assumed to account for convective and radiative heat transfer

Table 14 Properties of air, including data provenance

5.2.4 Geometrical representation and material properties of retrofits

5.2.4.1 Geometrical representation

The retrofit of four insulation products is discussed in this case study. The products and their installation have has already discussed in the Section 5.1.3. Each retrofit measure consists of several materials, which are represented as vertical layers added to the inside surface of the base wall. Depending on the insulation product, the materials include insulation, plasters, plasterboards, adhesives, vapour barriers and air cavities. The geometrical models of the retrofitted base wall, as used in the case study assessments including material thicknesses, are described in Table 18.

5.2.4.2 Material properties

The properties of the materials used in the base wall have already been defined. The material properties of the retrofits are listed in the tables below, together with the data provenance. Table 15 lists the material properties for insulation, Table 16 those for vapour barriers and AVCLs and Table 17 those for adhesives and plasters. As before, the data chosen for the assessments is partly taken from the British Standard and partly from the WUFI database. A complete list of all material properties used in the case study is available in Appendix 4 Material properties used in the case study.

Material properties		**Cellulose fibres**	**Aerogel blanket**	**Phenolic foam boards**	**Calcium silicate boards**
Bulk density	[kg/m^3]	50 MD	146 WD	43 BS	222 MD
Porosity	[m^3/m^3]	0.95 MD	0.92 WD	0.95 WD	0.92 MD
Specific heat capacity	[J/(kg·K)]	2000 MD	1000 WD	1400 BS	1303 MD
Thermal conductivity	[W/(m·K)]	0.04 MD	0.014 WD	0.023 BS	0.057 MD
Vapour diffusion resistance factor	[-]	1.8 MD	4.7 WD	50 BS	5.4 MD
Free water saturation (100 % RH)	[kg/m^3]	426 WD	213 WD	0 WD	815 MD
Liquid transport coefficient	[m^2/s]	2.3×10^{-7} WD	1.3×10^{-11} WD	0 WD	4.9×10^{-6} MD

Data provenance: BS: *BS EN 10456* / MD: manufacturer’s data / WD: WUFI data

Table 15 Properties of the insulation, including data provenance

Material properties		**Intello membrane†**	**PE mem-brane†**	**PVC foil facing†**
Bulk density	[kg/m^3]	115 WD	130 WD	130 WD
Porosity	[m^3/m^3]	0.086 WD	0.001 WD	0.001 WD
Specific heat capacity	[J/(kg·K)]	2500 WD	2300 WD	2300 WD
Thermal conductivity	[W/(m·K)]	2.4 WD	2.3 WD	2.3 WD
Vapour diffusion resistance factor	[-]	26000 WD	50000 BS	20000 MD
Free water saturation (100 % RH)	[kg/m^3]	85 WD	0 WD	0 WD
Liquid transport coefficient	[m^2/s]	0 WD	0 WD	0 WD

Data provenance: BS: *BS EN 10456* / MD: manufacturer's data / WD: WUFI data

† Foils are listed as being 1 mm thick for the sake of simulation; the actual sd values are divided by 0.001 m.

Table 16 Properties of the vapour barriers and AVCLs, including data provenance

Material properties		**Adhesive (for CSB‡)**	**Gypsum plaster-board**	**Gypsum fibre-board**	**Lime plaster (general)**	**Lime plaster (for CSB‡)**
Bulk density	[kg/m^3]	1410 MD	700 BS	1153 WD	1600 BS	1600 MD
Porosity	[m^3/m^3]	0.468 MD	0.65 WD	0.52 WD	0.3 WD	0.3 MD
Specific heat capacity	[J/(kg·K)]	1059 MD	1000 BS	1200 WD	1000 BS	850 MD
Thermal conductivity	[W/(m·K)]	0.06 MD	0.21 BS	0.32 WD	0.8 BS	0.7 MD
Vapour diffusion resistance factor	[-]	22.89 MD	8.3 BS	16 WD	10 BS	7 MD
Free water saturation (100 % RH)	[kg/m^3]	280 MD	400 WD	502 WD	250 BS	250 MD
Liquid transport coefficient	[m^2/s]	7×10^{-10} MD	4.5×10^{-6} WD	1.1×10^{-9} WD	1.5×10^{-7} WD	1.5×10^{-7} MD

Data provenance: BS: *BS EN 10456* / MD: manufacturer's data / WD: WUFI data

Table 17 Properties of adhesives and plasters used in the installation of the retrofits, including data provenance

Wall part	**Layer**	**Material** including simulation alternatives		**Width**[*] [mm] Layer	Subtotal	Total
B. Base wall						
masonry	stone	Stone A	Stone B	180	600	650
	mortar core	lime mortar (general)		240		
	stone	Stone A		180		
original fin-ish	air	air (unvented cavity)		25	50	
	plaster	lime plaster, general use		25		
1. Base wall retrofitted with cellulose fibre insulation, sprayed						
retrofit	render	lime mortar (general)		20	20	20
masonry	stone	Stone A		180	600	669.3/755.5
	mortar core	lime mortar (general)		240		
	stone	Stone A		180		
retrofit	insulation	cellulose fibres, sprayed		55.8/142	69.3/155.5	
	AVCL	Intello membrane	PE membrane	1		
	plaster	gypsum plasterboard		12.5		
2. Base wall retrofitted with aerogel blanket insulating boards						
retrofit	render	lime mortar (general)	not applicable	20	20	20
masonry	stone	Stone A	Stone B	180	600	651/678.5
	mortar core	lime mortar (general)		240		
	stone	Stone A		180		
retrofit	air	air (unvented cavity)		25	51/78.5	
	insulation	aerogel blanket		16/43.5		
	plaster	gypsum plasterboard 2		10		

3. Base wall retrofitted with phenolic foam insulating boards

retrofit	render	lime mortar (general)	20	20	20
masonry	stone	Stone A	180	600	668.5/721
	mortar core	lime mortar (general)	240		
	stone	Stone A	180		
retrofit	air	air (unvented cavity)	25	68.5/121	
	Vapour barrier	PVC foil facing	1		
	insulation	phenolic foam board	30/82.5		
	plaster	gypsum plasterboard	12.5		

4. Base wall retrofitted with calcium silicate insulating boards

retrofit	render	lime mortar, general use	not applicable	20	20	20
masonry	stone	Stone A	Stone B	180	600	688
	mortar core	lime mortar (general)		150		
	stone	Stone A		200		
retrofit	plaster	adhesive		5	88	
	insulation	calcium silicate board		79		
	plaster	lime plaster		4		

Colour coding: grey shades: stone and mortar (bedding, pointing and rendering) / blue: air cavities / orange: vapour barrier or AVCL / green: plasters, including plasterboards and adhesive mortars / yellow: insulation

Hatched areas indicate material options used in the assessments for comparison

* Where two widths are stated, the first is used in assessments for target U-values of 0.5 W(K·m^2), the second for those of 0.25 W(K·m^2).

Table 18 Layers used in the simulation models for the base wall and the four retrofit measures

5.3 Hygrothermal assessments

5.3.1 Glaser method assessment of the base wall

For this case study, all interstitial condensation risk assessments using the Glaser method have been carried out using the software BuildDesk U 3.4 and following the procedure set out in *BS EN ISO 13788:2002*. Prior to assessment, the construction of the base wall has been entered into the software. (Figure 72)

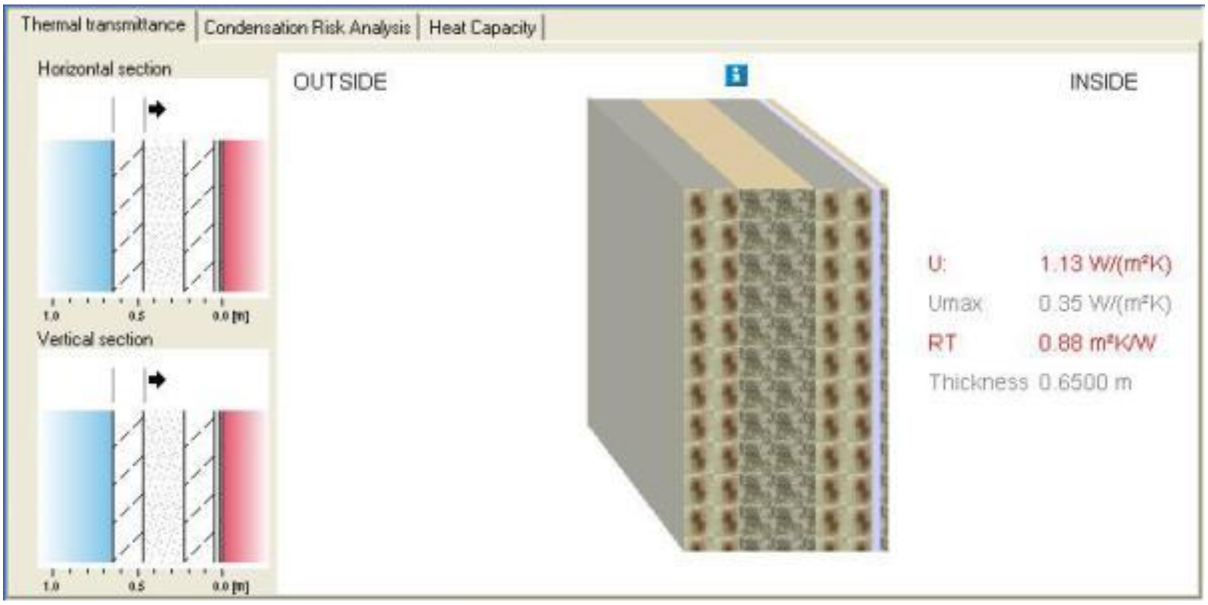


Figure 72 BuildDesk U screenshot showing model of the base wall with the following layers (starting on the left): stone, mortar core, stone, air space (light blue colour) and plaster

The software automatically determines the *critical point* for condensation to assess the interstitial condensation risk, based on surface temperature. Figure 73 shows the results of the assessment, using a *low occupancy* setting. With its visual interface, BuildDesk U is easy to use, displaying results clearly with either *green checkmarks* or *red crosses*. It is easy to understand why this assessment tool has been embraced by many in the construction industry.

The base wall was assessed for a twelve month period always starting in October. The assessment indicates that, during this period, interstitial or surface condensation is not a concern. Although the assessment shows that the interface between the mortar core layer and the outside stone layer would drop below the dewpoint during the winter months, the warmer spring temperatures allow this accumulated condensation to evaporate completely by March.

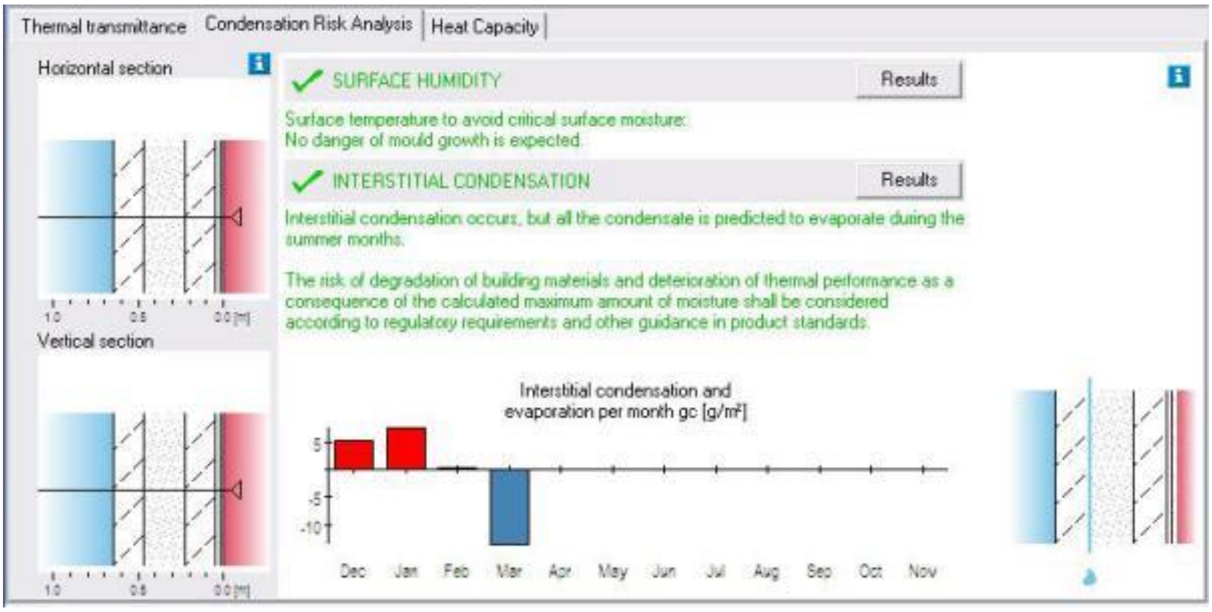


Figure 73 BuildDesk U screenshot showing the results from the Glaser method assessment of the base wall, for a *low occupancy* setting.

In Figure , under the green checkmark for interstitial condensation, the software states: “The risk of degradation of building materials and deterioration of thermal performance as a consequence of the calculated maximum amount of moisture shall be considered according to regulatory requirements and other guidance in product standards.” This statement is only displayed, when a month with moisture accumulation occurs. Changing the occupancy setting to *high* results in greater interstitial condensation. (Figure 74)

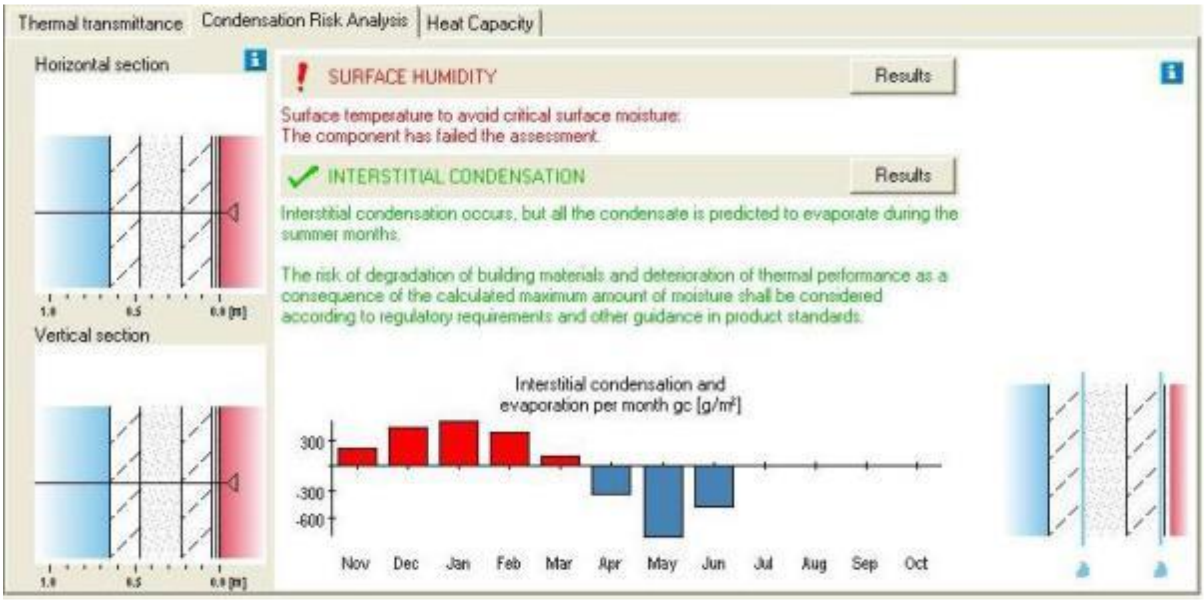


Figure 74 BuildDesk U screenshot showing the results from the Glaser method assessment of the base, for a *high occupancy* setting.

For this increased condensation to evaporate completely out will now take until June, instead of March. This time, the software displays a warning that surface condensation is likely and surface temperatures will need to be increased to avoid this.

Ground, rain or surface water transport do not feature in BuildDesk U, as the transport of liquid is not accounted for in Glaser method.

5.3.2 Numerical simulation assessment of the base wall

5.3.2.1 Humidity, moisture and temperature fluctuation

For this case study, all numerical simulations have been carried out using the software WUFI Pro 5.3. Similarly to BuildDesk U, the construction of the base wall should be entered into WUFI prior to simulation, using the simplified geometrical model described in the Section 5.2.3.1. (Figure 75)

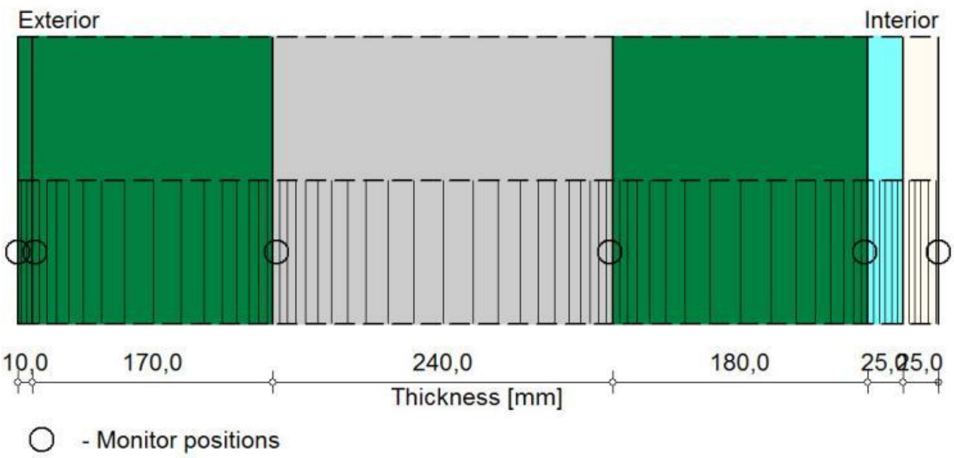


Figure 75 WUFI screenshot (excerpt) showing model of the base wall with the following layers (starting on the left): stone, mortar core, stone, air space (light blue colour) and plaster.

As with the Glaser method assessment, a first run of the numerical simulation indicates that the base wall is performing within usual parameters. (This includes a relative humidity of the room surface which is notably higher than the ambient relative humidity – a condition that could lead to surface condensate at thermal bridges if the room were regularly occupied, heated and moisture released.) Establishing a sufficiently accurate moisture content for wide masonry walls is critical at this stage as the annual fluctuation can take years to reach equilibrium, i.e. reach a steady annual performance cycle, if set at inaccurate levels initially. This is particularly the case if a vapour retarding insulation or membrane is included on the room side of the model. The simulation of the uninsulated wall was thus run for a period of 20 years. (The authors find that seven years is often an adequate length for solid walls, though one 900 mm wide concrete wall took 70 years to reach equilibrium.) (Figure 76)

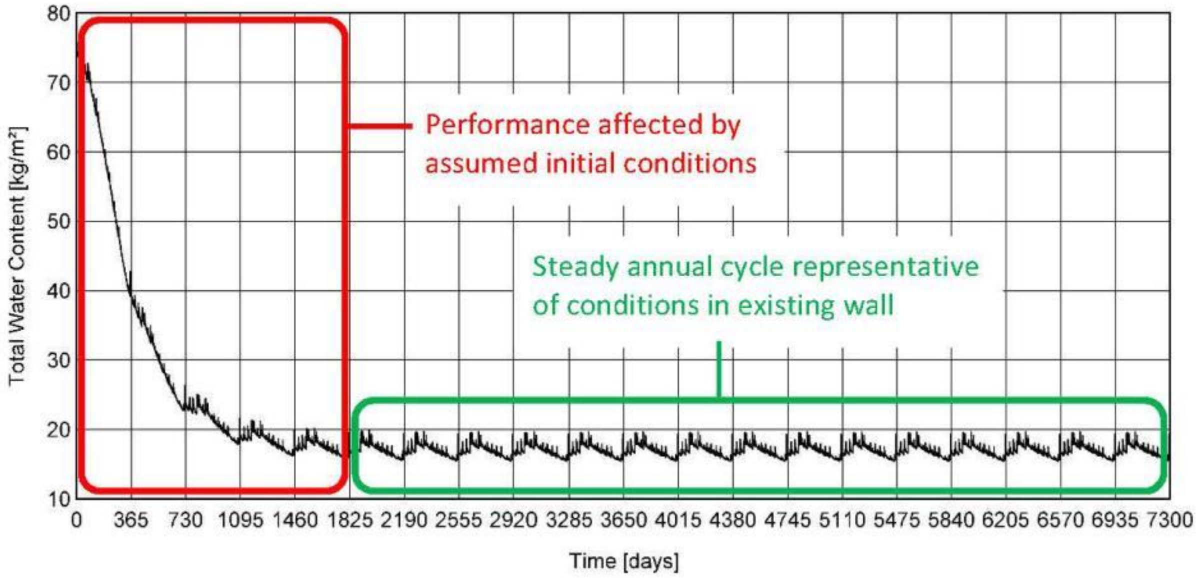


Figure 76 Total water content of base wall simulation with WUFI, for a 20 year simulation period (7300 days in total, with 365 days per year) to eliminate the influence of assumed initial moisture in the existing construction.

Once the construction reaches equilibrium, it is possible to compare the results of the Glaser method assessment to the annual performance calculated with the numerical simulation. The Glaser method predicted condensation, i.e. 100 % RH, at the interface between the mortar core layer and the outside stone layer for three months of the year when a *low occupancy* setting is selected, and for five months when *high occupancy* is used. A *normal moisture load* was selected in WUFI, in accordance with recommendations for dwellings with ventilation systems. (Fraunhofer IBP, 2010) Figure 77 shows the temperature and relative humidity at this location, based on the numerical simulation for one year.

The numerical simulation results show that the relative humidity at this location of the wall is extremely high throughout the year (see green line in the figure). However, the high hygroscopicity of the mortar and sandstone ensures that vapour is absorbed as liquid by the pore walls of the materials before the relative humidity rises high enough for condensation to occur. Capillary action transports liquid away from this location, redistributing it within the material. This reduces the amount of vapour present and maintains the relative humidity level below 100 %.

Figure 78 shows the fluctuation of the wall's moisture content during the cycle of one year, demonstrating that the wall is actually maintaining various amounts of moisture throughout this period. Whereas the Glaser method assessment does not account for the wall's moisture content, other than vapour and condensed vapour transporting through it, the hygrothermal simulation shows a varying moisture content due to several moisture transport mechanisms that is quite close to what happens in reality.

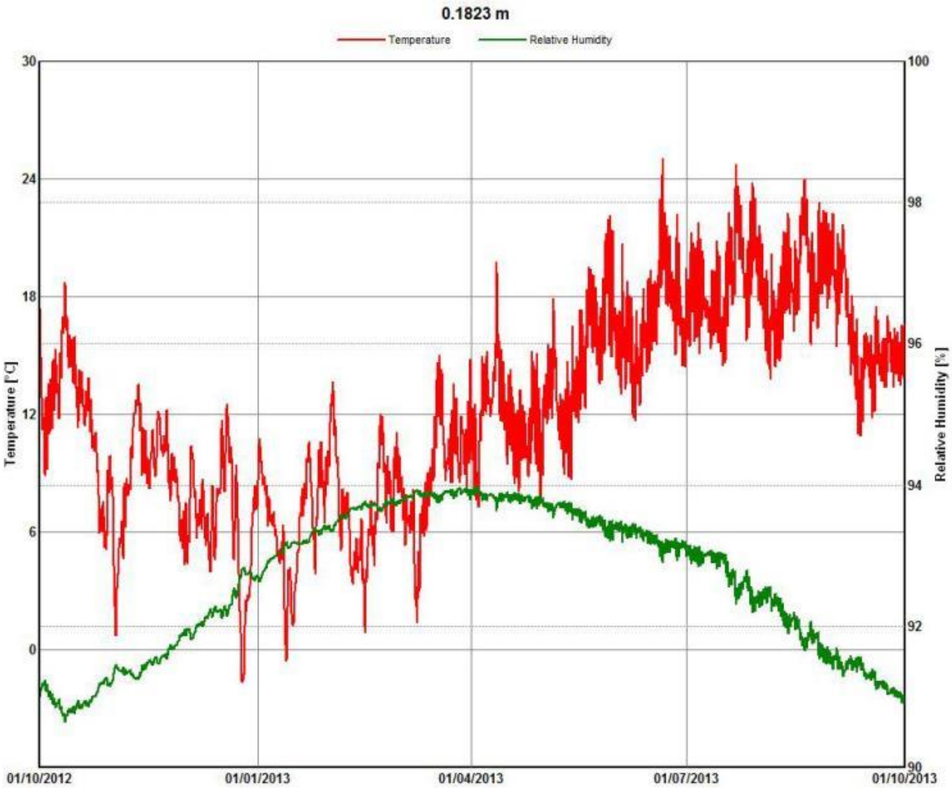


Figure 77 Temperature and relative humidity, as simulated with WUFI for one year, at the interface between the external stone and mortar core layers.

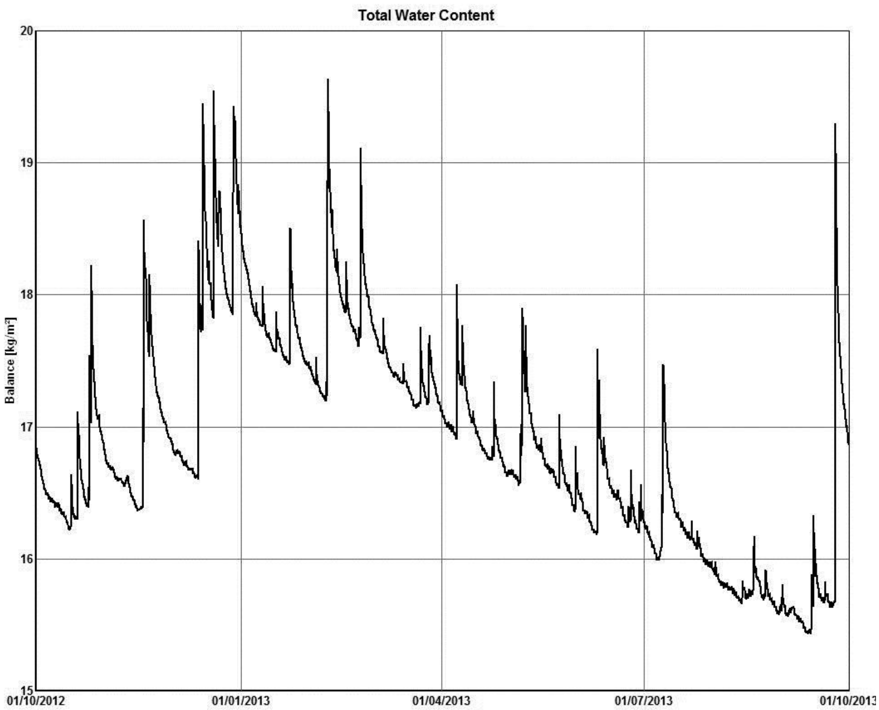


Figure 78 Fluctuation of total water content of the base wall, as simulated with WUFI for the period of one year.

5.3.2.2 Water content and relative humidity

Using WUFI to generate a wall profile can paint a clearer picture of what is happening in the wall hygrothermally. Such a profile, a snapshot in time, is illustrated in Figure 79, showing fluctuations of temperature, relative humidity and water content simultaneously. The outer portion of the outside stone layer (left in the diagram) shows significant variations in water content. (See the light blue shadow tracing the water content levels of the annual cycle)

If the water absorption ability of the wall surface were reduced or inhibited, e.g. by a good render, the water content at this location would also be reduced. The profile graph of the relative humidity continues across all material layers of the wall in an arc, smoothly dropping to the inside. However, the figure also shows a striking drop in the water content for the mortar core layer. The reason for this is that the mortar has a lower moisture storage function, which means that, for the same relative humidity, it would store less water.

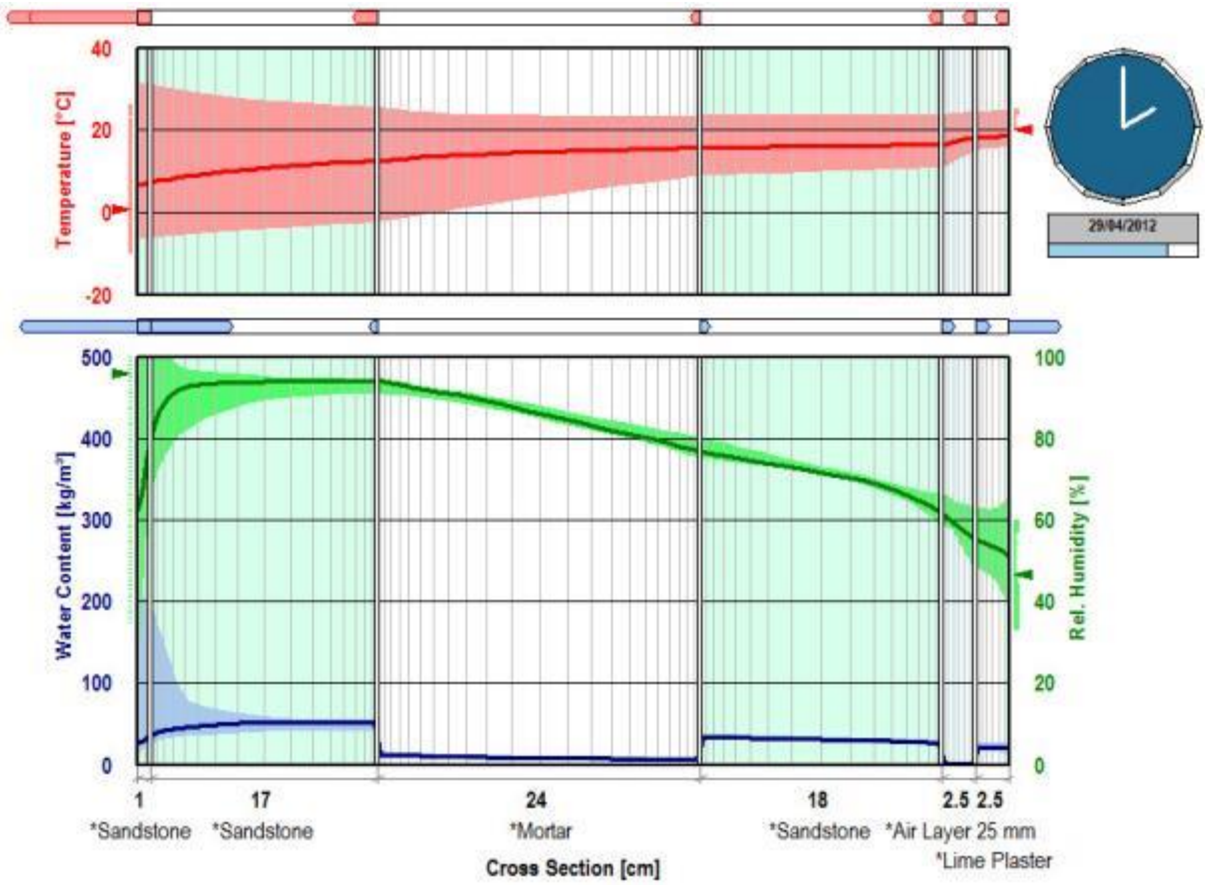


Figure 79 WUFI screenshot showing relative humidity, temperature and water content profiles of the base wall, taken as a snapshot at a single one-hour time-step in April.

The majority of the rain water is retained within the outer portion of the outside stone layer and allowed to evaporate from the external wall surface. The small quantity of moisture that does move through the entire thickness of the masonry to the inside (during which time it may change state more than once) diffuses through the final few millimetres of the room surface and is taken away by air currents in the room. While this is only a small portion of the total moisture content, it is important to acknowledge its existence. When internal insulation retrofits prevent roomside moisture evaporation and cool the masonry, the relative humidity and, as consequence, moisture content will rise, as will be demonstrated in Section 5.3.

Figure 80 is of the same snapshot in time as the previous figure, but shows the wall's vapour pressure profile (coloured in magenta) instead of relative humidity. While the internal vapour pressure (ca. 11 hPa) is indeed higher than the external pressure (ca. 9 hPa), the pressure is highest in the centre of the wall (ca. 13 hPa). Therefore, rather than a vapour pressure differential driving accumulated vapour through the wall from the interior to the exterior, as assumed in the Glaser method, the differential here is actually driving vapour out of the wall in both directions.

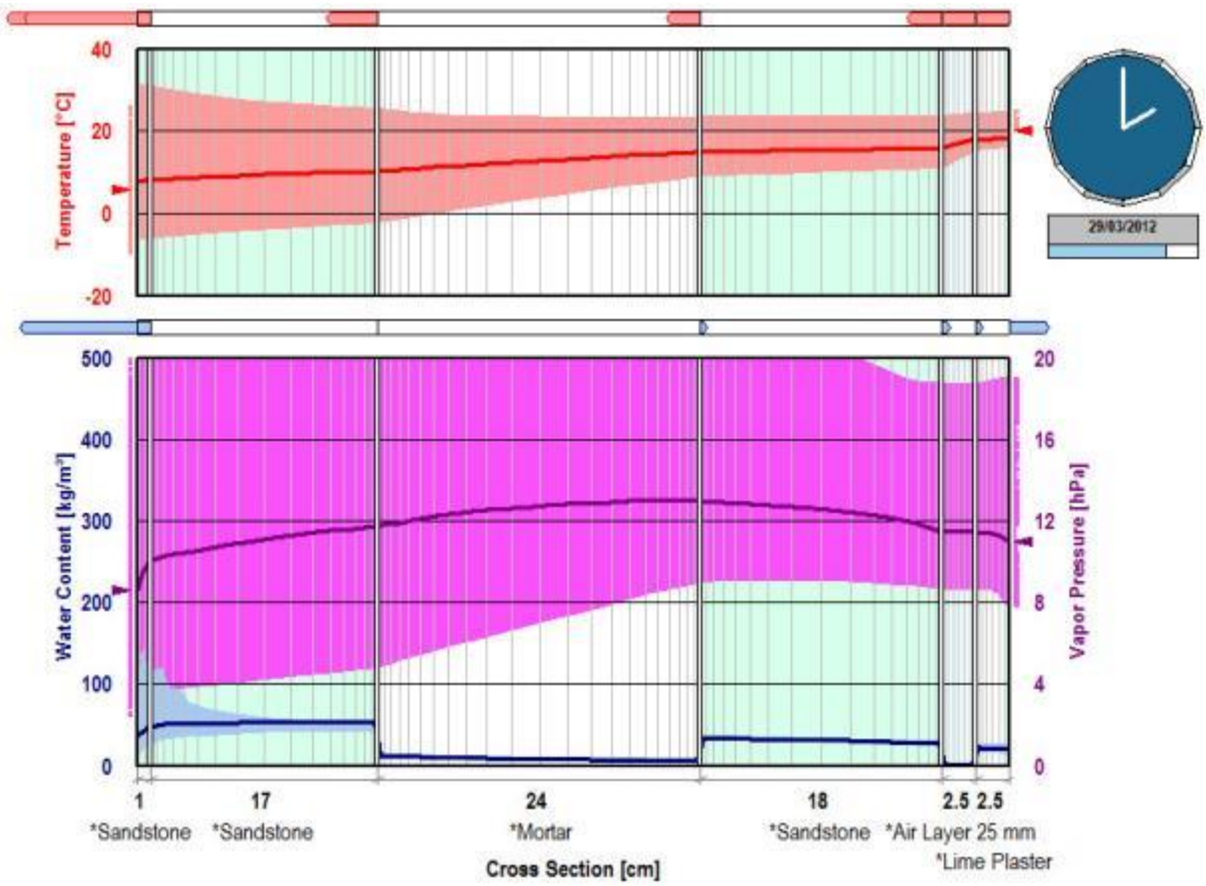


Figure 80 WUFI screenshot showing temperature, water content and vapour pressure profiles of the base wall, taken as a snapshot at a single one-hour time-step in April.

This phenomenon of centre-of-wall vapour pressure exceeding both the external and internal vapour pressures occurs for most of the year. Figure 81 compares the vapour pressure in the wall centre to that at the external and internal wall surfaces. For more than 80 % of the year the centre of this wall has the highest vapour pressure and is therefore driving vapour outwards in both directions. This is contrary to the general perception in the construction industry that vapour moves outwards only.

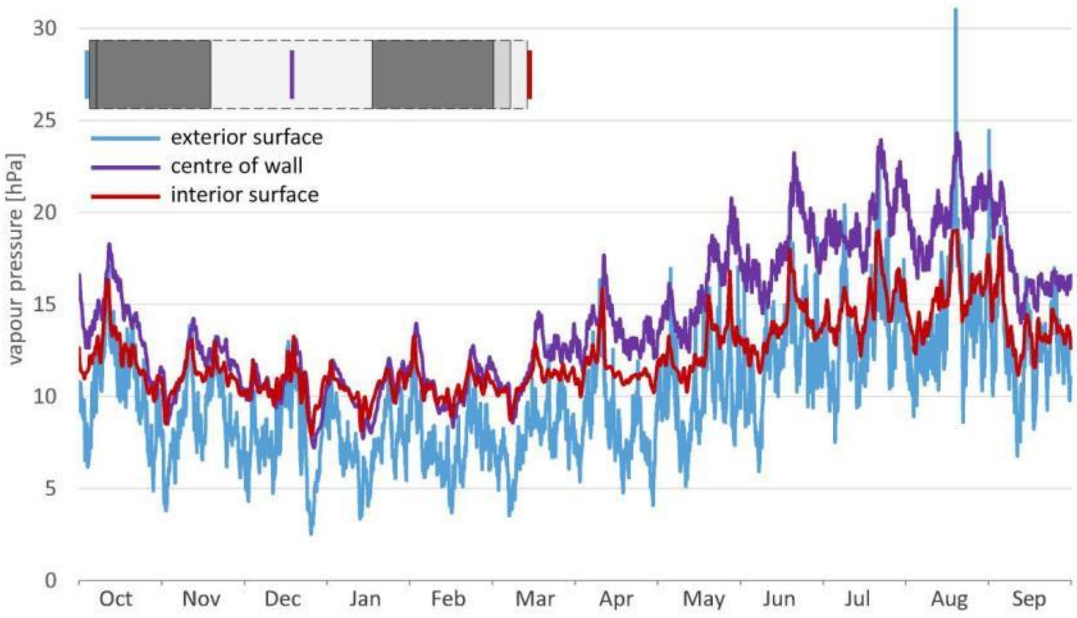


Figure 81 Vapour pressures at the exterior and interior surfaces of the wall and at the centre of its mortar core layer

5.3.2.3 Validity of the one-dimensional model

The numerical simulations in this case study are based on a one-dimensional model of a wall with a mortar core layer. The stone and mortar chosen for the assessment have distinctly different moisture storage properties. However, the amount of moisture that these materials can store also depends on how easily water can be redistributed through capillary action. It was shown that in a one-dimensional simulation, the outer portion of the external stone layer acts as a continuous buffer that slows down the redistribution of moisture to the mortar core layer. This model gives an apparent hygrothermal advantage that may not be realistic, because, in reality, each stone is surrounded by mortar. These mortar joints form a network, which also connects the mortar core to the outdoor environment.

In order to assess the validity of the one-dimensional approach, used in this case study, three different wall models will be compared with increasing levels of accuracy. (Figure 82)

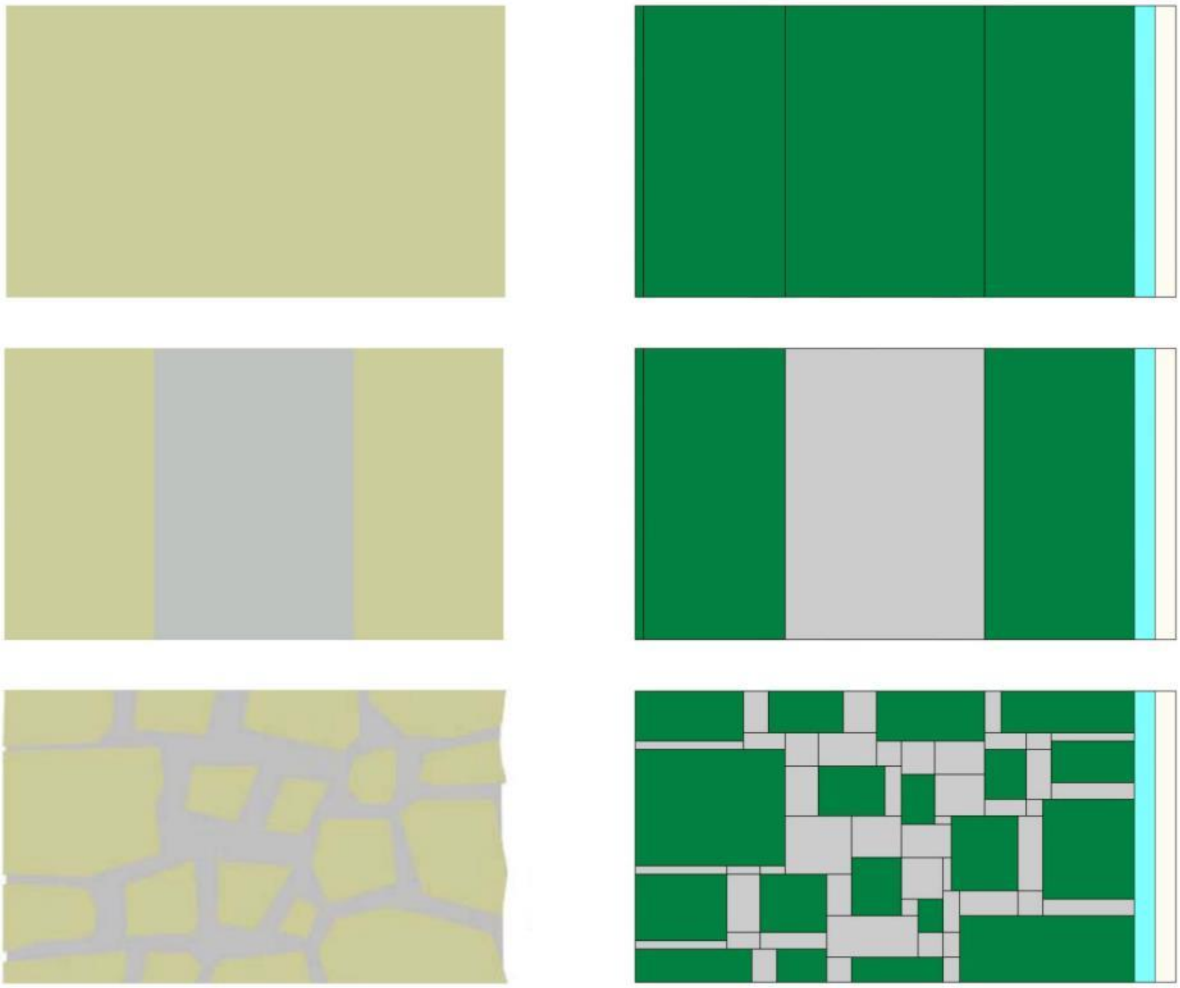


Figure 82 Three conceptual geometrical models of the existing wall and their translation into WUFI simulation models, with increasing levels of accuracy starting at the top (compare to Figure 69)

The models are:

- one-dimensional model of a wall, disregarding any mortar
- one-dimensional model of a wall with a mortar core layer, but with no mortar joints (which is the base wall model used in this case study)
- two-dimensional model with mortar joints and a mortar core

Figure 83 shows the water content profiles for these three models. Figure 84 shows their relative humidity profiles. To avoid convergence errors in the two-dimensional simulation, the moisture storage property of the mortar has been approximated. For the sake of consistency, the same value has been applied to the one-dimensional model with a mortar core layer.

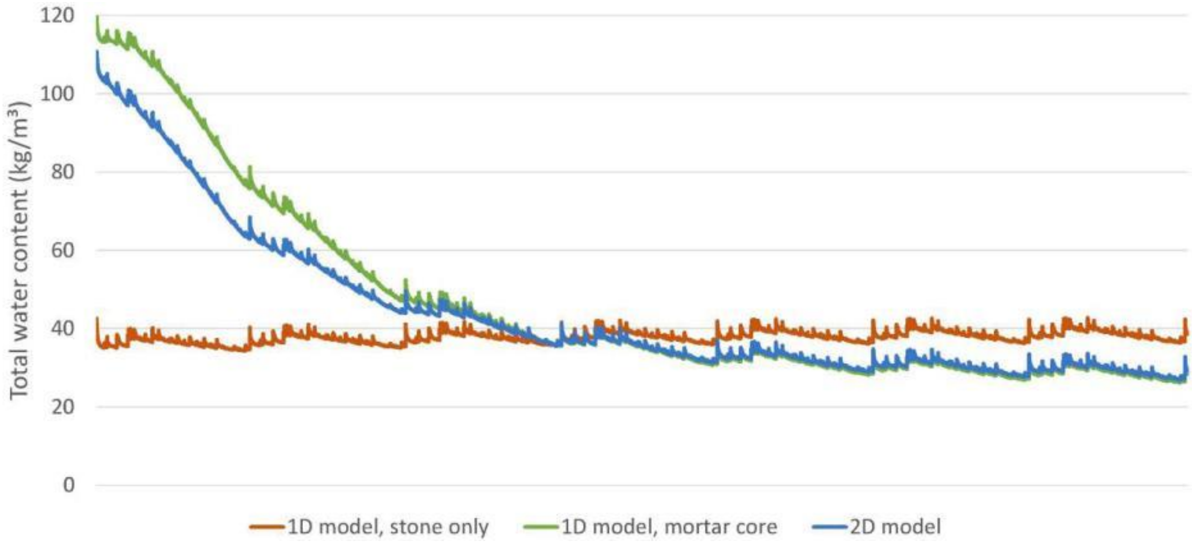


Figure 83 Total water content of the three wall models, generated with WUFI for a seven year simulation period

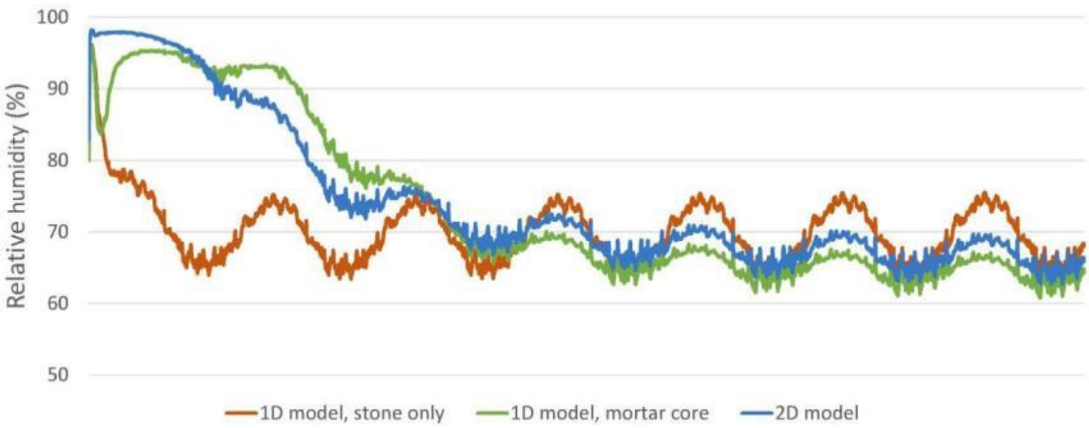


Figure 84 Relative humidity of the three wall models, at the interior wall surface (plaster surface), generated with WUFI for a seven year simulation period

The comparison of the simulations shows that the one-dimensional model with the mortar core remains close to the two-dimensional model: both curves follow closely a similar pattern, and, once a steady annual cycle is reached, variations in values remain within an acceptable tolerance. Comparing the two-dimensional and one-dimensional with mortar core models, the maximum difference in water content is less than 1 kg/m³ and that of the relative humidity less than 3%. On this basis, the one-dimensional model with three layers – stone, mortar core, stone– can be considered sufficiently accurate to allow the use of one-dimensional simulation for this case study.

5.3.3 Glaser method assessments of the retrofitted wall

Thirteen different scenarios were assessed in the case study, for combinations of two target U-values and the optional use of AVCLs. (Table 6-3) As with the Glaser method assessment of the base wall, a one-year period was used. The occupancy was set to *low*. Layers of high thermal resistance, i.e. insulants were sub-divided into equal thickness with thermal resistance not greater than 0.25 $(m^2K)/W$, as per ISO standard.

The results of the assessments are presented in Table 19. This shows which retrofit scenarios have passed the checks for interstitial and/or surface condensation, together with the maximum moisture accumulated at any time in the year, the final figure accumulated at the end of the twelfth month, i.e. September, and how many months are condensate free.

Retrofit product	**Target U-value** W/(m²·K)	**AVCL**	**Scenario ID**	**Condensation risk** surface	interstitial	**Accumulated condensate** months free (-)	max. (g/m²)	final (g/m²)
cellulose fibres, sprayed	0.50	none	**1.1.1**	√	X	0	4042	1325
		Intello	**1.1.2**	√	√	11	1	0
		PE	**1.1.3**	√	√	12	0	0
	0.25	none	**1.2.1**	√	X	0	3372	2450
		Intello	**1.2.2**	√	√	5	34	0
		PE	**1.2.3**	√	√	12	0	0
aerogel blankets	0.50	none	**2.1.1**	√	X	0	2889	543
	0.25	none	**2.2.1**	√	X	0	3084	2115
phenolic foam boards	0.50	none	**3.1.1**	√	√	1	408	0
		foil *	**3.1.2**	√	√	4	254	0
	0.25	none	**3.2.1**	√	X	0	227	66
		foil *	**3.2.2**	√	X	0	231	95
calcium silicate boards	0.50	none	**4.1.1**	√	X	0	1003	58

Table 19 Results of Glaser method assessments for all retrofit scenarios, with those passing both interstitial and surface condensation checks highlighted in green. (In actual construction, where a foil is used facing a void the effective U-value would be slightly lower than that listed, due to reduced radiant heat transfer within the void. This would only have a minimal effect in the overall hygrothermal performance of the wall, and for the sake of simplicity, the U-value is shown unchanged.)

Only six of the thirteen assessments pass the checks for both interstitial and surface condensation risks. For all other seven scenarios, the Glaser method assessment calculates an accumulation of moisture, albeit to different degrees. Only the cellulose fibre retrofit with an AVCL passes for both target U-values. The phenolic foam board retrofit passes for the higher, less challenging, U-value level, whether a foil membrane is present or not, but fails at the lower, more challenging, level even when a foil membrane is used: this is explored below. The aerogel blanket retrofits, which do not feature vapour resistant barriers, fail the interstitial condensation risk assessment for both U-value levels, but interestingly the calcium silicate board, which also has no membrane, dries completely by the tenth month despite registering quite a high amount interstitial condensate in March.

As three key tenets of the Glaser method are that:

1. The only form of moisture considered is vapour that has condensed at 100 % RH.
2. This vapour is either from the room or the external environment.
3. Each month's calculation uses an interior and exterior set of temperature and relative humidity values.

It is not surprising that the Glaser method always shows vapour moving *from* the room in the temperate conditions of Maritime Europe, and that vapour resisting layers always reduce the condensation risk in assessments. As will be seen below, the presence of a vapour resisting layer is not enough, it must have sufficient vapour resistance and be in the right location too. Nonetheless retrofitting a solid stone wall without a vapour resistant layer(s) will always appear to present unacceptable risks when assessed using the Glaser method.

In these assessments, the location at which the dewpoint occurs is usually the back of the insulation. Only in the case of calcium silicate do two dewpoint conditions occur at one time (the interface of original plaster and masonry and the interface of original plaster and insulation). If the insulation is permeable, such as aerogel blankets or cellulose fibres, vapour loads at this location will relate to that of the indoor space. The more vapour resistant the applied assembly is made, the less vapour reaches the critical location from the room.

The phenolic foam board retrofits (scenarios 3.1.1 to 3.2.2) demonstrate the importance of knowing the materials used. Phenolic foam has a high vapour resistance, compared to the other insulations used in the case study. This makes each part of it behave like a weak vapour barrier or retarder, even when no foil is incorporated. (In reality phenolic foam board is always sandwiched between either fibreglass or foil facings as part of its manufacturing process. To give a better thermal resistance to the void the composite board often has the following layers from inside to outside: plasterboard on fibreglass facing, on phenolic foam, on foil facing). To achieve the less challenging target U-value (0.5 W/(m^2·K)), a retrofit with a thickness of 30 mm foam insulation is required. This would result in the most vapour resistant layer in the retrofitted masonry wall being the foam with an s_d-value of 1.5 m (see scenario 3.1.1 in Table 17). If foil is used, it instead becomes the most vapour resistant layer with an s_d-value of 20 m (scenario 3.1.2), 13 times more vapour resistant than the foam board alone. For the more challenging target U-value (0.25 W/(m^2·K)), 83 mm of phenolic foam is required with an s_d-values of 4.15 (scenario 3.2.1). The foil in scenario 3.2.2 is now only 4.5 times more vapour resistant than this thicker foam board but the air cavity and wall behind are much colder.

In the Glaser Method assessment the phenolic foam retrofit without foil and a U-value of 0.5 W/m^{2}K (scenario 3.1.1) shows 408 g/m^2 of moisture forming on the face of the original plaster in the six months up to March. (Figure 85) But the steadily rising external temperatures after that month increases the amount of vapour capable of being held in the air at the critical point, i.e. raises the saturation vapour pressure, enabling evaporation till the point when condensate has disappeared. In scenario 3.1.2 the dewpoint temperature, the temperature at which 100 % RH occurs, is still at the cool void-plaster interface, but the use of a foil facing causes condensate to form within the insulation on the foil's warm side.

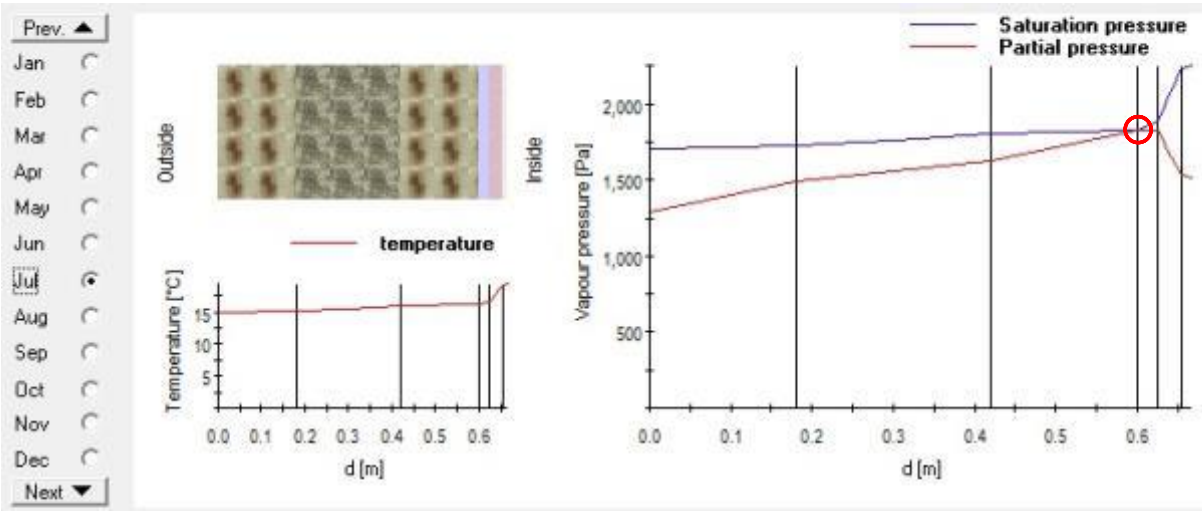


Figure 85 A partial screen shot from BuildDesk U showing the outputs of the July calculations of scenario 3.1.1 graphically, with the point of condensation circled

The next two scenarios (3.2.1 and 3.2.2) are primarily different because the void and original plaster behind the increased insulation are now significantly closer to external temperatures than before resulting in higher relative humidity there. However, as before, the use of foil moves the point of condensate from the void-plaster interface (227 g/m^2 in scenario 3.2.1) to the foil-insulation interface (231 g/m^2 in scenario 3.2.2). (Figure 86) It may be suggested that condensate forming within a non-hygroscopic insulant in this way is a sign of bad design: The most vapour tight layer should always be on the warm side of an insulant to protect it.

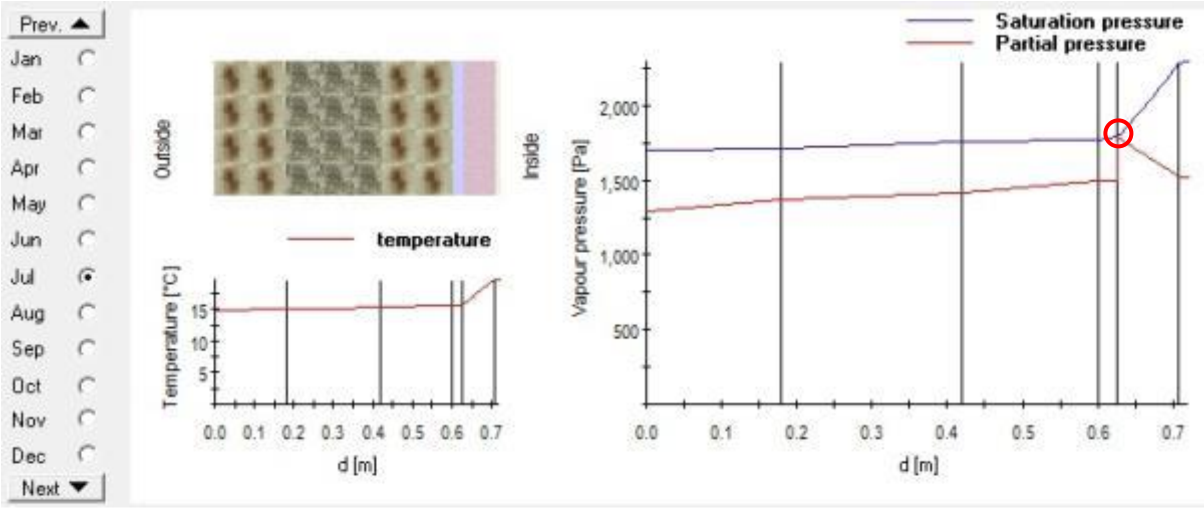


Figure 86 A partial screen shot from BuildDesk U showing the outputs of the July calculations of scenario 3.2.2 graphically, with the point of condensation circled

Calcium silicate assembly provides another interesting case: despite having no evident vapour barrier and being very vapour permeable it performs surprisingly well in the Glaser method. The largest moisture accumulation at the insulation-original plaster interface is 1,003 g/m^2 and 336 g/m^2 at the masonry-original plaster interface yet by the end of the tenth month (July) all dew has evaporated from the first interface and only 58 g/m^2 remains at the second by the end. Two reasons are proposed to explain this: firstly the new wet plaster finish facing the room acts as a vapour retarder reducing the amount of vapour entering the assembly, and secondly the area on which dew forms is far larger meaning that evaporative drying can occur more effectively once external temperatures raise the saturation vapour pressure sufficiently at this point. (Figure 87)

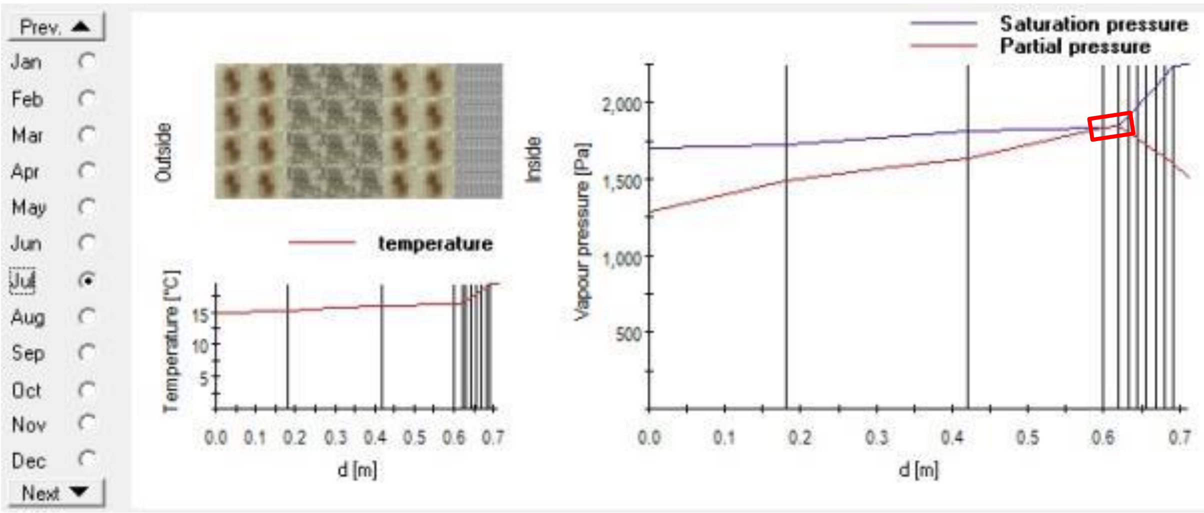


Figure 87 A partial screen shot from BuildDesk U showing the outputs of the July calculations of scenario 4.1.1 graphically, with the line of condensation marked

Accepting the different but interesting cases of calcium silicate and phenolic foam assemblies, the vapour permeable insulation strategies (without membranes) register the greatest moisture accumulation after twelve months, ranging from 543 to 2,450 g/m^2. This is not surprising. As a general rule, Glaser method assessments will give positive results to any form of construction with a high enough vapour resistance to its room side. For completeness, it should again be noted that vapour diffusion is the only moisture transport allowed for in the Glaser method: short term events like driving rain, freeze-thaw cycles and reverse diffusion (the reversal of vapour diffusion during periods when radiative heat gain on the wall surface raises temperature above the room) are not accounted for in Glaser method. A full exploration of the limitations is discussed in Section 4.2.1.

5.3.4 Numerical simulation assessment of the retrofitted wall

5.3.4.1 Impacts of internal insulation retrofits

Relative humidity as an indicator for risk

Numerical simulation assessments were undertaken for all 13 retrofit scenarios. In numerical simulation wall constructions should be simulated until they reach equilibrium or fail unquestionably. While three years is normally enough time for equilibrium to be reached for a lightweight structure, several decades might be required for an especially thick masonry wall. All cases discussed below have been simulated for fifteen years, though only six or eleven years are shown in the diagrams, depending on the length of time required to reach equilibrium. To accurately reflect the moisture content in the existing wall, the initial moisture content profile for the retrofit simulations was the final (moisture) profile obtained from the base wall simulations after equilibrium was reached.

In the following sections, the results from the simulations will be described and discussed, assessing relative humidity levels at the interface between insulation at masonry. In numerical simulation, there is recognition that the full hygroscopic characteristics of the materials generally prevents condensation forming at this critical location. However, high relative humidity levels can equally lead to mould growth or moisture-related damage. Relative humidity levels of 80 % and 95 % RH will be presented as appropriate in the discussion of different simulation results. (Section 3.2.2.1)

Figure 88 describes the changes of the relative humidities over time for all 13 retrofit scenarios. For these assessments, Stone A was used as material for both stone layers.

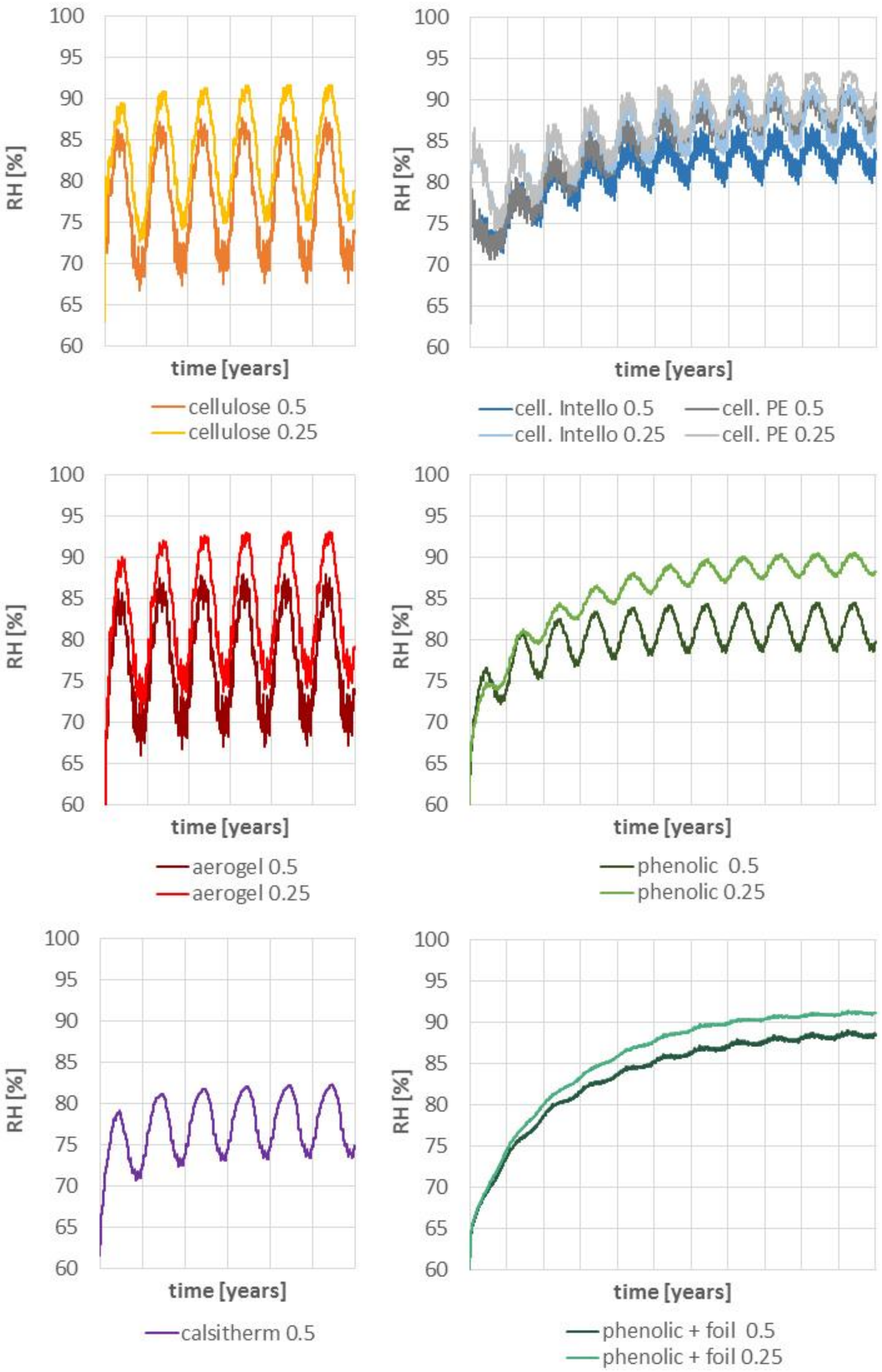


Figure 88 Relative humidity levels for the different retrofit options at the condensation critical location, namely the insulation-masonry interface, generated with WU-FI using *Stone A* (The numbers behind the materials refer to the target U-values of 0.25 or 0.5 W/(m^2·K).)

The first observation to note is that, in all assessments, relative humidity rises due to a colder original substrate after internal insulation is applied. This increase is not necessarily a sign of failure, as long as an increase in humidity eventually reaches an equilibrium within acceptable conditions. The key for assessing suitability is to establish how much RH increases and what the implications of the new conditions could be. With regard to reaching equilibrium, the permeable retrofit options (cellulose fibres, aerogel blankets and calcium silicate boards –all without AVCLs– shown on left side of Figure 88) are the quickest in reaching a steady annual cycle. The more impermeable options (cellulose fibres with AVCLs and the phenolic foam boards shown on right side of figure) take longer to reach equilibrium.

Cellulose fibre retrofits without AVCL

For the cellulose fibre retrofit without AVCL (scenarios 1.1.1 and 1.2.1), Figure 88 shows that the relative humidity levels immediately jump by about 10 % and, thereafter, fluctuate annually between 68 to 88 % for scenario 1.1.1 and 75 to 92% for scenario 1.2.1, i.e. respectively for the less and more challenging target U-value scenarios. This jump is associated with the immediate drop in temperature of the insulated wall. Additionally, as the cellulose fibres are *wet applied* they contribute a certain amount of moisture to the wall's overall moisture content. However, because the cellulose fibre retrofit is highly permeable, this initial moisture content diffuses easily out to the room, thereby having little to no impact on the wall's moisture performance long-term. The ease of diffusion allows the vapour pressure at the insulation-masonry interface to remain close to the indoor vapour pressure. The relative humidity at the insulation-masonry interface varies seasonally, as indoor environment changes. However, year-on-year, there is only a small net increase in relative humidity, which equilibrates in the third simulation year. The fully adhered nature of the insulation retrofit ensures that air gaps at the insulation-wall junction and air paths to that area are unlikely. As the elimination of air at this junction is a key criterion of the WTA it may give an assessor some latitude in deciding whether this is an acceptable insulation strategy or not.

Figure 89 shows, for the seventh simulation year, the seasonal variation in the relative humidities of the indoor air, of four of the six cellulose fibre retrofit options at the insulation-masonry interface and of the base wall at the same location. For the cellulose fibre retrofits without AVCL (scenarios 1.1.1 and 1.2.1), the humidity fluctuations are obviously more dramatic during wintertime, the more the wall is insulated internally. This is almost entirely due to the temperature variation at the insulation-masonry interface, compared to the relatively stable indoor air temperature. Compensating for these temperature differences, the actual moisture contents are quite similar. This means that the liquid water within the wall is able to evaporate and then diffuse, with relative ease, through the insulation out into the room, similar to the performance of the base wall. Moisture is therefore not accumulating at the critical location. This is confirmed by the observation that the oscillations in relative humidity at this location, for both the base wall and the wall retrofitted with cellulose fibres without AVCL, closely respond to the internal humidity during summertime, in terms of locations of peaks and troughs, when external and internal temperatures are also closest.

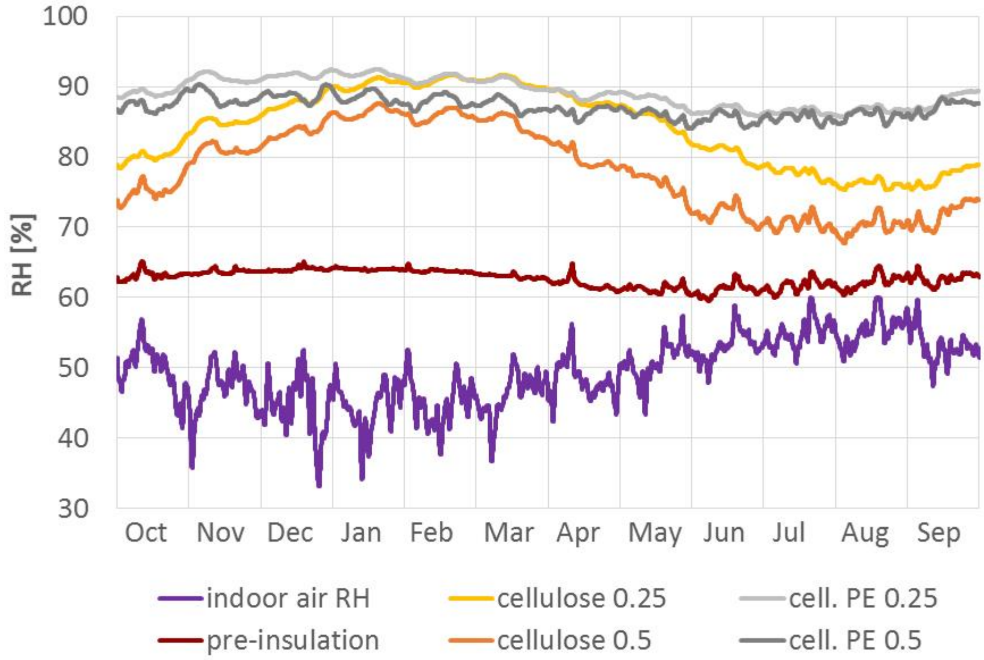


Figure 89 Relative humidity of indoor air and at the insulation-masonry interface prior to retrofit and with four different cellulose fibre retrofit options installed, for the seventh simulation year

Cellulose fibre retrofits with AVCL

In Figure 88, the graphs for cellulose fibre retrofits without an AVCL (top left diagram) and with AVCLs (top right diagram), show how the addition of AVCLs changes the performance considerably. Whereas the relative humidities fluctuate annually between 65 to 95 % when no AVCL is used, the lower limit of the annual fluctuations eventually reaches more than 80 % with an Intello (variable diffusion) membrane (scenarios 1.1.2 and 1.2.2) and more than 85 % with a PE (fixed diffusion) membrane (scenarios 1.1.3 and 1.2.3). (The graphs for the PE membrane retrofits are also shown in Figure 89).

With regard to the 80 % threshold, whereas the retrofits without AVCL exceeds this threshold only temporarily, those with AVCLs eventually exceed the threshold consistently all year round. This means that the AVCL retrofits result in moisture accumulation above the threshold long-term. These retrofits, therefore, have the potential to cause moisture-related damage over time. It should be noted that the performance of the Intello and PE membranes yield very similar results for this particular case. The variable diffusion characteristics of Intello are less advantageous than in lightweight construction, due to the large quantities of moisture absorbed by the masonry (requiring a constantly low vapour resistance to enable drying towards the room), and the comparatively much weaker reverse diffusion effect due to the thermal mass of the substrate. This shows that understanding the physical context is important to benefit from the advantages of variable diffusion membranes.

Aerogel blanket retrofits

For the aerogel blanket retrofits (scenarios 2.1.1 and 2.1.2), Figure 88 shows (in the mid-left diagram) that the annual oscillation in relative humidity is very similar to those of the cellulose fibre retrofit without AVCL (top left diagram). This is to be expected, as both retrofit products are similarly vapour permeable. Again relative humidity fluctuates with the seasonal variations in the indoor environment. Liquid water, moving inward, evaporates within the masonry's pore structure, eventually diffusing through the insulation back into the room. Although the 80 % threshold is exceeded by both retrofit options, this only occurs temporarily and not for prolonged periods of time. Any moisture accumulating at some point in time, dries out again during the annual cycle. The manufacturer has informed the authors that this system can be supplied fully bonded to the wall or as a battened system (as used here). There are implications for the threshold relative humidity. Fully bonding the system would be considered favourably using WTA criteria (see Clarification on 95 % RH threshold, Section 3.2.2.1).

Phenolic foam board retrofit

For the phenolic foam retrofits, Figure 88 (middle and bottom right diagrams) shows that the relative humidities at the insulation-masonry interface rise more slowly and for a longer period. This can be said equally of the retrofits with a foil vapour barrier (mid-right diagram, scenarios 3.1.2 and 3.2.2) and those without a foil vapour barrier (bottom right diagram; scenarios 3.1.1 and 3.2.1). Because phenolic foam is not hygroscopic, it has no initial moisture content when installed. However, at the void-masonry interface, relative humidity increases rapidly over the first six months after installation. From that point onward, there are annual humidity fluctuations, due to the wall's seasonal temperature changes. The overall trend, however, is a continual increase in relative humidity. This is because, like with AVCLs, the vapour resistance of the phenolic foam inhibits accumulated moisture from evaporating and diffusing through the insulation back into the room.

As already noted, most composite foam insulation boards include foil facings. This is often promoted as beneficially increasing vapour resistance. However, the simulations (comparing the mid- and bottom right diagrams) show that the retrofits incorporating foil experience a higher increase in relative humidity at the critical location, because the ability of moisture to evaporate and diffuse through the insulation back into the room is further reduced. (It should also be noted that this one-dimensional study does not take account of any two-dimensional effects of the gaps or joints between the phenolic foam boards.)

Calcium silicate board retrofit

The retrofit with calcium silicate boards (scenario 4.1.1) appears to be the safest of all retrofit products assessed, in terms of hygrothermal wall performance. As Figure 88 shows (in the bottom left diagram), relative humidity reaches an equilibrium quickly, with annual fluctuations between 70 to 85 %. These fluctuations are similar to those of the aerogel and cellulose retrofits without AVCL (top and mid-left diagrams), except that, for the calcium silicate board retrofit, the maximum relative humidity is lower (below 85 %) than compared to those of the aerogel blanket and cellulose fibre retrofits (both between 85 and 90 %). (This comparison is based on the graphs for the less challenging target U-value, as this was the only target U-value for which the calcium silicate board retrofit was assessed.) The ability of calcium silicate boards to easily transport moisture, through capillary action, increases the drying potential of the wall to the room and therefore greatly reduces peaks in moisture content at the critical location. Finally being a fully bonding system means it meets a WTA criterion (see Clarification on 95 % RH threshold, Section 3.2.2.1).

5.3.4.2 Impact of the external wall layer

The assessments above show the impacts that different internal wall insulation retrofits can have on solid stone wall construction. In those assessments, Stone A was the material of both inner and outer stone layers. As the properties of the sandstone of the actual case study building are unknown, the question arises to how closely Stone A matches the existing stone. As no invasive investigation of the masonry was undertaken in the Historic Scotland retrofit project, this question remains highly pertinent and in need of exploration.

The response to that question in this report was to use bracketing, previously mentioned in Section 5.2.3.2. Specifically, simulations of the full range of internal insulation strategies layered onto the same solid wall were analysed with three different external wall finishes. The first finish assessed above is Stone A itself. In the second type of external wall finish, the outer portion of Stone A is replaced with the more absorptive Stone B. (For sake of simplicity, Stone A remains in use as the material of the inner stone layer.) The external wall surface could also be protected by a rainscreen or a render. Therefore the third finish selected was traditional lime render added to the outside of the outer stone layer, ‘built’ with Stone A.

The results of the simulations for all 39 assessments (13 retrofit options X 3 different external wall layers) are described in Figure 90. As with the diagrams before, the graphs show the relative humidities at the insulation-masonry interface. The mid-column, is a repetition of the previous assessments of the Stone A wall without a render finish (Section 5.3.4.1), already shown in Figure 88. The left column in Figure 90 corresponds to Stone B without a render finish, the right column to Stone A with an external render.

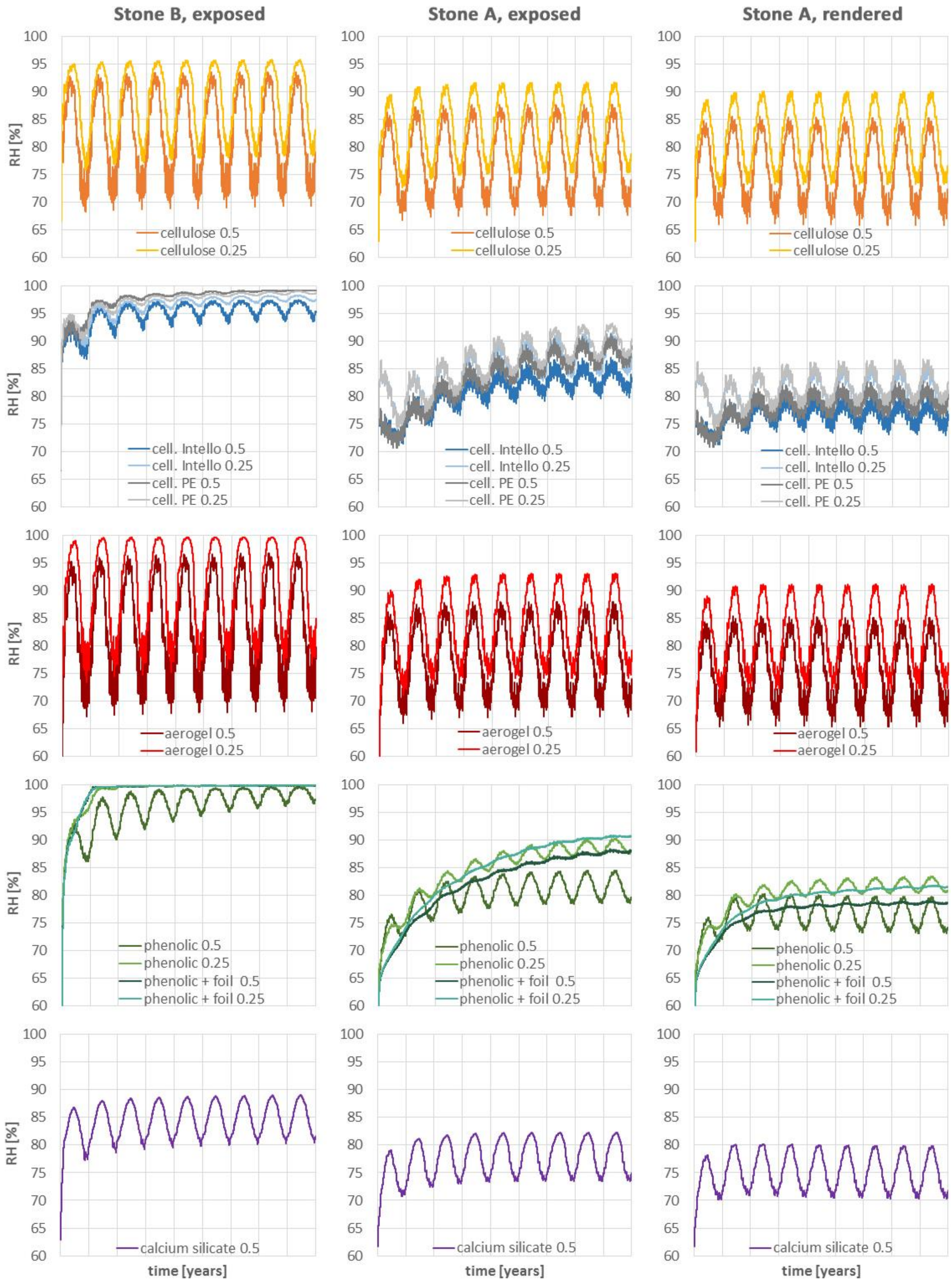


Figure 90 Impact of three different external wall surfaces on the previously modelled numerical simulations (Figure 88): relative humidity levels at the condensation critical location (insulation-masonry interface), generated with WUFI simulations, for the 13 retrofit options, with external surfaces as follows: exposed Stone B (left row of diagrams), exposed Stone A (mid-row) and Stone B with a 20 mm render lime finish (right row). Results generated with WUFI, using, for all simulations, Stone A for the inner stone layer.

The graphs in this figure show that a reduced rain water absorption at the external wall surface results in lower relative humidities at the insulation-masonry interface. In all graphs, relative humidities shown in the left column (more absorptive Stone B) are higher than those in the mid-column (less absorptive Stone A), which, in turn, are higher than in the right column (external render). This was to be expected. Comparing the different retrofit options, the differences in relative humidity are particularly significant for the more impermeable retrofit options, namely the phenolic foam boards (penultimate row in the figure). With Stone B, the simulation of the phenolic foam boards predicts relative humidities that eventually exceed 95 % RH for the lower U-values, but are unacceptable in all cases When the phenolic foam boards are used in conjunction with an external render, the relative humidities at the insulation-masonry interface(ranging between 73 and 84 % RH eventually) are significantly lower than that of Stone B, but also significantly lower than that of unrendered Stone A (which range between 79 and 92 % RH eventually). This suggests that reducing driving rain uptake is of benefit to all retrofit scenarios, but especially beneficial for scenarios featuring more impermeable layers. This suggests that internal wall insulation systems with membranes or fossil-based insulants may be better suited to rendered solid stone walls than those with exposed stone finishes. Further exploration is required.

To understand the impact of AVCLs, the simulation of the cellulose fibre retrofits can be compared: the results for retrofits without AVCL are shown in the top row of the figure, those for retrofits with AVCLs in the second row. Whereas the differences in relative humidities caused by the external wall layer are minimal in the top row (69 to 96 % RH in the left column compared to 66 to 90 % RH in the right column), the differences in second row are far more pronounced (eventually 94 to 99 % RH compared to 73 to 87 % RH). This shows that cellulose fibre retrofits without an AVCL appear to be sensible regardless of the material forming the external wall layer, but that the combination of an insulation retrofit featuring an AVCL with a more absorptive external surface can result in significant moisture accumulation (a more accurate term than 'interstitial condensation' in this case) at the insulation-masonry interface.

Table 20 below shows the judgement of the authors based on their analysis of all retrofit scenarios. Besides the graphed outputs from numerical simulation and associated assessments (Section 5.4), this judgement is also based on principles-based assessment (Sanders and May, 2014) and an understanding of the issues and risks that are specific to each insulation strategy, as identified in Section 5.3.4.1. The table may be compared to Table 19, which shows the results of Glaser method assessments for the same scenarios.

This can be compared to Table 19, which shows the results of Glaser method assessments for the same scenarios.

Retrofit product	Target U-value W/m² K	AVCL	Scenario ID	Exposed stone % RH after equilibrium: average (min-max)			Rendered stone % RH after equilibr.: average (min-max)	
				Stone A exposed	Stone B exposed	Judgement	Stone A rendered	Judgement
cellulose fibres, sprayed	0.50	none	**1.1.1**	78 (68-88)	83 (70-94)	No	76 (66-85)	Caution
		Intello	**1.1.2**	84 (80-87)	96 (94-97)	No	76 (73-80)	Caution
		PE	**1.1.3**	89 (86-92)	99 (99-99)	No	80 (76-83)	Caution
	0.25	none	**1.2.1**	84 (75-92)	89 (79-96)	No	82 (73-90)	No
		Intello	**1.2.2**	88 (84-92)	98 (97-98)	No	81 (77-85)	No
		PE	**1.2.3**	91 (88-94)	99 (99-99)	No	83 (79-87)	No
aerogel blankets	0.50	none	**2.1.1**	78 (67-88)	84 (68-97)	No	76 (65-85)	Caution
	0.25	none	**2.2.1**	85 (74-93)	92 (77-100)	No	82 (72-91)	No
phenolic foam boards	0.50	none	**3.1.1**	82 (79-85)	99 (98-100)	No	76 (73-80)	Caution
		foil *	**3.1.2**	89 (88-89)	100 (100-100)	No	79 (79-79)	No
	0.25	none	**3.2.1**	89 (88-91)	100 (100-100)	No	82 (81-84)	No
		foil *	**3.2.2**	91 (91-92)	100 (100-100)	No	82 (82-82)	No
calcium silicate boards	0.50	none	**4.1.1**	78 (74-82)	85 (81-89)	Yes	75 (70-80)	Yes

Table 20 Results of numerical simulation assessments for all retrofit scenarios. Colour code for judgement: green (acceptable); yellow (acceptable with caution); orange (not recommended); red (not acceptable). (In actual construction, where a foil is used facing a void the effective U-value would be slightly lower than that listed, due to reduced radiant heat transfer within the void. This would only have a minimal effect in the overall hygrothermal performance of the wall, and for the sake of simplicity, the U-value is shown unchanged.)

It should be noted that the insulation systems shown here may perform far better in other locations and on other walls with different hygrothermal characteristics. Equally many excellent insulation systems, for instance fully bonded woodfibre systems, have been excluded due to the constraints of a limited study - not due to any perception of unsuitability.

Assessing against established thresholds

When using the 80 % threshold as an assessment criterion (i.e. exceeding 80 % RH long-term), the following can be observed: the median relative humidities of the cellulose fibre retrofits without an AVCL (first row of the figure) for a U-value of 0.5 W/m²K fluctuate at just above 80 % for Stone B, around 80 % for Stone A and just below 80 % for render. The oscillations above and below this median quickly reach equilibrium. That the troughs fall considerably below the 80 % threshold suggests that the insulation-masonry interface dries sufficiently over the period of a year to prevent long-term moisture-related fabric deterioration. (That said, the drying periods are relatively short in the Stone B simulations; further investigations would be sensible to establish for how long the 80% threshold is exceeded during a year.)

As already noted, the external wall layer has a significant impact on the cellulose fibre retrofits with AVCLs (second row in the figure). For both Stone A and Stone B, the relative humidities for all variants move quickly above the 80 % threshold, albeit this is more exaggerated for Stone B. The use of a render appears to make these retrofit options acceptable when higher (i.e. poorer) U-values feature. For the scenarios featuring lower U-values though, the threshold is still exceeded.

The 80 % threshold assessment for the aerogel blanket retrofits (third row in the figure) is similar to that of cellulose retrofits without an AVCL (first row), as already discussed above, except that the aerogel retrofits show slightly larger fluctuations.

The impact of the external wall layer on the phenolic foam board retrofits (penultimate row in the figure) have already been discussed above. With regard to the 80 % threshold, the impact is similar to that of the cellulose fibre retrofits with AVCL (second row).

One may argue that the WTA's 95 % RH threshold applies to the calcium silicate board retrofit (bottom row in the figure), for Stone A and B given the positive characteristics of its chemistry, hygrothermal performance and application method. However given that driving rain is not reduced by the wall finish, a cautious approach would propose further research is required (see Clarification on 95 % RH threshold, Section 3.2.2.1). However the authors are confident that it applies to the third case featuring a render finish as driving rain is indeed managed in this case. The Stone B simulation suggests that there is a condensation risk at the insulation-masonry interface, which would need consideration in the planning of a retrofit. However, calcium silicate boards, mortar and stone are all products which do not generally deteriorate when in contact with liquid water (except for freeze-thaw deterioration which is not to be expected at that position in a Glasgow wall). That said, the impacts of salt migration and the presence of timber embedded into or in contact with the masonry would need to be addressed.

Conclusions from assessment using bracketing

To summarise the assessment of the three different external wall layers:

- General location and exposure, and specifically how an external wall surface imbibes moisture during a driving rain event have a significant effect on the vulnerability of an internal insulation system;
- Where external wall surfaces are highly absorptive, conventional insulated plaster-boards and insulation systems featuring membranes may heighten hygrothermal risks. Additionally the voids they leave behind the insulation may provide the moisture and oxygen that mould needs to grow;
- Where solid walls are exposed brick or stone, moisture managing insulation systems (i.e. vapour permeable, hygrosopic and even better capillary active) perform better;
- Where the impact of driving rain is minimised, the freedom to use a range of different insulant strategies grows. Strategies that manage the internal moisture load can begin to perform better;
- Higher (i.e. poorer) U-values are hygrothermally less risky when insulating solid walls. A sensible low risk value may be in the range between 0.6 and 0.45 W/m^2K, but this needs formal assessment;
- Formal hygrothermal risk assessment including bracketing clearly highlights the potential range of performances possible (of walls made of unmeasured materials) and promotes a cautious approach to specification.

5.3.5 Comparison of Glaser method and numerical simulation assessments

The base wall and 13 retrofit scenarios were assessed using both the Glaser method (BuildDesk U) and numerical simulation (WUFI). The Glaser method assessments predicted moisture accumulation (at 100 % RH) in six of the 13 retrofit scenarios after a single year. The numerical simulation assessments, however, have shown that this situation occurs in none of the retrofits. (That said, in the simulations of the phenolic foam board retrofits achieving 0.25 $W/(m^2{\cdot}K)$, the relative humidity levels come close to 100 % eventually.)

The reason why numerical simulation does not predict moisture accumulation at 100 % RH is that the simulations include the full range of moisture transport mechanisms and hygric functions that porous hygroscopic materials have in reality. These material characteristics allow moisture to change state, in response to changing conditions, and naturally redistribute away from critical locations, before enough moisture accumulates to reach 100 % RH.

The fact that Glaser method assessment over-predicts condensation risk is often cited as an argument that these assessments are more conservative than numerical simulation assessments. However this case study confirms, to the contrary, why the limitations and scope set out in *ISO IS EN 13788:2013* (see Section 4.2.1) should be understood to rule out this method for hygrothermal risk assessments of hygroscopic solid walls *of any kind*. The Standard is right: the overly broad application of the Glaser method is not. The Glaser method assessments gives an 'all clear' to the six mostly impermeable retrofits options, while hygrothermal analysis using numerical simulation (under *BE EN 15026:2007*) of the same retrofits predicts year-on-year increases in relative humidity and elevated risk. This demonstrates that a hygrothermal assessment using the Glaser method may not only be less risk averse than a hygrothermal analysis using numerical simulation, it may be utterly inaccurate.

The usual 80% threshold that is typically cited for mould growth (Section 3.2.2.1) is exceeded in all of the cases assessed. In the retrofits using vapour open insulation, it is exceeded for the coldest months of the year, with more significant drying during summer; whereas for those retrofits with vapour resisting insulation or AVCLs, RH is consistently above 80 % RH. The impact of elevated relative humidity on potential mould growth will be discussed in greater detail in the next section, using a biohygrothermal model.

5.4 Associated assessments

5.4.1 Assessment of mould growth risk

Mould is a health risk to building occupants. Its growth is reliant on the existence of a suitable substrate and specific environmental conditions. (Section 3.2.2.1) The hygrothermal assessment results from numerical simulations can be used to establish the risk and predict the patterns of mould growth. Such biohygrothermal assessments can be conducted with software, such as WUFI-Bio, a postprocessor for use with WUFI Pro. (Section 5.4.1)

For the case study, the software WUFI-Bio 3.0 has been used to assess the impact of the previously discussed retrofit options with respect to potential mould growth. For this, a biohygrothermal model has been created, based on the data of relative humidity and corresponding temperature. (Section 5.2.2) The assessments of mould growth risk were, however, only conducted using the data from the numerical assessments of Stone A. (Also using the Stone B data was, unfortunately, outside the scope of this report, although higher mould growth risks might be expected, given the higher relative humidity levels of the Stone B wall at the critical location.) A substrate class II was assumed, suitable for mineral-based building materials. (Section 3.2.2.1)

Based on these inputs, WUFI-Bio assesses when the humidity and temperature conditions are sufficient for spore germination and predicts the rate of mould growth at any time after that. For the case study, the mould growth risk was determined for each retrofit option in its seventh year of installation. These growth rates were assessed using three reference thresholds: *Pass* (< 50 mm/year), *Caution* (50 to 200 mm/year) and *Fail* (> 20 mm/year).

(Section 4.5) Although the transient biohygrothermal model of WUFI-Bio is designed to be used at internal surfaces of the room, it can still be used as a comparative tool to perform a conservative risk assessment. In such assessments, a *Fail* does not mean that actual mould growth will necessarily occur, and a *Pass* indicates that no mould growth is expected. Theoretically, the model is only directly applicable to surfaces facing an air space with a certain airflow. This can happen in the base wall, where an air space exists between the masonry and the plaster-on-laths finish, and in the aerogel blanket and phenolic foam board retrofits, both installed with an air space between the masonry and the insulation. In these two retrofit cases, avoiding air leakage from the room, by ensuring good airtightness, would be crucial to reduce the risk of mould growth. The cellulose fibre and calcium silicate board retrofits should not be at risk of mould growth, if installed properly, due to the absence of air. However, for the sake of comparison, they have been included in the WUFI-Bio simulation for this case study. The results of the mould growth risk assessment are summarised in Table 21. The predicted annual growth rates are also shown in Figure 91.

Looking first at the threshold assessment in Figure 91, the modelling results show that many of the retrofit options are considered at risk of significant mould growth. Regardless of the retrofit products, only those scenarios aiming at achieving the less challenging target U-value, i.e. 0.5 W/(m^2·K), *pass* the assessment. All other scenarios achieve either a *Caution* or *Fail*. None of the scenarios with an AVCL *Pass* the assessment. Of the scenarios without an AVCL aiming at achieving the more challenging target U-value, i.e. 0.25 W/(m^2·K), the cellulose fibre and aerogel blanket retrofits achieve a *Caution*, the phenolic foam retrofit *fails*. (The calcium silicate retrofit was not assessed for this target U-value.)

The results show the importance of understanding how the U-values affect the overall wall performance when making retrofit decisions. It is not sufficient to select insulation product by their thermal performance only. Instead, all relevant impacts must be assessed. The proposed insulation level, at times, needs to be limited to that level which can be considered as *safe*, i.e. has no detrimental impact on building fabric and occupants' health.

In addition to the threshold assessment, a comparison of the predicted annual growth rates in Figure 91 show easily that the use of AVCL and foils increases growth rates, with PE membranes having a greater impact than Intello membranes. The use of foils in the phenolic foam retrofits results in the highest mould growth rates. The calcium silicate board retrofit achieves the lowest growth rate.

Retrofit product	**Target U-value** [W/(K·m^2)]	**AVCL**	**Scenario ID**	**Mould growth prediction**	
				Growth [mm/year]	**Threshold assessment**
no retrofit	n/a	None	**B**	0	Pass
cellulose fibres,	0.50	None	**1.1.1**	30	Pass*

sprayed		Intello	**1.1.2**	63	Caution*
		PE	**1.1.3**	304	Fail*
	0.25	None	**1.2.1**	136	Caution*
		Intello	**1.2.2**	233	Fail*
		PE	**1.2.3**	373	Fail*
aerogel blankets	0.50	None	**2.1.1**	36	Pass
	0.25	None	**2.2.1**	180	Caution
phenolic foam boards	0.50	None	**3.1.1**	30	Pass
		Foil	**3.1.2**	425	Fail
	0.25	None	**3.2.1**	317	Fail
		Foil	**3.2.2**	573	Fail
calcium silicate boards	0.50	None	**4.1.1**	3	Pass*

* Mould risk assessment not directly applicable, due to the absence of an air space between masonry and insulation

Table 21 Assessment of mould growth risk, using biohygrothermal modelling with WUFI-Bio: the base wall and retrofits options were assessed, using humidity and temperature data from the numerical simulations for Stone A and substrate class II.

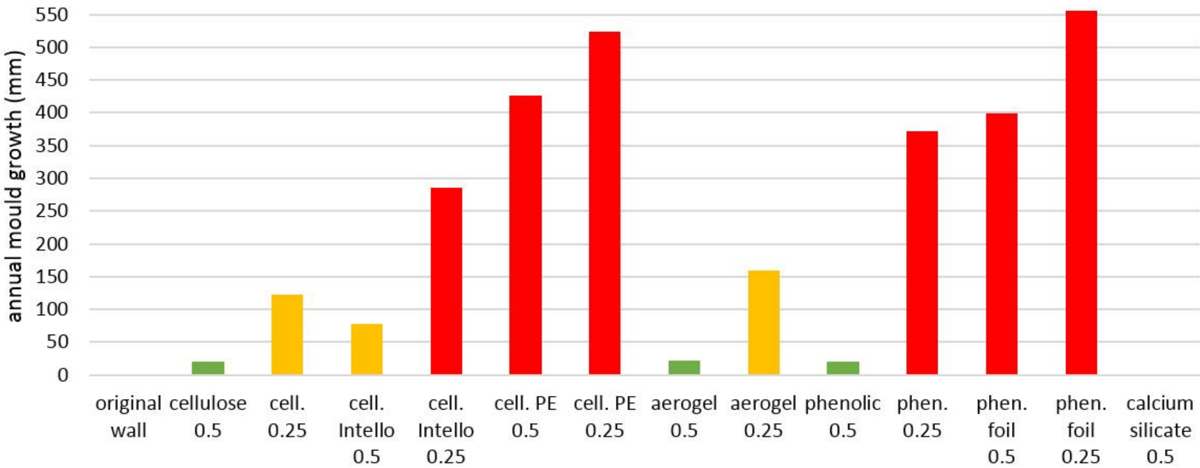


Figure 91 Predicted annual mould growth, using biohygrothermal modelling with WUFI-Bio for the Stone A solid wall substrate

When comparing this study with the previous relative humidity-focused study (Section 5.3.4.1) silicate comes out as the clear winner, followed by cellulose, aerogel quilt and phenolic foam all at 0.5 W/m^2K. Phenolic foam is perhaps the most surprising of these, however this insulant is not supplied to the market without fibreglass or foil facings as they form part of the manufacturing process and are essential to prevent off-gassing throughout its service life. The phenolic foam with foil is therefore more relevant – and clearly unacceptable. The only insulants that perform even marginally at the higher insulation level are cellulose and aerogel. This is because their vapour open structure allows hood drying characteristics every summer through reverse diffusion. If repeated for the rendered wall they would likely score very acceptably from a biohygrothermal perspective.

As said previously, biohygrothermal modelling is a field of building research that is still in development, and more research is needed to refine the accuracy of these models.

5.4.2 Assessment of freeze-thaw deterioration risk

When sufficient moisture is present in the near-surface layers of a wall during time periods at or below freezing temperature, the volumetric expansion of the freezing water can cause the weakening of the material structure. Repeated freezing and thawing actions can thereby lead to the deterioration of the material surfaces. These freeze-thaw cycles are often short-term weather events, which can be assessed with hygrothermal simulation, because of its use of hourly data and its capability of modelling liquid transport. WUFI Pro allows the export of a range of data for any grid element, i.e. monitoring positions, across the cross section of the building fabric analysed as well as indoor and outdoor environmental data. The data includes temperature, water content, relative humidity, vapour pressure, heat flux and rain water. By determining the thickness of a construction layer and the number of grid elements within it, an almost infinite range of outputs can be created.

The location at risk of freeze-thaw deterioration is the outdoor surface of the wall. In the case of a wall with exposed stonework, this location is the near-surface layer of the masonry, consisting of stone bedded in mortar. To determine the freeze-thaw deterioration risk, the near-surface layer of the stone will be analysed with hygrothermal numerical simulation. For this, two 5 mm thick slivers at the outer part of the wall have been assessed to provide a better understanding of the localised water content in these masonry locations.

Freeze-thaw deterioration is chiefly influenced by moisture content and the number of freeze-thaw cycles. As the critical assessment threshold, a free water saturation of 90 % was chosen, since this is regarded as a conservative threshold level for brick and natural stone. (Section 3.2.2.3)

The assessment was conducted for the base wall and all retrofit scenarios, using hygrothermal data for Stone A. The free water saturation of this stone was assumed to be 210 kg/m^3. Stone B has not been assessed for freeze-thaw deterioration.

The moisture content and temperature for the two near-surface slivers of the stone were checked for every hour over the whole length of the simulation to assess the number of hours that the moisture content was higher than 90 % of free water saturation and, at the same time, temperatures were lower than 0 °C. Over a simulation period of fifteen years, i.e. 131,400 hours, *not once* were these conditions reached, in any of the assessment scenarios. This is a positive result, considering that there is less heat to dry out the masonry where higher levels of internal insulation are used.

As with the assessment of mould growth risk, freeze-thaw assessment is a field of building physics still under developed, and the results presented here should be interpreted as an indicator of potential risk, rather than a conclusive prediction, particularly as the assumed material properties of the simulated might not match those of the original and other factors, such as soluble salt content, cannot yet be simulated hygrothermally using WUFI.

5.4.3 Assessment of thermal bridging

The assessments above have focused on the one-dimensional performance aspects of different retrofit options, comparing their impacts on heat and moisture transfer through plane building elements. This section illustrates the two-dimensional aspect of thermal bridging, using software simulation.

As an example of thermal bridging, a stone wall below a window will be analysed. This area is a recessed window breast, i.e. the wall below the window cill is thinner than the adjacent walls. In this location, two linear thermal bridges are essentially close to each other: one is the junction between wall and window, with a cill in between; the other is the floor-wall junction. Both thermal bridges affect each other.

Three assessments have been carried out: firstly, the base wall, without any insulation retrofit, has been simulated. Secondly, an assessment has been conducted of the same wall retrofitted with internal wall insulation. Lastly, the retrofit has been reassessed, after addition of further insulation at locations identified in the second assessment as thermal bridging.

The assessments have been conducted in accordance with the *Conventions for Calculating Linear Thermal Transmittance and Temperature Factors* (Ward and Sanders, 2007), using the software THERM 5.2. The assessments are steady-state simulations, assuming, as per the convention, an internal temperature of 20 °C and an external temperature 0 °C. As part of the assessment, temperature factors have been calculated, as set out in the convention, and assessed against a minimum threshold of 0.75. (Ward, 2006) In accordance with the convention, the window itself has not been included in the thermal bridge assessment, as the cill-window junction is considered adiabatic, i.e. not transferring heat. The ordinarily thick wall is assumed to have a U-value of 2.29 W/(m^2·K).

Starting with the assessment of the uninsulated wall, Figure 92 shows a cross section of the concerned window breast area. The left illustration in the figure presents the construction details. The middle and right illustrations show respectively the heat flow and temperature distributions in this area.

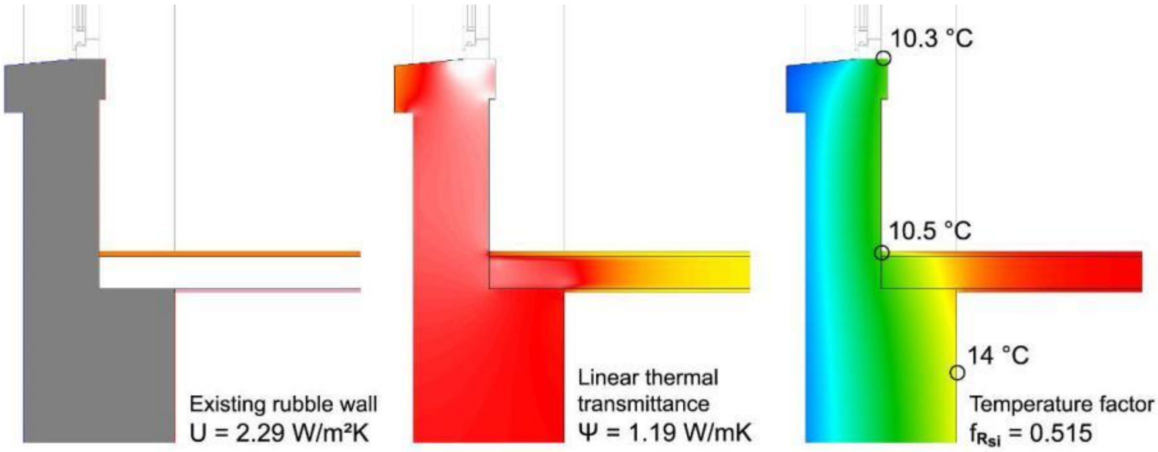


Figure 92 Cross section of a wall with a window breast, generated with THERM: the left illustration shows the construction. The middle illustration shows the heat flux, which is larger at the window breast (pink), particularly near the window-cill junction (white). The right illustration shows the temperature distribution and select surface temperatures. The latter relates to the heat flow illustration, with 14 °C at an ordinarily thick wall, 10.5 °C at the window breast and only 10.3 °C at the cill-window junction.

The middle illustration shows that a larger heat flow occurs at the thinner window breast wall (shown in pink) compared to the relatively uniform heat flux elsewhere in the wall (red). The largest heat flow, however, occurs at the cill-window junction (white). The heat flow through the ordinarily thick wall results in a surface temperature of 14 °C. At the thermally bridged window breast, the surface temperature is considerably lower, just above 10 °C. This equals a temperature factor of 0.515, well below the 0.75 threshold. If this room would be occupied normally, this temperature would pose a risk of surface condensation.

For the second assessment, 100 mm thick blown cellulose fibre insulation was applied to the internal wall surface, achieving a U-value of 0.38 W/(m^2·K) at the ordinarily thick wall. As in the previous figure, Figure 93 shows the construction details in the left illustration, the heat flow in the middle illustration and the temperature distribution and select surface temperatures in the right illustration.

The middle and right illustrations in the figure show that the heat flow has decreased and surface temperatures are higher, compared to the uninsulated wall. The colour scheme in the middle illustration has shifted from red to orange. The window breast appears to be less of a thermal bridge. The cill-window junction, however, remains a thermal bridge of significance, albeit with some heat flow reduction. In addition to this, the floor-wall junction has now become a thermal bridge: where the floor joists meet the wall, no insulation has been installed. The heat flow at this location, therefore, remains unchanged (red). In the previous scenario, this was the 'standard' heat flow through the wall. However, now that the insulation has improved this standard, the floor-wall junction has to be considered a thermal bridge. In the solid wall below the floor, where heat flow is nearly one-dimensional, the colour bands are almost parallel to the surfaces. In the thermally bridged areas, the additional heat loss results in cooler temperatures, with temperature bands curving inward toward the room.

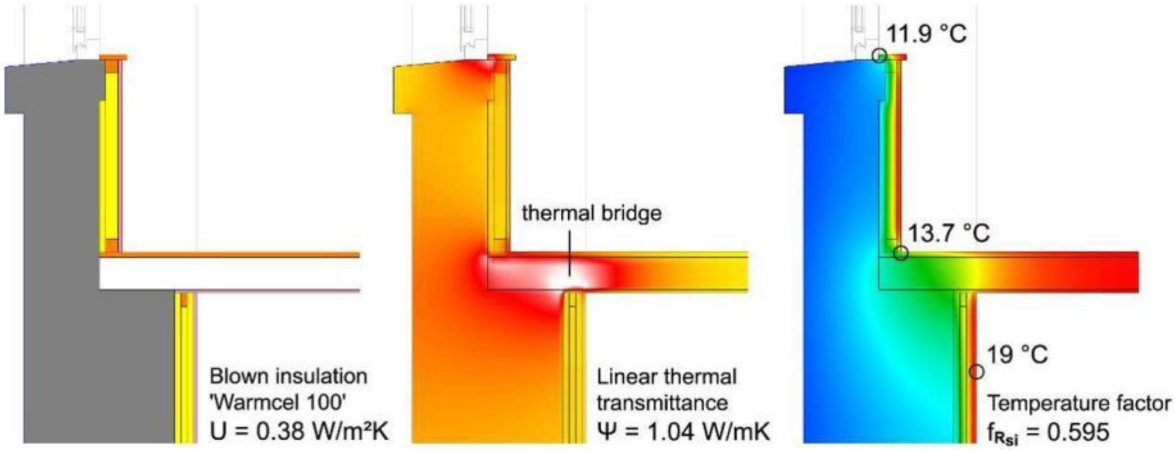


Figure 93 Cross section of a wall with a window breast, which, in comparison to Figure 92, is now retrofitted with internal wall insulation: the location of the most significant thermal bridge is now the floor-wall junction; the cill-window junction remains a thermal bridge also, albeit of lesser significance. Although the surface temperatures have significantly increased, the temperature factor is only marginally higher than in the uninsulated scenario.

Adding cellulose insulation reduced the heat flow through the plane elements of the solid wall, resulting in an internal surface temperature of 19 °C, compared to 14 °C when uninsulated. The surface temperatures at the windows breast and cill-window junction have also improved, from 10.5 to 13.7 °C and 10.3 to 11.9 °C respectively. However, because of the substantial thermal bridging across the building fabric, the temperature factor has only improved marginally, from 0.515 to 0.595. It, thereby, remains well below the recommended threshold of 0.75, indicating surface condensation risk.

This retrofit scenario illustrates that, when internally insulating an existing wall, the original fabric received less heat, as is shown in blue colour in the temperature illustration. Care has to be taken when planning such retrofits to ensure that the now colder fabric is not in direct contact with room air, e.g. where insulation is locally discontinued, in order to avoid surface condensation and associated mould growth. This assessment demonstrates that an unsuitably detailed wall retrofit can increase the condensation risk locally. The uninsulated window cill, however, remains the most problematic junction in this example, with the lowest surface temperature. This is an all too common issue with internal insulation retrofits, leading to surface discolouration and, eventually, mould growth.

To avoid the thermal bridging at the cill-window and floor-wall junctions, additional insulation has been added for the third assessment scenario: at the cill-window junction, a thin aerogel insulation blanket has been installed below the internal cill board. At the floor-wall junction, insulation has been placed in between the floor boards. Figure 94 shows the construction details, together with the heat flow and temperature distributions.

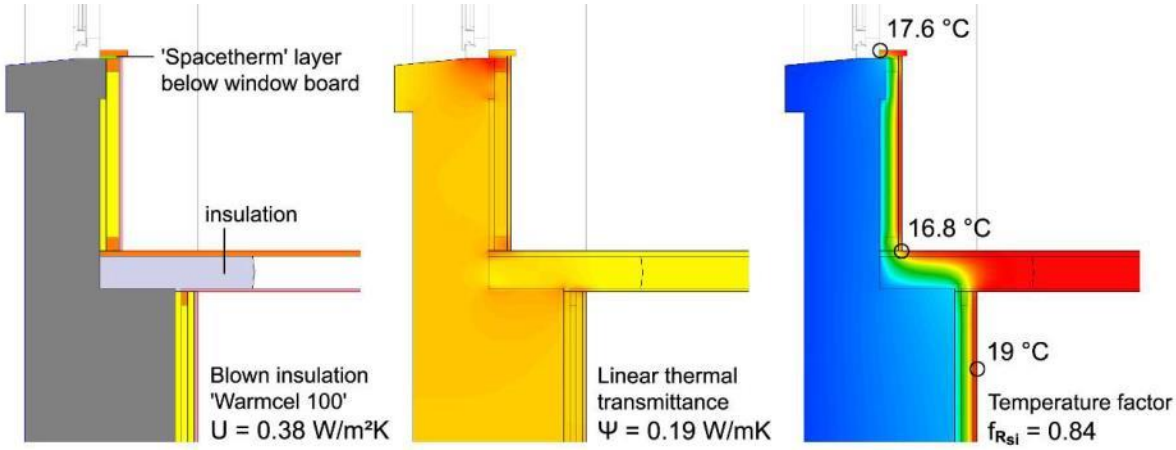


Figure 94 Cross section of a wall with a window breast, which, in comparison to Figure 93, has received additional insulation at the cill-window and floor-wall junctions: in this advanced retrofit scenario, thermal bridging has reduced significantly, surface temperatures have increased, and the temperature factor is now above the 0.75 threshold.

This advanced retrofit scenario has achieved a significant reduction in thermal bridging, with only the cill-window remaining in red colour. The surface temperatures at the cill-window junction and the window breast have also improved significantly and are now 17.6 and 16.8 °C. Interestingly, unlike in the other two scenarios, the lowest temperature is now at the bottom of the window breast and no longer at the cill. The resulting temperature factor is now 0.84, which is above the recommended threshold of 0.75. The construction detailing used in this advanced retrofit is therefore sufficient to prevent surface condensation and mould growth.

Planning retrofits so that thermal bridging is minimised, in order to not only reduce heat loss but also to eliminate the risk of surface condensation, is often complex, requiring careful detailing, particular at construction junctions. The three assessment scenarios above have illustrated how software can be used as an assessment tool to aid the design construction details.

6 Conclusion

The authors hope that this report about hygrothermal assessment methods and a comparative case study forms a small part in what may be considered a revolution, in both Ireland and the UK, in how existing buildings are assessed and understood and, therefore, how they can be cared for and retrofitted for future generations and a more sustainable future.

In Ireland and the UK, construction guidance and practice are still heavily influenced by the *diffusion paradigm*, a reductionist but deeply held view that vapour diffusion is the only relevant moisture transport mechanism in building fabric and the use of a vapour barrier to control it is always best practice. It is common to find builders, architects or guidance documents that express this view even though they may not know or refer to the simplified calculation methods from which this view originated. The first of these methods was designed in the 1920s to support assessment of timber frame in America, and a later method, created by Dr. Glaser, was created to evaluate freezer compartments in Germany. For many decades the latter method has been commonly used, wherever ISO standards are in use, to evaluate the hygrothermal risk of all building types, in all exposures.

The Glaser method is suited for the comparative hygrothermal assessment of lightweight building fabric with well-vented rain screens in relatively sheltered conditions, but has little place in the evaluation of solid wall traditional buildings, as is clear from the limitations set out in the standards associated with it, *BS EN ISO 13788:2002* and *2012*. The Glaser method's simplified, steady-state approach excludes several hygrothermal transport processes from consideration, such as liquid transport by capillary action or surface diffusion, and short-term weather events such as driving rain and freezing conditions. All of these are of particular importance in the hygrothermal assessment of traditional building construction, particularly when internally retrofitted with insulation. As this report demonstrates, using the Glaser method to assess conditions and building fabric that are outside of the method's scope can generate results that do not resemble and *can even contradict* the more accurate results of numerical simulation, when generated correctly in accordance with *BS EN 15026:2007*.

As all construction systems tend to perform better with an AVCL or vapour tight materials (on the room side of an assembly) *when assessed using the Glaser method*, and as it was the only hygrothermal assessment method used (outside of laboratories) for many decades, it is not surprising that many manufacturers have developed building products that achieve particularly good results when assessed with this method. The assessment method which influenced the creation of the systems was then used to test the performance of specified or installed examples of those systems: a closed loop. It was not until 2007 when an international standard was published (against which leading hygrothermal numerical simulation software programmes could be validated) that a change in practice and paradigm could begin to happen on a large scale. Adoption has been slow in the UK and Ireland. Now in a context of national retrofit programmes client bodies need to start insisting on the right risk assessment method, and the construction industry using the right method, for the relevant building systems and conditions each time.

The Glaser method is still being taught as an introductory method for all forms of hygrothermal assessment in many built environment and engineering colleges, without regard to the fact that while it *is indeed* an excellent, albeit simplified, hygrothermal assessment method for some building and component types, it is utterly inappropriate for others. Its inappropriate use facilitates and maintains misconceptions.

Progress is being made. An increasing number of UK universities are researching hygrothermal performance, using physical testing and/or numerical simulation software. An increasing number of construction professionals in Ireland and the UK have been trained in its use and a limited number of colleges are creating formal academic programmes in hygrothermal assessment. While manufacturers of conservation products have been quickest to adopt numerical simulation software, many mainstream manufacturers of construction products now have personnel using numerical simulation to assess new products. Thus, a good basis is being created to allow a shift to occur in how risk assessment of buildings is carried out. This is good news, particularly for traditional buildings.

The case study has demonstrated that moisture transport in solid, unrendered stone walls is predominantly in the form of liquid migrating through the materials' capillaries, due to capillary action and surface diffusion. Vapour diffusion plays a lesser role. The moisture absorption characteristic of an external wall surface determines the relative importance of the different transport mechanisms. When liquid transport is stopped within the building fabric, either by reaching a non-capillary active material or any another form of capillary break, the liquid must be able to diffuse and evaporate to the indoor or outdoor environment. Anything impeding this drying of the wall results in moisture accumulation and can lead to moisture-related deterioration and potential health risks to occupants. When moisture transport in brick or stone-faced solid walls occurs predominantly in the form of liquid transport by capillary action and surface diffusion, AVCLs appear to have a poorer performance than vapour-open or capillary active insulation retrofits, even where AVCLs are designed to allow variable diffusion. Reducing the absorption characteristics of the outer wall surface, e.g. by applying a traditional two coat render, can allow greater freedom to insulate or install AVCLs specifically because it reduces the water uptake during a driving rain event.

The numerical simulations of this case study demonstrate the importance of specific material properties, such as capillary transport coefficients, vapour diffusion resistance, hygroscopicity and porosity. But even with the right assessment standard and validated software tools, how are we going to predict the risks of interstitial condensation, mould growth, rot infestation and freeze-thaw deterioration, if the data sets to be used are incomplete or incorrect? Standards and tools are not enough on their own. Their users must have sufficient understanding of building construction and physics, must be well-trained in the software tools must select assessment methods adequate to the level of unknowns, and have access to sufficiently accurate performance data and, where that is still insufficient, techniques to deal with uncertainty. They must also be cautious, always questioning the simulations results critically.

In the case study a real, fully measured German sandstone called Baumberger ('Stone A') was initially assessed hygrothermally, but a 'bracketing' approach was then introduced by including a rendered version of the same wall and an alternative sandstone ('Stone B') to see how those material properties changed the outcomes. Without question bracketing places an immediate and clear emphasis on the assessor's judgment and encourages caution.

The accuracy of hygrothermal assessments could be improved significantly if better hygrothermal material data were available. Laboratory measurement of a carefully chosen selection of traditional building materials, commonly used in Scotland, could significantly advance the accuracy of risk assessments. No existing materials from any building in Ireland or the UK have yet been subjected to the full range of hygrothermal testing (as far as the authors can establish). Moving forward, it is without doubt a great weakness that the UK doesn't already have a dataset of existing material properties comparable to that of, say, Germany, and that an extensive physical testing period didn't precede the rollout of the Green Deal and other ambitious national retrofit programmes. Then again it is better late than never: Government action is needed.

An increasing number of innovative insulation products are being developed specifically for use with traditional masonry construction. Interestingly, manufacturers of such specialist products tend to have measured the full range of hygrothermal characteristics of their products, thereby aiding independent numerical calculation by third parties. The authors would advise that all measures which could significantly alter the hygrothermal performance of traditional construction, such as use of membranes or insulants, be assessed using numerical simulation. Retrofit measures should be *low risk* for the occupants and the building itself. As an initial step, clients and professionals embarking on retrofit projects would benefit from using the excellent *Responsible Retrofit Guidance Wheel* of the Sustainable Traditional Buildings Alliance (STBA, 2015) and the extensive, peer-reviewed literature resource available through it.

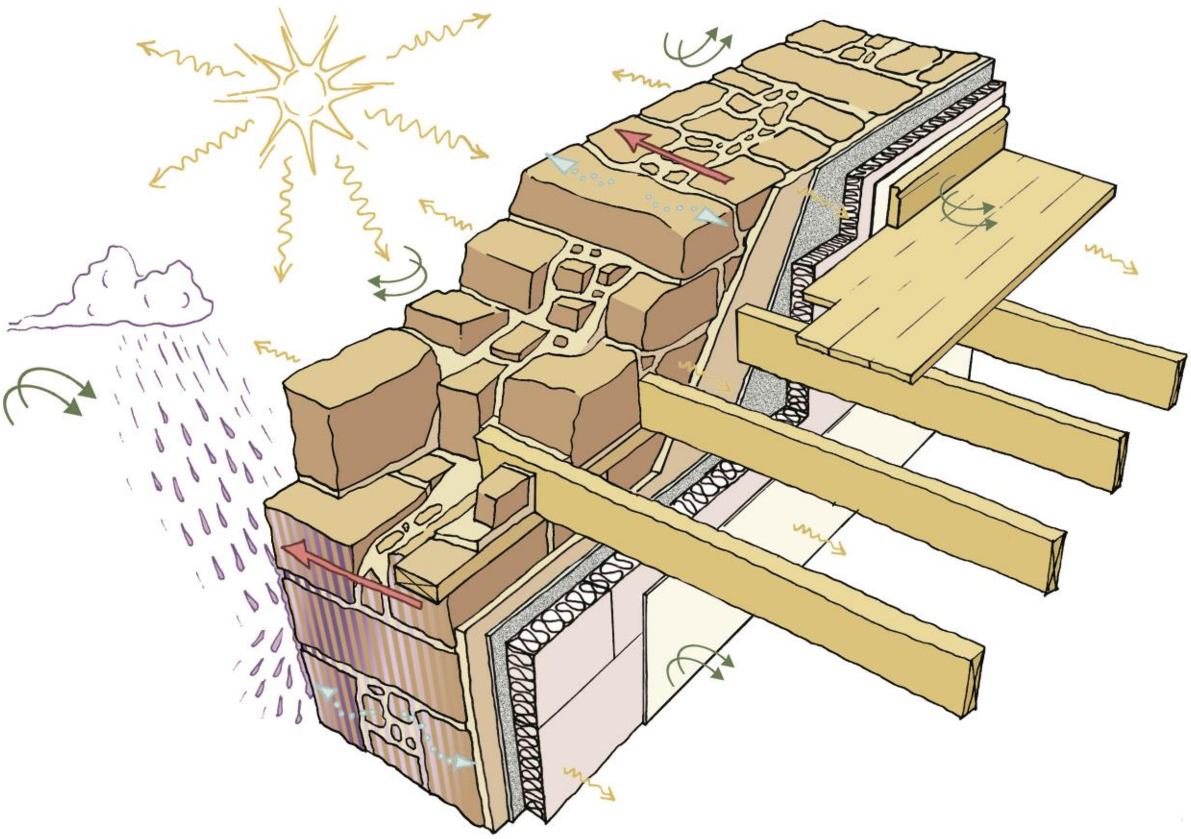


Figure 95 A graphic representation of a *moisture managing* internal wall insulation system featuring a fully-bonded, hygroscopic and capillary active insulation assembly

Unlike the Glaser method, numerical simulation (under *BS EN 15026:2007*) can allow detailed hygrothermal assessment of a wide range of issues, such as rot infestation, mould growth and freeze-thaw deterioration. It allows users to assess not only geographic location, but also the impact of different orientations, exposures, altitudes and even the radiative absorptivity of surface colours and night time radiative heat losses. Crucially, it can be used to assess short-term climatic events, inside or outside the building, with wind-driven rain being a particularly important factor when assessing solid walls. WUFI goes further than the international standard to also allow assessment of the impact of imperfect construction by allowing one to simulate water penetration on the outer portion of the assembly and varying rates of air leakage from the room on the inner portion. Numerical simulation can of course be combined with field measurement, for instance water absorption levels (see Appendix 2 Measuring absorption of masonry walls with Karsten tubes), or measured internal and external climate data. As the level of knowledge about the site conditions or desired specification grows the accuracy of the inputs and therefore outputs can grow too.

Thermal bridging, i.e. a non-uniform heat loss through the building fabric over and above plane element heat loss, can increase dramatically after an internal insulation retrofit, due to discontinuities of insulation. Internal insulation is particularly vulnerable in that these gaps, such as at a window reveal, can result in surface temperatures that are lower than they were before the insulation was fitted, increasing the risk of mould. As insulated rooms can generally retain a higher temperature for longer, the vapour component in the air can also be greater: therefore the potential for greater condensation on colder spots after an ill-considered internal insulation retrofit is all too likely. In the authors' view fitting whole dwelling ventilation systems when carrying out internal insulation retrofit work is highly advisable: there are many kind of systems – some of which are unobtrusive and robust.

Insulation retrofit in Ireland and the UK is gathering pace. The retrofit of new materials or systems within a traditional building often creates new conditions. Nationwide increasing cases of building fabric deterioration are resulting in additional expense and possible health risks to building occupant, unless more field research is carried out and the switch to hygrothermal analysis using numerical simulation speeds up. National retrofit campaigns, such as the UK's *Green Deal* and Ireland's *Better Energy Homes Scheme* aim at achieving significant improvement of the energy efficiency of the existing building stock quickly. These retrofit campaigns have provoked a sense of urgency in many quarters about the need to carry out knowledge gap studies, significant research and a shift to assessment under *BS EN 15026:2007*, but the retrofits themselves are also increasing the complexity of the traditional building stock and due to their lack of focus on the issues raised in this and other similar reports must surely be increasing hygrothermal risks, without giving all the promised energy savings.

One-size-fits-all insulation strategies will not work in national retrofit programs. Energy-related retrofit to traditional, moisture managing construction, carried out without careful and appropriate risk assessment, will be neither durable nor sustainable. Continuing to live within the diffusion paradigm by accepting unsuitable hygrothermal risk assessment methods is not in the national interest and should no longer be acceptable. The stakes are too high.

Appendices

Appendix 1	Key research works
Appendix 2	Measuring absorption of masonry walls with Karsten tube
Appendix 3	Input parameters for the WUFI simulations in the case study
Appendix 4	Material properties used in the case study

Appendix 1 Key research works

The purpose of this report is to present and compare two alternate hygrothermal assessment methods and the standards that define their use, namely *BS EN ISO 13788:2002* and *BS EN 15026:2007*. The case study in Section 5 is intended to help focus attention on these methods' potential impacts on specification and the understanding one gains using them. The case study insulation retrofits are based on hygrothermal modelling, not monitoring. The authors acknowledge that the assessors' judgment is critical: the methodology and the conclusions of the study rely on a wide variety of reputable sources. Virtually every claim or conclusion derived from use of numerical simulation in the case study has antecedents previously published by respected scientists, in peer-reviewed journals or at conferences.

Summary of relevant scientific papers

This section gives a quick overview of a small sampling of papers that touch on issues raised in the case study. They are fully referenced in the Bibliography.

Building physics is at a very exciting stage internationally. Focus has shifted (in the last ten years in Central Europe, and more recently in the UK) to retrofit and the issues that are particular to making traditional buildings energy-efficient. Internationally there are many dedicated international conferences on building physics, building simulation, and now internal insulation, besides wider-ranging conferences, such as the annual International Passive House and international Passive and Low Energy Architecture (PLEA) Conferences, where hygrothermal issues associated with traditional buildings receive more attention. There are also more specialist conferences, such as the first 'Internationaler Innendämmkongress' (International Internal Insulation Congress) held in Dresden in 2011, which go into far greater depth. The collected papers of such conferences can become benchmarks for the state of the science.

In recent years Historic Scotland has led the way through commissioning a series of technical papers and carrying out case studies that explore the knowledge landscape of energy efficient retrofit work that is appropriate in terms of hygrothermal building physics and conservation. English Heritage is in the process of publishing ten (significantly revised) volumes of its Practical Building Conservation series: a remarkable body of work. While all of the books in the series address hygrothermal issues related to care and maintenance of historic buildings, the (600 page) book titled 'Building Environment' deals with building and system interactions as well as occupant health and sustainable retrofitting.

It is important to say a lot of issues are very clear while others are still being explored, but in general there is widespread agreement on the characteristics of hygrothermal performance in the scientific community internationally. There is a lot of expertise in the UK and much research going on in UK universities. University College London, University of Cardiff, University of Nottingham, Leeds Metropolitan University, Salford University, Napier University and Glasgow Caledonian University, to name but a few, are all engaged in exciting hygrothermal research to the best knowledge of the authors. That research work, alongside equivalent work internationally will, must surely find its way into new official UK guidance, but how long will this take?

It may be that the greatest issue now is the lack of coherence in official guidance - from advice pamphlets published for homeowners to the technical guidance published for building professionals, all the way to national and internationals standards. There is much to be done.

Annex 24 - Heat, air and moisture transfer in highly insulated building envelopes

Annex 24 was launched in 1990 and made a final report in 1996 (see Section 4.1). What is quoted below comes from a Technical Synthesis Report from 2002 writing about the earlier work. These conclusions directly support the findings of this technical paper:

- *Airtightness is the most important performance requirement. If not achieved no guarantee can be given in relation to thermal performance and durability.*
- *A sufficient vapour retarder at the warm side of the thermal insulation is a second order requirement. Only in case air-tightness is realised and the indoor climate is rather severe (ICC3 and ICC4), vapour diffusion may become a real threat in terms of unacceptable moisture accumulation by interstitial condensation.*
- *In case of built in moisture, a vapour retarder may harm the durability of an envelope part. In such cases, the retarder may prevent the part from drying or induce an unwanted moisture distribution."*

(Hens, 2002, p. 9)

Responsible Retrofit of Traditional Buildings

Responsible Retrofit of Traditional Buildings (May and Rye, 2012) is a DECC-commissioned report by STBA, identifying both existing research and knowledge gaps relating to the retrofit of traditional buildings. It provides an exhaustive list of interesting sources of information.

The report ascertains a lack of understanding of the performance of traditional buildings both in industry and in policy. Figure 96, taken from the report, illustrates the scarcity of relevant, rigorous research assessing walls for retrofits of traditional buildings.

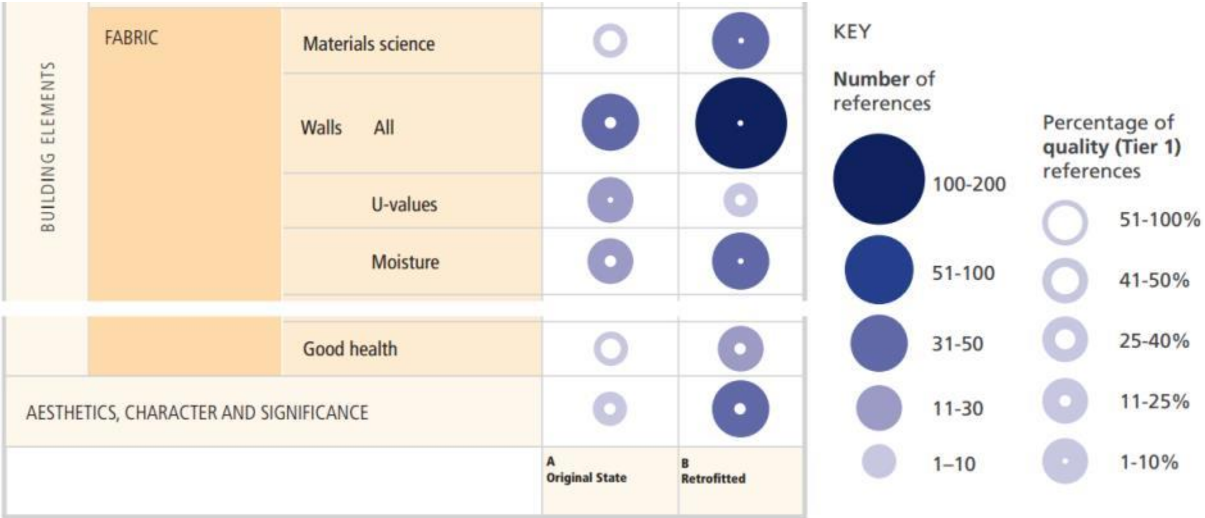


Figure 96 Extract of the 'Populated intelligence map' showing quantity & quality of existing research for different key topics of relevance to traditional building performance and retrofit. (STBA / Image © Sustainable Traditional Buildings Alliance)

The report recognises a lack of connection between research, standards, guidance and practice. Ultimately, it states that a new convention, with a more ample scope than *BS 5250:2011*, is required for assessing all the risks posed by moisture to traditional buildings.

The executive summary clearly identifies areas of required research:

> *A considerable programme of research into the following is required:*
>
> - *The performance of traditional buildings in terms of energy, heat, moisture, overheating, indoor air quality, and comfort.*
> - *Case studies of retrofit programmes in traditional buildings (both technical and user-focused) to further understand rebound effects and opportunities for better and more cost-effective retrofit programmes. The Green Deal provides an ideal opportunity for large-scale monitoring and feedback at low cost.*
> - *Data for the material properties of traditional UK building materials for use in modelling software.*

- *Better models for traditional buildings including the effects of driven rain, location-specific weather data and improved understanding of moisture mechanisms.*

- *The development of systemic understanding, methodology, and analysis of traditional buildings (as existing and when retrofitted) which incorporates the many interactions both within specific elements and at a whole house level and includes both technical factors and user behaviour.*

(May and Rye, 2012)

The authors fully agree with these conclusions and see the present work as part of that much required body of research.

The behaviour of water in porous building materials and structures

The behaviour of water in porous building materials and structures (Pender, 2004) is the title of an enlightening paper about the current understanding of moisture behaviour in porous materials (such as stone, brick and mortar). Besides a well-informed discussion on the principles behind moisture transport and the relevance of building-scale processes, the paper states that many insights from excellent research have not yet become part of the common understanding in conservation circles, let alone the general construction industry. Furthermore, she acknowledges that critical misconceptions are unfortunately integrated into standard advisory practice. Some of these are listed below as they are directly relevant to this study:

- The force that drives water transport in a building component is the vapour pressure differential between the exterior and interior of the building.

- Condensation within the structure occurs only if the air in the pore of the material has reached 100 %.

- There exists a 'zone' of condensation in a wall, determinable by equating increasing vapour pressure with decreasing material temperature.

These misleading simplifications, mostly related to the ‘diffusion paradigm’ (Rose, 2003), have led to the misuse of the Glaser method for quite different conditions than originally intended. In fact moisture driven by convection is normally far more relevant than vapour diffusion, and capillary transfer can be the dominant form of moisture movement in traditional walls, as determined by the conclusions in Section 6, based in a hygrothermal assessment of the case study in Section 5.

WTA Technical Sheet 6-4

WTA Technical Sheet 6-4 *Innendämmung nach WTA I: Planungsleitfaden* (WTA, 2009), only available in German and French, is a guidance document assessing internal wall insulation retrofits and their associated hygrothermal risks. It is published by the WTA, an international organisation based in Central Europe, with more than 32 workgroups and 300 active members. It has regional groups in Germany, Switzerland, the Netherlands and the Czech Republic. They represent the very pinnacle of knowledge in building physics, and their focus is on promoting the practical application of research, enhancing the actual application of new findings and the latest technology.

This document brings nuanced and detailed insights, backed by robust and up-to-date research, as opposed to simple advices and rules of thumb (predating numerical hygrothermal simulation) often found in national standards. It is frequently referred to by the Fraunhofer Institute for Building Physics as a state-of-the-art reference source for interpretation of results from hygrothermal simulations of IWI retrofits.

WTA Technical Sheet 6-4 states that, when the façade has only a limited protection to rain, preserving the drying capacity of the wall is particularly important and therefore in this context vapour permeable build-ups are preferred over vapour tight build-ups. It also states that capillary active insulants reduce the risk of moisture accumulation and can theoretically be installed without an AVCL, albeit backed up by a hygrothermal risk assessment in every case.

Internal Insulation: Building Physics Aspects, Problems and Limitations

Worch (2010) is an intriguing paper, the title of which translates as *Internal Insulation: Building Physics Aspects, Problems and Limitations*. Worch seems to be in close agreement with the tentative conclusions in this study. Despite its many simplifications these authors think this study shows results that are of interest, and directly contradictory to the results of the Glaser method assessment and the general perception of many in the construction industry that AVCLs are always 'best practice'. It shows how membranes blocking vapour diffusion become less appropriate as water uptake from driving rain increases for internally insulated solid walls.

Figure 97, extracted from the mentioned study, is the output from a hygrothermal simulation of an existing exposed brick solid wall, internally insulated with mineral wool insulation. It portrays the averaged total water content of the build-up as a function of insulation thickness, for 3 different levels of rain absorption (0 %, 50 %, 100 %) and the presence or absence of an AVCL.

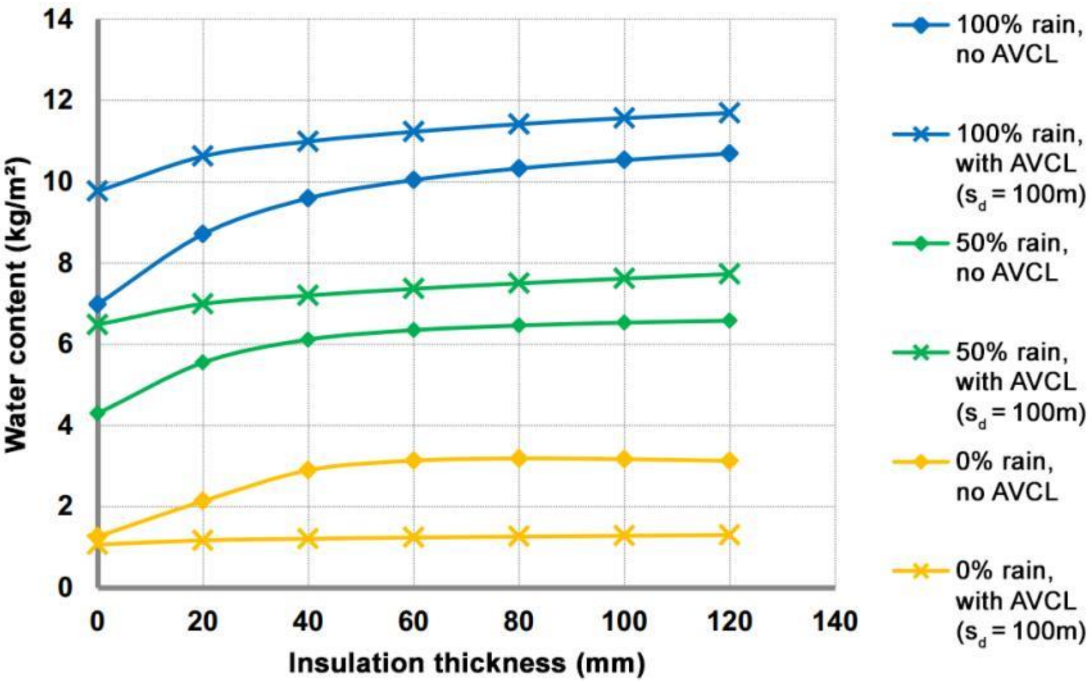


Figure 97 Average total water content (from hygrothermal simulation) of an existing exposed brick solid wall internally insulated with mineral wool insulation, as a function of insulation thickness (x axis), driving rain absorption (colour code) and presence or absence of an AVCL (point shape). (Image © Worch)

According to these calculations, the AVCL is only advantageous for the case with no absorption (0 %) of driving rain. For this case, the main cause of the increase in moisture content is interstitial condensation.However, for the cases of 50 % and 100 % rain water absorption, the main cause of the increase in moisture content is precisely rain absorption. For these cases, the inwards drying capacity is more significant than preventing interstitial condensation caused by vapour diffusion. Indeed in these cases installing an AVCL causes an increase in water content. The cases with rain absorption also show a more pronounced increase in water content with increasing insulation levels.

Appendix 2 Measuring absorption of masonry walls with Karsten tubes

Theory

The *Karsten tube test* is a method to measure in situ water absorption rates of a material surface. The test is relatively simple, quick, low-cost and non-invasive. This appendix describes the equipment, the testing method and the evaluation of the results.

The test is named after its inventor Rudolf Karsten, who first described the test method in 1963. (*Karsten, 2002*) The specific methodology recorded by RILEM (Réunion Internationale des Laboratoires d'Essais et de recherches sur les Matériaux et les constructions) is known as RILEM Test Method II.4. (RILEM TC 25-PEM, 1980; AMT Laboratories, 2006; Saldanha, & Eichburg, 2013). Variations or revisions to the method since then are more generally termed Karsten tube test methods. Using a tube attached to material surfaces, the test measures the rate of liquid absorption of vertical or horizontal surfaces under low pressure. *"When a water column is applied on a porous material, the water penetrates the material. The water volume absorbed after a definite time is a characteristic of the material."* (RILEM TC 25-PEM, 1980, p. 201) The rate of absorption and the pattern formed are directly related to the nature of the material's pore structure and its ability to transport liquid by capillary action.

Equipment

For the RILEM test method, the tube used for vertical applications is composed of two cylinders at right angles. (Figure 98) The shorter, horizontal cylinder having an internal width of 2.7 cm and an end surface area of 5.7 cm^2. The longer, vertical cylinder is 0.84 cm wide, with graduations down its length from 0.0 cm^3 to 4.0 cm^3, and divided into subgraduations of 0.1 cm^3. The end surface of the horizontal cylinder is applied to the wall surface, using a flexible, non-permanent sealant. When filled with water to the 0.0 cm^3 line, the pressure applied at the centre of the horizontal tube is 961.38 Pa, equivalent to a wind speed of 39.6 m/s or 142.6 km/h.

The time required to perform the test can vary depending on the porosity of the material tested. Usual test points are 5, 10, 15, 30 minutes and 1 hour. "In situ, one sometimes limits the measurements to the three first times … The water pressure decreases in function of its absorption by the material. By adding water manually and regularly one can limit the decrease of water pressure (maintain the water level ± constant in the tube)". (ibid., 1980) The results "are represented in the form of a water absorption graph (volume absorbed in cubic centimetres) in function of time in minutes". (ibid., 1980)

Figure 99 shows such a multi-tube test set-up. Deeply recessed mortar joints, undulating or very rough surfaces and surfaces with cracks are hard to test, as achieving a suitably tight seal at the surface-tube interface is often impossible.

Figure 98 Karsten tube fitted to the surface of mortar joint in brick masonry

Figure 99 Array of Karsten tubes being filled

Procedure for setting up in-situ tests

To minimise the risk of measuring anomalies, the authors recommend the adoption of a setting-up procedure for the testing:

- Ensure that the weather is suitable, as rain fall and hot sunshine may have an impact on absorption rates
- Create a standard table on which to record the field test results
- Record testers, date and location
- Record the ambient temperature and relative humidity, present at beginning and end of the test (It may be of benefit to also record the climatic conditions on the two previous days: this can be obtained from the website of the national meteorological office.)
- Walk around the building and select what area of wall is to be measured. Different wall finishes or repair work may prompt additional Karsten tube tests. As the tubes need to be relatively close to allow tracking of water content and refilling distance alone may determine that an additional test is necessary
- Choose a location for each tube, positioning them so that they can capture the broad moisture conditions that the wall is experiencing. The pattern in Figure 98 shows various joint locations – THJ top of heat joint for instance – that are relevant to brick, but can be easily adapted for stone-faced walls. For practical reasons it is advisable that no tubes are vertically aligned, as leakage from a tube at a higher location can conceal wetting patterns of the tube below.)
- Get a qualitative sense of the moisture content of the wall through use of a non-invasive moisture meter (Figure 100). Getting readings across the subject wall in this way is a useful survey procedure in its own right (potentially highlighting issues such as rising damp) but may also be useful in uncovering an anomaly that could affect the water uptake at a Karsten tube
- Choose locations for the test tube, so that the measurements can reflect the broad conditions the wall is experiencing (Figure 101) (Tubes should not be vertically aligned, as leakage from one above can conceal wetting patterns of the tube below. The pattern in the figure is intended for brick masonry, but can be easily adapted for stone walls.)

- Affix tubes to the wall (Seals made from Plasticine, polyurethane, butyl rubber or silicone rubber can be used. The seal should be carefully applied with some physical pressure. As the sealant compresses, care must be taken that the area of water making contact with the surface is not reduced, as this will make the measurement inaccurate.)

- Check each tube for leaks, before starting the measurement. (There may be no time to reapply a leaking tube at a new location during the test, if the wall is quite absorbent.

Figure 100 Karsten tubes, putty and Tramex MRH III moisture meter laid out ready for use.

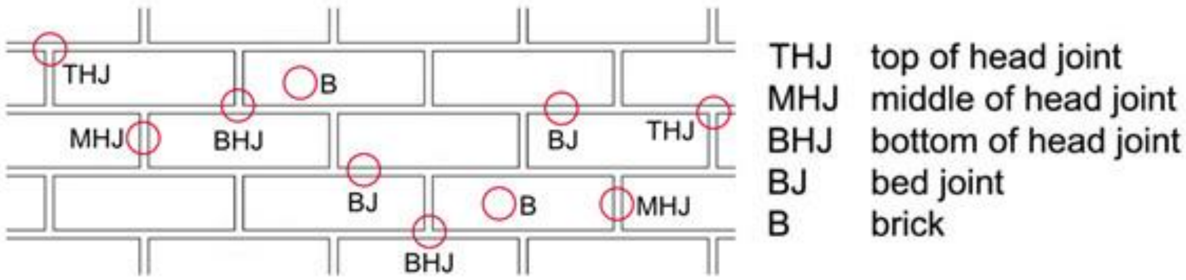


Figure 101 Positions have been marked on a drawing where tubes are to be installed.

Duration of measurement

No reference is made in the RILEM Test Method to the number of tubes required, but, usually, the mean value of five to ten readings is calculated to gain a good sense of the overall performance of an area of wall judged to have a similar character. For painted or rendered walls, significant variation in water absorption normally only occurs at an anomaly, and five to six tubes are usually considered sufficient. For brick surfaces, ten tubes are normally used, as the normal pattern of joints and bricks can lead to significant variance in absorption

The authors measure every 5 minutes over an hour (instead of Karsten's approach of 5, 10, 15, 30 minutes and 1 hour) for the following reasons:

- For low absorption surfaces a tube may not need to re-filled for a period as long as 15 minutes. In this case, a long period of the test could pass when the head of pressure at the face of the horizontal tube is considerably less than 961.38 Pa, thereby introducing inaccuracy.

- Filling all tubes every 5 minutes ensures a longer period of the test for which a pressure close to, or at, 961.38 Pa applies.

- Recording measurements at regular short intervals ensures that errors are more easily discovered, both on site and back in the office when evaluating the data.

- A constant time regime is easier to work with.

Testing procedure

The following is the procedural variation used by the author.

1. start stop clock

2. top up tubes to the 0.0 cm^3 mark (The tubes should have already been filled sufficiently to test them for leakage.)

3. refill the tubes, within five minute intervals, every time the water drops to 4.0 cm^3, recording the amount in a table

4. stop the clock, when a period is reached, recording timely in the same table the water height in each tube

5. restart stop clock, when filling recommences

In all cases, the tubes are measured or filled in the same order, e.g. from left to right. By using the stop clock in the way described above and always filling in the same order, the duration of water absorption measured is one hour, though the time spent from start to end of measurement period is longer. Obtaining consistent, reasonably accurate results for an absorptive wall would be difficult, if the clock would be kept running.

Interpretation of the results

Once complete, the results of the test measurements can be transferred to a spreadsheet and presented in the form of a water absorption graph. This shows volume of water absorbed (in millilitres or cubic centimetres, both units are equivalent) reported as a function of time (in minutes). The lines are generally straight, though inaccuracies represented as kinks can sometimes be seen. Figure 102 shows this graph for a brick-faced solid wall in Albany Road, Dublin. (Figure 106 shows a photographs of the tubes fitted to the brickwork.)

From this figure, quite a lot can be learnt about the wall simply by looking at the pattern of results for joints and centre of bricks:

- Are the bricks more or less absorbent than the joints?

- Could there be an issue with poorly laid head joints, etc.?

- Crissinger (2005) adds that the test allows one compare results between areas exposed to driving rain and unweathered areas of a wall, as well as to see the impact of a water repellent treatment. He states that it has been demonstrated that a solid wall could be vulnerable if the average water absorption of exposed areas is approximately twice that of unweathered areas. In addition, leakage to the inside face of a solid wall is more likely to occur during heavy wind-driven rain if a water absorption rate of 5 ml or more in less than five minutes has been measured during a Karsten tube test.

- A mean for the overall water absorption of the whole wall can be generated from these values in units of kg/m²√s. This result can be compared with values from other walls to give an assessor a good sense of how much liquid water the wall imbibes during driving rain. The assessor can quickly build up a database of values or share with others. This mean absorption value for the whole wall must not be confused with the water absorption coefficient or A-value, despite sharing the same units (kg/m²√s). The former relates to three-dimensional water absorption from the Karsten tubes, while the latter is based on one-dimensional water absorption.

- However, further software can be used to convert readings from the test into an A-value (also in units of kg/m²√s). Funcosil Aw-calc (available from Jens Engel at Remmers) solves a cubic equation to convert the three-dimensional water absorption measured during the Karsten tube test into an A-value. The resulting value can be used in hygrothermal risk assessments, using software compliant with BS EN 15026, such as WUFI Pro.

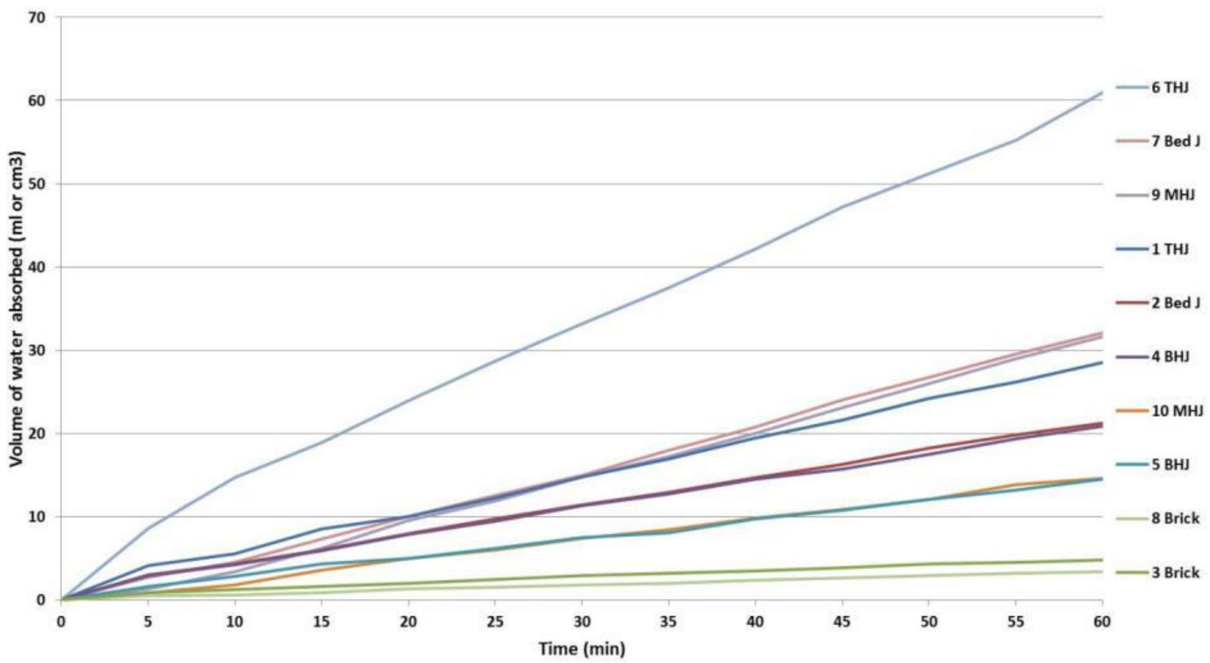


Figure 102 Absorption progression for each location tested on an exposed brick wall of a house in Dublin: The lower two graphs (green) represent measurements made directly on brick surfaces, the others were taken from mortar joints.

The author has carried out thirty absorption tubes tests on different types of wall in Ireland, the majority of them in Dublin City. Among these tests, 18 were carried out on brick walls, 8 on rendered walls, 3 on stone walls and 1 on a concrete wall. The graph in Figure 103 depicts the absorption patterns measured for some of these walls.

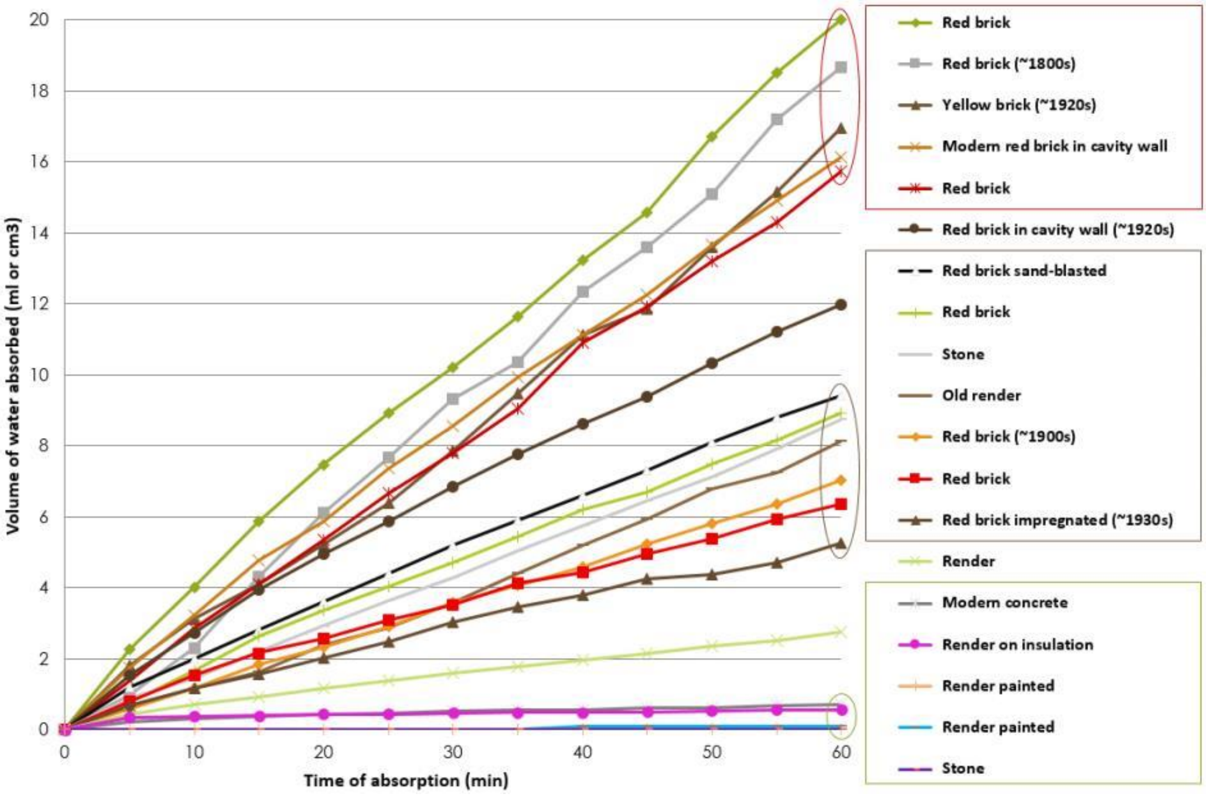


Figure 103 Absorption of a range of different buildings tested in Dublin: the mean progression is shown for each wall

At this stage, four broad categories of absorption have become evident and are listed in Table 22: They may act as guide values for readers interpreting their own results.

Absorption categories	Range of water absorption when the mean for the whole test is calculated [ml/h] or [cm³/h]	Materials
Non-absorptive	0-1	concrete, rendered and stone walls
Low absorption	1-9	concrete, rendered, stone and brick walls
Medium absorption	9-16	brick-faced walls
High absorption	> 16	brick-faced walls

Table 22 Range of commonly found values for the water absorption in ml after one hour

Absorption patterns observed on previous walls studied

During tests of porous, hygroscopic materials an absorption pattern beyond the sealant ring quickly becomes evident: This indicates areas of greatest absorptivity. (Figure 104) These patterns give further information about the permeability of the masonry. (Basham and Meredith, 1995) It is important to note this wetting pattern is not a leak: the latter would appear at a crack in the surface or dramatically after a breach in the sealing medium has occurred. It would be irregular in shape and downward oriented due to a clear flow of water affected by gravity. Firstly, when the brick is porous and fully homogeneous, a wetting pattern can begin as a circular pattern. In some cases, for tubes positioned on the brick itself, no wetting patterns can be observed and the volume of water absorbed is lower than the water absorbed by the joints.

Figure 104 Circular wetting patterns for the homogeneous surface

For tubes placed on joints the ideal pattern is shown in Figure 105 where the pattern spreads along the line of mortar joints proving that they absorb and transfer more moisture than the bricks they bond. This helps to protect the facing bricks or stones from freeze-thaw and spalling, and ensures a shorter life for the mortar pointing (which is appropriate). A maintenance regime of repointing (with the correct materials) every few decades therefore follows from a requirement to protect the brick.

Figure 105 Spread of water along an absorbent joint

A different pattern may also be found: Figure 106 shows an almost circular pattern with less absorption in the joint. This may be evident of too strong a cement mortar or of inappropriate maintenance work where an old lime joint was repointed with cement mortar. The brick or stone is now absorbing and transferring more than the joint. The pointing may even be blocking moisture stored in the weaker joint behind it. This increased localised water content can lead to the old lime joint breaking down behind the cement pointing. All of this can result in elevated moisture content in the bricks, especially at the junctions of brick and mortar joints, making the outer few millimetres vulnerable to spalling. The outer surface such a wall would be especially vulnerable after an inappropriate, moisture blocking, internal wall installation, as the moisture content of the wall would be greatest and its temperature lowest in winter, when conditions for freeze thaw are most common.

Figure 106 Specific wetting patterns on joint-brick interfaces can appear, as for the Dolphin House's brick wall

Unpainted render presents a specific behaviour in terms of water penetration. The spreading of the patterns is quicker at the beginning of the test than at its end. This can be explained by a saturation of the first millimetres of the render. Their absorption patterns are not really defined but will spread in the direction of cracks. Painted render may absorb little or nothing during a test. An undercoat and overcoat of paint on render or masonry will be capillary closed but should be quite vapour permeable. Repeated coats, especially of synthetic paints, become increasingly vapour impermeable. It is common for paintwork on older buildings, and particularly on garden walls, to blister, due to moisture accumulation.

Figure 107 The water absorption pattern in render is totally different.

Appendix 3 Input parameters for the WUFI simulations in the case study

The following input parameters were used to make the comparative study as transparent and replicable as possible.

1. **Simulation period:** The simulations were run for 15 years, from 1st October until 30th September.
2. **Orientation of building element:** The notional elevation, analysed, was facing north-west, like that of the associated, real building in Glasgow. (see Section 5.2.1.2)
3. **Material properties:** Relevant material data is listed in Appendix 4. The rationale behind the selection process of material properties is discussed in Section 5.2.3.2.
4. **Material thicknesses:** To allow close comparison between the scenario, using exact U-value, insulation thicknesses were assumed that achieved exact U-values, regardless if such thicknesses are commercially available.
5. **Heat resistances:** As heat resistance of external and internal surfaces, the software's default values of 0.04 and 0.13 m^2K/W respectively were used.
6. **Radiation:** Absorptivity and emissivity values were both set to 0.9 and the ground reflectivity to 0.2. Further details are given in Figure 108.

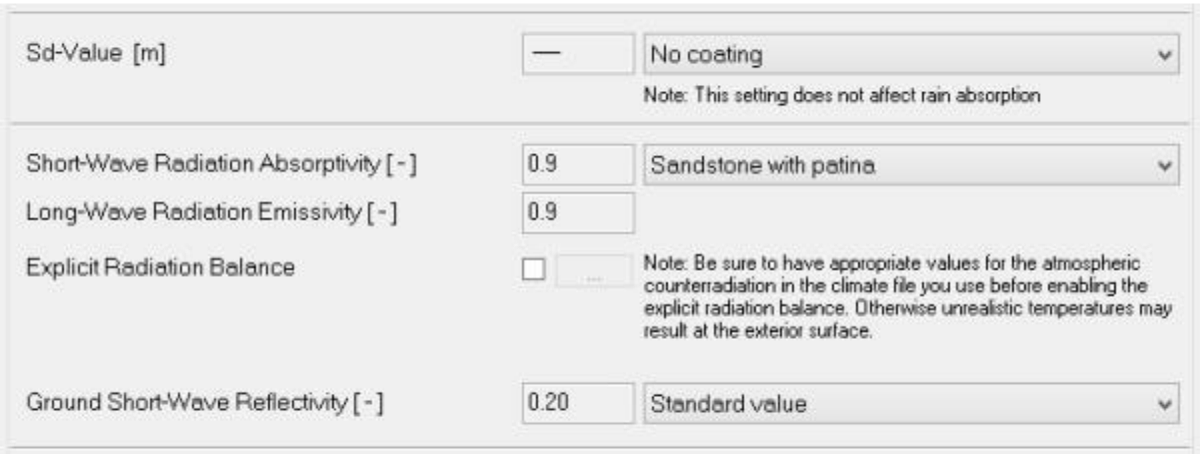


Figure 108 Screen shot of WUFI Pro showing the radiation values used in the case study simulations

7. **Weather file:** A design reference year file was created, using Meteonorm 6.1. The following settings were selected to create the file: default radiation model, 10-year extreme (hour), Perez-tilt radiation model and the latest time periods for temperature and radiation. For a seven-year simulation, the same weather file is used seven times.

8. **Rain load:** The rain load was calculated, using the default values for wind-driven rain co-efficients in WUFI, for the middle part of a buildings of between 10 to 20 m height: R1 = 0, R2 = 0.1.

9. **Water absorption:** The rain water absorption factor was left at the default value of 0.7, which means that 70 % of wind-driven rain is available for absorption at the wall surface, the rest splashes off immediately.

10. **Indoor moisture:** The indoor moisture load is predetermined by *BS EN 15026*. **Initial moisture content:** The following procedure was used to account for moisture already present in the existing wall prior to retrofit and for the moisture introduced into the wall by the retrofit measure: The initial hygrothermal conditions of the wall were simulated, until a state of equilibrium was reached. The water content profile at this point in time was exported, as a spreadsheet. To this were added the thicknesses and construction-stage moisture values of the retrofit measures. This adjusted profile was then imported into the software, as the starting position. (Figure 109)

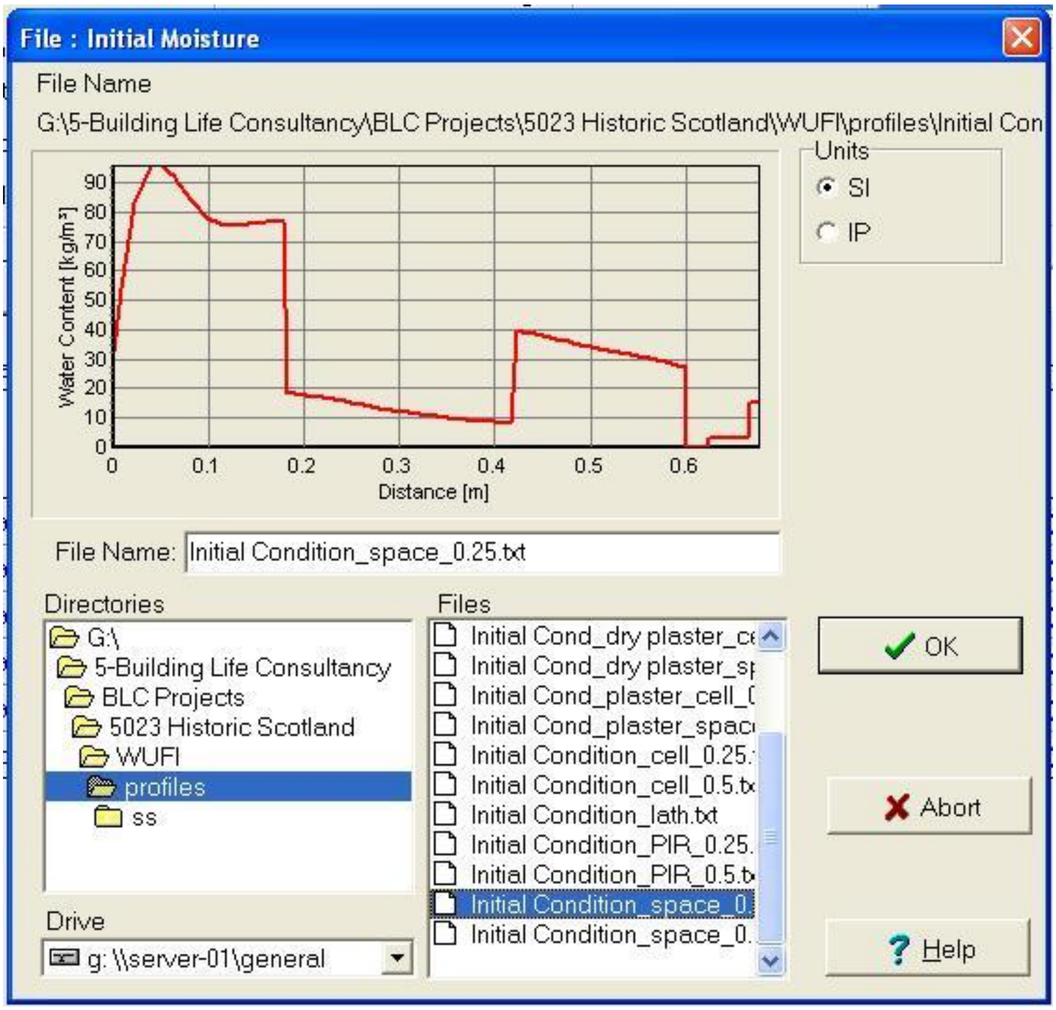


Figure 109 Screen shot of WUFI Pro showing a profile prepared for a simulation start: The graph right of the 0.6 m mark represents the moisture content of the retrofits.

Appendix 4 Material properties used in the case study

The thickness-independent material properties used in the case study assessments are listed in Table 23 overleaf.

Material	Bulk density [kg/m³]	Porosity* [m³/m³]	Specific heat capacity [J/(kg·K)]	Thermal conductivity [W/(K·m)]	Vapour diffusion resistance factor [-]	Free water saturation (100 % RH) [kg/m³]	Liquid transport coefficient [m²/s]
Adhesives and plasters							
Adhesive (for CSB†)	1410 MD	0.468 MD	1059 MD	0.6 MD	22.89 MD	280 MD	7×10^{-10} WD
Gypsum plasterboard 1	700 BS	0.65 WD	1000 BS	0.21 BS	8.3 BS	400 WD	4.5×10^{-6} WD
Gypsum plasterboard 2	1153 WD	0.52 WD	1200 WD	0.32 WD	16 WD	502 WD	1.1×10^{-9} WD
Lime plaster (general)	1600 BS	0.3 WD	1000 BS	0.8 BS	10 BS	250 BS	1.5×10^{-7} WD
Lime plaster (for CSB†)	1600 MD	0.3 MD	850 MD	0.7 MD	7 MD	250 MD	1.5×10^{-7} MD
AVCLs							
Intello membrane	115 WD	0.086 WD	2500 WD	2.4 WD	26000 WD	85 WD	0 WD
Polythene membrane	130 WD	0.001 WD	2300 WD	2.3 WD	50000 WD	0 WD	0 WD
PVC foil facing†	130 BS	0.001 BS	2300 BS	2.3 BS	20000 BS	0 WD	0 WD
Insulation							
Air	1.23 BS	0.999 BS	1008 BS	0.139§ BS	1 BS	0 BS	0 WD
Aerogel blanket	146 WD	0.92 WD	1000 WD	0.014 WD	4.7 WD	213 WD	1.3×10^{-11} WD
Calcium silicate board	222 MD	0.92 MD	1303 MD	0.057 MD	5.4 MD	815 MD	4.9×10^{-6} MD
Cellulose fibres, blown	50 MD	0.95 MD	2000 MD	0.04 MD	1.8 MD	426 WD	2.3×10^{-7} WD
Phenolic foam board	43 BS	0.95 WD	1400 BS	0.023 BS	50 BS	400 WD	4.5×10^{-6} WD
Masonry							
Lime mortar	1785 BS	0.28 WD	1000 BS	0.7 WD	15 WD	247.6 BS	1.63×10^{-6} WD
Sandstone (silica)	2600 BS	0.23 WD	1000 BS	2.3 BS	30 BS	210 BS	3×10^{-7} WD
Stone A (Baumberger)	2600 BS	0.23 WD	1000 BS	2.3 BS	30 BS	210 BS	3×10^{-7} WD
Stone B (Obernkirchner)	2600 BS	0.14 WD	1000 BS	2.3 BS	30 BS	110 BS	2.3×10^{-6} WD

Data provenance: BS: BS EN 10456 / MD: manufacturer's data / WD: WUFI data

* porosity not accounted for in BS EN 13788; used in numerical simulation only

† Foils are listed as being 1 mm thick for the sake of simulation; the actual s_d values are divided by 0.001 m.

‡ for use with calcium silicate board (as per manufacturer's recommendation)

§ for air cavities, thermal conductivity calculated in accordance with BS EN 6946 to account for convective and radiative heat transfer

discontinuity

Table 23 Thickness-independent material properties

Glossary

λ-value See *Thermal conductivity (λ-value)*

μ-value See *Vapour diffusion resistance factor (μ-value)*

ψ-value See *Linear thermal transmittance (ψ-value)*

Absorption See *Sorption*

Adsorption See *Sorption*

Air and vapour control layer (AVCL) Membrane or layer of a *building component* that limits air and *vapour movement*. It must be continuous to be effective.

Airtightness layer Layer that prevents convective movement of air under the normal vapour pressure differences found in buildings and which may (or may not) also act as a vapour control layer. Such layers are sometimes known as 'convection tight'.

British thermal unit [Btu] Non-metric, non-SI unit that describes the amount of energy needed to cool or heat one pound of water by one degree Fahrenheit. 1 Btu = 1.05 kJ (kilojoule)

Building component Each building component has a specific assembly of building materials, with specific properties and performances. It may be pre-fabricated or erected on site at one time or, in the case of retrofit, over many years. See *Building element*

Building element The building fabric is broken down into building elements, such as floors, walls and roof. At times, a building element may be a building competent; in other cases, the element may be made up of many component parts. See *Building fabric* and *building component*

Building fabric The sum of the structural, fixed materials of which the building is made. This contrasts with furnishings which are loose. See *Building element* and *thermal envelope*

Capillary action The movement of a liquid in narrow spaces, either small tubes or porous materials, due to intermolecular forces between the liquid molecules and the surrounding surfaces. If the diameter of the tube is sufficiently small, the combination of surface tension and adhesion to the surface acts to draw the liquid along the tube. This is also referred to as 'wicking'.

Capillary active material Material with a pore size and structure sufficient to induce liquid movement by capillary action.

Capillary break Interface between a *capillary active material* and a non-capillary active material. This interface may also be at the surface of the capillary active material, i.e. interface between the material and air.

Condensation Process by which water is deposited from air containing water vapour when its temperature drops to or below dewpoint, or the vapour pressure rises above the saturated vapour pressure at a given temperature. Interstitial condensation occurs within layers of the building envelope and Surface condensation is on visible surfaces within the building.

Conduction, Thermal conduction Transfer of heat between stationary molecules; it is the primary mode of heat transfer in solids.

Conservation of energy States that the total energy of a closed system remains constant – it is conserved over time: it can only be transformed from one energy state to another.

Convection, Thermal convection Transfer of heat by a combination of advection (the movement of molecules from one location to another) and *conduction*. This is the primary mode of heat transfer in free-flowing liquids and gases. For movement of moisture by convection, see *Moisture convection*

Dalton's Law See *Law of Partial Pressures*

Density Mass per unit volume of a material, typically expressed in kilograms per cubic metre [kg/m^3]

Design Reference Year Climatic data for a whole year, assembled from data recorded during a number of years, to be used for design purposes. A Design Reference Year tends to represent extreme conditions to allow for risk, whereas a Test Reference Year represents averaged conditions.

Desorption See *Sorption*

Dewpoint, dewpoint temperature Dewpoint is the temperature to which a given parcel of humid air must be cooled, at constant barometric pressure, for water vapour to condense into water. The condensed water is called dew. The dewpoint is a saturation temperature.

Differential equation Mathematical equation for an unknown function of one or several variables that relates the values of the function itself and its derivatives of various orders.

Diffusion paradigm The diffusion paradigm is that version of building physics which explains hygrothermal performance of building envelopes in terms of water vapour diffusion, which uses the steady-state profile method and leads to recommendations in the USA for vapour barriers and attic ventilation. It is the predisposition toward prescriptive guidance inhibited the development of an engineering approach.

Driving force, Driving potential A differential within a system which forces the movement of mass or energy to allow the system to reach equilibrium. Example: a temperature differential is the *driving potential* which forces heat from warm areas to cold areas to establish a uniform temperature

Gaseous state State of matter distinguished from the solid and liquid states by: relatively low density and viscosity; relatively great expansion and contraction with changes in pressure and temperature; the ability to diffuse readily; and the spontaneous tendency to become distributed uniformly throughout any container

Glaser method Well-established method of assessing *hygrothermal performance* under BS EN ISO 13788. See also *Numerical simulation assessment*

Heat Transfer of energy from a hotter to colder body other than by work or transfer of matter**,** often expressed in joules (J). The total *heat* in a system can be expressed as the sum of latent heat and sensible heat. See also *Heat movement*

Heat transfer See *power*

Hygroscopicity, Hygroscopic material The ability of a material to take in moisture from the surrounding environment by either absorption or adsorption, and to hold it within its molecular structure. As moisture accumulates, the physical properties of a material change (for example, materials may swell or become sticky), but are returned to their original state when the moisture is released. See also *Non-hygroscopic material*

Hygrothermal performance It can be assessed using, for example, the *Glaser method assessment* or *numerical simulation assessment*. These methods assess heat and moisture transfer through a building component under a range of boundary conditions

Hysteresis The manner in which the equilibrium moisture content of a porous material for a given RH may differ depending on whether it is reached during wetting or drying. This can be due to a number of reasons, such as water caught behind a narrow pore passage or the different contact angles between water and pore wall during wetting and drying.

Isopleth Contour line (often used in geography) joining points having the same value of some quantity. In the context of mould risk assessment, isopleths can be used to describe mould growth conditions independent of temperature and relative humidity levels

Joule [J] SI unit, describing the measure of energy used or work done in applying a force of one newton through a distance of one metre

Latent heat The quantity of heat absorbed or released by a substance undergoing a change of state, such as ice changing to water or water to steam, at constant temperature and pressure. See also *Sensible heat*

Law of Partial Pressures A scientific principle which states that in a gas mixture (such as air) the partial pressures of each component are independent of each other and that the total pressure equals the sum of the partial vapour pressures. This is also called Dalton's Law of Partial Pressures.

Linear thermal transmittance (ψ-value) Linear thermal transmittance is the measure of the additional heat loss, or thermal bridging, that occurs at component junctions, over and above the plane element heat losses. It is measured in W/(m·K). See also *Thermal transmittance (U-value)*

Liquid water See *Moisture*

Moisture Water in its solid, liquid or gaseous/vapour states. See also *Moisture content*, *Moisture convection* and *Moisture movement*

Moisture content Mass of water (in any state) per unit volume of a material, often expressed in kilograms of water per cubic metre (kg/m^3)

Moisture convection Movement of water vapour through a space via air currents or bulk air movement (as opposed to by *diffusion*). For thermal convection, see *Convection*

Moisture diffusivity (D_w) This describes the capillary transport of moisture in the liquid phase, which is the predominant moisture transport mechanism in capillary porous materials. In the context of building physics it is sufficiently accurate to regard the liquid transport in the pore spaces as a diffusion phenomenon (although it is basically a convective phenomenon). WUFI measures it through two liquid transport that depend on both material properties and boundary conditions (see *Wetting diffusivity* and *Drying diffusivity*).

Wetting diffusivity (D_{ws}) This is defined in WUFI as the liquid transport coefficient for suction, measured in units of square metre per second (m^2/s). It describes the capillary uptake of water when the imbibing surface is fully wetted. In the context of building physics this describes rain on a façade or an imbibition experiment. The suction transport is dominated by the larger capillaries, since their lower capillary tension is more than compensated by their markedly lower flow resistance.

Drying diffusivity (D_{ww}) This is defined in WUFI as the liquid transport coefficient for redistribution, measured in units of square metre per second (m^2/s). It describes the spreading of the imbibed water when the wetting is finished, no new water is taken up anymore and the water present in the material begins to redistribute. In a building component, this corresponds to the moisture migration in the absence of rain. The redistribution is dominated by the smaller capillaries since their higher capillary tension draws the water out of the larger capillaries. See also *Moisture* and *Moisture movement*.

Moisture movement, Moisture transfer Mode of transfer is very dependent on the state the moisture is in. Water can exist in the same material as a solid, a liquid and a gas in all three states simultaneously and can change state as conditions change. This is well explained in Section 3.2 of this paper. See also *Moisture*

Moisture storage function Property of a hygroscopic material which serves as the regulator for how much liquid water it can store: for each relative humidity a different water content will be present. This can be tabulated for each material.

Non-hygroscopic material Material which lacks the ability to take in moisture below *saturation vapour pressure*. Moisture accumulation in a *non-hygroscopic material* results in a liquid water build-up on the surfaces of the material, which can lead to permanent damage if the quantity of water exceeds certain thresholds (e.g. slumping mineral wool becoming compressed). See also *Hygroscopicity*

Numerical Simulation This is the prediction of transient heat and moisture transfer in multi-layer building envelope components, subjected to non-steady-state climate conditions on either side. The software solves transient differential equations for each cell of a model repeatedly to do this. BS EN 15026 is the relevant standard. See also *Glaser method assessment*

Partial pressure See *Law of Partial Pressures*

Plane element Component of a building with defined two-dimensional surfaces, such as walls, roofs, windows. Plane element heat flow (termed thermal transmittance, or U-value) is considered uniform across its extent allowing for any repeat thermal bridges within it. Linear thermal bridging (termed linear thermal transmittance, or ψ-value) occurs at junction of plane elements.

Porosity Fraction of airspace within a material, often expressed as cubic metres of air per cubic metre of material (m^3/m^3) or a percentage of the total volume which is composed of air.

Power Rate at which work is done or energy is transferred, often expressed in watts (W). One watt corresponds to rate of one joule per second (1 W = 1 J/s)

Radiation Transfer of heat by electromagnetic waves emitted from or absorbed by a surface. It one of three heat transfer modes convection and conduction.

Relative humidity (RH) Measure of vapour within a space relative to its saturation point at the same temperature, strictly defined as the fraction of the partial vapour pressure over the saturation vapour pressure at the same temperature.

Reverse diffusion This refers to the movement of vapour molecules in capillaries within the component towards the interior of the building, due to higher temperatures on the outside surface of the wall.

Saturated air Air in which the water vapour has reached its *saturation vapour pressure.* This state corresponds to 100 % *relative humidity* and the temperature corresponds to the *dew-point temperature.*

Saturation vapour pressure The maximum *vapour pressure* (i.e. maximum amount of vapour) possible in air at a specific temperature.

Sensible heat is heat exchanged by a body or thermodynamic system that has as its sole effect a change of temperature. The term is used in contrast to latent heat, which is the amount of heat exchanged that is hidden, meaning it occurs without change of temperature.

Solid water See *Moisture*

Sorption The process in which a material takes up a liquid or vapour, usually moisture. Sorption is a combined term that includes both *ab*sorption and *ad*sorption: whilst spelt similarly these are very different. In the context of a porous material, absorption is the uptake of moisture from the environment into the volume of the solid material, combining with its molecular structure. Adsorption is the adhesion of a very thin layer of liquid to the surface of the pore wall, drawn by molecular forces. Desorption (the opposite of sorption) refers to the release of moisture from the porous material, and is often caused by a rise of temperature.

Specific heat capacity Material property used to describe the amount of thermal energy required to change the temperature of a unit mass of material, often expressed as the number of joules required to change one kilogram of material by one kelvin [J/(kg·K)].

Steady-state State where conditions are assumed to be constant, i.e. not changing over time. Steady-state calculations do not take account of changes over time: they analyse a system under fixed conditions. On the other hand, transient calculations take account of changes in the system over time, such as oscillations in temperature. See also *Transient*

Surface diffusion Where vapour is pulled to the surface of pores of hygroscopic materials by adhesion and then cohesion forces causing it to condense and line the surface as a film of water to.

Temperature Temperature is not heat, it is the degree of 'hotness' of a body. More precisely, it is the potential for heat transfer.

Temperature differential The difference in temperature between two objects or areas.

Temperature factor (f_{Rsi}) Ratio of the temperatures used to assess the risk of surface condensation, or mould growth, near a thermal bridge. It represents the coldest internal surface temperature relative to the temperature difference between inside and outside.

Temperature profile Visual representation of the temperature at every point through a cross section of a material.

Thermal bridge Part of a structure of lower thermal resistance which bridges adjacent parts of higher thermal resistance and which can result in localised cold surfaces on which condensation, mould growth and or pattern staining can occur. Source: BS 5250 Control of Moisture in Buildings. See *plane element* and *linear thermal transmittance*

Thermal bypass Heat transfer that bypasses the conductive or conductive-radiative heat transfer between two regions. It may well be a major contributor to the performance gap that appears to exist between predicted and actual thermal performance. Bypass mechanisms include air leakage, thermal looping, wind washing etc.

Thermal conductivity (λ-value) A material property describing the rate at which *heat* is transferred through a length of material at a specific *temperature differential. It is f*requently expressed as the number of watts transferred across one metre of material at a temperature differential of one kelvin (W/mK).

Thermal convection See *Convection*

Thermal envelope Part of the *building fabric* which separates the indoor climate from outdoors.

Thermal transmittance (U-value) A value to describe the steady-state heat transfer through *plane elements* in a building, which is dependent on conductivity of each material and the thickness of each layer within the component. Empirical relationships have been developed to incorporate radiation and convective heat transfer at the surfaces of the component. *Thermal transmittance* is often expressed in units of watts transferred per square metre of plane surface area per kelvin of temperature difference (W/m^2K). See also *Linear thermal transmittance*

Thermodynamic temperature Measure of the average energy of all of the vibrational, rotational and translational motions of the molecules, atoms and sub-atomic particles of a body

Traditional buildings Buildings constructed with natural materials that tend to be moisture managing and are often vapour permeable, hygroscopic and capillary open. Examples of *traditional building materials* include clay bricks, stones, timber and lime plasters and mortars. Construction methods tend to focus on managing moisture and throw off rain rather than blocking and sealing.

Transient A state where conditions and the response of the system to the conditions are assumed to change over time. See also *Steady-state*

U-value See *Thermal transmittance*

Vapour diffusion The movement of vapour molecules in capillaries within a component, in an attempt to equally distribute themselves and reach equilibrium. It always occurs in the direction of high vapour pressure to low vapour pressure. See also *Surface Diffusion*, *Vapour diffusion resistance factor (µ-value)* and *Vapour movement*

Vapour diffusion resistance factor (µ-value) Material property describing the rate of vapour diffusion in a material as compared to still air: By definition, still air has a µ-value of 1; all other materials have a µ-value greater than 1. See also *Vapour diffusion*

Vapour movement See *Vapour diffusion* and *Surface Diffusion*

Vapour pressure This is part of the atmospheric pressure due to water vapour present in the air. Vapour pressure is measured in kPa, with 1kPa = 10 mbar = 1000 N/m^2.

Vapour-open / vapour-closed Qualitative description of how easily vapour can diffuse through a material. *Vapour-open* materials, such as mineral wool or wood fibre, have low µ-values and allow vapour diffusion to occur relatively easily. *Vapour-closed* materials, such as a PE-membrane or foil layer, have high a *vapour diffusions resistance factor (µ-value)*, which greatly restricts vapour diffusion.

Vapour transfer See *Vapour diffusion* and *Surface Diffusion*

Water vapour See *Moisture*

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Abbreviations

AECB	Association of Environment Conscious Building; formerly: Association of Environment Conscious Builders (*UK*)
AIP	American Institute of Physics (*USA*)
ANSI	American National Standards Institute (*USA*)
Ar	argon
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers (*USA*)
AVCL	air and vapour control layer
BBA	British Board of Agrément
BRE	BRE (*UK*; formerly: Building Research Establishment; predecessor: *BRS*)
BRS	Building Research Station (*UK*; successor: *BRE*)
BS	British Standard
BSI	British Standards Institution (*UK*)
CEN	European Committee for Standardization (French name: Comité Européen de Normalisation)
CIB	International Council for Building (French name: Conseil International du Bâtiment)
CIBSE	Chartered Institution of Building Services Engineers (*UK*)
CMHC-SCHL	Canada Mortgage and Housing Cooperation (French name: Société canadienne d'hypothèque et de logement; Canada)
CO_2	carbon dioxide
DCLG	*HM Government*, Department for Communities and Local Government (*UK*)
DECC	*HM Government*, Department of Energy and Climate Change (*UK*)

DEFRA	*HM Government*, Department for Environment, Food and Rural Affairs (*UK*)
DIN	German Institute for Standardization (Germany; German name: Deutsches Institute für Normung)
DIT	Dublin Institute of Technology
DPC	damp proof course
e.g.	for example (Latin: exempli gratia)
EN	*CEN* standard
EST	Energy Saving Trust (*UK*)
EURAC	European Academy of Bozen / Bolzano (Italy)
Fraunhofer IBP	Fraunhofer Institute for Building Physics (Germany)
Fraunhofer IRB	Fraunhofer Information Centre for Planning and Building (Germany; German name: Fraunhofer Informationszentrum für Raum und Bau)
GCI	Getty Conservation Institute (*USA*)
H_2O	water
HAM	heat, air and moisture
HM Government	Her Majesty’s Government (note: government of the *UK*)
HMSO	Her Majesty’s Stationary Office (*UK*)
IBP	see *Fraunhofer IBP*
ibid.	‘in the same place’ (Latin: ibedem)
i.e.	that is (Latin: id est)
IEA	International Energy Agency
IRB	see *Fraunhofer IRB*
ISO	International Organization for Standardization

KTH	Royal Institute of Technology (Swedish name: Kungliga Tekniska Högskolan; Sweden)
LBNL	Lawrence Berkeley National Laboratory (*USA*)
LIM	lowest isopleth for mould
MASEA	Collection of material properties for energetic building renovation (German: Materialdatensammlung für die energetische Altbausanierung)
N	nitrogen
n/a	not applicable
NASA	National Aeronautics and Space Administration (*USA*)
n.d.	not dated
NBS	NBS (formerly: National Building Specification; *UK*)
O	oxygen
ORNL	Oak Ridge National Laboratory (*USA*)
p.	page
PDF	portable document format
PE	polythene
PIR	polyisocyanurate
pp.	pages
PUR	polyurethane
PVC	polyvinyl chloride
RH	relative humidity
RICS	Royal Institution of Chartered Surveyors (*UK*)
RILEM	International Union of Laboratories and Experts in Construction Materials, Systems and Structures Materials and Structures (formerly: International Union of Testing and Research Laboratories for Materials and

	Structures; former French name: Réunion International des Laboratoires d’Essais et de Recherches sur les Matériaux et les Constructions)
SI	International System of Units (French: Système International d'Unités)
TU Dresden	Technische Universität Dresden (Germany)
UK	United Kingdom of Great Britain and Northern Ireland
UK GBC	*UK* Green Building Council
UK Parliament	Parliament of the United Kingdom of Great Britain and Northern Ireland
USA	United States of America
SPAB	Society for the Protection of Ancient Buildings (*UK*)
STBA	Sustainable Traditional Buildings Alliance (*UK*)
TIS	German Insurance Association, Transport Information Service (Germany)
WHO Europe	World Health Organization, Regional Office For Europe
WUFI	Heat and Moisture Intransient (note: software by *Fraunhofer IBP*; German name: Wärme und Feuchte instationär)
WTA	International Association for Science and Technology of Building Maintenance and the Preservation of Monuments (German name: Wissenschaftlich-Technische Arbeitsgemeinschaft für Bauwerkserhaltung und Denkmalpflege)

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