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Hygrothermal Risk Evaluation for the Retrofit of a Typical Solid-walled Dwelling

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Abstract

There is increasing evidence that current mainstream guidance for assessing moisture risk of insulation retrofits in Ireland and the UK is unsuitable for traditional solid-walled buildings. This guidance is still based on simplified hygrothermal risk assessment methods, despite the availability of more advanced numerical software for two decades and a relevant standard in place since 2007, EN 15026. Two-dimensional versions of these software applications can extend simulation beyond one-dimensional assemblies to more complex junctions.

This exploratory study makes use of one of these advanced simulation tools, aided by physical measurement, to explore hygrothermal risks of solid wall retrofits at the junction with uninsulated and insulated ground floors. A brick-faced traditional dwelling in Dublin has been selected as a case study, and four scenarios have been simulated: its original condition and three retrofit approaches. Results indicate that (a) the moisture content at the base of the wall increases in all retrofit scenarios examined, and (b) the assemblies with high vapour permeability and no membranes result in the lowest hygrothermal risk. The findings should be supported by further research and could have great relevance to guidance, specification and grant policy for energy retrofits of solid wall properties in Ireland and the UK.

Keywords:

Energy-efficient retrofit; Vapour control layer; interstitial condensation; WUFI.

Glossary:

- Vapour control layer (VCL);
- Damp-proof membrane (DPM).

Note

- WUFI Pro and WUFI 2D: A suite of tools developed by the Fraunhofer Institute for Building Physics since the early 1990s. WUFI Pro is validated against EN 15026 (2007). WUFI 2D two-dimensional numerical simulation falls outside the scope of the standard, but has been repeatedly validated.

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1. Introduction

In Ireland and the UK, the energy-efficient retrofit of the existing building stock plays an increasingly large role in meeting national targets for energy efficiency and carbon emissions. Current guidance provided to industry and homeowners for energy-efficient retrofit works in Ireland and the UK encourages the use of vapour control layers (VCL) and impervious materials such as damp-proof membranes (DPM), regardless of hygrothermal characteristics, orientation and location of existing structures[1,2] (see glossary). Indeed, grant aid can be contingent on following this guidance[3]. This paper considers whether such guidance and grant aid is appropriate or misguided.

The guidance has arisen due to the use of the Glaser method (and its antecedent, the dewpoint method) for many decades to consider hygrothermal risks by assessing the likelihood of condensation forming within building fabric assemblies. This simplified, steady-state calculation method, which assumes vapour diffusion is the only moisture transport mechanism[4], is repeated for each month using mean values. Given its limitations, it is most accurate when used to assess buildings in this climate where vapour from the room is the dominant source of moisture, e.g. low rise, airtight structures with ventilated, water-tight rainscreens[5]: its results cannot be depended on in other cases. However, the method is still dominant in Ireland and the UK[6] and is frequently used to assess assemblies (such as solid brick masonry) that are outside the scope of its standard[7].

This dominance appears to exist because of (a) the length of time for which the method and its antecedent were the only assessment standard available to the UK and Irish construction industry, (b) its ease and speed of use, and (c) the inadequate referencing to EN 15026:2007[8] in BS 5250:2011[2] – the central document used in understanding and controlling condensation in British buildings.

Figure 1 – Case study house in Ranelagh, Dublin.

Ill-considered retrofits, or retrofit work specified after a risk assessment using an inappropriate method, can result in moisture-related damages such as decay of bricks due to freeze-thaw, rot of timber joists, condensation in attics, or mould growth at cold surfaces, which is a potential health risk for occupants. With occupant health, building heritage and taxpayer's money at stake it is essential low-risk retrofit strategies are undertaken based on sober evaluation under the appropriate standards.

It is particularly inappropriate to use the Glaser method to assess brick or stone-faced traditional buildings, where liquid transport of wind-driven rain and ground moisture are typically of far greater significance than the transport of moisture via vapour diffusion. Numerical simulation tools, under the relevant standard[8], allow a much more accurate hygrothermal analysis of construction assemblies, by including all relevant moisture loads and transport mechanisms under realistic boundary conditions.

The present study is an original contribution intended to extend recent research on the hygrothermal performance of traditional solid walls to their junction with ground floors, using two-dimensional transient numerical simulation software and limited physical measurement. Four different scenarios are compared:

(a) the wall-ground junction as originally built;

(b) in its current condition;

(c) a mainstream retrofit using membranes as per current guidance; and

(d) an alternative retrofit strategy based on vapour-permeable assemblies for both wall and ground floor.

2. Literature review

In 2001 Pender[10] concluded that critical misconceptions of the moisture performance of solid walls were integrated into standard advisory practice. Despite the existence of solid findings from research, these had not become part of the common understanding in conservation circles or the construction industry.

The International Energy Agency's Annex 24 project[9] reported that (a) airtightness is the most important performance requirement, (b) vapour diffusion from the room only poses a threat in absence of airtightness or for severe indoor climates, and (c) a vapour retarder may prevent drying of built-in moisture.

The convenience of vapour control layers for internal insulation of solid walls in Continental Europe has been challenged by many independent studies in Germany[11], Denmark[12], Belgium[13] and Switzerland[14]. Hygrothermal risk assessments of traditional solid walls in the climates of Ireland[15] and Scotland[6], carried out by these authors using transient numerical simulation, also concluded that (a) preserving drying capacity is more critical than preventing vapour ingress from the room, and (b) the addition of impervious layers (as recommended by mainstream guidance) can result in moisture accumulation. Similar findings have been reported from physical measurement in a recent field study in Dublin[16].

In contrast with the growing number of empirical and desktop studies on insulation retrofits of walls, the volume of research on ground floors remains very limited, possibly due to their greater complexity to simulate and measure.

3. Case study

A two-storey terraced house in Ranelagh, Dublin (Figure 1) has been selected as a case study. It is a modest-sized, mid-terrace Edwardian red brick dwelling, characteristic of the beginning of the 20th Century. The front wall is laid in solid brick masonry featuring a Flemish bond. Its original lime pointing was replaced with sand-cement jointing in the 1970s and internal lime plastering was replaced by tanking in the mid-1990s.

According to the owner, the edges of bricks have been spalling for many years at interface with mortar joints and, more recently, whole bricks have lost, or are losing, their facing (see damage in Figure 2). Spalling is usually caused by the mechanical action of water (freezing and thawing) stressing the pore structure of the masonry unit: it is a clear indicator of hygrothermal stress.

Four scenarios have been modelled for the wall-ground junction of the case study house. These are detailed below:

(a) **Original condition.** The house as originally built circa 1905:

Figure 2 – Damage to brick in case study house: (above) whole brick spalling, (below) loss of brick edge and surface at base of external wall.

- Lime mortar joints with lime pointing;
- Lime plaster as internal finish;
- Suspended timber floor with ventilated underfloor space;
- No damp-proof membranes.

(b) **Current condition.** After retrofit carried out in the mid-1990s, following what were then understood to be best practice measures:

- Sand-cement jointing over lime mortar;
- Sand-cement render with waterproofing admixture applied internally, with skim plaster finish;
- Concrete floor over damp-proof membrane and expanded polystyrene insulation.

(c) **Mainstream retrofit.** A likely low-cost insulation retrofit to the wall, following current mainstream guidance and attracting grant aid:

- Internal wall insulation to U = 0.27 W/m²K: composite boards with polyisocyanurate (PIR) insulation, vapour-closed foil facing and plasterboard finish;
- No works in ground floor over current condition.

(d) **Proposed retrofit.** An alternative approach encouraging free transport and dissipation of moisture:

- Removal of cement jointing and repointing with lime;
- Removal of internal waterproofing render and re-application of lime plaster;
- Internal wall insulation to U = 0.60 W/m²K: calcium silicate bonded to wall with lime-based adhesive and lime-based plaster finish;
- New lime screed flooring slab over insulating layer of recycled foamed glass aggregate (in lieu of original suspended floor or later concrete floor with DPM); materials and specification broadly based on (17);
- No vapour control layers or damp-proof membranes.

4. Methodology

The hygrothermal performance of the four scenarios described above has been numerically simulated using WUFI software[18] developed by the Fraunhofer IBP (see glossary). Given that a junction of wall with floor is assessed, involving two-dimensional heat and moisture flows, the variants in this case study have been modelled using WUFI 2D v3.4. This software has been experimentally validated numerous times, including through the simulation and measurement of the two-dimensional effects of rising damp[19].

The external climate data (a reference year with hourly inputs including driving rain) has been generated using Meteonorm v6.1[20], based on interpolated weather data for Dublin Airport in accordance with the procedure in the standard[8]. The rainwater exposure model within WUFI[21] for buildings up to 10m high has been applied. The internal climate is based on a normal moisture load[8] as a function of external climate data, resulting in an indoor relative humidity range of 40–60%. For the ground boundary condition, a constant relative humidity of 99% has been assumed, with temperatures defined by

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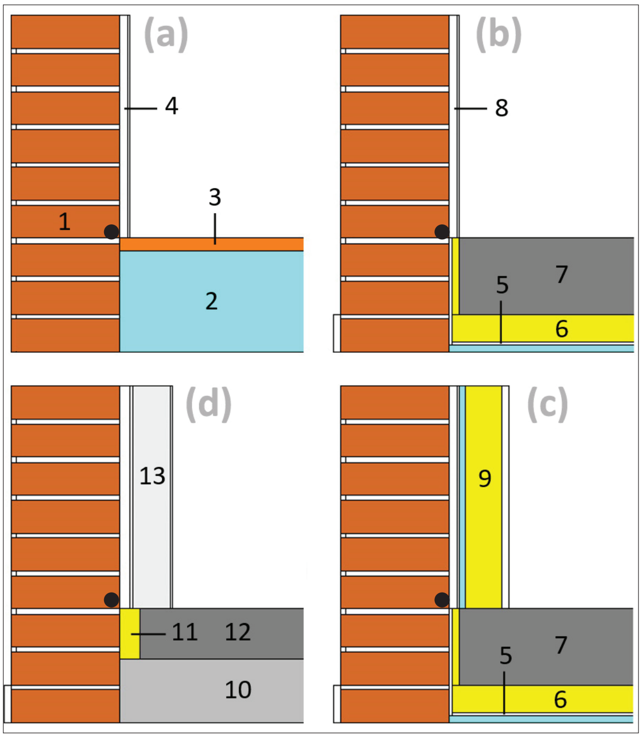
a sine curve fluctuating between 5°C and 15°C (an extrapolation of ground measurements by the Fraunhofer IBP in Holzkirchen, Bavaria, to the Dublin climate).

The two-dimensional models built for the simulations are depicted in Figure 3. Due to the significant computational time involved, the duration of the simulations has been limited to three years (26,280 hourly calculations), starting on 1st October as per usual convention. (Note: a three-year duration was judged acceptable after a longer one-dimensional assessment using WUFI Pro.)



(1) brick, (2) ventilated air layer, (3) softwood floor, (4) lime plaster, (5) DPM, (6) EPS insulation, (7) concrete slab, (8) waterproof cement plaster, (9) PIR composite plasterboard, (10) compacted aggregate of foamed glass, (11) cork edge insulation, (12) lime screed, (13) calcium silicate insulation.
• Reference points for relative humidity.

Figure 3 – Two-dimensional models for wall-ground junction, clockwise from top left: (a) original condition; (b) current condition; (c) mainstream retrofit; (d) proposed retrofit.

5. Material properties

When determining the hygrothermal performance of a solid masonry wall, the most critical properties of the substrate are its moisture absorption and storage characteristics[6].

The water absorption of the wall has been measured by an in-situ, non-invasive, test using ten Karsten tubes (Figure 2 bottom), following RILEM Test Method II.4, in which the imbibed amount of water is measured at regular time intervals[6]. The assessed wall sits in a mid-low range of absorption, when compared to other brick walls measured by the authors in Dublin (Figure 4): that is to say it is far more absorbent than rendered walls measured but less absorbent than the mean absorption rate for brick walls measured to date.

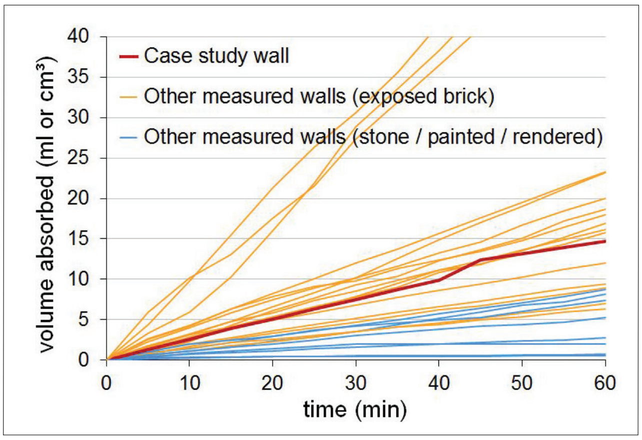


Figure 4 – Water absorption measured for wall of case study house, compared to other walls measured in Dublin.

The readings obtained from Karsten tubes have been converted into a water absorption coefficient[6], a measure of one-dimensional water uptake over square root of time, to allow use within the WUFI software. The A-value obtained is 0.18 kg/m²√s.

The moisture sorption characteristics of a given material are described by its moisture storage function, which indicates the equilibrium water content of the material as a function of relative humidity (see glossary). The moisture storage function is measured in laboratories using sorption isotherms and pressure plate measurements of a material sample[22]. Approximate values can also be simply measured by suspending materials above salt solutions (of known relative humidity) but require destructive testing which was not possible in this case.

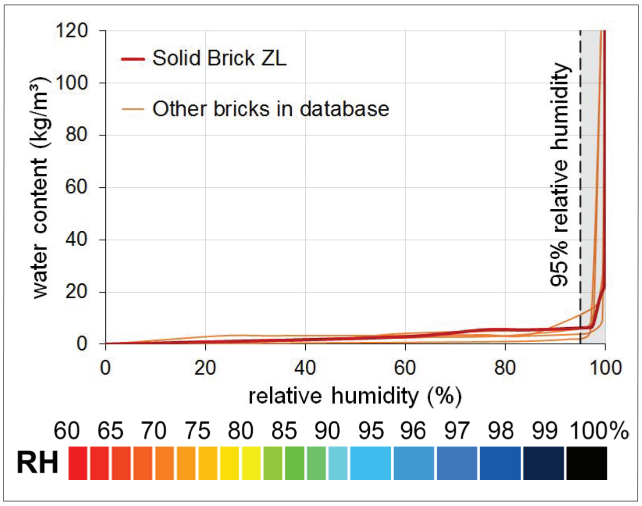


Figure 5 – (Top) Moisture storage function of bricks in the MASEA database that match the measured water absorption of the case study wall, (bottom) a scale where colour is used to graphically indicate level of water content present.

Figure 5 plots the moisture storage function of six bricks in the MASEA database[23] that match the water absorption coefficient measured for the case study house. For the purpose of this study one of the bricks (Solid Brick ZL) has been selected as its moisture storage characteristic is representative (see red line in Figure 5). As can be seen in Figure 5, the increase in moisture content is relatively steady and below 95% relative humidity (driven by diffusion and absorption of water as vapour) but increases dramatically above that threshold as capillary flow of liquid water becomes dominant. The scale below the graph conveys this significance through colour.

Table 1 lists all the materials used in the two-dimensional models with their most relevant hygrothermal characteristics. Moisture storage functions are indicated by the reference water content (w_{80}) and the free water saturation (w_f), corresponding to equilibrium moisture contents at 80% and 100% relative humidity, respectively.

Table 1 – Material data for simulated scenarios

Wall substrate	μ, vapour diffusion resistance factor	w_{80}, reference water content (kg/m³)	w^f, free water saturation (kg/m³)	A, water absorption coefficient (kg/m²√s)
Solid Brick ZL(1)	13	5.5	216	0.183
Lime mortar(3)	15	6.5	248	0.153
(a) Original condition				
Lime plaster(2)	7	30	250	0.050
Softwood(1)	200	60	575	–
Underfloor air layer(3)	0.07	–	–	–
(b) Current condition				
Cement pointing(5)	50	25.7	210	0.057
Cement plaster with(5) waterproof admixture	750	35	280	0.008
Skim plaster(2)	8.3	6.3	400	0.287
DPM(5)*	100m	–	–	–
EPS insulation(1)	50	–	–	–
Concrete(1)	180	85	150	0.003
(c) Mainstream retrofit				
Air gap around dabs(3)	0.73	–	–	–
PIR insulation(4)	60	–	–	–
Foil facing(4)*	20m	–	–	–
Plasterboard(2)	8.3	6.3	400	0.287
(d) Proposed retrofit				
Lime-based adhesive(4)	22.9	35	280	0.004
Calcium silicate board(4)	5.4	7.1	815	0.930
Lime-based plaster(4)	7	30	250	0.047
Insulating hardcore(5)	1	5	50	–
Lime screed(5)	25	8	152	0.016
Cork edge insulation(2)	10	–	–	–

Source of data: (1) MASEA database in WUFI; (2) Fraunhofer IBP database in WUFI; (3) other databases in WUFI; (4) manufacturer data; (5) adapted by assessor

* Vapour resistance given as s_d value.

For reasons of space values less pertinent to a discussion about moisture are not listed here.)

The floor assembly of proposed retrofit (d) is the "Sublime Insulated Limecrete Floor" supplied by Tŷ-Mawr Lime Ltd in Wales. This system has approval from LABC and LABSS bodies in the UK. The insulating hardcore that forms the most novel part is recycled foamed glass manufactured in Germany by GLAPOR (see Figure 6). This highly-vapour-permeable layer which acts as floor base, capillary break and insulant (λ= 0.078 W/mK), is compacted on site to ~75% of its initial height. The water content values listed in Table 1 for this material are estimates based on comparisons with other granular materials. Except in areas of high radon, the manufacturers recommend that the only membranes below and above the hardcore are geotextiles, so as to ensure a fully-vapour-permeable assembly.

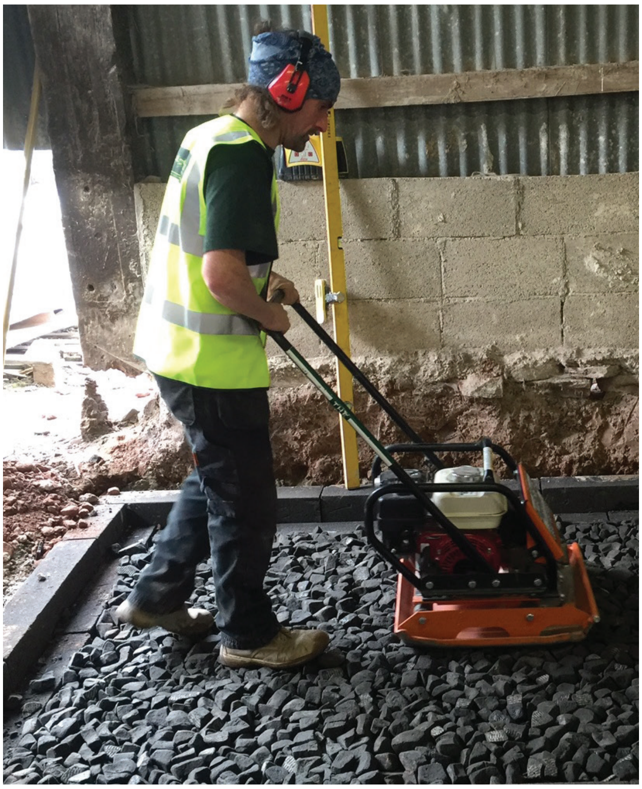


Figure 6 – Construction worker compacting recycled foamed glass aggregate during installation of "Sublime Insulated Limecrete Floor" (image supplied by Tŷ-Mawr Lime Ltd).

6. Assessment criteria

Moisture, warmth, oxygen and nutrients are all necessary ingredients for mould growth[24]. Mould is generally prevented from forming on the internal surfaces of buildings by ensuring that relative humidity on those surfaces is maintained below 80%[2].

Within the layers of a building component it has also been long accepted that relative humidity, should not exceed 80% for sustained periods, where temperatures are sufficiently high to support mould growth and a potential exists for mould to affect occupants. Where unintended air paths allow the interchange of air between the room and a void behind insulation (e.g. through gaps under the skirting or at a pattress box) it seems logical to apply the same threshold value;

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but this threshold may not be as relevant where there is no void or the materials present inhibit mould growth.

Internal wall insulation systems that are fully bonded to the wall should provide additional safety, especially if the adhesive, and in some cases the insulant, are alkaline (as they can act as biocides, i.e. mould suppressants). This suggests that a higher risk assessment threshold than 80% relative humidity could make sense in those cases. The WTA (a European transnational scientific-technical association involved in the development of standards)[25] has in fact reported that if the potential for mould growth is removed, the acceptable interstitial relative humidity threshold for certain assemblies may be shifted upwards to 95%, as the risk of material decay and freeze-thaw damage become the key concerns[26].

Given the increasing importance of energy-focused retrofit work and the need to ensure low-risk interventions, it is advisable that the WTA research and the appropriateness of using a higher relative humidity threshold than 80% for certain conditions be studied for applicability to retrofit work in the UK and Ireland.

7. Evaluation of results

Figure 7 makes use of a coloured scale to portray the distribution of relative humidity over the wall-ground junction, for the four assemblies simulated (each in a different column), at three particular moments during the simulation. These moments are a rain event (top diagrams), a drying-out period (middle diagrams), and a relatively dry period (bottom diagrams), allowing comparison of the relative performance of the four assessed scenarios.

The correlation between relative humidity and water content is critical for assessing moisture-related risks such as mould growth

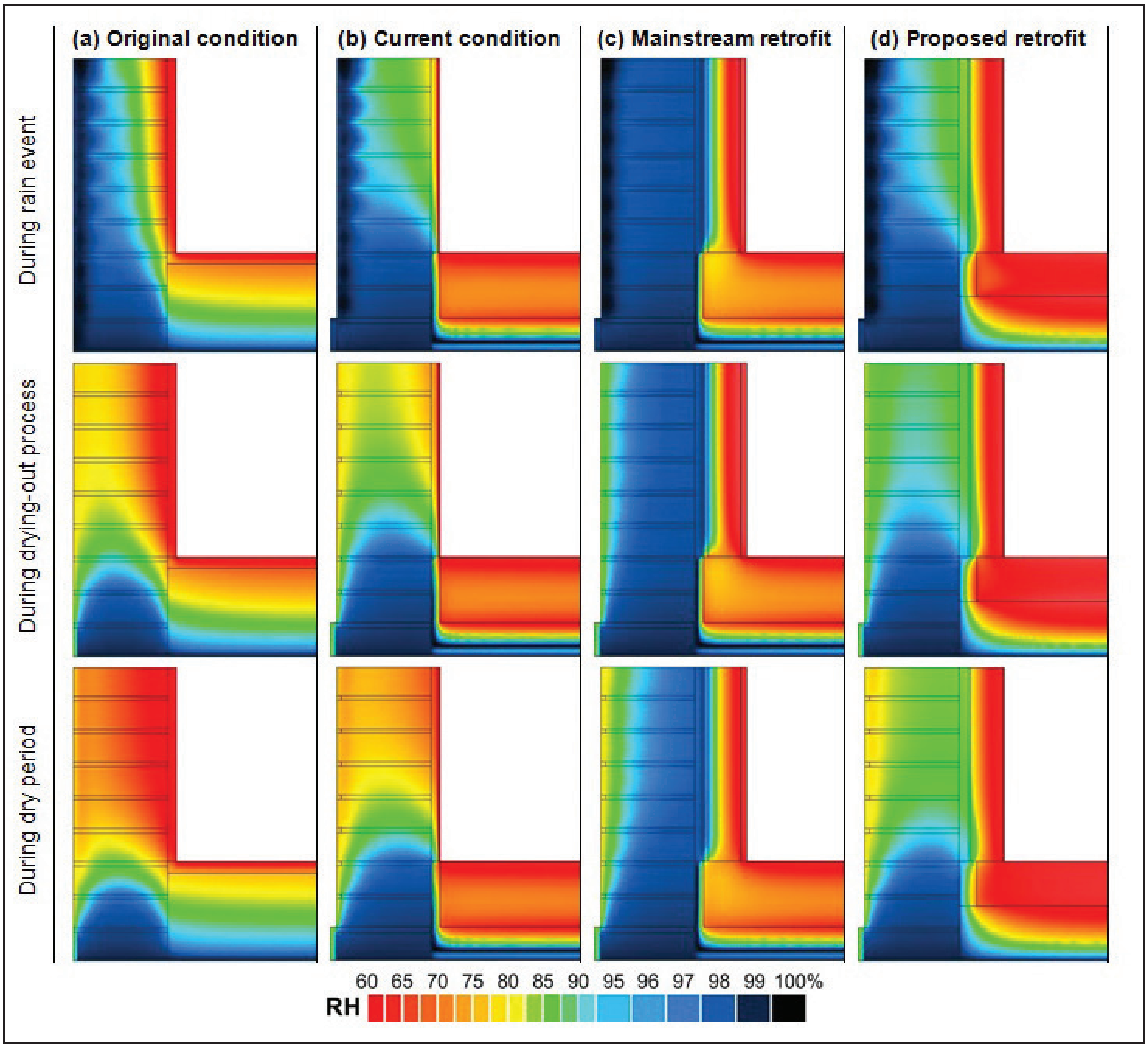

Figure 7 – Distribution of relative humidity in four numerical simulations with coloured scale. Columns, left to right: (a) original condition, (b) existing condition, (c) mainstream retrofit, (d) proposed retrofit. Within each column: during a rain event (top), during the drying-out process (middle), during a relatively dry period (bottom).

or brick spalling. This is especially so above 95% relative humidity, where the quantities of water involved rise dramatically (Figure 5). The significance of this change has been conveyed in the scale for relative humidity in Figure 7, where every percentage point above 95% is identified by a unique shade of blue.

Driving rain tends to cause a sudden increase in the moisture content of outer part of the wall substrate (top diagrams in Figure 7). After the rain event, the outer face of the wall dries out first (middle diagrams in Figure 7), while part of the absorbed moisture migrates towards the core of the wall. Note that, in every case, the lowest brick courses show higher moisture content (blue and dark blue tones in Figure 7) due to capillary absorption of moisture from the ground[27].

In the original condition of the wall (column (a) in Figure 7), the absorbed moisture is freely transported to the inner and outer surfaces and evaporates to the air volumes on each side. In a well-built and well-maintained traditional building some level of equilibrium is reached, wherein such cycles occur annually without negative impact on building fabric or occupants. Similarly, any moisture at the base of the wall can dry outwards or inwards to the ventilated underfloor space below the suspended floor, thereby keeping the internal surfaces (lime plaster and timber flooring) at safe relative humidity levels (i.e. below 80%).

The current condition (column (b) in Figure 7) shows a noticeable increase in humidity within the lowest brick courses. This is caused by (1) a drop in temperature in this area of the wall after the addition of floor insulation and (2) the removal of the ventilated underfloor that allowed local evaporation from the rising wall. Note how the DPM between the wall substrate and the floor insulation prevents the passage of vapour and creates a build-up of condensation (black colour in Figure 7) between floor insulation and membrane. Above the floor, there is also an increase in the overall moisture content of the wall, due to the waterproofing plaster that inhibits the moisture in the wall from drying out towards the room. These increases in water content might be related to the observed brick spalling (Figure 2).

For the mainstream retrofit (column (c) in Figure 7), the masonry substrate remains consistently moist at the junction with the insulation. The accumulated moisture cannot dry towards the room due to the presence of vapour resistant materials (the waterproofing plaster and the foil facing within the PIR insulation). As composite insulated plasterboard systems of this kind feature a cavity behind the insulation (due to the use of dabbing or studs), which is likely to be linked to the room through unintended air paths, mould growth at the internal face of the wall substrate behind the internal insulation should be considered a specific risk. The floor assembly is unchanged from condition (b), but due to the overall increase of moisture in the wall, the thin black zone indicating 100% relative humidity and greatest water content grows higher, reaching internal floor level. This condensate could remain hidden to the view, leading to slow degradation of adjacent materials, or could manifest internally as a source of moisture below the skirting.

The proposed retrofit (column (d) in Figure 7) features a fully-bonded capillary-active internal insulation system (calcium silicate boards) and vapour-permeable flooring (lime screed) over an insulating

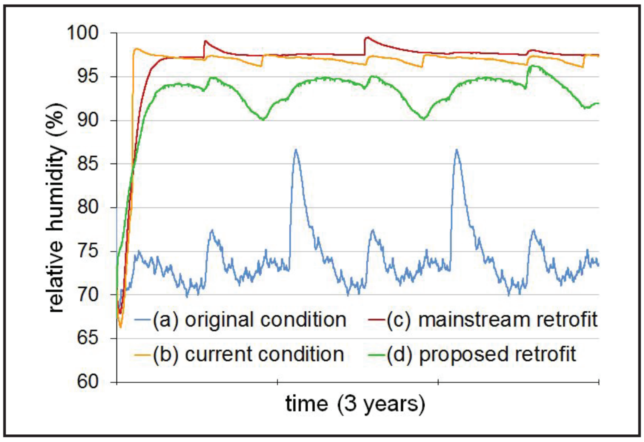

Figure 8 – Evolution of relative humidity in numerical simulations, at inner face of brick above internal floor level (black dots in Figure 3), for the four scenarios assessed.

capillary break of foamed glass aggregate[17]. This approach results in significantly lower relative humidity levels than the mainstream retrofit scenario (c), and all areas in the vicinity of internal surfaces remain uniformly dry (red colour in Figure 7). It is therefore considered to entail lower risk of mould growth and material decay.

Figure 8 compares relative humidity levels for the four scenarios over the length of the simulation. The internal edge of the brick above internal floor level (black dots in Figure 3) has been chosen as an important location to study as it is simultaneously affected by conditions at wall and ground floor, and is a sensitive location due to its proximity to the room surface.

In the context of the moisture storage function of the selected brick (red line in Figure 5), it is apparent from Figure 8 that:

- The original condition (a) has the lowest relative humidity and thus lowest moisture content. It also displays a clear seasonal nature, averaging less than 75% RH.
- The current condition (b) results in greatly increased humidity at the assessed location averaging 97% RH with little drying effect: this shows the base of the wall is already hygrothermally stressed, as can be seen in Figure 2.
- The mainstream retrofit (c) results in an increase that on average is only 0.8% higher than (b) but exhibits no drying effect and peaks extending to 99.5%. In the context of the marked increase in moisture content after 95% RH and even more so 97% RH (Figure 5), the associated stressing is significant. The moisture-related risk of this retrofit should be considered unacceptable.
- The proposed retrofit (d) results in lower humidity levels (averaging ~93.8% RH) than conditions (b) and (c) with the absence of the damp-proof membrane having a beneficial effect on local drying. While (d) has a far higher relative humidity at the measurement point than (a), it does exhibit a summer drying effect that ensures the overall performance is out of the vulnerable zone above 95% where pores are increasingly filled and capillary action dominates moisture transfer. This will help protect the masonry, reducing the potential for spalling of the wall's outer surface. As the location is behind alkaline lime plaster and a fully-bonded internal wall insulation assembly, the likelihood of mould forming is low and the risk to occupants negligible.

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In Table 2, results are summarised in the form of a matrix, considering both thermal insulation (x axis) and associated hygrothermal risk within the wall substrate (y axis). The original condition (a) has the lowest risk of damage to the wall substrate, at the cost of a poor thermal performance. If an insulation retrofit is to be carried out, the proposed retrofit (d) is the safest option according to this risk assessment using transient numerical simulations.

It should be borne in mind that any internal wall insulation retrofit will compromise the drying ability of the wall substrate as it isolates it from the internal heating system. This effect is amplified as internal insulation levels increase[6]. Insulants that are vapour closed such as used in (c) will also limit drying to the room. The current condition (b) stresses the masonry substrate because drying to the room is inhibited by tanking, even though the wall surface is heated by the dwelling's heating system. Retrofit condition (c) adds to the risk by also thermally isolating the substrate, while (d) thermally isolates it but allows vapour and capillary movement in both directions.

	no insulation	floor insulation	wall & floor insulation
high risk		**current condition**	**mainstream retrofit**
moderate risk			**proposed retrofit**
low risk	**original condition**		

Table 2 – Result matrix indicating insulation (x axis) and hygrothermal risk within wall substrate (y axis).

8. Discussion/conclusion

In this study, the hygrothermal performance of four different scenarios (original condition and three retrofit approaches) has been assessed for the ground junction of a traditional brick-faced house, using two-dimensional numerical simulation. While limited to one case study house in the Dublin climate, the findings appear to indicate that vapour permeable assemblies should be favoured for insulating ground floors and external walls of brick-faced solid wall buildings.

The use of damp-proof and vapour-resistant membranes appears to result in higher moisture content within the wall and ground slab. These findings are consistent with recent research on the hygrothermal performance of walls[6,16] but contradict current guidance[1,2], which is based on simplified assessment methods that are unsuitable for assessing traditional buildings[5,7].

While a choice of vapour-permeable insulants and strategies are now available for internal wall insulation, the range of products for floors remains much more limited. The suitability of this ground floor assembly without a damp-proof membrane is contingent on the following:

- The floor insulation should be designed to act as a capillary break preventing rise of ground moisture;
- Ideally the dwelling would also feature mechanical extract ventilation that constantly removes indoor air contaminants, as an indoor air quality measure;
- In high radon areas the suppliers of the floor system acknowledge that a radon barrier should be used. (The role of mechanical extract ventilation systems in managing radon in low and medium radon areas falls outside the scope of this paper)

This study shows clearly the kind of risk assessment possible using transient numerical simulation like WUFI Pro and 2D. This is not possible for a wide range of reasons with the Glaser method as discussed. The study raises serious questions about current construction practice, mainstream guidance and grant aid policy in Ireland and the UK, especially where a mainstream approach appears to increase hygrothermal risks to historic dwellings. There is a need for parametric modelling to expand this assessment to a range of wall and ground assemblies, insulants and locations: ideally, this would be supported by selected physical testing.

Acknowledgements

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