Avoidance and diagnosis of problems associated with internal wall insulation

Matthew Smith

Natural Building Technologies, The Hangar, Worminghall Road, Oakley, Buckinghamshire HP18 9UL
Website: www.natural-building.co.uk; Tel: 01844 338338; E-mail: m.smith@natural-building.co.uk

***Matthew Smith** is technical manager for Natural Building Technologies, focusing on energy efficiency for traditional buildings. An expert in moisture transfer in porous building materials, and student of building conservation, he sits on the UK Centre for Moisture in Buildings technical working group for monitoring and modelling moisture in buildings.*

Abstract

Improving energy efficiency and comfort of traditional buildings affects how moisture moves through the building fabric. Internally insulating solid masonry walls can have a hugely positive impact on comfort, but doing so without regard for this relationship can lead to undesirable consequences, including trapped moisture and mould growth. A well-designed specification informed by a good understanding of the building and its context will preclude any unintended consequences.

Keywords: moisture, insulation, masonry, risk, drying, condensation, breathable

Internally insulating a solid walled property can lead to a dramatic increase in comfort and energy efficiency. The high density of stone or brick that makes masonry walls so stable and resilient is associated with high thermal conductivity; a significant level of heating is therefore required to provide comfort in these buildings. A minimal level of insulation can reduce the heat loss through masonry by over 60 per cent,[1] and while quantifying the impact of this on the thermal performance of a whole building requires further research, the potential benefit is obvious. Internal solid wall insulation is among the top three measures for potential fuel savings from domestic buildings.[2]

The unintended consequences of insulating internally are poorly understood, however, and a tendency to regard the installation of internal wall insulation (IWI) as akin to wallpapering can result in defects that impair structural integrity and occupant health. The majority of these issues are related to moisture, due to the impact on drying potential of the masonry and the relocation of potential dewpoint (temperature at which condensation occurs for a defined vapour pressure) within the wall. As insulation and airtightness levels increase to maximise energy efficiency, management of water vapour is proving increasingly difficult to achieve. IWI is the most sensitive test-bed for a successful approach.

MOISTURE TRANSFER IN SOLID MASONRY

Survey and assessment of defects associated with IWI should be guided by an understanding of best practice specification and installation, as well as a grounding in basic building physics. Insulating a solid wall radically alters the hygrothermal dynamics of the building from its uninsulated state, disturbing an equilibrium between moisture absorption

Journal of Building Survey, Appraisal & Valuation
Vol. 6, No. 1, 2017, pp. 1–15
© Henry Stewart Publications, 2046–9594

and drying potential that will have served the building well for many years. Solid masonry buildings rest on different principals to those which apply to modern masonry construction. Modern buildings are designed to limit the access of moisture to the structure with a DPC, a cavity and hydrophobic insulation serving as a capillary break to prevent moisture tracking across from the external leaf, drainage and low level of airflow within the cavity to enable drying, and vapour-resistant internal finishes. In contrast, traditional solid masonry buildings function as moisture reservoirs with capacity to absorb and store a great deal of moisture when the strength of sources outweighs drying potential (winter), until such time as conditions for drying predominate (summer), thereby balancing the sources of moisture acting on the building with drying potential. The thicker the wall, the more capacity for moisture storage.

The nature of the materials involved facilitates this process; masonry is porous, vapour permeable, hygroscopic (adsorbs vapour as relative humidity increases and releases it as humidity drops), and capillary active (contains interconnected pores which redistribute moisture at high concentration to areas of lower concentration by capillary action). In the walls' original state, moisture evaporates from both surfaces, enabled by permeable finishes inside and out. Historically, a high level of airflow internally through chimneys and other draughts facilitated this process and ensured the balance between moisture sources and drying was maintained.

Modern living habits have increased internal moisture load in buildings: A typical family in a three-bedroom house generates between 9 and 15 litres of water as vapour per day, draughtproofing has reduced air exchange with drier external air, and central heating has increased the capacity of the air within the building to hold moisture. These factors combine to raise the vapour pressure within the internal environment (water vapour exerts a partial pressure like any other gas) to roughly double the external level during the heating season.[3] The resulting vapour pressure gradient causes vapour diffusion through the porous walls, even with an adequate ventilation system. In an uninsulated solid wall, the steepness of the

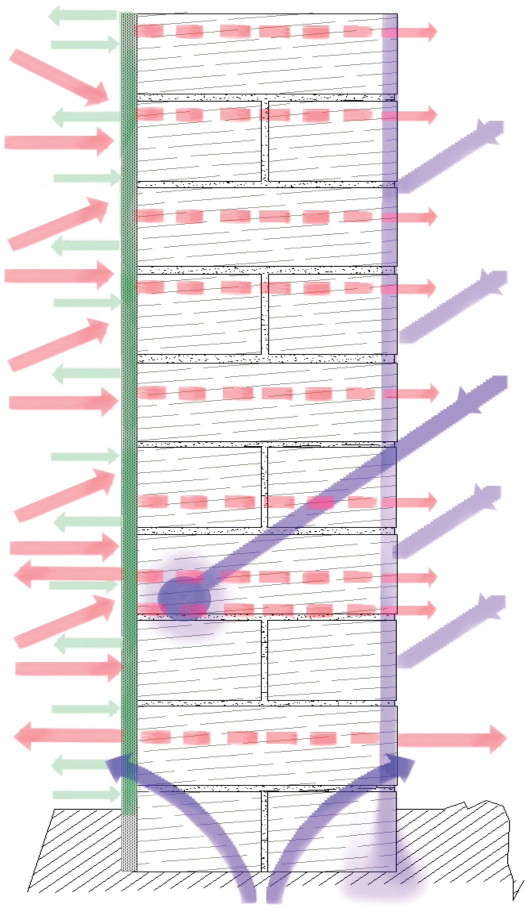


Figure 1: Simplified depiction of moisture flow through solid masonry: Blue arrows: rain absorption at external surface, direct penetration of rain water at weak points (eg window sills), capillary redistribution of moisture from areas of high (eg wall base) to lower moisture content. Red arrows: vapour diffusion in heating season from inside to out and evaporation from both internal and external surface. Green arrows: hygroscopic adsorption and desorption by internal plaster. (Image courtesy of NBT)

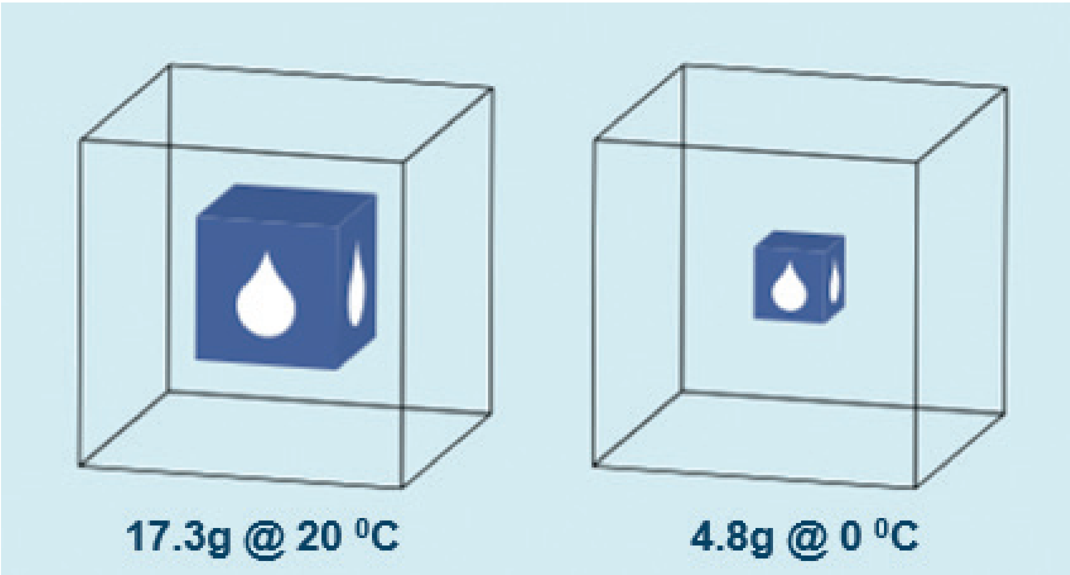


Figure 2: Maximum absolute humidity at different temperatures for a cubic metre of air — illustrative of the dependence on temperature of the moisture-carrying capacity of air and the concepts of saturation vapour pressure (SVP) and relative humidity (RH). (Image courtesy of NBT)

vapour gradient is roughly relative to that of the temperature gradient due to proportionality of the thermal conductivity and vapour resistivity of the masonry. As vapour passes through the wall, it is adsorbed and condenses within it towards the external surface, while moisture evaporating from the external surface and the thermal gradient from warm interior to cold exterior help drive the process. The masonry has a very high capacity to absorb any condensation without any adverse effect.

The key concept in understanding the potential for interstitial condensation when applying IWI to such a wall is the inextricable link between heat transfer and moisture transfer. Warmer air has a higher potential absolute humidity, so temperature determines the saturation vapour pressure (SVP) — the pressure above which condensation occurs for a given vapour pressure, and thereby determines both dewpoint temperature and relative humidity (RH = vapour pressure of a sample as a percentage of its SVP at constant temperature). If heat transfer through the wall is altered, moisture transfer is affected.

INTERSTITIAL CONDENSATION/ EXCESSIVE HUMIDITY WITHIN THE WALL

Insulating internally significantly cools the internal surface of the masonry. The temperature gradient in the insulation can be steeper than the dewpoint gradient, so vapour diffusing or carried via infiltration of warm moist air will condense at the interface of insulation and cold masonry where temperature and dewpoint gradients intersect. The thicker the insulation, the colder the interface with the masonry, and therefore the higher the relative humidity.

This interface is where the most vulnerable elements in solid masonry construction are located: timber lintels and joist ends that wick up moisture due to their relatively high adsorption rates and capillary conductivity.

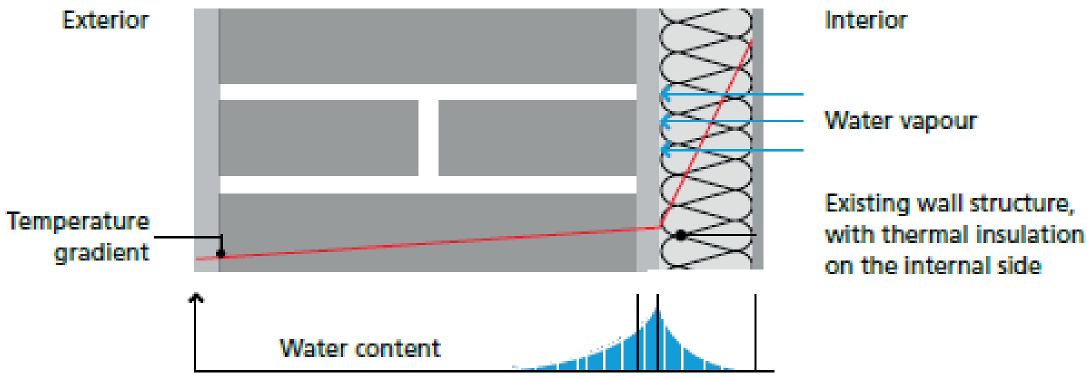


Figure 3: The potential condensation plane when insulating internally. (Image courtesy of NBT)

Some types of insulation have no moisture-carrying capacity, so the potential for moisture accumulation is high in such cases, and the risk of decay of vulnerable structural elements increases. Even without accumulation of liquid moisture, mould growth on interstitial surfaces will result due to excessive relative humidity. This can have an adverse impact on the health of the buildings' occupants.

The most common specification designed to address this problem is the inclusion of a vapour control layer (VCL) on the warm side of the insulation: a layer of plastic or foil of high vapour resistance, theoretically sealed to prevent moisture migration by air movement (according to wind or temperature-induced air pressure differences), as well as vapour diffusion from inside.

The specification of a VCL is based on a calculation methodology known as the Glaser calculation, which is set out in BS EN 13788. It is the ideal tool for the purpose for which it was designed: to assess condensation risk from occupancy-generated moisture in lightweight build-ups that include a capillary break behind an impermeable rain-screen, roof covering, or outer brick leaf. Such build-ups often have the additional safety factor of airflow behind the rain-screen (whether designed in or by default), which permits any vapour that diffuses through the insulation to be harmlessly carried away.

For solid masonry functioning as a massive reservoir of moisture, the Glaser calculation is incomplete and inaccurate. It only assesses vapour diffusion from inside, without accounting for hygroscopic adsorption, or liquid transfer such as surface diffusion and capillary conduction, which are important transfer processes for porous materials. It is run on a steady state basis (monthly averages) and, critically, cannot assess the impact of transient conditions such as rain, wind or sunshine.

In a Glaser calculation, with vapour from inside as the only source and the impact of rain absorption ignored, the inclusion of a VCL theoretically eliminates condensation regardless of exposure. Moisture load resulting from rain absorption is, however, more important than internal vapour load for porous walls without a capillary broken outer leaf,[4] and any measure that reduces the drying potential of the masonry is likely to increase risk.

Until recently, the VCL approach had been recommended in the British Standard that governs condensation control in buildings (BS 5250), despite the authors' recognition of serious shortcomings in the Glaser calculation when applied to solid walls.[5] It is also recommended in BRE's best practice guide for insulation (BR 262).[6] BS 5250 was amended in 2016 pending a full reissue, citing the recognition that VCLs 'may cause more harm than good' and should only be specified with a full understanding of context.[7] BR 262 is also now under review.[8]

A VCL might be appropriate for a relatively dry, rendered wall, or a stone wall with low water absorption in a low wind-driven rain exposure zone (especially if the VCL is not totally vapour impermeable), but it is wholly inappropriate for use in some contexts, and is likely to create problems when used in a system on highly porous exposed stone or brick.

In practice, perfect installation of vapour barriers is very difficult to achieve in existing buildings, especially within intermediate floor voids and around embedded joists. This can result in a strong likelihood of interstitial condensation of vapour in moist air finding its way through inconsistencies in the vapour barrier. In isolation, this is not ideal, but if the substrate had been well prepared (impermeable paint removed to leave a permeable absorbent surface behind), a wall at low rain exposure might have the capacity to harmlessly absorb and redistribute the condensation and prevent accumulation.

The ingress of moisture in the heating season is, however, coupled with significantly reduced drying potential in the summer when a VCL is included. Drying due to sunshine on the wall does not just occur through evaporation from the external surface: Even in February, the effect of sunshine on south-facing solid walls is enough to raise the moisture content of internal air within a house by 8 per cent over that of an overcast day.[9] This demonstrates the magnitude of vapour diffusion possible when the vapour pressure gradient through the wall is reversed by high temperature on the external surface, and the rate of evaporation from internal surface increases. When prevented from evaporating harmlessly into the building by the vapour barrier, the humidity between the masonry and VCL rises and condensation can form on the external surface of the vapour barrier. This is termed reverse or summer condensation. Trapped moisture leads to high humidity in a season favourable to microbial growth, thereby increasing the risk of decay to structural timbers.[10]

The net effect of moisture infiltration in winter, coupled with reduced drying

Figure 4: Problems associated with VCL-based insulation systems. (Left) Interstitial mould growth (image courtesy of Simmonds.Mills Architects) revealed during strip out for remedial work. (Right) Condensation accumulation (image courtesy of Acara Concepts).

in summer, is moisture levels rising year on year; leading, albeit more gradually, to the problems that the VCL is intended to eliminate.

Issues related to the use of a VCL are revealing themselves in practice, both when buildings insulated with this approach are stripped out, exposing mould growth behind the insulation, and — more alarmingly — shortly after installation with liquid condensation pooling at the wall base.

Summer condensation resulting from solar-driven vapour diffusion can be observed as staining immediately above skirting boards from condensation tracking back through fixings (similar to the symptoms of excessive moisture in uninsulated solid walls, but more likely to be associated with mould growth due to lower salt concentration).[11] Surface mould is, however, also associated with excessive surface humidity resulting from thermal bridges.

Observation of excessive humidity within or behind the insulation is not possible without an invasive survey, unless the problem is extreme. So where a problem is suspected, lifting the floorboard immediately adjacent to a wall with embedded joists may be the least destructive means of assessment. This will allow moisture content readings to be taken near joist ends, and observance of any condensation accumulation, staining or mould growth on the substrate. Floor voids are where most drying will occur for a VCL-based system, so this assessment should be supplemented by removal of backboxes on insulated walls to enable further examination.

For composite plasterboard/foil-backed foam insulation boards, assessing the internal finish for cracks is a means of assessing the likelihood of infiltration of moist internal air behind the insulation. The internal plaster layer serves as the VCL at corners and junctions of these boards, and they are usually dot and dabbed on, so have small air gaps behind which contribute to thermal resistance as a low emissivity cavity, but which can also become excessively humid. Despite good compression resistance, the boards are vulnerable to soft body impact, causing the finish to crack out. In this case monitoring the cavity with digital hygrometers may be the best means of assessing risk to timbers. Long term datalogger monitoring[12] of timber moisture content and RH behind insulation over at least one heating season is the best way of assessing risk, and can be combined with spore count monitoring to assess impact on health. These methods can be prohibitively expensive, however, so assessing evidence of staining combined with limited invasive surveys can be a practical alternative.

Lowering heat transfer into the masonry in the winter reduces drying further, and can tip walls of particularly absorbent brick or stone toward vulnerability to frost damage on the external surface.[13] A certain level of heat transfer through the wall is advantageous in winter when drying conditions are not ideal. Again, the more insulation is applied, the higher moisture levels are likely to be in the masonry, and combined with repeated freeze thawing cycles, this can lead to spalling for certain brick and stone types. Although low risk for most areas, tracking the progress of frost damage following insulating and comparing with the wall's historic vulnerability can help identify whether the insulation is part of the problem.

A lack of understanding about management of occupancy produced moisture has led us to the adoption of an inappropriate assessment method with a skewed focus on vapour that still guides most specifications, despite internal vapour's minor contribution to the overall moisture level in solid walls, relative to wind-driven rain absorption.

ACCOUNTING FOR EXTERNAL CONDITIONS

There is an alternative assessment methodology to the Glaser calculation that does account for dynamic conditions, liquid transfer mechanisms, vapour adsorption and moisture storage. This methodology, set out in BS EN 15026, is now recommended in BS 5250 for assessing walls with high exposure to driving rain, southerly orientation, or absorbent masonry.[14]

In addition to calculating how water vapour behaves, dynamic modelling assesses how driven rain soaking into the masonry is absorbed and re-distributed, how sunshine affects drying and vapour gradients in the wall, and how occupancy-related moisture

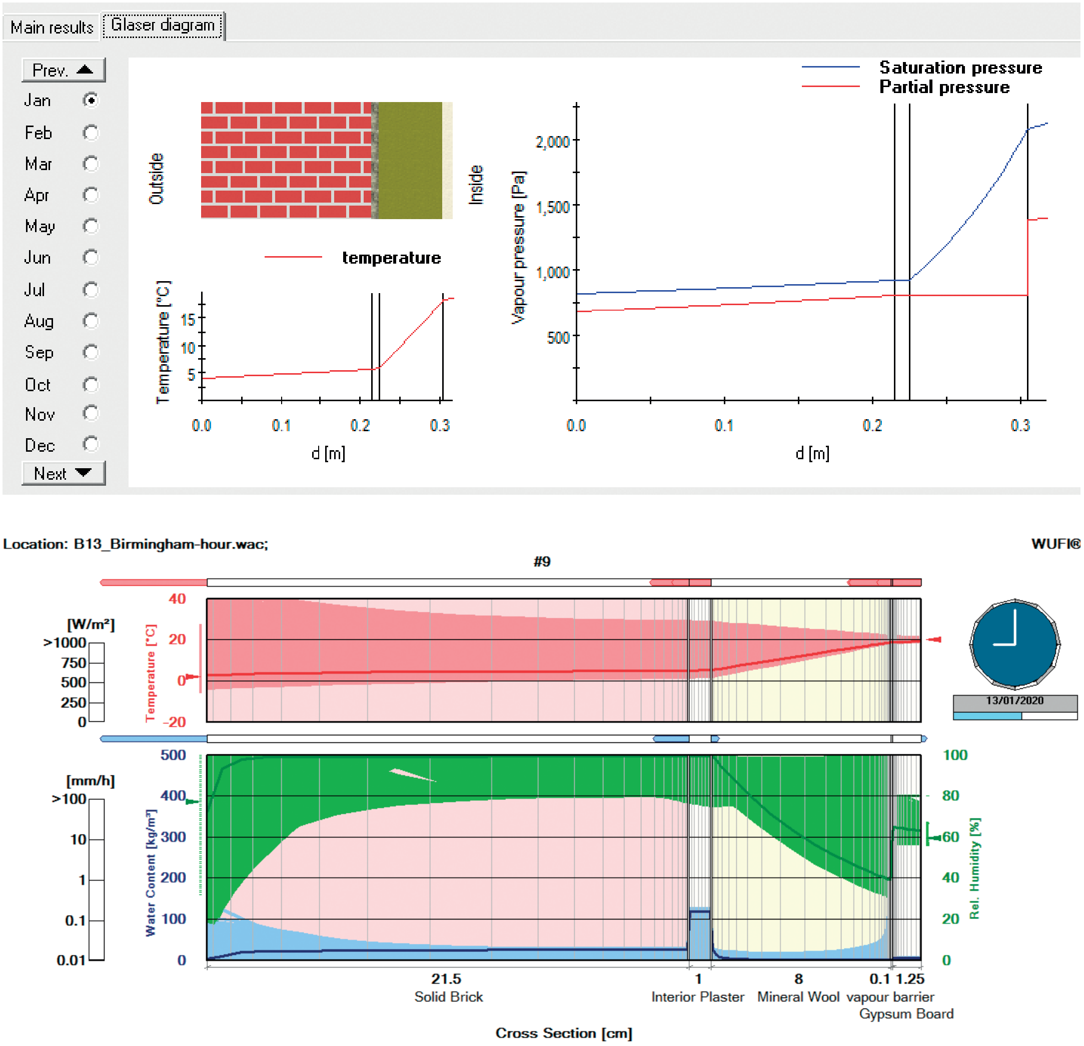


Figure 5: Comparison of moisture assessment methodologies.

Comparison of moisture profiles for identical internal wall insulation build-ups (lightweight hydrophobic insulation and VCL on 215mm plastered brick) in the same location (Birmingham) in winter (pair above) and summer (pair on following page), using BS EN 13788 (top profile of each pair from BuildDesk) and BS EN 15026 (lower profile of each pair from WUFI). Note the much higher humidity (green line, with RH distribution over five years in light green) at the interface of plaster and insulation in winter in the WUFI profile than that suggested by the divergence of vapour pressure and SVP in the BuildDesk profile, and the very high humidity throughout the insulation layer in summer in the WUFI profile compared to the low humidity suggested in the summer BuildDesk profile.

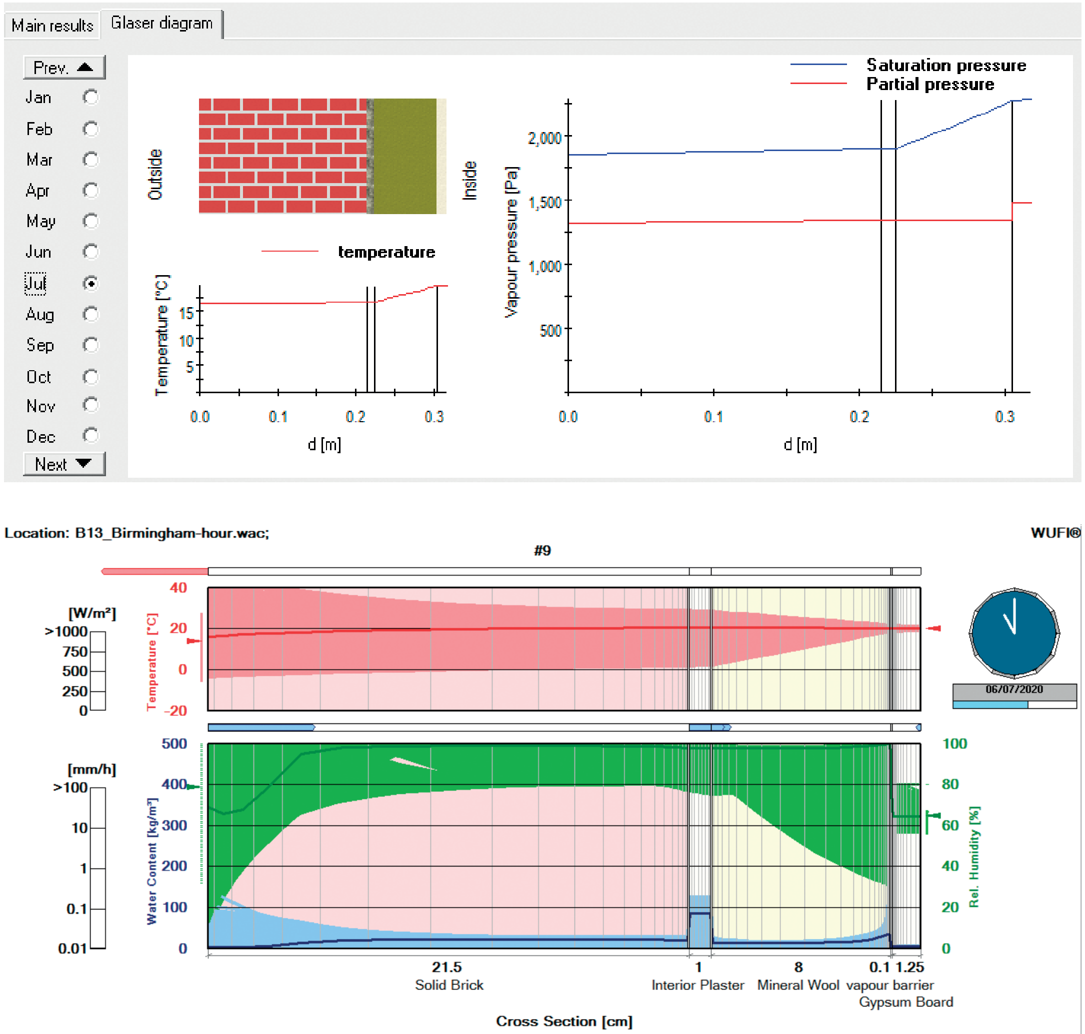


Figure 5: Comparison of moisture assessment methodologies (continued).

can be adsorbed and released by insulation (if the insulation has this capacity). These are critical elements of moisture movement for porous materials that are impossible to assess with a calculation based on monthly averages. Calculations are based on hourly data from climate files that include all relevant environmental conditions according to orientation and location, as well as internal temperature and relative humidity. Conditions in the wall are calculated at hourly intervals across as long a period as necessary, which can stretch to decades.

APPROPRIATE SPECIFICATION

BS EN 15026 is increasingly regarded as a silver bullet that will enable us to eliminate interstitial condensation; however, it is by no means perfect as an assessment tool for wider use. It is currently only supported by a limited number of software applications (WUFI and DELPHIN). It requires a thorough understanding of building physics to interpret results. It is very sensitive to minor differences in material properties (limited data exists for UK brick and stone), surface transfer coefficients and weather data (average years are most commonly cycled, rather than worst-case climate files). WUFI modelling is one-dimensional and does not model airflow,[15] so can only assess vapour movement through cracks in the wall based on empirical data. Simple, definitive failure criteria are not possible, so the results can be misleading in the hands of uninformed or unscrupulous operators; calculations where the rain load has been turned off to paint a rosy view of a system's performance are not unknown.

Cautionary principals based on experience or extensive modelling, which can be laid down in standards, are likely to be the best way of guiding IWI specification going forward. This approach is recommended in the recent BSI White Paper on Moisture in Buildings,[16] the Sustainable Traditional Building Alliance's Moisture Risk Assessment and Guidance[17] and is being developed by the UK Centre for Moisture in Buildings.

Risk can be addressed by using insulation systems that deal with moisture in a complementary way to the moisture transfer through masonry. Eschewing a conventional vapour barrier and thereby not inhibiting drying of the wall, these systems are based on vapour-permeable materials (woodfibre, calcium silicate or perlite), with varying hygroscopic and capillary properties, and a capacity for moisture storage derived from density — ie having enough bulk material that sufficient levels of moisture are absorbed as vapour passes through in the heating season, to reduce vapour pressure at the cold masonry surface and avoid excessive humidity. These systems are usually bonded onto walls with an alkali lime plaster (to retard mould growth), and require good contact with the wall to eliminate the potential for warm moist air finding its way behind the insulation. Impermeable finishes should be removed prior to installation so vapour can move freely between wall and insulation.

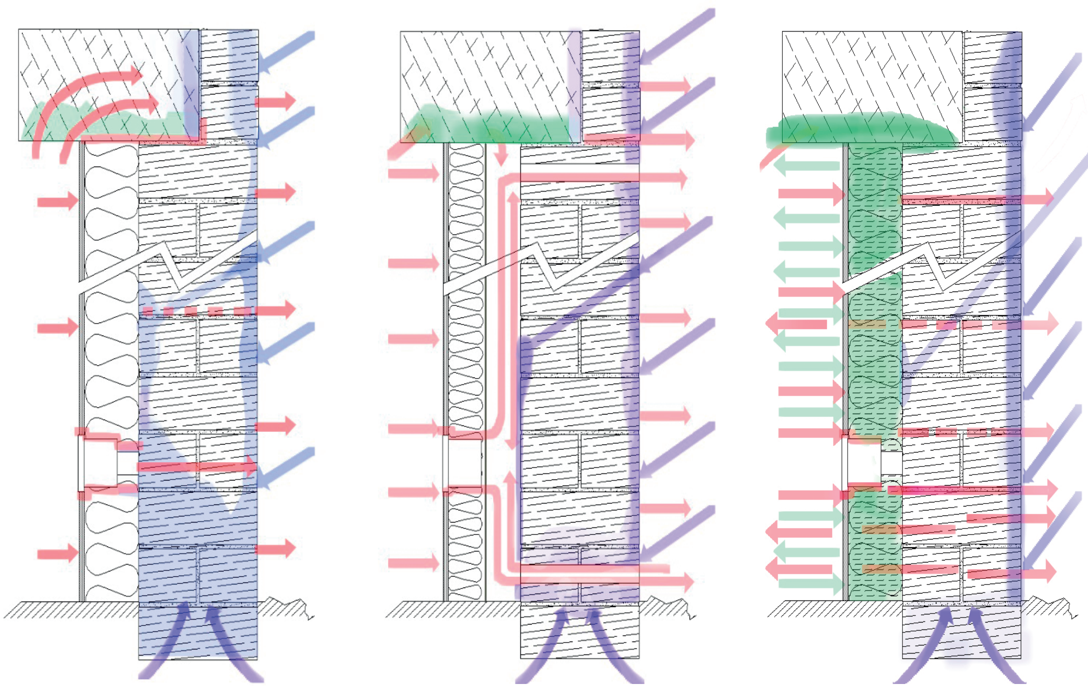
The ideal material would have low thermal conductivity, vapour permeability matching, or marginally lower than the masonry (for uninhibited drying), show a high level of vapour adsorption below 85 per cent RH (to safeguard embedded timbers by avoiding excessive humidity levels at the interface) and capillary conduction approaching that of the masonry (to wick unbound moisture molecules from areas of high to low moisture content towards the warmer interior). No such material exists, but woodfibre's tendency to adsorb vapour at relatively low RH means it lends itself well to reducing humidity for embedded timbers, while mineral-based boards may be a better option for unusually thin walls, or walls in very severe exposure zones, due to higher potential capillary conductivity (removal of embedded timbers should be considered for any significant reduction in U-value in this case). Breathable IWI is more forgiving of imperfect installation than VCL-based systems, as it relies on innate materials properties for managing moisture rather than effective sealing at junctions.

The lower the U-value, the higher the risk, whatever the system used, especially in colder and more exposed areas. The more insulation is applied, the colder the masonry will be, so the higher the RH, and the greater the risk of condensation. The Building Regulations apply 'special considerations' to upgrading U-values of 'traditional buildings' wherever there is potential for risk,[18] thereby permitting designers to aim for a wall U-value that accords with guidance from building physicists and conservation bodies (somewhere between 0.4 W/m^2K and 0.7 W/m^2K according to context).[19] Hygrothermal modelling should be undertaken for U-value targets below 0.5 W/m^2K.

Recent research[20] has found that the extent of thermal bridges at window reveals accentuates the diminishing returns curve for increasing insulation thickness, so the more openings are present and the deeper the internal reveal where insulation thickness is constrained, the less sense there is in increasing insulation thickness on the main areas of wall.

The flexibility in the Regulations is often overlooked, and the default target of 0.3 W/m^{2}K used, so a simple assessment of potential risk to an internally insulated building is possible by ascertaining the thickness of insulation used. This can help in diagnosing whether water penetration or interstitial condensation is the source of a moisture problem. BRE has recommended highlighting the flexibility in the regulations as a means of avoiding unintended consequences.[21]

The only viable approach where very low U-values are required (and extensive monitoring and modelling is not possible) is to combine a VCL based system with a cavity between insulation and masonry, ventilated to outside through airbricks to provide drying potential. There are a number of drawbacks with this approach, however. It only works with a good airtight seal of the VCL, otherwise an air pressure difference immediately across the insulation layer causes thermal bypass of the insulation and a convection current in the cavity. This can dramatically reduce the effectiveness of the insulation, but will also reduce the risk of condensation (partly as a result). A fine eye for detail is required to achieve a sufficient level of airtightness during installation. Drying potential depends on the level of airflow in the cavity, so it is important that sufficient



VCL system with reduced drying potential and risk of net annual moisture increase due to summer condensation.	VCL system with drying potential from ventilated cavity but risk of thermal bypass if not hermetically sealed.	'Breathable' system based on vapour-permeable material with moisture adsorption and storage capacity.

Figure 6: Three different approaches to Internal Wall Insulation. (Images courtesy of NBT)

airbricks are used and maintained, otherwise the cavity becomes a pocket of stagnant air at high humidity (the practicality of installing airbricks is often underestimated, especially for thick rubble stone walls). Perhaps most importantly, the thermal resistance of the masonry is not exploited. Recent research by SPAB,[22] Historic Scotland[23] and BRE[24] has led to a re-evaluation of the baseline thermal resistance of masonry walls. Due to the inherent inhomogeneity of masonry walls, their U-values are lower when measured in situ than when calculated according to BR 443[25] (especially thick, dry walls with rubble cores). As a result, the SAP default U-value for solid walls is under consultation for adjusting down from 2.1 W/m^2K to 1.7 W/m^2K.[26]

IMPACT OF BUILDING CONDITION

Old buildings are very robust in relation to dealing with moisture, so even where IWI is installed with a lack of understanding of the building physics and an inappropriate assessment of the moisture transfer, the possibility remains that the building can cope with the reduced drying potential. Due to the way solid walls function, however, a tipping point exists at which problems escalate, and there is no guaranteed way to predict where this is, so a cautious approach should be adopted.

The most acute problems will occur when the effects of insulating are misunderstood *and* the building condition is inadequately assessed prior to insulating. IWI will make any existing issues with building condition worse, and should not be used to conceal any symptoms of excessive moisture without dealing with the cause.

A building condition survey is therefore an important part of IWI specification. Weather resistance of the external surface and its level of exposure to rain is critical: porosity of the surface (rate of rain absorption), wall orientation and roof overhang (exposure and drying potential), thickness of the wall (capacity to store moisture), state of repair of pointing or render, vulnerable points such as window frame seals, sills, flashings, copings and abutting garden walls (potential for water ingress) should all be assessed. Staining, salt contamination, rotten timbers and high external ground levels should also be noted. All existing issues should be resolved, and IWI specification derived from the survey. Good maintenance of the external surface and of rainwater goods is essential for eliminating moisture issues associated with IWI in the long term.

Figure 7: Water penetration through cracked render. Internal wall insulation should not be used to conceal existing issues and should only be applied as part of extensive repairs to the property.

When surveying a property for defects in which IWI has already been installed, a survey should initially focus on these same areas to identify whether condensation or water penetration is the primary problem. The two often go hand in hand, as wetter walls mean cooler masonry (thermal conductivity increases with moisture content) and higher risk of interstitial condensation, so the diagnosis is not simple. A resistance meter will be of little use in assessing condensation accumulation, but can help identify sources of water penetration or leaks in services behind insulation (although not if the insulation consists of a foil-backed foam board). Thermographic imaging can be a useful tool for locating hidden water penetration or acute condensation, given favourable ambient conditions — ideally winter, but thermography can locate localised moisture in less ideal conditions.

THERMAL BRIDGING AND INTERNAL SURFACE MOULD GROWTH

Internal surface condensation or excessive surface humidity leading to localised mould growth is a simpler issue to identify and resolve. Thermal bridges are areas where insulation is either omitted or only a minimal level is possible, resulting in increased localised heat flow, and a colder area than neighbouring surfaces. Thermal bridges of one degree or another are almost inevitable when insulating internally. Thick layers of insulation around inset window reveals would adversely affect daylighting, excessive insulation within intermediate floor voids is likely to increase risk to embedded joists, and fully insulating masonry partitions unnecessarily isolates thermal mass that would otherwise contribute to mitigating potential for overheating in an internally insulated building. Every effort should, however, be made to reduce the surface temperature differential by installing a thin layer of insulation over potential cold spots. Coombed ceilings between insulated cold lofts and walls are also potential thermal bridges.

Tackling thermal bridging is especially important in rooms with high humidity (bathrooms and kitchens). An acute surface temperature differential leads to high humidity on the surface of the thermal bridge; if this is sustained, then black mould will grow. Higher surface humidity means

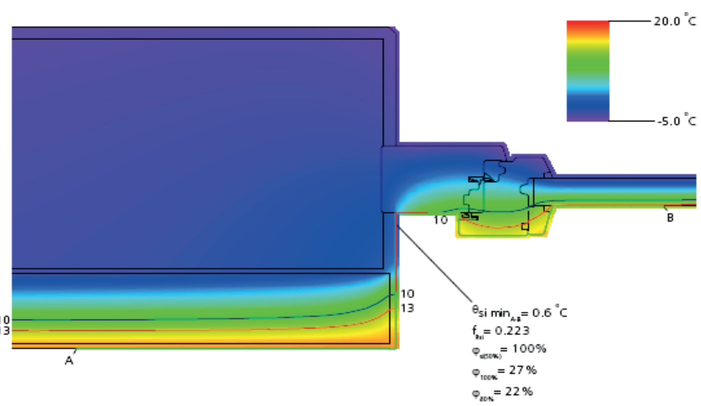


Figure 8: A Psi-value calculation showing thermal gradient through an uninsulated window reveal, and the visible consequences of the acute surface temperature differential. (Image courtesy of NBT)

less time is required before spore germination, so the higher the internal air humidity, the greater the likelihood of mould growth.

Ventilation is therefore a critical consideration when insulating solid walls. Installation of insulation can increase the airtightness of a building by default, as gaps are ideally plugged up. The reduced air infiltration needs to be compensated for to maintain good indoor air quality. Inset window reveals where insulation is omitted will always be the most acute thermal bridge, so window reveals in bathrooms and bedrooms should be the first place to look for mould growth when surveying internally insulated buildings. If mould growth is evident here, then the work has been poorly designed, and is indicative of other potential issues that may require more in-depth assessment.

Effective extract ventilation in bathrooms and kitchens (ideally humidity controlled[27]) is also important for reducing risk of interstitial condensation, as it reduces the vapour pressure gradient through the wall. Lack of evidence of adequate ventilation is a good indicator of potential hidden condensation even where surface condensation or mould growth is not evident.

Maximising the benefit of IWI and avoiding the issues outlined above is possible only when it is applied as part of an integrated approach to the whole building. This should involve maintenance, repair, a level of design often lacking as part of insulation work, integration of complementary services and fabric measures, and an appropriate insulation system specified and installed according to manufacturer's guidelines. Recognition by specifiers that internal insulation disturbs complex interactions of moisture and heat transfer through the wall is critical.

There is no universal solution without regard to context: Location, exposure, porosity of the substrate, masonry and insulation thickness, and internal air humidity level all have an effect, so a building survey is the basis from which the process should begin.

Once a full understanding of the building is developed, interaction between designer and client is required to raise awareness of detailing requirements and manage expectations in relation to wall U-value. When an insulation system is specified, designer and insulation manufacturer should liaise to agree where manufacturer's standard details[28] are applicable or where bespoke detailing will have to be devised; and when work begins, a consistent dialogue between designer, supplier and installer during the work should be maintained to ensure a good level of quality control on site. Only in this way can a new thermal envelope be designed and installed within the building, that maximises comfort and energy efficiency without any to risk to the structure or health of its occupants.

Notes

(1) U-value reduction from 40mm Pavadentro woodfibre on a solid wall with baseline U-value of 1.7W/m^{2}K.

(2) Element Energy, 2013 — Review of potential for carbon savings from residential energy efficiency — Report on behalf of EST for Parliamentary Committee on Climate Change, available at https://www.theccc.org.uk/wp-content/uploads/2013/12/Review-of-potential-for-carbon-savings-from-residential-energy-efficiency-Final-report-A-160114.pdf (accessed 25th March, 2017).

(3) British Standards Institute, BS 5250-2011 A.2-[Section h], London.

(4) BSI, BS 5250 + A1-2016, also: The Society for the Protection of Ancient Buildings, Archimetrics *Building Performance Survey 2016: February 2017 Interim Report*, available at https://www.spab.org.uk/downloads/SPAB%20BPS%20II%20Report%202016.pdf (accessed 29th April, 2017).

(5) BSI, BS 5250:2011 — Section D.3.1: — Glaser 'does not provide an accurate

prediction of moisture conditions within the structure under service conditions'.

(6) BRE, BR262, Stirling, C. (2002), *Thermal Insulation: Avoiding Risks*, BRE Press, Watford.

(7) BSI, BS 5250 2016 Amendment overview at http://shop.bsigroup.com/ProductDetail/?pid=000000000030339579 (accessed 25th March, 2017).

(8) BRE, King, C. *Solid wall heat losses and the potential for energy saving-Consequences for consideration to maximise SWI benefits: A route-map for change* (p.9), available at https://www.bre.co.uk/filelibrary/pdf/projects/swi/UnintendedConsequencesRoutemap_v4.0_160316_final.pdf (accessed 25th March, 2017).

(9) BRE, Garratt, J & Nowak, F. (1991), Tackling Condensation: a guide to the causes of, and remedies for, surface condensation and mould in traditional housing, BRE Press, Watford.

(10) Wilkinson *et al.* (2007), *Understanding Vapour Permeance and Condensation in Wall Assemblies*, 11th Canadian Conference on Building Science and Technology Banff. Alberta. 2007, available at http://www.becor.org/content/downloads/POTENTIAL%20FOR%20MOISTURE%20PROBLEMS%20DUE%20TO%20PLASTIC%20SHEETING%20IN%20~1.pdf (accessed 19th August, 2010)

(11) BRE, Stirling, C. Good Repair Guide 33-1, p. 2, BRE Press, Watford.

(12) BRE, Stirling, C. Good Repair Guide 33 Part 2, see also Archimetrics, Hygrotrac, ibutton dataloggers, Hutton & Rostron Curator.

(13) Künzel, H. M and Holm, A. H. (2009), *Moisture Control and Problem Analysis of Heritage Constructions*, IBP, Fraunhofer Institute, available at https://www.ibp.fraunhofer.de/content/dam/ibp/de/documents/Publikationen/Konferenzbeitraege/Englisch/K%C3%BCnzel_2009_Moisture-control-problem-analysis-Heritage_tcm45-86541.pdf (accessed 29th April, 2017).

(14) BSI, BS 5250:2016 + A1 (2016).

(15) Sustainable Traditional Buildings Alliance for DECC (N. May & C. Sanders) (2014), *Moisture Risk Assessment and Guidance*.

(16) BSI, Sanders, C. & May, N. *BSI White Paper on Moisture in Buildings*, available at http://shop.bsigroup.com/Browse-by-Sector/Building--Construction/Whitepaper-Moisture-in-buildings/ (accessed 8th April, 2017).

(17) Ibid. ref. 15.

(18) DCLG, Building Regulations Approved Document L1b, Sections 3.8[c] & 3.9, available at https://www.planningportal.co.uk/info/200135/approved_documents/74/part_l_-_conservation_of_fuel_and_power/2 (accessed 29th April, 2017)

(19) Little, J. (2014), *Historic Scotland Technical Paper 15: Assessing insulation retrofits with hygrothermal simulations — Heat and moisture transfer in insulated solid stone walls*, available at https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=8a2a7b9d-e3b2-4c7d-8c17-a59400a8387b (accessed 29th April, 2017), Also: English Heritage, 2011, *Energy Efficiency and Historic Buildings — Application of Part L of the Building Regulations to historic and traditionally constructed buildings,* available at https://content.historicengland.org.uk/images-books/publications/energy-efficiency-historic-buildings-ptl/eehb-partl.pdf/ (accessed 29th April, 2017), also: STBA, 2016, *Bristolians Guide to Solid Wall insulation*, available at https://warmupbristol.co.uk/content/solid-wall-insulation (accessed 26th March, 2017).

(20) Marincioni, V., UCL (2013), *Internal Insulation of solid masonry walls — practical limits due to thermal bridging and moisture performance,* University College London, available at: http://stbauk.org/stba-guidance-research-papers (accessed 29th April, 2017).

(21) BRE, King, C. (2016), *Solid wall heat losses and the potential for energy saving — Consequences for consideration to maximise SWI benefits: A route-map for change* (p. 8), available at https://www.bre.co.uk/filelibrary/pdf/projects/swi/

UnintendedConsequencesRoutemap_v4.0_160316_final.pdf (accessed 20th March, 2016).
(22) SPAB, C Rye & C Scott, 2010, *SPAB Research Report 1* — revised 2012, available at https://www.spab.org.uk/advice/energy-efficiency/ (accessed 29th April, 2017).
(23) Historic Scotland Technical Papers 2 & 10 (Paul Baker), available at https://www.historicenvironment.scot/archives-and-research/publications/?publication_type=30 (accessed 25th March, 2017).
(24) Ongoing research — https://www.bre.co.uk/page.jsp?id=3397 (accessed).
(25) BRE, BR443, Anderson, B. (2006), *Conventions for U-value calculation,* BRE Press Watford.
(26) BRE, Consultation Paper 16 — *Review of default U-values for existing buildings for SAP 2016*, available at http://www.bre.co.uk/sap2016/page.jsp?id=3619 (accessed 26th March, 2017).
(27) See Demand Controlled Ventilation — eg https://www.aereco.co.uk/technology/demand-controlled-ventilation/ (accessed 26th March, 2017).
(28) See NBT Catalogue of Standard Detail Drawings — Pavadentro for sample: https://www.natural-building.co.uk/system/internal-wall-insulation-lime-plastered-finish/ (accessed 26th March, 2017).