Identifying a Suitable Climate File for the Moisture Risk Assessment of Internally Insulated Walls Exposed to Solar-Driven Vapour Diffusion

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Abstract

In the UK, 20% of the building stock is subject to solar-driven vapour diffusion due to the un-rendered external surface of solid walls. Energy efficient interventions such as the installation of internal wall insulation can help to reduce greenhouse gases emissions and improve the thermal performance of those buildings. However, if the interventions are incorrectly designed, moisture accumulation may occur, which could be detrimental to the building and the health of its occupants. The moisture-related risk of such interventions is usually evaluated using hygrothermal simulations, however some of the input data required for the evaluation are not always suitable for the purpose; in particular, this is the case for external climate data.

The aim of this study is to identify a suitable climate file for the risk assessment of internally insulated walls affected by solar-driven vapour diffusion. This paper presents an evaluation of the commonly used *typical* and *near-extreme* reference climate files for moisture risk assessment. Hygrothermal simulations were carried out for both types of climate files and 19 years of measured data. Results indicate that the near-extreme files under-represent the worst-case scenario and that the penetration of rainwater does not significantly affect the output of the hygrothermal simulations. A distribution of climate files was found to be more accurate and representative for the moisture risk assessment when considering solar-driven vapour diffusion.

Introduction

The UK has a legally binding commitment to reduce greenhouse gases emissions by 80% from 1990 level by 2050. Improving the energy efficiency of the existing housing stock is one of the key measures required for the fulfilment of such emission target. Around 20% of the UK building stock has solid masonry walls; internal or external wall insulation are the available options for the energy efficiency improvement of such walls. However, these measures can lead to moisture accumulation within walls, which can be detrimental to the building (e.g. causing mould growth, corrosion, wood rot, freeze-thaw damage) and the health of its occupants.

Moisture risk assessment considers the risks related to moisture accumulation occurring in the insulated walls. Moisture risk is usually assessed considering appropriate boundary conditions (i.e. internal and external climate, boundary parameters) and specific physical mechanisms that could lead to failure (e.g. outward vapour diffusion, rainwater penetration, air infiltration and solar-driven vapour diffusion).

Several studies on solar-driven vapour diffusion have been mainly conducted to document its occurrence and to identify the driving potentials for the mechanism (Derome and Carmeliet, 2010; Karagiozis, 2009). However, few have focused on the risk related to solar-driven vapour diffusion (Wellesley Smith, 2010), which has been found to occur in solid masonry walls exposed to wind-driven rain and solar radiation (Marincioni and Altamirano-Medina, 2014).

The aim of this study is to identify a suitable climate file for the risk assessment of internally insulated solid walls affected by solar-driven vapour diffusion. The study evaluated the suitability of available climate files for the moisture risk assessment of a building component (solid masonry wall) subject to one failure mechanism (solar-driven vapour diffusion).

Literature review

A reference year is a yearly climate file that is able to represent the weather conditions found at a location over a long period of time. It can represent typical or more extreme weather conditions. Yearly climate files that could represent normal or typical weather conditions over a long period of time are usually called typical years; for energy analysis, their selection is based on a combination of parameters that gives an average energy demand. These climate files are commonly available for hygrothermal simulations and are used for moisture risk assessment. However, climate files for risk assessment need to consider more severe conditions than the typical conditions. This is true for the assessment of moisture risk in buildings, where a once-in-ten-year scenario, where

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conditions leading to risk can occur in maximum 10% of cases, is commonly accepted (Kumaran and Sanders, 2008). More severe issues (e.g. in structural design) will require more extreme scenarios. Hence, for moisture risk assessment we are considering the development and selection of near-extreme years.

Typical years

The two most common typical years are the Test Reference Year (TRY) and the latest version of the Typical Meteorological Year (TMY3).

The TRY was developed for energy analysis and is commonly used in the UK. The Chartered Institution of Building Services Engineers (CIBSE) provides guidelines for the construction of TRY files in the UK (Levermore and Parkinson 2006). It is a collection of months with typical conditions; those conditions are based on the following climate indices:

- Daily mean dry bulb temperature, T (°C)
- Daily mean global solar horizontal irradiation, GHI (kWh/(m^{2}d))
- Daily mean wind speed, WS (m/s)

The month with typical conditions has an empirical cumulative distribution function (CDF) which is the closest to the long-term cumulative distribution function, CDF_{lt} (e.g. the CDF of all the Januarys in 19 years). This is calculated with the Filkensten-Schafer statistic:

$$FS = \frac{1}{n}\sum_{i}^{n} |CDF_{lt,i} - CDF_i| \quad (1)$$

With n = number of daily readings in a month

The minimum value among the weighed sums of the FS statistic for each climate parameter (i.e. dry bulb temperature, global radiation and wind speed) will determine the month with typical conditions. Simple to construct, the TRY doesn't consider the variability of values within the months, but only the mean values.

The Typical Meteorological Year (TMY), developed for the U.S. Department of Energy, is a more advanced method for constructing a typical climate file. It can be used for building simulations, but also for photovoltaic applications, and it considers a larger number of climate indices:

- Daily maximum, minimum, mean dry bulb temperature (°C)
- Daily maximum, minimum, mean dew point temperature (°C)
- Daily maximum, mean wind speed (m/s)
- Daily total global horizontal solar irradiation (kWh/(m^{2}d))

The typical month selected has the minimum weighted sum of FS statistic values based on the indices above; the indices have different weights. Also, the TMY includes additional criteria to exclude years with extremely warm days, extremely cold days or days with extremely low global solar radiation (Wilcox and Marion, 2008). A further modification lies in the TMY3 (Wilcox and Marion, 2008), widely used in the field of building simulation and currently the default climate file for various energy analysis software. The main difference from the TMY lies in the addition of the daily direct irradiation (kWh/(m^{2}d)) to the previous indices and in the weighting system, which gives less importance to wind speed and more to temperature.

Near-extreme years

The development of suitable climate files for moisture risk assessment has been a focus of building physicists for the past 20 years (Sanders, 1996). Moisture reference years have been developed to represent near-extreme years (i.e. once-in-ten-year scenarios) in relation to specific failure mechanisms.

Some moisture reference years only take into account relative humidity and dry bulb temperature, considering failure mechanisms such as lack of drying and low temperature at the external surface (Kalamees and Vinha 2004), or once-in-ten-year lower or higher temperature (BSI, 2007).

The standard on hygrothermal simulations EN 15026 (BSI, 2007) suggests the use of the year with the 90th percentile of rainfall for the specific assessment of moisture problems associated with rainwater penetration.

Another method for the assessment of moisture risk caused by rainwater penetration through porous materials and based on a Moisture Index (MI) was developed by Cornick et al (2003). The MI is the ratio of a wetting index and a drying index. Wetting is represented by an annual or directional driving-rain index, which is simply the product of average wind speed and the total rainfall of the year, sorted according to wind direction in case of directional driving-rain index. The drying index is the difference between the humidity ratios at saturation and of ambient air, and is a measure of the ability of air to take up water vapour from the saturated surface of the assessed building component. Ranking the years according to the MI allows the identification of the year with the lowest, mean and highest MI. Some failure mechanisms can be assessed through the addition of safety margins to the reference year selected. In particular, for the moisture risk assessment related to rainwater penetration through cracks within the building fabric, it is suggested to add 1% of wind-driven rain penetration to the reference year (WTA, 2013). According to the ASHRAE standard 160 (ASHRAE, 2009), adding 1% of the incident wind-driven rain could represent worst-case scenario when rainwater penetration occurs; this was developed for timber-frame buildings with masonry cladding, but it is believed to be acceptable for other wall types (Künzel, 2014).

This paper presents the analysis of construction-independent reference years, which were developed without considering specific building components. The advantage of these reference years lies in the fact that they can be used without considering the construction type (Djebbar et al., 2001). Other methods for the selection of near-extreme years are based on the hygrothermal response of a specific building component and require hygrothermal simulations (Zhou, Derome, & Carmeliet, 2016; Zirkelbach et al., 2016).

Solar driven vapour diffusion is associated with wind-driven rain absorption followed by solar radiation. These parameters are considered in some reference years. The described typical years consider solar radiation, while some near-extreme years consider wind-driven rain; these near-extreme years are the year with 90th percentile rainfall and the year based on the 90th percentile MI. Adding 1% of wind-driven rain to a reference year is an alternative method for considering additional wind driven rain penetration. As there is no evidence of near-extreme years for solar-driven vapour diffusion, the years associated with near-extreme rainwater penetration have been assessed in this study.

Methodology

Moisture risk for an internally insulated wall affected by solar-driven vapour diffusion was evaluated considering near-extreme years and compared with 19 years of measured data. In addition, typical years (often used for moisture risk assessment) were included in the analysis. Finally, all the reference years were assessed with or without the safety margin of 1% of wind-driven rain penetration.

Climate files composed of measured data at weather stations were selected from the MIDAS database for Aberporth, Wales (Met Office, 2012). Only complete climate files between 1970 and 2000 were selected, reducing the dataset to 19 climate files (each one representing a complete year).

The typical years TMY3 and TRY were built as a combination of the selected 19 years, according to the literature; the typical years are described in Table 1.

Table 1: Months with typical conditions selected for the typical years

month	TRY	TMY3
January	1996	2000
February	1974	1974
March	1993	1999
April	1996	1996
May	1993	1997
June	2000	2000
July	1977	1977
August	1987	1999
September	1990	1979
October	1988	1988
November	1990	1975
December	1997	1997

Also, the near-extreme years were selected within the 19 years identified in the initial analysis. Table 2 shows the near-extreme years selected for the analysis.

Table 2: Near-extreme years selected

Method	Year
90th Percentile Moisture Index	*1974*
90th percentile rain	*2000*

The suitability of reference years was evaluated by performing hygrothermal simulations using the reference years and comparing the simulation results with the distribution of simulations results associated to the 19 years of measured data. The coupled heat, air and moisture transfer software Delphin is used for the hygrothermal simulations. For each climate file, the hygrothermal simulation was done for 4 years and only the last year was used for the assessment. Results were evaluated against available mould growth risk criteria.

Case study

The wall evaluated is located in Aberporth, Wales (UK), a place with high exposure to wind-driven rain and solar radiation (see Figure 1). In particular, the location is within a zone of very severe wind driven rain exposure, i.e. a zone with a maximum wall spell index greater than 100 l/m^2 per spell (BSI, 1992; Stirling, 2002). The location also has a high yearly global irradiation compared to the rest of the UK (Šúri et al., 2007). The assessed wall is oriented to the prevailing wind direction (West).

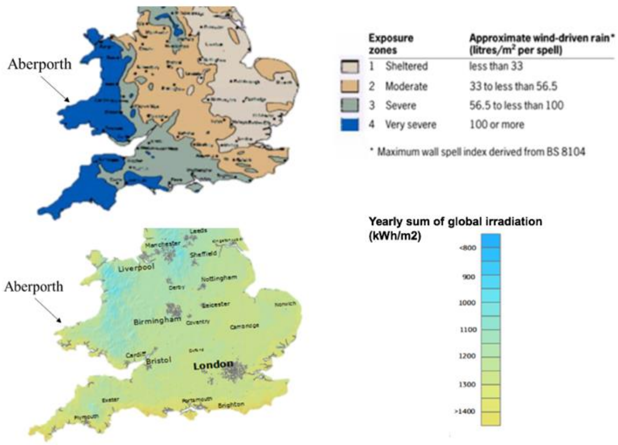

Figure 1: Case study location within (top) the UK wind-driven rain exposure map (Stirling, 2002) and (bottom) the UK global irradiation map (Šúri et al., 2007)

The analysis considered a 215 mm-thick solid brick wall, where the porous external surface has been left un-rendered and it has a dark red colour (short-wave absorption coefficient α = 0.68). The wall has a common closed-cell internal wall insulation system, composed of phenolic foam and a vapour barrier (see Figure 2).

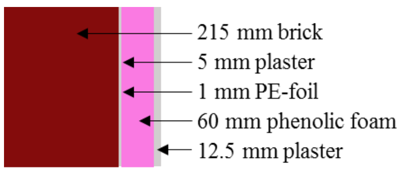

Figure 2: Internally insulated solid wall – construction assembly (external to internal)

The properties of the wall construction are taken from the simulation software database and described in Table 3.

Table 3: Material properties for hygrothermal simulations

Materials *Units*	**ρ** *kg/m³*	**λ** *W/(mK)*	**Ψₒ** *m³/m³*	**μ** -	**Aw** *kg/(m²s⁰·⁵)*
Brick	1734	0.656	0.346	24.5	0.107
Plaster	1498	0.412	0.434	9.3	0.019
Phenolic Foam	36	0.02	0.987	113.7	0.008
PE-foil	1500	0.23	$1.5 \cdot 10^{-6}$	10^5	10^{-6}

The internal climate is constant at a dry bulb temperature of 20 ºC and a relative humidity of 50%.

Mould growth risk criteria

Mould growth risk was evaluated considering a commonly used threshold of relative humidity and a more advanced criterion based on a combination of parameters affecting mould growth, called the dose-response model.

The 80% relative humidity threshold proposed in ISO 13788 (BSI, 2002) is commonly used among British professionals and has been suggested for solid-wall insulation interfaces that are not fully bonded (Little et al., 2015).

The dose-response model has been developed by Isaksson et al.(2010) for evaluating the risk of mould growth under varying climate conditions. It is based on the established isopleth system for a biological substrate (Sedlbauer, 2001) but considers the time of exposure to combinations of temperature and relative humidity favourable for mould growth. In the dose-response model, the mould growth threshold is a dose of 365 days, considering a year-long simulation.

Results and discussions

The relative humidity at the wall-insulation interface was obtained as a result of hygrothermal simulations; the boxplots in Figure 3 show the distribution of relative humidity in a year, for each of the 19 measured climate files considered in the analysis. Also, the relative humidity distributions were evaluated against a mould growth risk threshold of 80% relative humidity.

The boxplots show high values of relative humidity throughout the year and a small interquartile range for most simulations. These conditions alone are likely to trigger mould growth. Also, all simulations show a relative humidity at the solid wall-insulation interface higher than 80%.

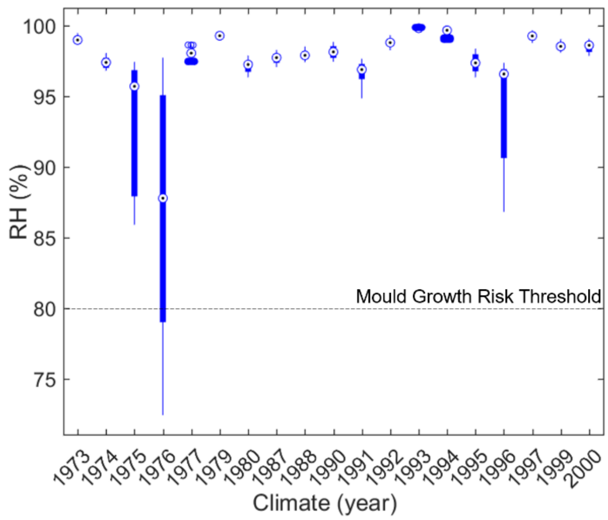

Figure 3: Relative humidity (RH) at the wall-insulation interface; 19 climate files (measured data)

Figure 4 shows the distribution of relative humidity in a year for the typical and near-extreme years, and a comparison with the case of 1% wind-driven rain penetration.

Here, the TRY file produced a lower relative humidity than the TMY3 file, yet both distributions are above the defined relative humidity threshold of 80%. On the other hand, the near-extreme years are similar, both at a very high relative humidity.

The addition of 1% of wind-driven rain penetration at the wall-insulation interface showed a minor, often negligible increase of relative humidity at the interface. Therefore, the safety margin of 1% wind-driven rain was not considered further in the analysis.

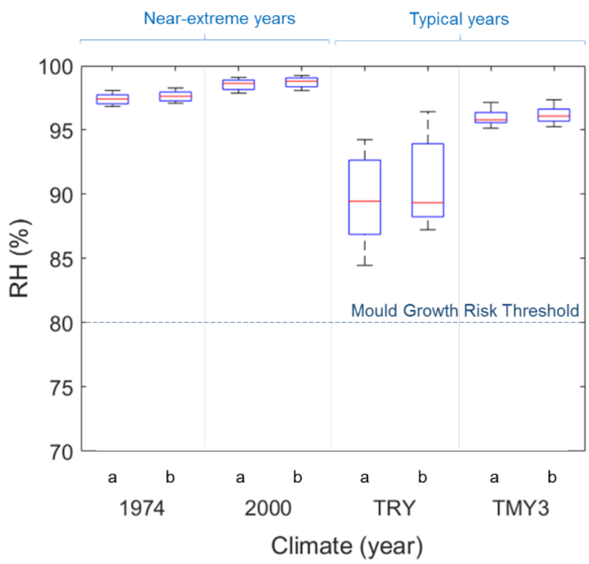

Figure 4: Relative humidity at the wall-insulation interface; (a) without 1% rainwater penetration, (b) with 1% rainwater penetration

The results of the hygrothermal simulations were then evaluated against a mould growth risk criterion based on the dose-response model. Figure 5 shows the yearly dose (i.e. the sum of daily doses in a year) as a function of the climate files used for the simulation. Considering a year-long simulation, the threshold for mould growth risk is a yearly dose of 365 days.

The yearly dose ranged between 368 and 1800 days; therefore, all values were above the mould growth risk threshold.

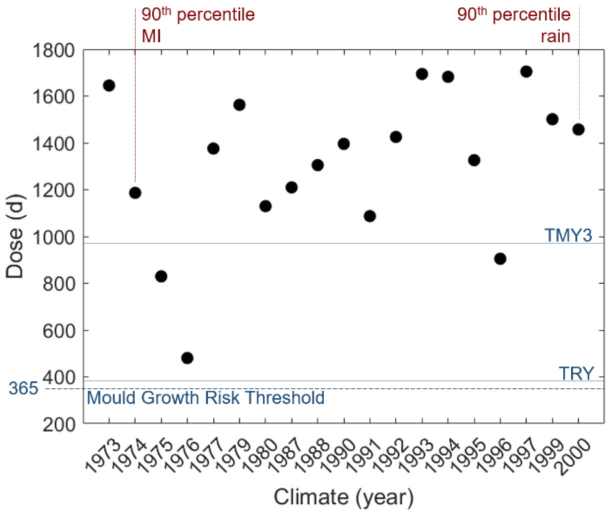

Figure 5: Dose and selected years

Figure 6 shows typical and near-extreme days within the empirical cumulative distribution function (CDF) of the dose. The CDF shows the inter-quartile ranges and allows to identify whether typical and near-extreme years fall respectively within the median and upper interquartile ranges, and how they relate to the risk factor of 10% assumed initially.

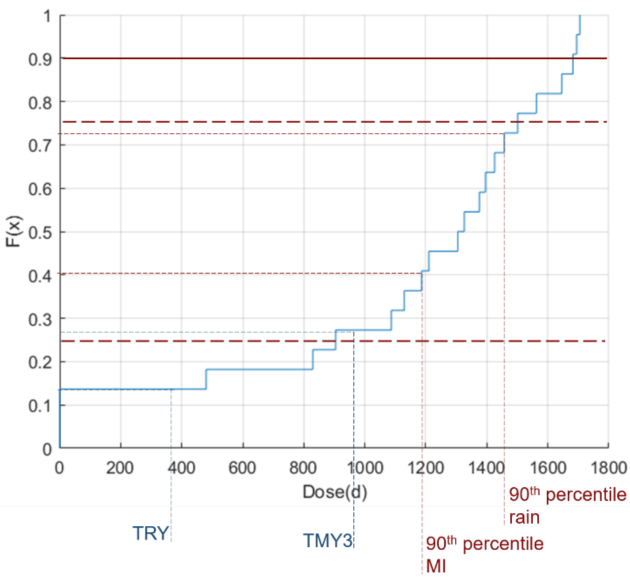

Figure 6: Empirical CDF of dose, with typical and near-extreme years

Regarding the typical years, the dose of the TRY was in the lower interquartile range, whereas the dose of the TMY3 was slightly above the lower interquartile range. This suggests that solar-driven vapour diffusion is under-represented in typical years.

The near-extreme value of 90th percentile rain led to a high dose (close to the upper interquartile range), which shows that rain is a good indicator; however, mould growth risk due to solar-driven vapour diffusion was underestimated with this climate file.

The 90th percentile Moisture Index did not give a high value for the dose (F(x) = 40%). This could be explained by the fact that the Moisture Index relies on a balance of a drying and wetting component; if the weights are not correct, it is hard to understand the actual risk using this index.

Conclusion

We assessed the validity of currently available typical and near-extreme climate files for the assessment of mould growth risk in case of solar-driven vapour pressure.

An internally-insulated solid wall located in an area exposed to rain and solar radiation was evaluated and various climate files used (through hygrothermal simulations) to identify a suitable climate file for the moisture risk assessment.

The results show that near-extreme climate files under-represent worst-case scenario, and accounting for rainwater penetration does not increase mould growth risk significantly.

It was not possible to find a climate file that could represent a once-in-ten-year scenario (i.e. a year constructed to cause the most severe conditions to occur once every ten years). The closest year to such climate file was the year with 90th percentile rainfall. This year considers rainfall – one important factor for solar-driven vapour diffusion – but does not account for solar radiation, which can exacerbate mould growth risk. The 19-year distribution of measured climate files provided the most comprehensive moisture risk assessment and should be the preferred method.

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