7th International Building Physics Conference

IBPC2018

Proceedings

SYRACUSE, NY, USA

September 23 - 26, 2018

Healthy, Intelligent and Resilient Buildings and Urban Environments

ibpc2018.org | #ibpc2018

Hygrothermal modelling of building enclosures: reference year design for moisture accumulation and condensation risk assessment

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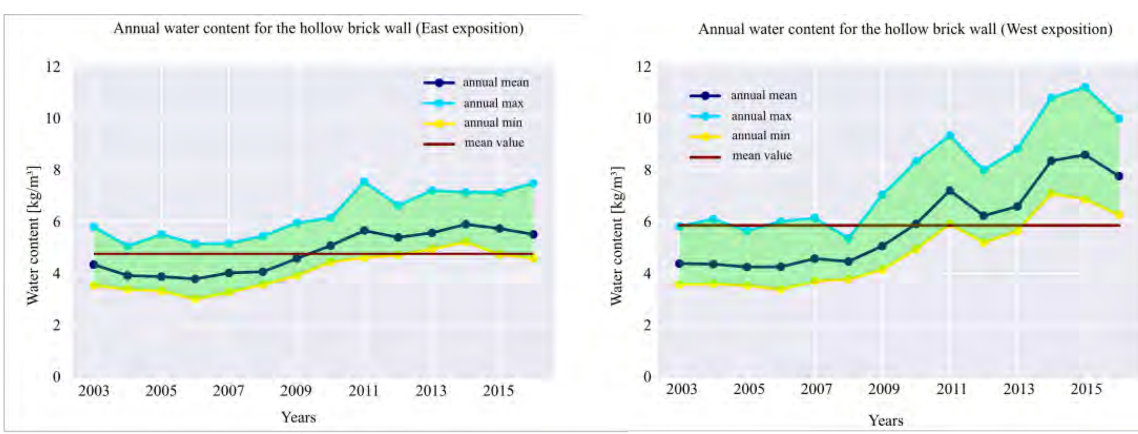
ABSTRACT
Interstitial condensation and water accumulation risk in building envelopes could be assessed with methods and models based on moisture migration through porous media coupled to heat transfer. One of the difficulties in evaluating the boundary conditions for the heat and mass transfer model is the choice of an appropriate weather file. The most advanced models, described by the standard EN 15026:2007, require the hourly values of rain, wind, radiation, temperature and relative humidity to compute the water content in the porous materials.
In this contribution, the method described by the standard EN ISO 15927-4:2005, typically used to design Moisture Reference Years (MRY), has been extended to the design of 34 typologies of representative weather files. The generation criteria have been based on the assumption that the simulation results are influenced by rain deposition on the considered wall. The procedure has been followed considering 5 different wall exposures that lead to different MRY. The years of the climate of Turin (Italy) between 2002 and 2016 have been considered for the generation of the reference years.
Finally, the annual mean moisture contents for two common wall types have been calculated using the obtained MRY and compared to the annual mean moisture contents obtained with the measured weather data, and the effects of the selection of the weather parameters is presented.

KEYWORDS
Building enclosures, condensation risk assessment, moisture accumulation, reference year, weather file, Moisture Reference Years.

INTRODUCTION
The building envelope design process requires the risk assessment for condensation and moisture accumulation of all the enclosures and their intersections to avoid mould growth conditions and material damage due to prolonged moisture exposure. Up to now, several evaluation methods, simplified and advanced, have been developed. The simplified and most used methods are based on stationary models, they consider monthly mean weather data and are not intended to simulate the real phenomena of the heat and moisture transfer (for example the Dew-Point method or the Glaser method). When more accurate methods are needed (and a simulation of the real physical phenomena is required) it is possible to use advanced models. These models are based on transient state heat, air and moisture transfer equations and require a deep knowledge of the material properties, with weather data files that have to include additional hourly normal rain, wind and solar radiation descriptions.
The standard EN 15026:2007 describes the commonly accepted models used for the advanced moisture accumulation and interstitial condensation risk assessment and refers to the EN ISO 15927-4:2005 for the boundary conditions; this standard describes a method intended to produce hourly data for assessing the annual energy use for heating and cooling. In this paper,

following the previous works of the authors (for example Riva et al. 2010, Riva et al. 2012 and Murano et al. 2016), a modification to the standard method of reference years generation is presented. It has to be noted that the methodology produces reference years and not extreme weather years. Reference years could be used only for moisture accumulation and interstitial condensation risk assessment; if water condensation in building components is not acceptable, even for short periods, other methods are available for the generation of extreme weather years. Various approaches have been investigated in the literature. Cornick et al. (2003) have selected Reference Years using a Moisture Index approach developed for Moisture Management of Exterior Wall Systems (MMEWS). The index comprises wetting function and drying function. In this approach wet and dry years are defined as those years that deviate more than one standard deviation from the mean value on long-term. MEWS is a building-independent method. The wet year is defined as the year with highest moisture index, the dry year as the year with lowest moisture index, and the average year as the year closest to the mean Moisture Index. MEWS can be assembled for problems such as long-term performance or limit-state design. There isn't a definitive method for selecting MRY's but different sets of MRYs should be produced to evaluate different problems.
Salonvaara et al. (2010) have developed a new method that provides an approach for selecting the most critical years in terms of hygrothermal performance. Performance data is analysed using various methods to provide a ranking of the weather years in terms of severity. Damage functions (time of wetness, mould growth index, and maximum moisture content) are used to quantify the moisture related performance of the building envelope. The analysis has included 30 years of hourly weather data for 12 locations in the U.S. and Canada.
Schönerl and Zirkelbach (2016) for the selection of the months of the reference years for the hygrothermal assessment (HRY) have used median, mean, minimum, maximum value, the 25%, and the 75% quartile of air temperature and normal rain. The results of HRY was compared with the standard methodology of EN ISO 15927-4 and with measured data on long-term. The simulations have shown that the mean water content based on the HRY was slightly higher than the one based on the measured data.
Considering the effect of climatic variability on the performance of the building envelope, Zhou et al. (2016) have developed a Climatic Index that considered wind-driven rain load and potential evaporation. This index was suitable for the evaluation of the level of moisture damage risk of wall assemblies where typical moisture problems are mainly caused by rainwater uptake or ingress. The combination of Climatic Index and RHT Index has allowed the creation of MRYs that have 10% level of failure.



a) b)

Figure 1. Annual mean water contents of the hollow brick wall for the measured weather files simulations for the East exposition (a) and the West exposition (b).

METHOD

The EN 15026 (European Committee for Standardization, 2007) refers to EN ISO 15927-4:2005 (International Organization for Standardization, 2005) for the creation of Moisture Reference Years. This method is intended for the creation of typical meteorological years and it is based on the Finkelstein-Schafer (FS) statistic method (Finkelstein and Schafer, 1971). In this research some modifications are introduced to extend the procedure to moisture migration related applications. From the observation that the total moisture content of a simulated wall depends also on the exposure of the wall itself (Figure 1) other rain related climate parameters (normal rain, driving rain) are alternatively considered to select the representative months of the reference year from the historical measured data, in addition to the standard ones (temperature, relative humidity, irradiation, wind speed). Then, the validity of the reference years generated for every combination is evaluated on two wall build-ups with a comparison in terms of the moisture contents against the historical years. The revised procedure for the generation of reference years is shown below. Let p be the generic measured parameter of the historical years required for the hygrothermal simulations. First, from at least 10 years of hourly values of p, for every day i, the daily mean $\overline{p_i}$ is calculated; then, for each calendar month (m), the values $\overline{p_i}$ are ordered in ascending order and 12 arrays for the whole data set are obtained. The cumulative distribution function $\Phi(p,m,i)$, associated to every $\overline{p_i}$ over all the years in the data set, is calculated using the Eq. (1), with i the considered day in the month, from 1 to N, and N the sum of the number of days in any calendar month, $K(i)$ is the position ("rank") in the ordered list of $\overline{p_i}$ of the month m;

$$\Phi(p,m,i) = \frac{K(\overline{p_i})}{N+1} \quad (1)$$

For each year y of the data set, the cumulative distribution function of the daily means within each calendar month (using Eq. (2)), $F(p,y,m,i)$, is obtained by sorting all the values for the month m and the year y, in increasing order. 12 arrays are obtained for every year. $J(i)$ is the "rank" of the value of the daily mean $\overline{p_i}$ for the month m and the year y, n is the number of days in the month m;

$$F(p,y,m,i) = \frac{J(\overline{p_i})}{n+1} \quad (2)$$

For each calendar month, for each year of the data set, the Finkelstein-Schafer statistic, $F_S(p,y,m)$, is calculated using Eq. (3):

$$F_S(p,y,m) = \sum_{i=1}^{n} |F(p,y,m,i) - \Phi(p,y,m,i)| \quad (3)$$

For each calendar month with the same m from all the years, the rank R is calculated for each value. Differently from the standard method, in this work the ranking is performed ordering the values ascending by the F_S, calculated from the multiyear record for the parameters selected among temperature (T), solar irradiance (I) and relative humidity (RHU) the driving rain (RDW obtained from the wind normal to the considered wall direction and from normal rain RIH), the wind speed (WS) and the normal rain (RIH); for each calendar month and for each year, the separated ranks (R) are summed for the climate parameters selected for the formation of MRY (the parameter selection used in this work is shown in Table I) and the total ranking $R_{tot}(y,m)$ is obtained; the month with the lowest $R_{tot}(y,m)$ is selected as the "best" month to be included in the Moisture Reference Years;

Once the months are selected, the weather file is completed substituting the unrealistic leaps between the values of adjacent months with a linear interpolation.

The validation of the proposed MRYs is carried out by comparing the hygrothermal behaviour of building components simulated with the new MRY, with the behaviour obtained with the weather conditions over the long term from the measured weather file. 34 MRYs weather files have been generated with 16 different criteria. The historic weather data series, from 2002 to 2016, are provided by the Regional Agency for the Protection of the Environment (ARPA) of the Piedmont Region (Italy).
The evaluation of the obtained reference years has been performed comparing the hygrothermal simulation results of two different building envelopes, a hollow brick wall and a timber wall. The simulations have been performed with the software WUFI Pro, based on the model presented in Künzel et al. (1996). The comparison is held evaluating the monthly mean moisture content and comparing it to the one evaluated with the historical data set.

Table I: Climate parameters selected for the formation of MRY.

ID	ISO	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
T	x	x	x	x	x	x	x	x	x					x	x	x	x											x		x	x		x		
I	x	x	x	x	x													x	x	x	x								x	x				x	
RHU	x	x	x	x	x	x	x	x	x	x	x	x	x													x				x	x	x			
WV	x																										x								
RIH																														x	x	x	x	x	x
RDW (South)		x				x				x				x				x				x													
RDW (East)			x				x				x				x				x				x												
RDW (North)				x				x				x				x				x				x											
RDW (West)					x				x				x				x				x				x										

T=Air temperature, *RHU*=Relative humidity, *I*=Solar irradiance, *RDW*=Rain deposition on vertical wall, *MRY*=Moisture Reference Years, *WS*=Wind speed, *WD*=Wind direction, *RIH*=Rainfall intensity on a horizontal surface

RESULTS

The reference years from number 1 to number 24 have been simulated considering the design orientation (for example the reference year 1, designed considering the rain deposition on vertical wall facing South has been used for the simulation of the wall build-up facing South), while the reference years from number 25 to 34 have been used for the simulations for the five expositions considered (since normal rain has a general effect on all the expositions). The walls passed the moisture accumulation assessment and the condensation risk assessment for every MRY considered and for the historical data set. For this reason the annual mean results (Figure 1) have been compared in terms of relative standard deviation from the annual mean values obtained by the measured weather data (Figure 2). The Timber wall results show better representative MRY, with lower values of the relative standard deviation, with respect to the Hollow brick wall results.

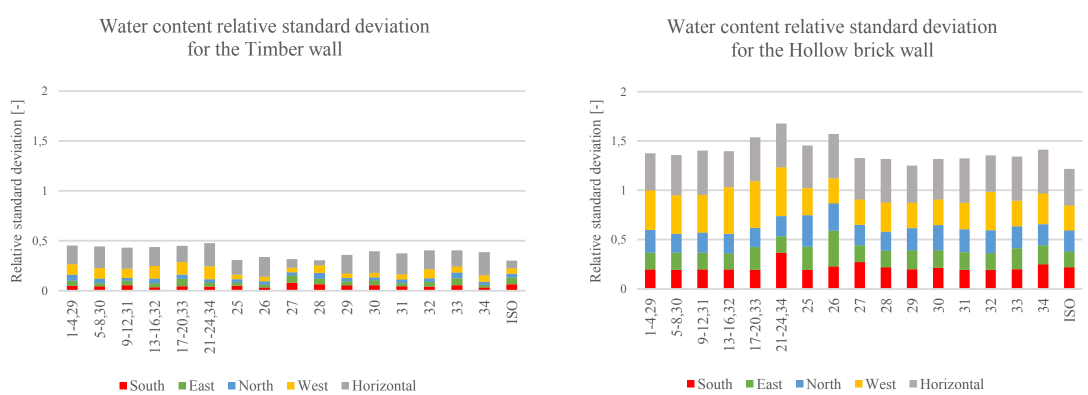


Figure 2. Relative standard deviations of the moisture contents between the simulation of the historical years and every reference year described in Table 1.

The results present exposition specific trends. For the Timber wall, the ID 34 (based on *RIH*) better represents the South, East and North expositions, while the West exposition is better described by the ID 25 (based on *RHU*) and the Horizontal by the ID 28 (based on *I*). The ID ISO and the ID 28 are the reference years better representing the walls in the five directions. The Hollow brick wall shows different exposition specific trends: the South facing exposition is better represented by the ID 34 (based on *T* and *RHI*), the East and West by the ID ISO, the North by the ID 7 (based on *T, RHU, RDW*) and the Horizontal by the ID 32 (based on *T* and *RHI*). From Figure 2 it is also possible to observe some overall results. The ID from 1 to 24, considering *RDW* are generally less representative for the most rain exposed directions (West and Horizontal). Exclusively *RDW* based years (21-24) are less representative than ID from 29 to 34, based also on *RIH*. For the Timber wall the ID from 25 to 28 and the ID ISO (not based on *RIH* or *RDW*) are better performing than the *RIH* based ones, while for the Hollow brick wall, their behaviour is similar.

DISCUSSION

The relative standard deviations of the Timber wall are lower than the Hollow brick wall. This difference is due to the different hygrothermal properties of the materials. The Hollow brick wall external layer has higher liquid transport coefficient values than the Timber wall, which has also higher moisture storage function values, and that could lead in faster responses to the rainfall (larger water content variations), with larger differences from the historical data set results.

The moisture reference years depending on rain deposition on vertical wall (obtained from wind speed, direction and normal rain) led to less representative years than the ones generated by the standard method. This result could be related to the features of the climate of Turin (Italy), whose rains are brief and quickly dried afterwards. On the other hand, one of the reasons could also be the fact that the external material layers do not respond instantly to the transient hourly rainfall excitations (slower than the heat excitations) and that the total water content of the wall is more influenced by the long term mean values of the environmental excitations, which is also been discussed in Libralato et al. (2017).

CONCLUSIONS

In this study, 34 moisture reference years (MRY, to be used for hygrothermal analysis of building structures) have been generated from a data set of measured weather files from the year 2002 to the 2016, in the city of Turin (Italy). Each MRY has been generated selecting the months from the historical data set, with a modified EN ISO 15927-4:2005 method, based on the rain deposition on vertical walls with different expositions. From the simulation of two wall types to all the 34 MRY, it has been observed that an orientation differentiation does not lead to more representative MRY for the two considered building structures in the considered climate.

The results suggest that, when the use of a single MRY is preferred, the MRYs obtained with the standard procedure EN ISO 15927-4:2005 better reproduce the results obtained with the simulation of the measured weather files and that is could be used, not only for the energy consumption simulations, but also for the moisture migration in building envelopes simulations. Considering exposition and material specific applications, that could benefit from the use of more than one MRYs, other generation methods presented in this work could be taken in consideration, depending on the building material properties and on the wall orientation.

Further work will be carried out to establish if this approach could be extended to critical weather data design for moisture accumulation risk assessments and if the proposed MRY generation method could be used proficiently for other applications, like energy simulations in which the efficiency of the components of the systems depends on moisture related environmental conditions, such as evaporative towers (De Angelis et al. 2013), evaporative cooling systems for industrial buildings (De Angelis et al. 2017a), shopping malls (De Angelis et al. 2017b) and other heat recovery systems (Chinese et al. 2017).

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