A new procedure for selecting moisture reference years for hygrothermal simulations

Xiaohai Zhou[1, 2], Dominique Derome[2] and Jan Carmeliet[1, 2]

[1]Chair of Building Physics, ETH Zürich, 8093 Zürich, Switzerland

[2]Laboratory of Multiscale Studies in Building Physics, Empa, 8600 Dübendorf, Switzerland

Abstract

Hygrothermal models allow designers to evaluate the hygrothermal performance of building envelopes. However, hygrothermal modeling needs the input of the external climate loading, a moisture reference year, to evaluate moisture damage risk of building envelope. In this paper, a new procedure is proposed for selecting moisture reference years. A metric, called Climatic Index, combining wind-driven rain load and potential evaporation is developed in this study. Climatic Indices over 30 years are determined for a wall envelope located in Zurich, Switzerland. The hygrothermal performance of the wall envelope and its moisture damage risk are simulated and evaluated using a hygrothermal risk indicator, called the RHT Index. A clear correlation between Climatic Index and RHT Index is found for the specific moisture damage considered, mold growth. The selection procedure combines a first selection of three years around the 10% level criterion based on the Climatic Index, followed by a careful comparison of different years based on RHT Index and a final selection of the year with the largest RHT Index as moisture reference year. The combination of Climatic Index and RHT Index allows for the selection of moisture reference years with known level of damage risk.

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1 Introduction

Moisture is the most important agent of building envelope deterioration. It is essential for building designers to understand and assess correctly the moisture damage risk of building envelopes exposed to a specific climate. Hygrothermal models are regularly used to assess the long-term risk of moisture damage of building envelope. For such assessment to be meaningful, it is necessary to select representative climatic data as input to the hygrothermal models. A common approach is to select a moisture reference year from a set of available long-term climatic data. Different criteria have been applied to select moisture reference years. In general, the methods used for the selection of moisture reference years are either based on wetting potential or drying potential. The wetting of building envelopes is mainly influenced by wind-driven rain and is determined by wall orientation, rainfall intensity, wind speed and direction, position on the wall and built environment. The drying of moisture from building envelopes occurs through evaporation, which is determined by air temperature, air humidity, wind speed, water availability and supply of heat by e.g. radiation.

The aim of this paper is to develop a procedure for selecting a moisture reference year for hygrothermal simulations. A metric, called Climatic Index, combining wind-driven rain load and potential evaporation is developed considering the wetting and drying environmental conditions of the building envelope.

2 Procedures

The new procedure we propose for selecting a moisture reference year for hygrothermal simulations involves four steps: 1. calculation of the Climatic Index for the set of considered years; 2. selection of three years around the 10%-level Climatic Index; 3. performance of hygrothermal simulations for the selected three years and determination of the related RHT values; 4. selection the year with the highest RHT value out of this set of years.

2.1 Climatic Index

The moisture reference year should be selected by considering both wetting and drying components. A Climatic Index is introduced as a measure of the balance between wetting and drying, as follows,

$$Climatic\ \ Index = \frac{annual\, wind\, driven\, rain\, load}{annual\ potential\, evaporation} \tag{1}$$

The numerator represents the wetting component while the denominator represents the drying component. Therefore, a higher Climatic Index value represents a higher moisture damage risk for the building envelope. The Climatic Index considers the influence of façade orientation, rain exposure, air temperature, air relative humidity, wind speed and direction, solar radiation as described below.

The wind-driven rain load for different wall orientations can be calculated according to ASHRAE Standard 160 - Criteria for Moisture Control Design Analysis in Buildings [1], where the WDR intensity (R_{WDR}) is defined by the following equation:

$$R_{WDR} = R_h \times F_E \times F_D \times 0.2 \times V_{10} \times \cos\theta \qquad (2)$$

where R_h is the horizontal rainfall amount (kg m^{-2}h^{-1}); F_E is the rain exposure factor; F_D is the rain deposition factor; V_{10} is the wind speed at 10 m above ground (ms^{-1}); θ is the angle between the wind direction and the normal to the façade (rad). Factor F_E depends on the surrounding terrain and the height of the building, while Factor F_D describes the influence of the building itself. The annual WDR load is calculated as the sum of hourly R_{WDR} and the unit is kg m^{-2}a^{-1}.

The Penman equation [2], based on a combination of energy balance and convective transport considerations, is widely used in the field of agricultural and environmental physics for predicting potential evaporation from a surface. The Penman equation for predicting the potential evaporation from a vertical surface is as follows:

$$E = \frac{\Delta}{\Delta+\gamma}\frac{K+L}{I} + \frac{\gamma}{\Delta+\gamma} h_m (e_a - e) \qquad (3)$$

where Δ is the gradient between saturation vapor partial pressure and air temperature (PaK^{-1}); γ is the psychrometric constant (PaK^{-1}); K is the net short-wave radiation (Wm^{-2}); L is the net long-wave radiation (Wm^{-2}); I is the latent heat of vaporization (Jkg^{-1}); h_m is the convective vapor transfer coefficient (sm^{-1}); e_a is the saturated vapor partial pressure of the air (Pa); e is the vapor partial pressure in the air (Pa). The Penman equation consists of two terms: the radiation term ($\frac{\Delta}{\Delta+\gamma}\frac{K+L}{I}$) and the convective term ($\frac{\gamma}{\Delta+\gamma} h_m (e_a - e)$). The radiation term is determined mainly by the radiative energy balance at the surface, while the convective term is related to the atmospheric convective conditions. The annual potential evaporation (kg m^{-2}a^{-1}) is calculated as the sum of the daily potential evaporation. More details on the derivation of potential evaporation can be found in Zhou *et al.*[3]. Both terms of Eq. 1 have the same units.

2.2 Moisture damage risk criterion

Compared to energy reference years that use mean values of climate data for locations under consideration [4-6], a moisture reference year should represent a climate that allows a correct evaluation of the moisture damage risk of the building envelope. The choice of a proper damage risk or failure level is commonly based on the economic consequences of such damages (repair costs, insurance) and on their impact on health (e.g. mold growth) and social acceptance of such damages (esthetics). A 10% damage risk or failure level criterion is regularly used to select moisture reference years. The choice of a 10% damage risk is justifiable, since this choice refers to a return period of 10 years, which for hygrothermal problems is appropriate, allowing moisture accumulated during a wet year to dry out in the following years, as such accounting properly for long term behavior and possible deterioration [7].

However, a 10% level selection based on the Climatic Index does not guarantee the selection of a proper selection of a moisture reference year, since the Climatic Index only considers the wetting and drying potentials and not the real hygrothermal and moisture damage response. The uncertainty in selecting the appropriate moisture reference year based on a 10% level Climate Index criterion necessitates a comparison of several years around the 10%-level criterion. In the new method, it is proposed to select the year with the largest hygrothermal risk factor among these specific years as moisture reference year.

Building materials are subjected to hygrothermal deterioration under the combined effect of temperature and moisture. Risk of moisture degradation mechanism such as mold growth could be evaluated by the RHT Index [8], where the relative humidity and temperature at a specific location within the building envelope at different output time steps are used to determine the RHT Index. In the present case of mold growth as moisture damage, 10-day interval averaged relative humidities RH (%) and temperatures T (°C) are used for determining the RHT Index. The RHT Index is defined as:

$$RHT = \sum (RH - RH_x) \times (T - T_x), \quad for\ RH > RH_x\ and\ T > T_x \qquad (4)$$

where threshold values RH_x =80 (%) and T_x =5 (°C) are used, as the degradation mechanism considered here is that of mold growth. Relative humidity and temperature in the wall component are here obtained from hygrothermal modeling.

3 Example

The example considered for the study is an internally insulated masonry wall located in Zurich, Switzerland (Fig. 1). As an example, the wall orientation chosen is west-northwest (300 degrees), but any other directions could be chosen. Zurich is a city north of the Alps. The prevailing winds come from westerly direction transporting wet air to the city and are responsible for the high amount of wind-driven precipitation. The historical masonry building assembly consists of the following materials from outside to inside: lime plaster, 3 layers of bricks with cement mortar, aerogel insulation plaster as inside insulation material and an interior plaster. The material properties of lime plaster are from the WUFI material database [9], the material properties of brick are from Hagentoft et al. [10], the material properties of aerogel insulation plaster and mortar are from Guizzardi et al. [11] and the material properties of interior plaster are from HAMFEM database [12].

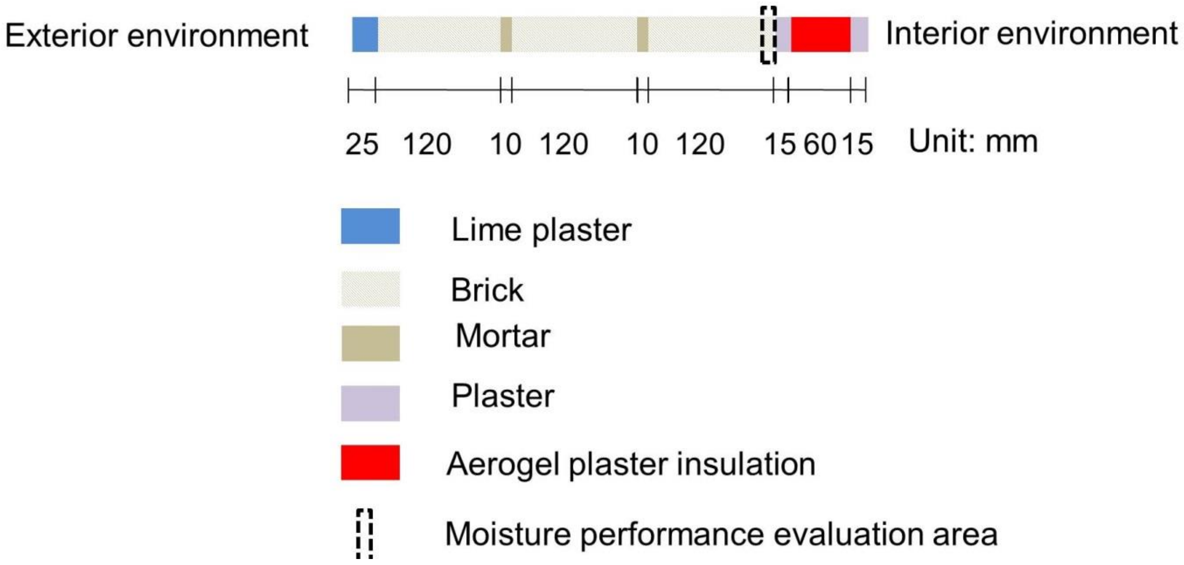

Fig. 1: Schematic representation of the internally insulated masonry wall envelope

It is common practice for hygrothermal analysis to define meteorological years beginning in October and ending in September, as the moisture conditions during the winter affect the hygrothermal behavior during the summer. In this study, 30 years of meteorological data (1981-2010) from MeteoSwiss are used for calculation of wind-driven rain load, potential evaporation and Climatic Index. Fig. 2 shows the annual wind-driven rain load, annual potential evaporation and Climatic Index for the 30 years. Amongst the 30 years, the largest annual wind-driven rain load is 453 kgm^{-2}a^{-1} in 1989, while the smallest one is 197 kgm^{-2}a^{-1} in 1990 (Table 1). For comparison, the largest annual potential evaporation is 1053 kgm^{-2}a^{-1} in 2002, while the smallest one is 878 kgm^{-2}a^{-1} in 2000. The largest Climatic Index is 0.484 in 1994, while the smallest one is 0.208 in 1984. It is noted that there is no direct correlation between WDR and drying potential. According to the ranking of the years based on the Climatic Index, the year 1998 would be selected as moisture reference year according to the 10% level criterion (third rank out of 30).

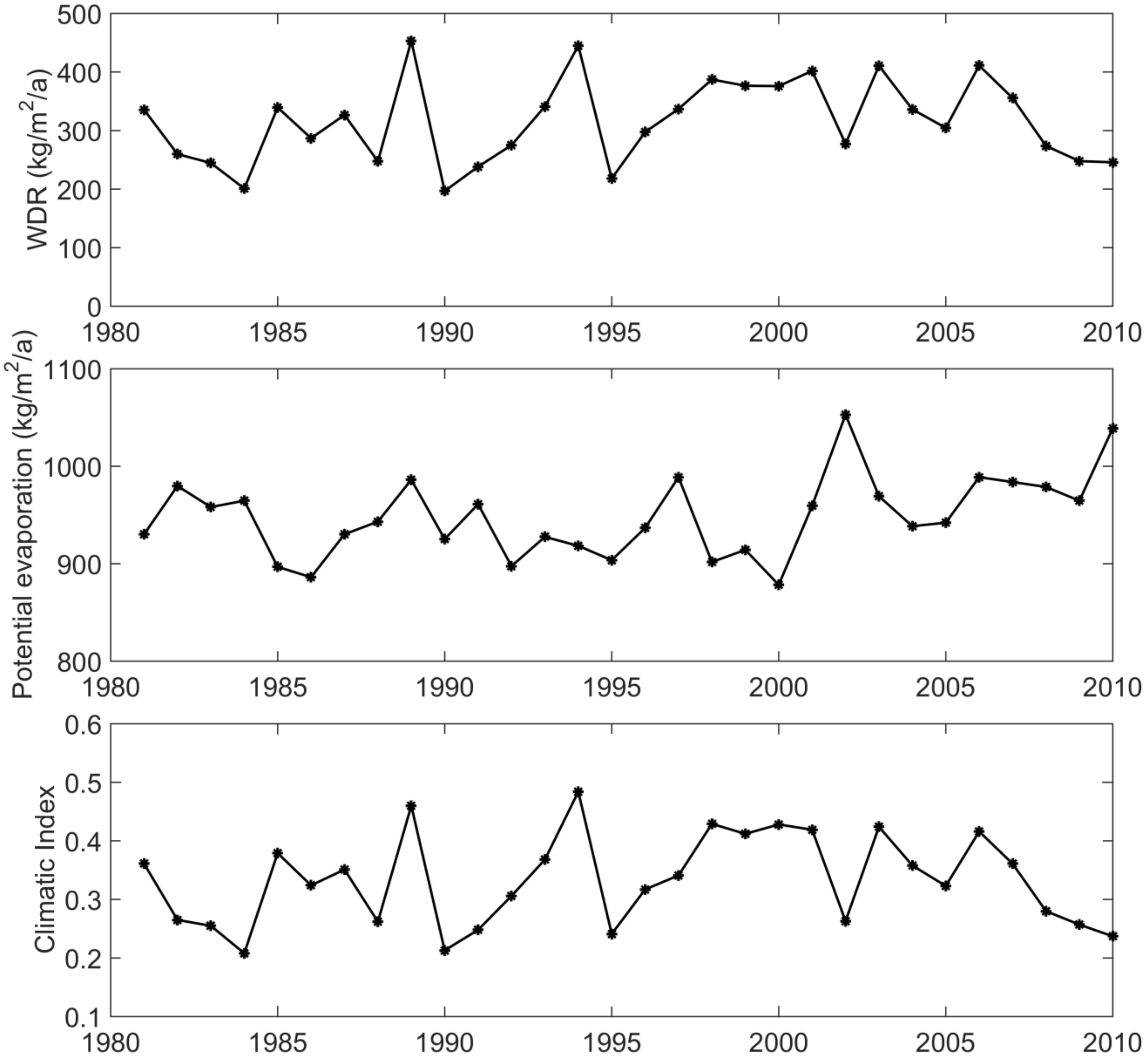

Fig. 2 Annual wind-driven rain load, annual potential evaporation and Climatic Index for Zurich from 1981-2010 at the selected orientation of 300 degrees.

Table 1. Ranking of years according to annual wind-driven rain load (WDR), potential evaporation (PE) and Climatic Index from 1981 to 2010

Rank	Zurich (wall orientation: 300 degrees)					
	Year	WDR ($kgm^{-2}a^{-1}$)	Year	PE ($kgm^{-2}a^{-1}$)	Year	Climatic Index
1	1989	453.2	2002	1053.0	1994	0.484
2	1994	444.7	2010	1039.0	1989	0.460
3	2006	411.0	2006	988.8	1998	0.429
4	2003	410.8	1997	988.7	2000	0.428
5	2001	401.9	1989	986.2	2003	0.424
6	1998	387.1	2007	983.8	2001	0.419
7	1999	376.5	1982	979.8	2006	0.416
8	2000	375.9	2008	978.8	1999	0.412
9	2007	355.6	2003	969.3	1985	0.379
10	1993	341.1	1984	964.7	1993	0.368
11	1985	339.5	2009	964.6	2007	0.361
12	1997	336.9	1991	961.1	1981	0.361
13	2004	336.2	2001	959.3	2004	0.358
14	1981	335.6	1983	958.1	1987	0.351
15	1987	326.7	1988	943.2	1997	0.341
16	2005	304.6	2005	942.1	1986	0.324
17	1996	297.3	2004	938.5	2005	0.323
18	1986	286.8	1996	936.7	1996	0.317
19	2002	277.3	1987	930.2	1992	0.306
20	1992	275.0	1981	930.2	2008	0.280
21	2008	273.8	1993	927.6	1982	0.265
22	1982	259.8	1990	925.2	2002	0.263
23	2009	247.8	1994	918.3	1988	0.262
24	1988	247.5	1999	914.2	2009	0.257
25	2010	245.8	1995	903.7	1983	0.255
26	1983	244.6	1998	901.8	1991	0.248
27	1991	238.3	1992	897.5	1995	0.241
28	1995	218.1	1985	896.7	2010	0.237
29	1984	201.0	1986	886.2	1990	0.213
30	1990	196.6	2000	878.3	1984	0.208

In order to evaluate whether the selected year is indeed the year showing a 10% moisture damage risk, a hygrothermal model, is used to calculate the temperature and moisture distributions in the internally insulated masonry wall envelope. The governing equations for moisture and heat transport are the same as those in HAMFEM [12], and are solved using the finite element solver COMSOL. The RHT index is calculated based on simulation results, *i.e.* temperature and relative humidity in the wall component. The evaluation region for RHT Index is chosen at the innermost 1 cm of the third brick (Fig. 1). This region is in contact with the interior finishing, while still being considerably affected by the external climate conditions.

The RHT Index plotted in function of the Climatic Index from 1981 to 2010 is shown in Fig. 3 for the internally insulated masonry wall. In general, a good correlation between Climatic Index and RHT Index is observed with a correlation coefficient of 0.84. This indicates that the Climatic Index can be used in general as a proper indicator of moisture problems related to mold growth in order to compare the risks of moisture problems among different years. The advantage of the Climatic Index is that it can be easily determined for different wall orientations and, consequently, the moisture damage risk per orientation can be easily evaluated.

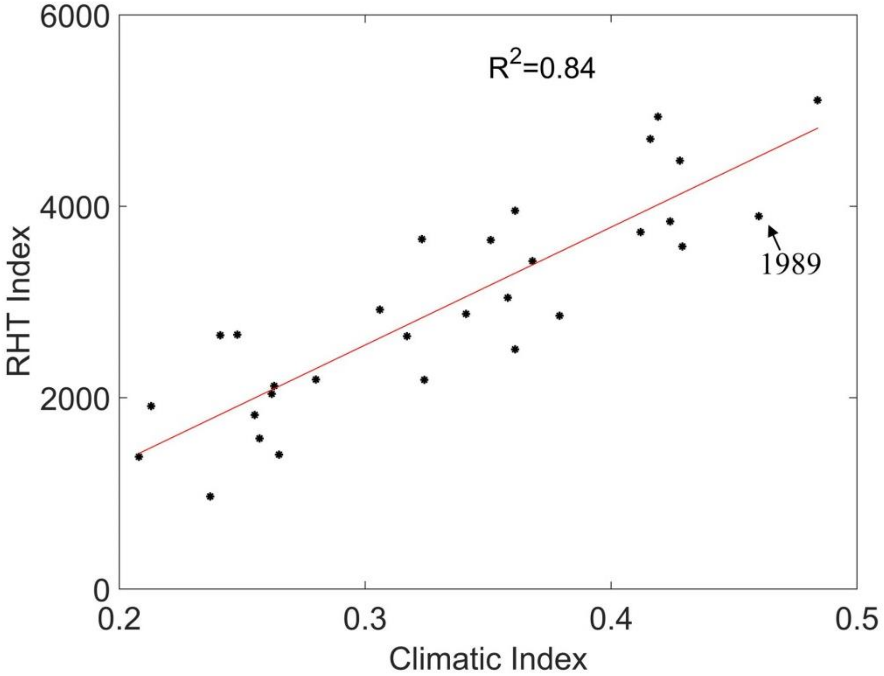

Fig. 3 Relation between Climatic index and RHT Index for the internally insulated masonry wall

However, the ranking of years based on Climatic Index may be very different from that based on RHT Index. For example, the year of 1989 ranks second based on Climate Index among the 30 years, whereas it ranks sixth based on RHT Index (Fig. 3). Therefore, the year with 10% criterion based on Climatic Index does not necessarily correspond to the year with 10% criterion based on RHT Index. The selection of the moisture reference year based on the third largest Climate Index does not guarantee the selection of a proper moisture reference year. However, the Climatic Index narrows down the selection of the years which are in 10% level range. Therefore, we compare the RHT Indices for the years with the third, fourth and fifth largest Climatic Indices, *i.e.* 1998, 2000 and 2003, respectively. For these three years, hygrothermal simulations are performed and the RHT indices are determined. The RHT Index for these three years is 3580, 4476 and 3843, respectively. The most severe year, showing the highest RHT index is the year 2000. Therefore, the year of 2000 is selected as moisture reference year for the internally insulated wall envelope at 300 degrees orientation. This procedure can be easily repeated for different wall orientations and wall compositions, leading to a set of moisture reference years guaranteeing a high reliability in the selection process.

4 Conclusion

A procedure is proposed to select the moisture reference year based on a new metric: the Climatic Index. The Climatic Index evaluates the climatic conditions to which building envelopes are exposed, and considers both the wetting load and evaporation potential for a typical climate region. A high correlation between Climatic Index and RHT Index is found, where the RHT index is used to evaluate the moisture damage risk, in the present case mold growth, as a combination of critical values of relative humidity (RH) and temperature (T). The combination of Climatic Index and RHT Index allows for a more reliable selection of moisture reference years in a two-step selection process. This easy and reliable procedure can be applied for different wall orientations and wall compositions for different climate regions.

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Reference

[1] *TenWolde, A.*: ASHRAE Standard 160 P-Criteria for Moisture Control Design Analysis in Buildings. ASHRAE Transactions 114 (2008), pp.167-71.

[2] *Penman, H.*: Natural evaporation from open water, bare soil and grass. Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences: The Royal Society; 1948. pp. 120-45.

[3] *Zhou, X., Derome, D., Carmeliet, J.*: Robust moisture reference year methodology for hygrothermal simulations. Building and Environment. 2016, accepted for publication.

[4] *Kalamees, T., Jylha, K., Tietavainen, H., Jokisalo, J., Ilomets, S., Hyvonen, R., Sakub, S.*: Development of weighting factors for climate variables for selecting the energy reference year according to the EN ISO 15927-4 standard. Energy and Buildings 47 (2012), pp. 53-60.
[5] *Bilbao, J., Miguel, A., Franco, J., Ayuso, A.*: Test reference year generation and evaluation methods in the continental Mediterranean area. Journal of Applied Meteorology and Climatology 43 (2004), pp. 390-400.
[6] *Pernigotto, G., Prada, A., Costola, D., Gasparella, A., Hensen, J.*: Multi-year and reference year weather data for building energy labelling in north Italy climates. Energy and Buildings. 72 (2014), pp. 62-72.
[7] *Sanders, C.*: Heat, air and moisture transfer in insulated envelope parts: Environmental conditions. International Energy Agency, Annex 24 Final report, volume 2, Acco Leuven, 1996.
[8] *Kumaran, M., Mukhopadhyaya, P., Cornick, S., Lacasse, M., Maref, W., Rousseau, M., Nofal, M., Quirt, J., Dalgliesh, W.*: A methodology to develop moisture management strategies for wood-frame walls in North America: Application to stucco clad walls. In: Proceedings of the 6th Symposium on Building Physics in the Nordic Countries. Trondheim, Norway, 2002, pp. 651–658.
[9] *Künzel, H.*: Simultaneous heat and moisture transport in building components. Fraunhofer IBP (1995). PhD Thesis.
[10] *Hagentoft, C-E., Kalagasidis, A., Adl-Zarrabi, B., Roels, S., Carmeliet, J., Hens, H., Grunewald, J., Funk, M., Becker, R., Shamir, D., Adan, O., Brocken, H., Kumaran, K., Djebbar, R.*: Assessment method of numerical prediction models for combined heat, air and moisture transfer in building components: benchmarks for one-dimensional cases. Journal of Thermal Envelope and Building Science 27 (2004), pp. 327-52.
[11] *Guizzardi, M., Derome, D., Vonbank, R., Carmeliet, J.*: Hygrothermal behavior of a massive wall with interior insulation during wetting. Building and Environment 89 (2015), pp. 59-71.
[12] *Janssen, H., Blocken, B., Carmeliet, J.*: Conservative modelling of the moisture and heat transfer in building components under atmospheric excitation. International Journal of Heat and Mass Transfer 50 (2007), pp. 1128-1140.