Hygrothermal implications of low and zero energy standards for building envelope performance in the UK

Abstract

Driven by Climate Change legislation and high rates of fuel poverty, the UK faces multiple challenges both in new build and upgrading the existing stock. How these challenges are addressed will have long term impacts on building fabric, occupant comfort and wellbeing. Building performance simulation has an important role to play in this process, yet it is widely recognised that over-simplification in the modelling of physical phenomena leads to substantial sources of error. Moisture is a major cause of damage in buildings, and the Glaser method is a widely used steady–state method used to calculate the vapour pressure difference in a building's envelope. Although known for its limitations, it is the principal method used to assess moisture response in the UK. This paper evaluates the current situation in the UK, addressing fuel poverty targets, energy saving regulations and changing boundary conditions and their compounding implications for building envelope performance.

1. Introduction

Buildings play a major role in terms of the global energy consumption and Green House Gas (GHG) emissions (Winters, 2011). Consequently many Annex 1 governments have decided to drastically reduce their national carbon emissions by significantly increasing the thermal performance of their building stock (WAG, 2004). Overarching national emission reduction targets and corresponding guidelines are described in the report of Royal Commission on Environmental Pollution on the urban environment (DEFRA, 2008). At present, commercial, residential and industrial buildings use nearly 40% of the energy in the UK producing almost half of the CO_2 emissions at a national scale. Nearly 60% of this energy consumption is used for heating and cooling of the premises; the rest is consumed by electrical appliances, lighting and other uses (DTI, 2001; Winters, 2011). Despite a continued fall in the proportion of energy used for water heating and cooking since the 1970's, there has been a pronounced rise in the proportion used for lighting and appliances (DECC 2012); this coupled with an expanding housing stock (DCLG, 2007a) means that the overall situation is worsening. According to the UK Government Environmental Audit Committee: "unless significant measures are put in place to reduce emissions from the housing sector ,from their current level of around 40MtC a year, they could constitute over 55% of the UK's target for carbon emissions in 2050; nearly doubling the current 30% contribution." **(**House of Commons, 2005, p48 item 125).

In tandem with meeting its legally binding Green House Gas (GHG) emission reduction commitment (UK Parliament, 2008), the UK is facing many new challenges both in new build and upgrading of the existing stock, which will have long term impacts on building fabric and occupant comfort and wellbeing. Interventions in the existing stock such as the retrospective filling of cavity walls and the application of internal insulation in heritage buildings, or new requirements needed to meet advanced performance standards such as EnerPHit (Feist et al, 2012a) could significantly change the way these buildings perform. In new build, advanced performance standards such as Passivhaus (Feist, 2012b) and the Code for Sustainable Homes (CfSH) (DCLG, 2010) Level 4+ often result in a win-win situation where energy savings also result in improved fabric quality and occupant comfort, but this is not always the case. In terms of hygrothermal risk analysis the Glaser method, whilst known for its limitations, is still the main method used in the UK to evaluate the overall moisture response.

This paper sets out to evaluate some of the key issues inherent in current UK policy and praxis, in more detail. These issues are explored by examining the challenges imposed by the upgrading of the existing building stock whilst addressing fuel poverty targets, energy saving regulations and changing hygrothermal boundary conditions.

2. UK Building Regulations and current practice in hygrothermal assessment

2.1 Current practice

The 1985 Building Regulations were the first to include the UK's modern system of Building Control. Under the 1984 Building Act provision was made for future changes to technical specifications using a system of Approved Documents (England & Wales) and Technical Standards (Scotland and Northern Ireland) (Killip,2005).

Despite the adoption of Part L of the UK Building Regulations, which were designed to conserve fuel and power, there is currently only limited legislative scope for their application in partial refurbishment work (HM Government, 2010a). Alongside this, demolition and replacement rates in the UK housing stock are extremely low with figures suggesting that the existing housing stock is currently being replaced once every 1300 years (Boardman, 2007). This means that only a very small percentage of the UK building stock would comply with modern building regulations.

Even when new dwellings are built a number of reports suggest that there is often a large discrepancy between the design performance mandated by Part L of the Building Regulations and what is actually constructed. In an unpublished 2005 Sustainable Energy Authority of Ireland report (BBC, 2008) it was not only found that many new build homes failed to meet energy and building regulations; it also pointed out that "92 per cent of the houses failed to meet minimum insulation levels", whilst "42 per cent did not (even) meet minimum ventilation standards" (BBC, 2008) which are considered necessary to reduce surface condensation risks, dampness and associated problems to human health. A similar National Home Energy Rating report (NHER, 2005) showed that out of a sample of 200 new build dwellings, tested post completion, over 1/3 would not have met the Part L requirements. Studies demonstrating a marked difference between what building energy models predict and the reality of what is built are not uncommon (Norford, 1994; Doran, 2000; Oliver, 2001; Bordass et al, 2004; EST, 2004; Sanders & Phillipson, 2006).

In response to these findings the UK Governments Environmental Audit Committee (EAC) stated that they "are alarmed at the apparent ease and possible extent of non-compliance with part L of the Building Regulations" (House of Commons, 2005, p45 item 116). The EAC found that "The fact that compliance with Part L of the Building Regulations is not covered by new buildings insurance, combined with a lack of post-completion inspections by Building Control bodies, provides little incentive for developers to carry out work to a standard that ensures proper compliance with energy efficiency requirements" (House of Commons, 2005, p45, item 117).

The recently revised Building regulation Part L1A for new build dwellings (2010) provides current guidance on the conservation of fuel and power in UK homes, and aims to reduce CO_2 emissions by 25% over Part L1A 2006. Part L1A (HM Government, 2010b) is largely based on demonstrating that whole building carbon emissions comply with the method set out in the UK Standard Assessment Procedure (SAP) 2009. Approved document LIA (2010) also provides limiting (worst case) fabric U-value for external walls to $\leq 0.3\ W/(m^2{\cdot}K)$ and $\leq 2.0\ W/(m^2{\cdot}K)$ for windows ((HM Government, 2010b, p15). This is whilst Part F (2010) regulations address air tightness and ventilations issues. In order to harmonise these two standards recent revisions have been made to control the background air leakage from UK dwellings. Currently Part L1 (2010) specifies that air leakage should not exceed 10m3/m2.h at 50Pa. (HM Government, 2010b, p15). This level of airtightness is equivalent to allowing a hole the size of a twenty pence coin in each square meter of the building envelope (BRE, 2012). New legislation was also implemented in Part F (2010) to ensure that more airtight dwellings (<5m3/m2.h @ 50Pa) had adequate trickle ventilators or mechanical ventilation due to concerns regarding reduced Indoor Air Quality (IAQ) standards in airtight dwellings. Part L and Part F regulations are revised approximately every 3 years with the intention that by 2016 all UK new build dwellings should become 'zero carbon' by definition.

2.2 Part L and implications of the revised 'zero carbon' definition

Achieving CO_2 emission cuts of 80 % from the total UK housing stock by 2050 (UK Parliament, 2008) represents an enormous technological and logistical challenge (Boardman, 2007). Historically low stock replacement rates in the UK means that the majority of newly built dwellings will create additional stock that simply adds to the emissions problem (McLeod et al, 2012a). By 2050 it is estimated that there could be as many as 23% to 40% (DECC, 2010) more households in the UK with the anticipated construction of approximately 240,000 homes each year (DCLG, 2007a).

With respect to new build housing, the British government intend to incrementally increase the CO_2 emission reduction requirements implemented via the Building Regulations every three years between 2010 and 2016. The key points of these new standards are:

- Achieve a reduction of 25% in new build carbon emission in 2010 over the previous standard (2006) (CSH Energy Level 3)
- Followed by proposals for a 44% reduction in 2013 (CSH Energy Level 4)
- In 2016, all new homes will be defined as ‘zero carbon’ (CSH Energy Level 6).

The original definition of ‘true zero carbon’ stated that: “Net carbon dioxide emissions from all energy used in the dwelling are zero or better”. In addition, “a zero carbon home is also required to have a Heat Loss Parameter (covering walls, windows, air tightness and other building design issues) of 0.8W/m^{2}K or less, as well as net zero carbon dioxide emissions from use of appliances in the homes (i.e. on average over a year)” (DCLG, 2007, p29).

The revised ‘zero carbon’ definition however addresses only the portion of operational emissions that are accounted for in the UK Standard Assessment Procedure (SAP) (ZCH, 2009a; HM Treasury 2011). SAP (2009) accounts for the energy consumed by the main and secondary space heating systems, space cooling, domestic hot water, building services pumps and fans and fixed lighting, but not energy used for cooking or domestic appliance consumption (DECC, 2011)

The previous Part L (2006) methodology is estimated to have omitted between one third (Reason and Olivier, 2006) and a half (DCLG, 2007a) of the total CO_2 emissions from a UK dwelling. Given that domestic appliance consumption is rising (DECC, 2012) and that heating demand is falling as a result of climate change (McLeod et al , 2012b) it is likely that the revised definition of 'zero carbon' will affect substantially less than half of the total operational emissions from new build dwellings (McLeod et al, 2012a).

Where the new policy differs significantly from the previous definition is in the inclusion of a third tier based on the use of cost capped 'allowable solutions'. The concept of 'allowable solutions' was promoted by the ZCH since "rather than placing reliance solely on the development itself (through energy efficiency and on-site renewable energy) to deliver zero carbon, a range of additional, mostly off-site solutions, would be made available to developers in the new definition" (ZCH, 2009a). For further explanation and a detailed analysis of the concept of 'allowable solutions', please see McLeod et al. (2012a).

In terms of the net climate change impacts from new buildings it is not only the operational energy use that is registered in the atmosphere however. According to McLeod (2007) and Eurobuild (2012) the embodied carbon emissions in a conventional masonry Passivhaus dwelling may account for between 30 and 50% of the total 60 year GHG emissions (depending on the type of heating system used). Given the significance of these unregulated emissions and the fact that the vast majority of new dwellings create additional stock, any carbon emission savings achieved under the revised definition of 'zero carbon homes' are unlikely to make a positive contribution to the 80% emission reduction target, mandated for 2050, under the UK Climate Change Act (UK Parliament, 2008). When the net GHG emissions (including embodied energy) are considered in the context of a low energy dwelling the on-site savings achieved by the revised zero carbon definition diminishes to as little as one sixth of the total GHG emissions incurred over a sixty year period (Figure 1).

Figure 1

Given the magnitude of the existing stock, coupled with historically low replacement rates (Boardman, 2007) and generally poor standard of energy efficiency amongst the existing UK housing stock (DCLG, 2007c) (Olivier, 2001) suggests that a re-emphasis towards standards to upgrade the existing stock are likely to achieve far greater net energy and carbon savings.

In terms of legislation affecting the thermal upgrading of existing buildings, Part L1B applies to the removal and reinstatement of existing dwellings as well as upgrading the existing envelope (BR L1B, 2010). A large number of buildings in the UK are exempt from Part L1B legislation however, due to their conservation status (BR L1B, 2010). In England alone there are approximately 374,081 listed building entries (English Heritage, 2012). Although listing is not a preservation order, Listed Building Consent is required to make changes to the fabric of a listed building and this includes common replacement works such as changing windows and doors as well as any work affecting the building fabric (English Heritage, 2012). In buildings with Grade I or Grade II* status substantial thermal upgrading may not be permissible.

According to L1B the individual element limiting U-value for walls should not exceed 0.7 $W/(m^2 \cdot K)$. Although such backstop (or worst case) U values are stipified in Part L, they are rarely enforced. Part L compliance is typically evidenced via a 'whole building' carbon emission methodology based upon the outputs from a SAP calculation. As such, the predicted CO_2 emissions reductions -relative to a 'notional' building of the same format with a fabric specification designed to meet the previous Part L standards and with boundary assumptions derived from the National Compliance Methodology (NCM) - has become the defining standard. If the 25% reduction is made then the Dwellings Emission Rate (DER) will be less than the Target Emission rate (TER) and the dwelling is deemed to comply with Part L. In reality, no thermal upgrade may be needed to achieve compliance in this manner since simply switching from a conventional gas heating system to an equivalent biomass pellet heating system would effectively reduce the CO_2 emission intensity by a factor of 7 (SAP, 2009, p199), thus far exceeding a notional 25% improvement in the DER. Therefore contingent upon the fuel type, building format, heating system or installed Low and Zero Carbon Technologies (LZCTs) used to reduce the SAP regulated carbon emissions anything from a nearly Passivhaus standard envelope down to something that could have been the default elemental standard 10 years ago may still be permissible for Part L compliance.

In contrast to the emission reductions achieved via small LZC technologies and energy efficient appliances, many of which are unlikely to last beyond 10 -20 years (Phillips et al, 2007; Seiders et al, 2007), fabric measures implemented via quality assured design approaches such as the Passivhaus standard are likely to achieve carbon savings that will exceed 60 to 100 years (BLP, 2007). Likewise changing the carbon intensity of the fuel source does nothing to alleviate fuel poverty or improve Indoor Air Quality (IAQ) issues. Addressing all of these contiguous issues will only occur by focusing on the reduction of unwanted thermal losses and gains through the envelope of buildings as well as uncontrolled air infiltration losses. One of the most straightforward solutions is to use appropriate insulation in order to substantially improve the operational energy efficiency of a building, thereby directly reducing their long term energy consumption and to global CO_2 emissions.

In terms of the building fabric, under the revised definition of ‘zero carbon’, the Fabric Energy Efficiency Standard (FEES) would provide a national minimum energy efficiency specification for zero carbon homes (ZCH. 2009b). This performance specification has significant implications since it effectively defines a national minimum insulation and airtightness standard as well as having implications for the climate change adaptation and the mitigation potential of the UK’s future housing stock (McLeod et al., 2012a). The proposed FEES standards mandates limiting the specific heat demand (SHD) of detached, semi-detached and end terrace ‘zero carbon’ dwellings to 46 kWh/m2.yr and for apartments and mid-terraced dwellings to 39 kWh/m2.yr (ZCH. 2009) based on the SAP(2009) methodology. Modelling carried out by the ZCH suggests that, in order to comply with the FEES standards, fabric standards will have to meet or exceed those set out in Table 1.

Table 1

It should be noted that the SAP calculation takes account of thermal bridging, at junctions between elements and around openings. If linear thermal transmittance (Ψ) values are available for these junctions, they can be multiplied by the length of the junction concerned, and the total added to the one dimensional transmission heat transfer coefficient.

$$U = U_0 + \frac{\sum_{i=1}^{n} (\psi L)_i}{A}$$

Where U is the resultant U value after the two dimensional linear thermal bridging transfer coefficients are added. The three dimensional point bridging effects of fastenings and wall ties are normally included as adjustment factors in the U_0 calculation in accordance with (EN6946, 2007). If specific values for linear thermal bridges are not known, an approximation is permissible by including a notional ‘y-value’ allowance of 0.15 W/m^{2}K based on the total exposed surface area (SAP, 2009).

It should be noted that the use of a ‘y’ value in accordance with the UK SAP (2009) convention involves a notional adjustment to the elemental U value in order to incorporate the area weighted influence of linear thermal bridges (Ψ).

A y-value is therefore the sum of (L × Ψ) for all junctions divided by the total area of external elements, which includes exposed elements but not party walls, (DECC, 2011, p78).

$$y = \frac{\sum_{i=1}^{n} (\psi L)_i}{A_{exp}}$$

where A_{exp} is the total area of external elements

The assumption in the FEES standard is that the non-repeating thermal bridging can contribute to worsening the overall elemental U values by 0.04 W/m^{2}K for a detached house and 0.05 W/m^{2}K for all other dwelling types (ZCH, 2009b). As such the y values permissible under the FEES standard allow for a worsening of the backstop elemental thermal transfer coefficients (U_0) by approximately 25%.

Whilst the FEES standards are likely to be mandated as defining the minimum fabric standard for a 2016 ‘zero carbon’ dwelling, it is notable that they fall significantly short of those proposed by well-established low energy standards including the German Passivhaus standard (Feist, 2012) the Canadian R2000 standard (NRCAN, 2012) or the Swiss Minergie P standard (Minergie, 2012) . There is however nothing to prevent developers achieving ‘zero carbon’ compliance through the voluntary use of these more advanced specifications, and indeed an increasing number of UK social housing developers are exploring the adoption of such standards as a means of improving energy efficiency whilst alleviating fuel poverty.

2.3 Passivhaus (new build) and EnerPHit (refurbishment)

Passivhaus is currently the fastest growing energy performance standard in the world with approximately 40,000 buildings realised to date (PHI, 2012; BRE 2012). It is an ultra low energy standard which necessitates the use of mechanical ventilation with heat recovery due to very high level of air tightness (Feist, 2012a; Feist, 2012b). A map of certified UK PH Projects can be viewed on the PH Trust webpage (PHI, 2012). The first certified Passivhaus projects in the UK were completed in 2009 and as a result it is still too early to assess whether significant hygrothermal issues will arise as a result of the construction methods used to achieve this advanced thermal standard. In the majority of cases it seems likely that the use of external insulation and internal vapour barrier layers are likely to reduce the risk of interstitial condensate forming within the structural elements of the building. However, several of the projects completed in the UK to date have adapted more conventional construction methods including the use of cavity wall constructions and lime based pointing and renders.

The risk of cracking of parge coatings to masonry block work and the tearing of membranes in timber frame construction is always possible and carries an associated risk of introducing approximately 360g of water vapour through a 1m crack length (x 1mm wide) per day (BRE, 2012). Similar studies by the Institute of Building Physics, Stuttgart, have shown that under standard occupancy conditions as much as 800g of moisture can be convected through a 1m x 1mm crack per day when exposed to a pressure differential of 20Pa (IBP, 1989) . Where vapour diffusion to the outside is possible the risks associated with localised construction defects may be reduced. However, such risks need to be carefully evaluated in their specific context particularly in constructions where synthetic renders, render boards, and other rain screen materials are applied externally without a vented cavity.

According to Quirotte (2004) constant cavity cycling poses a risk in well-sealed cavities due to the pressure fluctuations inside the cavity driven by variations in external air pressure. This cyclic phenomena occurs when the external air temperature drops (at night) drawing warm moist air in to the cavity from the inside of the building, where it is likely to condense. During the day in the presence of substantially warmer sol-air temperatures the air pressure flux within the cavity may be reversed, thus creating a 24 hour cycle. This phenomenon poses a potential future risk in the UK where sealed unvented cavities are increasingly specified in an attempt to improve the thermal performance of cavity walled buildings. Figure 2 shows an example of a ‘partially filled’ timber frame and brick veneer cavity wall construction that is unvented (Cae Gleishon passivhaus).

Figure 2

According to the ideal gas law, the relationship between pressure, volume and temperature can be described by the following equation

$$PV = nRT$$

And $$P_1 V_1/T_1 = P_2 V_2 /T_2$$

Where P_1 and P_2 are absolute air pressure before and after temperature change (Pa)

And T_1 and T_2 are the initial and resultant air temperature during a cycle (K)

V_1 is the free air volume of the cavity (m^3) , ΔV is the displaced air volume (m^3)

Since the cavity volume is constant $V_2 = V_1 + \Delta V$

Hence, the volume of displaced air is $\Delta V = (P_1 V_1 T_2 / T_1 P_2) - V_1$

Thus, for a given change in sol-air temperature or barometric pressure the displaced air volume of the cavity can be calculated. According to Quirouette (2004) this phenomena is widely documented during winter months in Northern Latitudes. In practice the severity of this phenomenon is proportional to the extent of the temperature change and the duration of each cycle, and will only occur when the outer leaf of the cavity is well sealed.

Where more traditional constructions such as cavity walls have been constructed in a fully filled manner such as in the Denby Dale Passivhaus (Figure 3) (GBS, 2010) or BedZED (Lazarus, 2002) further investigations may also be warranted. Of possibly greater significance than the diffusion and convection driven interstitial condensation risks outlined above; are potential problems associated with driving rain entering an unventilated cavity, particularly one which is not properly drained. The influence of driving rain on unvented cavity constructions where the outer layer is constructed from a porous stone material or brick (which may also be prone to cracking at the joints) has not been extensively researched in the UK.

Figure 3 shows a cross section of the Denby Dale Passivhaus wall construction, an example of a fully filled undrained Passivhaus cavity wall which is faced in porous sandstone with a lime based pointing. Although water repellent mineral fibre has been used as a precaution in this construction (Butcher 2012), there is no egress for trapped water or condensate. As a result moisture accumulation in the cavity could lead to saturation of the lower course of facing stone over time.

Figure 3

Ice expansion damage can result in structural cracking when rainwater seepage freezes in poorly drained cavities (Figure 3). The risk of this problem is elevated in super insulated and thermally Passivhaus wall constructions as a consequence of the high temperature gradients across the construction.

Figure 4

Sol-air temperatures below freezing (at night) on the outside of super insulated buildings following spells of driving rain are likely to lead to spalling and frost damage where trapped moisture freezes within the outer layer of porous or sorbtive materials (Figure 5). Modern bricks are predominantly frost resistant however it is important to consider this issue before post filling existing cavity walls. Super- insulated timber frame constructions are also vulnerable to this phenomenon. Transient hygrothermal analysis accounting for the directional dependence of localised driving rain is recommended before the use of hygroscopic cladding materials, such as lime based renders, are specified as a surface coating to sorbtive materials such as woodfibre board (as for instance in the Lime Passivhaus at Ebbw Vale).

Figure 5

Further, even air alters moisture flow at the micro-scale (Descamps, 1997). Once a material is wet, the capillary sucked water displaces air out of the material's pores until only enclosed air bubbles are left (Hens, 2012). This phenomenon is known as the capillary moisture content and basically states that the value of the moisture uptake is sometimes limited to a value well below saturation.

None of these relationships are linear and as the air temperature increases, the Saturated Vapour Pressure (SVP) also increases exponentially (Tetens, 1930; Murray, 1967). This relationship has implications for the phenomena of reverse diffusion or summer condensation, where the moisture flux is reversed.

Buxbaum et al (2007; 2008) have demonstrated that there is a risk of moisture vapour entering the vapour permeable outside layers of some Passivhaus constructions and condensing on the external face of the internal Vapour Barrier. For this reason Buxbaum (2007) recommends that internal vapour retarders with high SD values should not be used in timber construction, and that vapour permeable materials such as OSB-3 or intelligent membranes offer a better solution. The high external temperatures needed to drive a strong reverse vapour pressure differential are relatively rare in the UK, however inward diffusion of moisture vapour may readily occur as a result short wave radiation absorption warming external surfaces saturated by driving rain (Kuenzel and Zirkelbach, 2011; Quirouette, 2004) . UK climate change projections indicate that increasingly warmer and wetter summers are likely for much of the UK (Jenkins et al, 2007) this suggest that pre-cautionary assessment of this risk is advised, particularly where the structural elements of timber frame or steel constructions may be at risk.

The EnerPHit standard was launched by the Passive House Institute, in 2010 as a trial standard for use in retrofitting existing properties that would otherwise be too difficult or costly to refurbish to the full Passivhaus standard (PHI, 2010). Where insulation can be applied externally in a continuous manner the EnerPHit standard is unlikely to present challenges from a hygrothermal perspective (except where water is trapped in the construction during installation).

The EnerPHit standard specifies that the overall thermal transmission coefficient of internally insulated walls must be < 0.35 W/m^{2}K (PHI, 2012a). Whilst in the case of internally insulated floors the thermal transfer coefficient multiplied by the ground temperature reduction factor (f_t) should be < 0.15 W/m^{2}K (PHI, 2010). The guidance documents also state that interior surface temperatures of the ground floor covering must result in an internal floor surface temperature of at least 17 °C for the design conditions (assuming an indoor set point temperature of 20°C) (PHI, 2010). Assuming a typical annual ground temperature reduction factor range in the UK of 0.62 (Central London) to 0.75 (Outer Hebrides) (Feist,

2012) then this would imply that the actual U values for the floor build up should be no greater than 0.2 - 0.24 W/m^{2}K, depending on the location. This would be equivalent to adding approximately 14cm (or more) of XPS insulation (lambda value 0.035 W/mK) to the warm side of an un-insulated concrete slab.

Such targets are necessary if radiant surface temperature asymmetry is to be minimised within the limits of acceptability set out in EN ISO 7730 whilst achieving an overall specific heating demand of $Q_H \leq$ 25kWh/m^2.yr (Feist, 2012a). Implementation of the EnerPHit standard can presents significant technical challenges where ambitious energy reduction targets are imposed in contexts where thermal bridging issues and interstitial condensation problems are likely to be exacerbated. When internal insulation is applied the temperature gradient across the wall/ floor or roof element will become more pronounced and existing structural elements will be at much lower temperatures in winter. This will reduce the drying potential of saturated walls and could also lead to significant frost damage where temperatures fall below freezing point.

Thermal bridges are likely to be exacerbated where internal insulation is used, particularly at junctions where the insulation is not continuous. Careful detailing around all junctions (including window reveals, party walls etc.) is needed to ensure that internal surface temperatures do not fall below a minimum threshold of 12.5°C (Pfluger, 2006). This guidance is based on the assumption that with an internal air temperature of 20°C the dewpoint temperature will occur at 12°C (with an internal RH of 60%). In such situations two and three dimensional analysis of thermal bridges and transient hygrothermal modelling will almost certainly be required to determine whether long term damage is likely to occur either via mould growth or moisture accumulation.

Thermal bypass, possess another serious risk where internal insulation is used. Warm air convected around or through internal insulation due to a breach in the airtight barrier (or an internal cavity) can lead to air with a high vapour pressure condensing on cold surfaces deep within the construction. Problem areas include window frame junctions and the ends of timber joists in floors and ceilings. Internal insulation must therefore be installed in an airtight manner; Pfluger (2006) suggests that a target q_{50} value below 0.6m^3/m^2.h should be maintained for this reason. A detailed study of the long term performance of 14 different internal insulation approaches (including capillary active insulation materials) used in conjunction with different types of vapour retarders across a range of driving rains zones can be found in AkkP 32 (2005).

The EnerPHit guidance was amended in 2012 to define a new standard 'EnerPHit^{+i}' which applies to situations where more than 25% of the opaque external wall area is to be internally insulated (Feist et al, 2012a). Although internal insulation is often the only acceptable route to refurbishing dwellings in the UK that are subject to conservation or planning restrictions, the risks inherent in this process cannot be neglected. In practical terms a comprehensive survey of the existing building fabric and services should be carried out before internal insulation is specified. Potential risks such as: inhomogeneous materials and voids, heating pipes embedded in the outer wall, air leakage paths at critical junctions, thermal bridges and convective bypass routes must be carefully assessed before internal insulation is installed. Altering the hygrothermal behaviour of an outer wall which is acting as a rain screen or buffering system could have significant consequences for the long term durability of the building fabric.

The revised EnerPHit guidance states that: for interior insulation proof of suitability must be provided by means of an expert report based on accepted testing procedures (e.g. hygrothermal simulation) (PHI, 2012a). This is the first time that an energy performance standard adopted in the UK has mandated third party indemnity procedures with respect to hygrothermal risk assessment.

2.4 UK legislative guidance Part C and EN 13788

Although rarely referred to, the UK Building Regulations Approved Document C (ADC) (BR ADC, 2010) addresses site contamination (Part C1) and moisture for new build construction (Part C2). Amongst other information ADC2 provides additional information for different wall constructions, insulation types and finishes or cladding to be specified appropriate to the regional driving rain location in the UK (see Figure 6).

Figure 6

For example, it is stated that in the regions prone to severe driving rain (zone 4) either an impervious rain screen or complete rendering of the facing masonry is advised (BR ADC, 2004, p35). Such guidance stands in significant contrast to what has actually been implemented in much of the recent UK building stock where brick walls often with recessed pointing are found in regions with 'severe'(zone 3) and 'very severe'(zone 4) driving rain exposure (Figure 6).

However, although Part C is an Approved Document and part of the UK building regulations, this section is considered to be 'guidance' rather than an enforceable requirement.

Moisture content has an important impact on the building performance. These effects range from modification of the thermal performance of insulation, through to structural collapse of buildings and chronic health issues. Moreover according to (Hens, 1990) there are serious risks of surface mould formation if the inside of the building envelope reaches equilibrium at 80% RH (relative humidity). Not only is building performance affected by moisture but indoor air quality (IAQ) and hygienic conditions become less favourable as moisture levels rise above an optimum threshold. Mould and dust-mites allergens are closely correlated to indoor Relative Humidity (RH) levels above 45%RH (Emenius et al. 2004; Franchimon, 2009) and are directly attributed as a causal agent of allergies and asthma (Pulimood et al., 2007). The UK has one of the highest rates of asthma in the world (Covey, 2004) and its regional prevalence is closely correlated to areas of high rainfall and fuel poverty (Asthma UK, 2008).

3. Hygrothermal consequences of high insulation values

3.1 The Glaser method (in practice) and its application and limitations

The Glaser method (BS EN ISO 13788-2002) analyses the moisture balance of a building component by considering vapour diffusion transport from its interior. Developed during the late 1950's the Glaser method was originally intended as a means to evaluate interstitial condensation on freezer walls (Glaser, 1959). Nevertheless, it became one of the most common tools used to analyse the moisture balance of building components, and is commonly referred to as the "dew-point method" in the USA (ASHRAE, 1993). It was subsequently upgraded by including capillary action and by the incorporation of more realistic indoor and outdoor boundary conditions (Hens, 2012).

Although it has become a commonly adopted method, it cannot always be relied upon to give a reliable indication of vapour diffusion and moisture behaviour through the building structure due to its simplified steady state assumptions. In reality, dynamic simulation tools that are capable of accounting for thermal and hygric inertia (sorption/desorption), for capillary moisture movement, as well as taking into account variations in non-homogenous material property values, whilst allowing consideration of wind-driven rain, building moisture sources etc. are more likely to produce reliable predictions. None-the-less, Glaser is still the most commonly used method in the UK and is widely used to determine surface and interstitial condensation phenomenon and the ancillary risk of mould growth and is incorporated in several widely used in building energy models and U-value calculators (including BuildDesk Energy, IES-ve, Hevacomp, JPA Designer, amongst others). As far as realistic transient heat and moisture simulation is concerned, it provides a general method to assess the suitability of a building component. This method states that it is possible to calculate the vapour pressure evolution in a building in a similar manner to which one determines the temperature evolution through the building component.

According to the Glaser method, condensation will appear on or within a layer where the calculated vapour pressure exceeds the saturation vapour pressure at a given temperature (i.e. the dew point temperature is reached). Generally, the overall moisture response is more pronounced in winter, as the vapour pressure gradient across a construction element is higher at this time due to lower external temperatures which limits the absolute moisture content (and hence saturation vapour pressure) of the external air. Since interstitial condensate typically accumulates at the interface between construction materials or within a porous material layer one often only discovers the consequences of this on the internal surface of the building after several years. In some circumstances, such as inside cellulose based insulation materials or structural timbers, the condensate may have caused irreversible damage at this point. Theoretically, the amount of interstitial condensate forming in winter and the amount of evaporable water in summer can be evaluated using the Glaser method as well. If the materials are able to seasonally absorb and desorb the amount of moisture without creating long term build up (Künzel, 2000) there is, in theory, no problem. The Glaser method assumes that a given amount of built-in water will dry out during the summer period based on the boundary conditions used, however this method does not take into account a number of important physical phenomena (including the transient nature of boundary conditions) and consequently the method is applicable only to structures where these effects are negligible. The application and limitations of the method have been described in BS EN ISO 13788-2002.

According to Künzel (2000) in one study comparing the interstitial condensation predictions in roof constructions, the Glaser method and the dynamic simulation software (WUFI) gave fairly similar results. However, Künzel points out that short time step variation in the boundary properties using the Glaser method are limited and that is why it is in some cases essential to use dynamic simulation tools. One example might be the effects of solar and long wave re-radiation on sol-air boundary temperatures or, perhaps more importantly in a UK context, the influence of driving rain or melting snow which may affect the moisture conditions but are neglected in steady-state calculations.

In the United Kingdom where large regions (such as Northern Ireland, and Western coasts of Wales, Scotland and the SW) are confronted with severe driving rain (see Figure 5), the use of dynamically coupled heat and moisture simulation becomes increasingly more important.

In a study conducted by May (2009), the difference of three different wall constructions, of approximately similar *U* values, located in two different climate zones is shown. One is modelled under a moderate climate in London and the other one being located in Swansea/ Wales facing severe driving rain (cf. Figure 5).

May's (2009) study shows the failure of conventional insulation materials such as using PU foam insulations by demonstrating the moisture content rising in the wall construction over time and reaching its critical failure point after only 2 years time in the relatively sheltered London location; even worse, the same construction is predicted to fail within the first 9 months if located in a more severe climate such Swansea.

In contrast to the Glaser method, dynamic hygrothermal simulation, incorporating transient heat and moisture transport in one/ two-dimensional assemblies, becomes possible. This approach includes the possibility of more realistic modelling of material properties. Some material properties are easy to measure (density, dry thermal conductivity, the sorption isotherm, vapour permeability and air permeability) (Hens, 2012), others however, for instance moisture diffusivity and thermal moisture conductivity demand complex and time-consuming tests (Roels, 2008; Hens, 2012).

3.2 Modelling uncertainty in material data and outputs

Hens (2012) points out that despite such advances limitations still exist in dynamic modelling due to "too simple material modelling and uncertainty in material properties". Figure 7 shows the results of a series of dry cup vapour resistance factor measurements on 30 facing brick samples from the same production batch in order to demonstrate the problem of non homogeneity in building materials.

Figure 7

Natural variation in material data creates uncertainty in modelling parameters which cannot be resolved in a straight forward manner. Building materials are heterogeneous by nature. In a study by Woloszyn and Rode (2008) it was shown via several whole building design calculation methods that relying upon the assumption that heat and moisture transfer can be neglected produces significant uncertainty in the outcome. This uncertainty increases even more when air and moisture transfer is taken into the account. The results show variations of up to 370%. Costola (2011) tries to minimize this modelling uncertainty by coupling building energy simulation with heat and moisture simulation and thereby reducing uncertainty in the modelling process.

Physical uncertainties are mostly identifiable as the standard input parameters in energy, thermal comfort or heat and moisture simulation. Physical uncertainties refer to physical properties of materials such as thickness, density, thermal conductivity, or hygrothermal properties etc., of wall, roof and floor layers. Due to the manufacturing processes and random variations occurring in natural materials such uncertainties are always present, and thus, inevitable (Hopfe, 2009; Hopfe and Hensen, 2011). Obtaining sufficient information about specific variations in material properties is not always straight forward - especially in the case of natural materials such as sheep wool, cork, hempcrete and strawbale. Information about the physical properties of such materials is often either very limited or differs significantly according to different sources and measurement techniques (e.g. Adensam et al., 2005; Christian et al., 1998; Hens, 2012). The introduction of new harmonised European product standards EN 13162 to EN 13171 (amongst others) is intended to establish a level European playing field for all commercially manufactured insulation materials. This has led to the adoption of what is known as the λ90/90 assessment method for insulation materials, which adopts a bench mark based on the 90th percentile confidence level being achieved by 90% of production output (Figure 8) (BBA, 2012) What may be more helpful in assessing the uncertainty in hygrothermal analysis would be to have information regarding the range of key parameters within an appropriate confidence level.

Figure 8

Variations or uncertainty regarding material moisture content or specific hygrothermal properties as well as variations in the sources or heat and moisture within the building envelope will in reality significantly affect the thermal and hygric performance of the building. If for example an insulation material becomes wet, the thermal conductivity of the insulation material will increase, which consequently affects the buildings energy consumption. Taking these compounding uncertainties into account is ultimately related to quality assurance. Despite the designers best attempt at quality assurance there will always remain a degree of uncertainty that he/she has no influence on.

In the case of strawbale for example, Walker et al (2011) observed changes in density varying from 100-130 (kg/m3) and in terms of thermal conductivity of 0.05-0.065 (W/mK). Organic materials such as straw, cork, etc. are strongly hygroscopic and therefore have non-linear vapour permeability characteristics. The influence of such transient material properties is likely to be underestimated in current data even that used in dynamic simulation, when considering the in-situ behaviour in high humidity regions such as the UK. Most material databases do not yet contain such data in relative humidity ranges and literature reviews often provide incomplete information. An example for different sources for bulk density, thermal conductivity and water vapour diffusion resistance for strawbale is shown in Table 3.

Table 3

3.3. Weather data uncertainty

The UK is a nation of varied micro-climatic contexts, and a diverse existing building stock. The adoption of dynamic hygrothermal simulation, if correctly implemented, can be seen as a step forward in both the diagnostic recognition of typological problem areas and the prevention of future damage to individual buildings.

Accurate in-situ prediction of moisture problems in buildings requires boundary data sets which reflect the internal and external conditions that the building is likely to face. The key parameters needed to model the climatic influences on a building include the following (IBP, 2010; Künzel, 2006.; Künzel and Zirkelbach, 2011):

- rain load vertically incident on the exterior surface in [L/m²h]
- solar radiation vertically incident on the exterior surface in [W/m²]
- temperature of the exterior air in [°C]
- relative humidity of the exterior air [0 -1]
- temperature of the interior air in [°C]
- relative humidity of the interior air [0 -1]

- barometric pressure in [hPa].
- long-wave atmospheric counter-radiation [W/m²], if night time radiative cooling is to be accounted for

Rain load and radiation are directionally dependent quantities, however in conventional weather station measurements they are usually only recorded on horizontal surfaces. With knowledge of the vertical rain load and the wind velocity and direction it is possible to compute the directionally dependent driving rain. Likewise the amount of radiation incident upon any given surface tilt direction or slope angle can be determined from knowledge of the global and diffuse radiation components incident on a horizontal surface for a given latitude and time (Muneer, 2004). WUFI performs these directional conversions automatically and will recognize data files in .WAC or .WET or .TRY or .DAT or .IWC format. In some cases an additional file (.AGD) is needed to supply geographical data regarding the climate location (IBP, 2010). Although data is available for a wide number of locations worldwide using the ASHRAE IWEC data (.iwc) caution is advised as this does not typically contain quantitative rainfall data (IBP,2010).

By integrating the dynamic hygrothermal capabilities of WUFI with the quasi steady state energy model PHPP the Fraunhofer Institute have produced WUFI-Passive (Fraunhofer IBP, 2012). This integrated design tool was originally developed for the U.S Passivhaus market where issues of cooling and dehumidification are more pronounced than in central Europe. The WUFI-Passive software avoids the double entry of common data from the building energy model to the hygrothermal model ensuring that valuable hygrothermal outputs are now available to designers at the early stages of design.

Currently the WUFI software does not contain any default climate data for the UK and this may be a factor in limiting its adoption by less experienced practitioners. None-the-less there are a number of options available to obtain suitable hygrothermal weather data for the UK. TRY data is readily available from the CIBSE for 14 UK locations. CIBSE is due to release future probabilistic weather files in the form of Test Reference Years (TRYs) and Design Summer Years (DSY) derived from UKCP09 scenarios that cover three time periods, three emissions scenarios, and three probability levels for each of the 14 locations available in the current CIBSE datasets. These future weather files were produced using the morphing method detailed in TM48: Use of climate change scenarios for building simulation (Shamash, 2012)

Several researchers have noted the limitations of using the “nearest neighbor method” of transposing climatic data from one micro regional context to another in building energy and moisture models (McLeod et al, 2012b) (Morehead, 2010) (Remund, 2010). In order to address this situation and provide a clearer statistical basis for decision making the PROMETHEUS project at Exeter University developed a new method for generating high resolution (5km grid data) in an EPW file format. Using primary outputs from the UKCP weather generator (Eames et al, 2010) created a series of probabilistic weather files in TRY and DSY format. The weather generator is a stochastic randomly seeded model which combines measured data from the UK Met Office with data downscaled from the Hadley Centre’s Regional Climate Model (HadRM3) for various future climate scenarios (DEFRA, 2009). The method used by PROMETHEUS allows the development of current and future probabilistic datasets, following the IPCC SRES emission scenarios (IPCC, 2000), for use in building programs requiring hourly simulation time steps. A full description of the methodology including that used to derive missing variables such as future wind speed, wind direction and atmospheric pressure can be found in Eames et al (2010).

A further option for deriving data at sites where either measured or synthesized data is unavailable is through the use of the Meteonorm interpolation software. Meteonorm uses interpolation methods (such as 3D inverse distance models for global radiation) to create weather files in almost any output format for any location in the world (Remund, 2010). Although the use of interpolation has been shown to entail a level of inaccuracy (Rawlins, 1984) (particularly for Global Horizontal radiation and ambient temperature) Remund (2010, p32) points out that the root mean square errors (RMSE) for this method are typically less than when the “nearest neighbor” approach is adopted. Analysis carried out by the Fraunhofer IBP suggests that driving rain and wind data produced by Meteonorm can be too homogeneous in its distribution and therefore not always reflective of local conditions (IBP, 2010). In Germany the Holzkirchen climate dataset is commonly used in hygrothermal simulations as a ‘worst case’ reference location for driving rain. No such location has yet been adopted in the UK as a proxy for ‘worst case’ analysis, however a number of locations situated within class 4 (ADC, 2004) ‘very severe’ driving rain exposure categories would make suitable candidates. EN 15026 (2007) suggests a simplified proposal for the generation of extreme climate years by creating simple shift functions of +2K for a warm year and -2K for a cold year. Such approximations may suffice as part of an initial sensitivity analysis depending on the accuracy and temporal period being considered. Regardless of the climate data used a sound knowledge of the uncertainty inherent in the modeling process and familiarity with micro climate of the building being modeled are important pre-requisite for interpreting the outcomes of hygrothermal simulation.

Uncertainties in modelling and climate data are just a few of many other limitations in dynamic simulation. To date most commercially available models overlook air and wind intrusion as important factors when looking to the hygrothermal response of walls and roof constructions. Other limitations exist with respect to the modelling geometry of building components (the reality compared to what the tool allows), perfect hydraulic contact conditions, boundary conditions (for instance the randomness of wind driven rain) (Blocken, 2004). Further to this in order to provide comprehensive outputs there is a need to judge indoor air quality, health and durability (Hens, 2012) – challenges which are yet to be addressed by dynamic simulation models .

4. Consequences of retro-fitted cavity wall insulation in response to carbon reduction targets and fuel poverty alleviation

A number of UK government funded strategies have been implemented over the past decade in order to reduce fuel poverty and improve the thermal performance of Britain’s worst performing housing. The current government carbon reduction scheme - Carbon Emissions Reduction Targets (CERT), is targeted towards electricity and gas suppliers to reduce the amount of carbon emissions from dwellings (Ofgem, 2011). The scheme was originally to be run from April 2008 to March 2011, but was extended to end in December 2012 (DECC, 2012).

Figure 9 shows different methods of saving carbon emissions under the CERT scheme, it can be seen that the most popular method was insulation, which included both loft insulation and cavity wall insulation (Ofgem, 2011).

Figure 9

By the end of the third year of the current scheme, 1,582,612 cavity walls had been insulated (Ofgem, 2011). This resulted in a saving of approximately 40.5 Mt of carbon emissions (Ofgem, 2011). The most popular material used for the insulation of the cavity walls under this scheme was mineral wool (Ofgem, 2011).

During the first decade of the 20th century there was a sharp rise in the use of cavity walls in UK dwellings as they were introduced to replace solid wall construction in order to reduce construction costs, and provide protection from rain penetration (English Heritage, 2010). It is estimated that 69% of dwellings in England have a cavity wall present; of which only 40% have cavity wall insulation (BRE, 2005).

Table 2

Comparing the percentage of dwellings with cavity wall insulation, across different regions of England, it can be seen from table 6, that the highest percentage of dwellings constructed with cavity wall insulation are located in the North East (BRE, 2005). 71% of dwellings constructed in the South West have a cavity wall, of which 38% have cavity wall insulation. This represents a slightly higher percentage of cavity wall insulation than the North East, where 36% of the dwellings have cavity wall insulation.

The cavity method of wall construction was first introduced in UK during the early Victorian period (English Heritage, 2010) and was widely adopted for dwellings during the 1920's, (Energy Saving Trust, 2002) to reduce the effect of rain penetration on the internal envelope. This allowed rainwater and moisture to be removed from the building envelope through the cavity area of the wall (Osbourn, 1985). Many factors need to be considered before cavity wall insulation material can be retrospectively injected into a dwelling, such as rain penetration (Energy Saving Trust, 2002), location of the dwelling (Smith, 2005) and exposure (Which?, 2011) as well as the type of insulation to be injected (BR ADC, 2004). Inbuilt and Davis Langdon (2010) state that by installing cavity wall insulation in a dwelling, the risk of cold bridging, condensation and frost damage is increased.

Figure 4 shows that wind-driven rain affects various location of the United Kingdom differently. It can be seen that there is a significant difference from zones less than 56.5l/m^2 to zones that receive approximately 100 litres/m^2 of driving rain per spell in the UK. According to Edwards (2011) no consideration is given to wind driven rain or location of the dwellings during pre-assessment of the suitability of applying cavity wall insulation in a specific dwelling, despite guidance in Approved Document C (p35). Dwellings in various locations will all receive different amount of moisture penetrating into the cavity wall area. This observation is confirmed by Gellert (2010a; 2010b) who believes that location, latitude and altitude of a dwelling should all be taken into consideration, before the installation of cavity wall insulation is specified.

The Energy Saving Trust (2002) also recommends that the wall construction of dwellings should be taken into account before installing cavity wall insulation. Problems such as leaking gutters may cause the wall to be saturated, therefore potentially exacerbating problems after insulation has been injected into the cavity area. The British Standards Institute (BSI) *BS 5618:1985* (1985) states that any defects that will subsequently affect the cavity wall after the injection of insulation, should be rectified before insulation is installed, and this should form a part of the contract.

6. Conclusion

It was aim of this paper to illustrate the current challenges facing the practice of hygrothermal assessment in the UK in the context of rapidly evolving building performance standards. The UK is characterised by highly localised climatic conditions and experiences extreme driving rain conditions along much of its Western border. The existing stock is characterised by a high percentage of historic buildings and historically low demolition rates (Boardman et al, 2005) ; this means that advanced thermal refurbishment measures will need to be applied to a very high percentage of the existing stock if the UK if it is to meet its climate change and fuel poverty abatement targets. Planning, space and aesthetic considerations suggest that a large percentage of the existing stock will need to be internally insulated in order to meet these targets (Boardman et al, 2005; Boardman, 2007; Killip, 2008).

The hygrothermal consequences of meeting ever higher standards of thermal performance have been widely overlooked in the race to reduce CO_2 emissions, fulfil the energy efficiency commitments of utility companies and address fuel poverty targets. The UK Building Regulations currently provides disparate information on the Conservation of Fuel and Power (Part L) and the provision of Ventilation (Part F). This guidance needs to be harmonised with the inclusion of more robust guidance in Part C2, particularly with respect to advanced refurbishment measures and the use of porous and hygroscopic cladding materials in super-insulated wall constructions.

This paper highlights why there is clearly a need for more research to be conducted and demonstrates the evolutionary role that transient hygrothermal modelling can play in the refurbishment and design of the future UK building stock. Unless accompanied by widespread building physics training schemes, for UK building professionals, it seems likely that achieving deep refurbishment targets will engender serious risks for the moisture response and structural integrity of many UK buildings. Current de-facto practice of using steady state modelling (Glaser method) and homogenous material properties as a means of condensation analysis has been demonstrated to be unreliable, particularly in complex refurbishment cases. The widespread adoption of dynamic heat and moisture simulation should form part of the precautionary approach, particularly where significant levels of internal insulation are used and the dew point falls inside the thermal envelope. The development of new tools (such as WUFI-Passive) that couple heat and moisture processes in an integrated platform offer a potential solution by providing more reliable hygrothermal information early in the design process .

As with all building simulation tools the results obtained can only supplement and further assist a detailed knowledge of the existing structure, local weather patterns and careful on site implementation; factors that are indispensable to the effective realisation of modelled predictions in reality. Only by better understanding the 'real world' behaviour of the system being modelled and the limitations of the model itself can more robust predictions be achieved.

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Figure Captions

Figure 1.Relative GHG emissions addressed by the revised UK zero carbon definition

Figure 2. Cross section showing the Cae Gleishon Passivhaus wall construction

Figure 3. Full fill 300mm cavity wall construction with sandstone cladding (image Green Building Store).

Figure 4. Ice expansion damage to the bottom of a poorly draining cavity wall, Ireland (source J. Morehead)

Figure 5. Typical spalling damage on external brick facade caused by driving rain penetration

Figure 6. Impact driving rain in the UK (from http://www.innovateuk.org/_assets/pdf/climate%20report-lib/designing4construction_bill_gething_climatechangereport-0510.pdf)

Figure 7. Dry cup vapour resistance value measured on 30 samples of bricks from a single production batch (Hens, 2012)

Figure 8. Showing the λ90/90 assessment method (BBA, 2012)

Figure 9. Comparison of different method used in the Carbon Emissions Reduction Targets to reduce CO_2 emissions up until August 2011 (Ofgem, 2011)

Table Captions

Table 1. Backstop fabric performance values required to meet the FEES standards (Adapted from ZCH, 2009a)

Table 2. Cavity wall insulation in dwellings dependent on location (Adapted from BRE, 2005)

Table 3 Thermal conductivity and water vapour diffusion resistance for strawbale according to literature

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