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*Original*

*Availability:*

This version is available <http://hdl.handle.net/11390/1213826> since 2021-11-13T00:19:30Z

*Publisher:*

IOP Publishing Ltd

*Published*

DOI:10.1088/1742-6596/2069/1/012043

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# Damage risk assessment of building materials with moisture hysteresis

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**Abstract.** Heat and Moisture Transfer (HMT) simulations are used for the calculation of moisture related damage risks in building envelopes. HMT simulations are commonly performed accepting the hypothesis of not considering the moisture hysteresis of materials. The results of HMT simulation of a timber wall with hysteresis are presented, and compared to the results of three simplified models, showing the effects of hysteresis on the simulation results and on the assessment of the risk of decay. Moisture content is the most influenced variable, while temperature and relative humidity are slightly affected, showing that mostly damage models based on moisture content are relevantly influenced by hysteresis. The wood decay risk analysis is performed using the simplified 20% moisture content rule. Similar temperature values and relative humidity values are calculated as simplified models, while the moisture content annual average values have differences up to 2.3%. The wood decay risk obtained with the simplified models could be overestimated if the simulation is performed using the desorption curve, while it could be underestimated with the adsorption curve. The best approximation is obtained with the mean sorption curve, while the desorption curve and the adsorption curve could be used to calculate the upper and lower boundary of the moisture contents respectively.

## 1. Introduction

To reduce the carbon footprint and energy consumption of buildings it is possible to produce high performance envelopes using sustainable materials. Unfortunately, moisture related damages could affect bio-based materials causing health hazards and structural damages. These could be avoided with careful design procedure and risk assessment. These are commonly performed using Heat and Moisture Transfer (HMT) simulations, for example, according the standard EN 15026:2007. The commonly used HMT models describe the coupled transport of heat and moisture in the building materials, which are considered as porous materials. The most accurate models consider transport properties that are variable with moisture content (and eventually with temperature). Even if the intent of the HMT model is to obtain a high level of accuracy, several uncertainties are introduced in the models, like the boundary conditions and the material properties. The adsorption property of the porous media is described by the sorption function, which associates to every value of relative humidity (RH) a single value of moisture content (MC) and vice-versa. This is an accepted simplification of the moisture accumulation behaviour, but as experience shows, several materials (especially bio-based materials such as wood) can reach

equilibrium at different moisture contents. The equilibrium states are dependent on the history of the previous equilibrium states. This behaviour, known as moisture hysteresis, could be modelled implementing the hysteresis of the sorption function in the heat and moisture transfer models, instead of using bijective sorption isotherm functions.

Different models of hysteresis are found in literature, [1] presents a comparison between two hysteresis formulations (the empirical model [2] and the phenomenological model, obtained as a modification of the Mualem model [3]), showing that that the hysteresis has a small influence on air RH in the room, while MC at the surface of the wall has larger differences, due to the difference of the considered sorption curves. In [4] the modification of the phenomenological model is compared with another model, presented in [5], considering hemp concrete.

In this work, the empirical model [2] will be used, and its results will be compared with three bijective sorption curves (the adsorption curve, the desorption curve and the mean sorption curve). A timber building envelope will be simulated and a simplified wood decay risk analysis will be performed on the timber structure, using the 20% MC threshold method, considered as lower limit value for wood decay with a reasonable margin of safety ([6, 7, 8]).

The relevance of considering moisture hysteresis in simulations depends on the studied phenomena and on the applications. In the last decade examples of research work on moisture hysteresis are found in literature, not only for bio-based materials, but also for cementitious materials ([9, 10, 11, 12, 13, 14]).

An analysis of the effect of hysteresis on advanced wood decay damage models is presented in [15], where the effect of external environment is evaluated using VTT wood decay model and the simplified dose-response model. In this work the effects of hysteresis have been found to be relevant for advanced wood decay models based on MC values and temperatures. The effect on the RH values and temperature is of a small order, and not relevant to advanced decay models.

## 2. Method

To evaluate the influence of hysteresis on the risk assessment procedure the case of wood decay of a timber wall is considered. The study case is chosen to be an extreme case with high moisture levels, in order to evaluate the different risk calculated by different sorption curve models.

The results of the model considering hysteresis is compared with three commonly used simplifications based on bijective sorption functions:

- **Adsorption curve:** obtained measuring the moisture contents with a gravimetric test starting from a dry state;
- **Desorption curve:** obtained starting the gravimetric test from the saturated state of the material;
- **Mean sorption curve:** obtained averaging the MC values of adsorption curve and desorption curve.

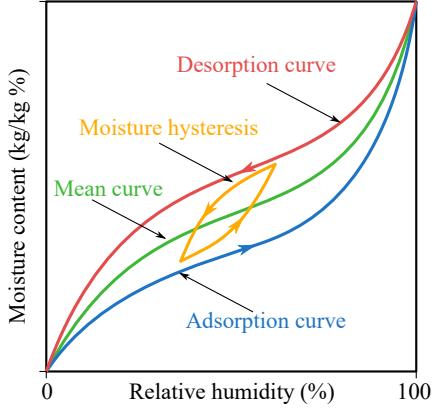
The sorption models used in the simulations are qualitatively presented in Figure 1.

### 2.1. Moisture Hysteresis

The simulations are performed using the software MATCH, which considers the “empirical hysteresis model”, presented in [2]. This model defines the moisture capacity  $\xi$  at each time step. Moisture capacity is defined as follows:

$$\xi = \frac{\partial u}{\partial \varphi} \quad (1)$$

and thus, if hysteresis is neglected it can be obtained before any calculation, from the sorption curve of the material.



**Figure 1.** Qualitative description of the hysteretic behaviour of a material and the simplified sorption curves used in the simulations.

In the software MATCH, moisture capacity is calculated at each time and position from the MC and the direction of the sorption process, adsorption or desorption. Once the moisture capacity is calculated, the MC and the moisture capacity for the considered value of RH is obtained. The  $\xi$  value is calculated from the values of  $\xi$  of the adsorption curve  $\xi_a$  and the desorption curve  $\xi_d$ , which are given as material properties. The  $\xi$  could be calculated with Eq.2, while  $u$  is obtained from the variation of relative humidity  $d\varphi$  in the time step  $t + 1$  with Eq. 3.

$$\xi = \begin{cases} \frac{(u-u_a)^2 \cdot \xi_d + 0.1 \cdot (u-u_d)^2 \cdot \xi_a}{(u_d-u_a)^2} & \text{for desorption} \\ \frac{0.1 \cdot (u-u_a)^2 \cdot \xi_d + (u-u_d)^2 \cdot \xi_a}{(u_d-u_a)^2} & \text{for adsorption} \end{cases} \quad (2)$$

$$u_{t+1} = u + \xi \cdot d\varphi \quad (3)$$

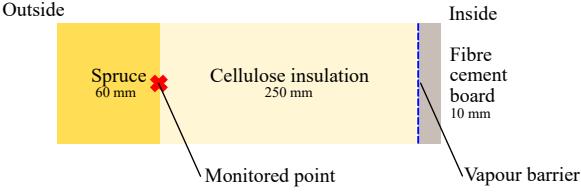
Where:

- $u_a$  = MC for the current RH, according to the adsorption curve (-)
- $u_d$  = MC for the current RH, according to the desorption curve (-)
- $\xi_a$  = moisture capacity for the current RH, according to the adsorption curve (-)
- $\xi_d$  = moisture capacity for the current RH, according to the desorption curve (-)
- $u$  = MC at the actual time step (-)
- $\xi$  = moisture capacity at the actual time step (-)
- $u_{t+1}$  = MC at the next time step (-)
- $d\varphi$  = variation of RH (-)

The empirical model is defined using only the adsorption and desorption curve and it is not defined on physical phenomena, but it could be adapted to different hysteretic behaviours. The coefficients 0.1 of Eq. 2 could be substituted with fitting parameters, obtaining an accurate representation of the hygrothermal states of the material.

## 2.2. Study case

The damage risk assessment is performed on a vertical timber wall located in Copenhagen, facing North with a 10-year-long simulation. The material properties are presented in Table 1



**Figure 2.** Layer description of the building envelope used in the simulations and location of the monitored point considered for the wood decay risk analysis.

while the build-up of the wall is presented in Figure 2. The material properties for Spruce and the Fibre cement board are taken from [16] and the sorption curves considered are obtained from the approximation functions, while the cellulose insulation is taken from the MATCH material database with data from [17]. The boundary conditions of the external environment are calculated cycling the DRY weather file provided in the MATCH weather file database. The interior environment is set to monthly constant values of temperature and RH, typically found in Copenhagen, reported in [18]. With these conditions the right surface of the timber wall is subject to high moisture loads. The initial conditions are set to 20°C and 80% RH, the MC values are obtained from the simplified sorption curves, while the initial conditions of the hysteresis simulation are set as the mean sorption curve initial MC. This case has been selected as an extreme case to simply present the effects of hysteresis in HMT simulations.

**Table 1.** Material properties

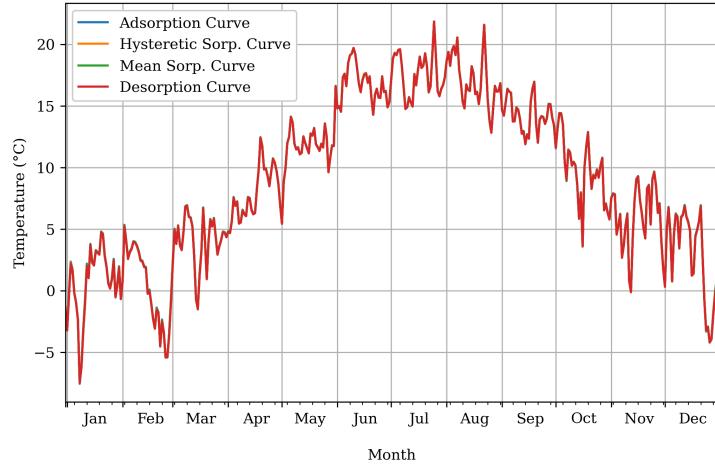
Material MATCH database name	$\rho_{dry}$ (kg/m <sup>3</sup> )	$c$ (J/K·kg)	$\lambda_{dry}$ (W/m <sup>2</sup> K)	$\mu$ (–)	$u_{a,80}$ (%)	$u_{d,80}$ (%)
Fibre cement board	1880	900	0.6	35	6.32	9.75
Cellulose insulation	80	1382	0.043	3	22.18	22.20
Spruce	420	2500	0.1	125	15.47	19.96

Note: the vapour barrier equivalent thickness is  $s_d=2500$  m,  $\rho_{dry}$  is the density of the dry material,  $c$  is the specific heat capacity,  $\lambda_{dry}$  thermal conductivity of the dry material,  $\mu$  vapour resistance factor,  $u_{a,80}$  and  $u_{d,80}$  are the moisture contents of the material at 80% relative humidity respectively of the adsorption curve and of the desorption curve.

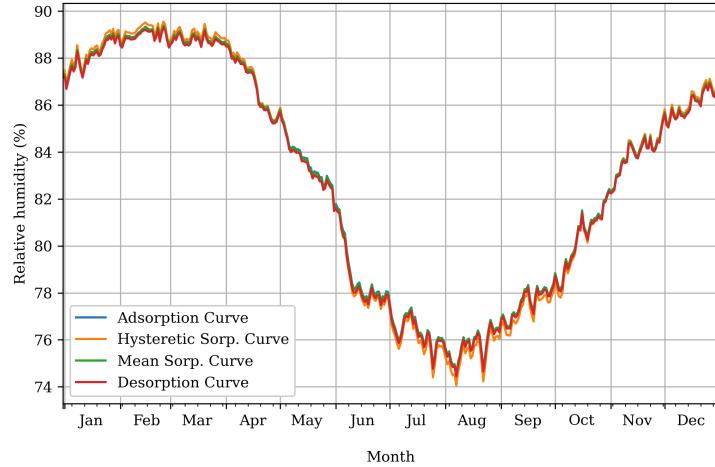
### 3. Results and discussion

The software MATCH provides as results the values of temperatures, RH and MC at a given point. These values are here shortly compared to evaluate the effect of hysteresis. From the results presented in literature [15], temperatures and RH are expected to be not influenced by hysteresis while MC is expected to have the larger differences between the different sorption curves. As expected, using the simplified sorption curves, the temperatures have maximum differences lower than 0.23 K from the hysteretic case. This is shown in Figure 3, where the four lines of the plot are overlapping.

When considering RH values, the larger differences are lower than 0.5% RH, while the larger annual mean difference is lower than 0.1% RH. The daily average RH values are presented in Figure 4. In this case, the RH values obtained considering hysteresis are higher than the other results during the wet months (from December to April) and lower during the dry months (from



**Figure 3.** Daily averaged temperature values at the monitored point for the four sorption functions at the 10<sup>th</sup> year of simulation. The four curves have similar values and they are superimposed.

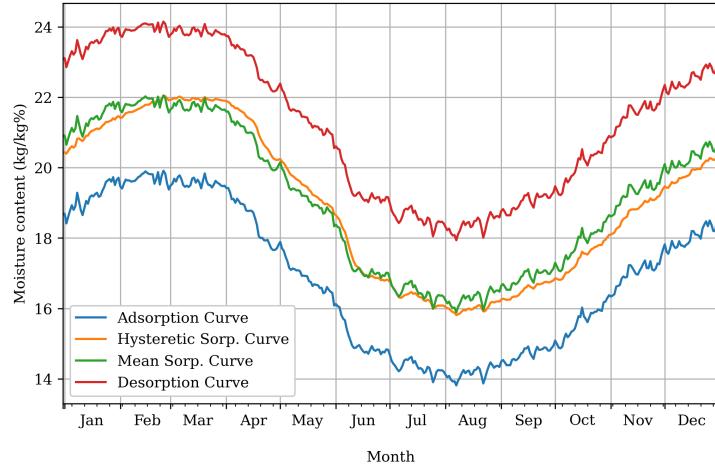


**Figure 4.** Daily averaged relative humidity values at the monitored point for the four sorption functions at the 10<sup>th</sup> year of simulation.

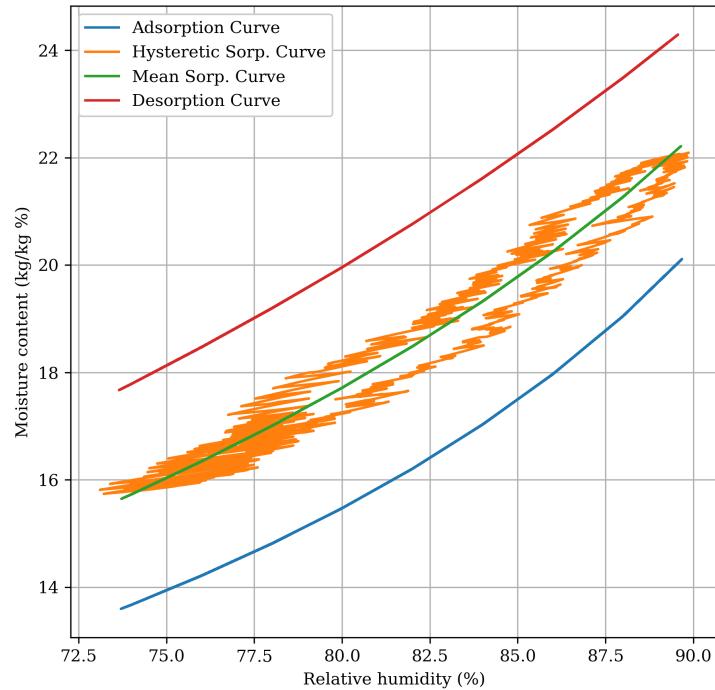
June to September). This effect is due to the different relation between RH and MC, later shown in Figure 6. Also, desorption curve simulations result in RH values lower than the ones of the adsorption curve, and mean sorption curve RH values in between the two as reported in [15].

MC values are presented in Figure 5. The curves have the expected relative position: the desorption curve MC values have a mean value of 21.3% MC, while the adsorption curve 16.9% MC. The maximum difference from the results with hysteresis is lower than 3% MC. The mean sorption curve and the hysteresis results are between the desorption and the adsorption MC values, with 19.09% MC and 18.94% MC mean values respectively.

The succession of the hygric states calculated in the simulations are presented on the RH-MC plane in Figure 6. The states calculated with bijective sorption curves correspond to the sorption curves, while the results of the simulation with hysteresis are bounded between the adsorption curve and the desorption curve. The path of the hysteretic states is the result of



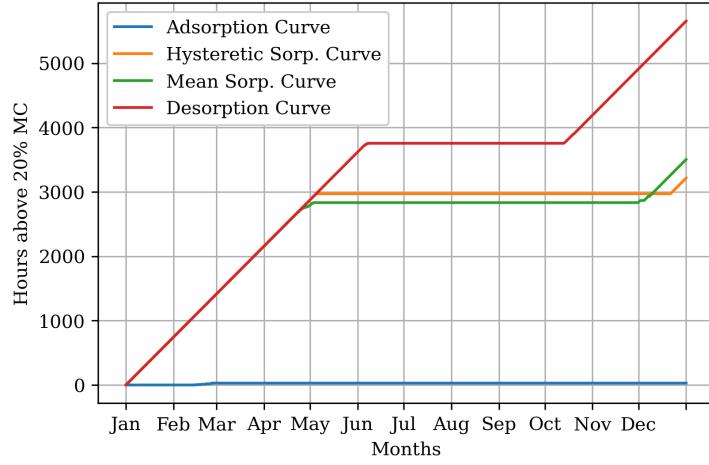
**Figure 5.** Daily averaged moisture content values at the monitored point for the four sorption functions at the 10<sup>th</sup> year of simulation.



**Figure 6.** Hourly values of the hygric state (moisture content over relative humidity) at the monitored point for the four sorption functions at the 10<sup>th</sup> year of simulation.

the yearly cycling of the internal and external boundary conditions. The reduced slope of the hysteresis curve, due to the hysteresis model (Eq.2), explains the small differences in the RH and temperature values (Figure 4).

Finally, the results of the wood decay risk assessment are presented in Figure 7. The cumulative function of hours of the year above 20% MC for each studied case show that the mean sorption curve is an acceptable approximation. At the end of the year, the hysteresis simulation obtained 3215 hours, while the mean sorption curve 3504 hours. The desorption curve is an



**Figure 7.** Cumulative number of hours over 20% MC at the monitored point for the four sorption functions at the 10<sup>th</sup> year of simulation.

upper boundary for the MC values with 5654 hours above 20% MC, while the adsorption is a lower boundary, with only 29 hours above 20% MC. Depending on the application, a risk assessment performed using the adsorption curve could lead to an acceptable risk level, while the desorption curve would lead to an unacceptable risk, forcing to a relevant change of the envelope design or to a change of the HVAC system of the internal environment. Using the mean sorption curve could lead to small modifications of the envelope design. For a conservative design procedure, the desorption curve results should be considered.

It is interesting to note that the desorption curve and the adsorption curve obtained different results, while both the mean curve and the hysteretic sorption model (not simplified) obtained a rather similar and intermediate result.

#### 4. Conclusions

The results of four risk assessments performed on a timber wall with four different sorption functions are presented. The simulations are performed with the software MATCH that allows to consider hysteresis in the simulations using the empirical model. The damage rate is evaluated with a simplified model, as the number of hours of the year with moisture content values over 20%. The results show that for the studied case, the temperature values and the relative humidity values obtained with the bijective sorption curves have small differences from the hysteresis results and thus they would cause small differences in damage models. The most relevant differences are found in the moisture content values, with annual average differences lower than 2.32% MC. When the risk assessment is performed, on one hand, the desorption curve obtains a higher decay rate, that could be considered conservative. The results of the adsorption curve, on the other hand, show very low risk, thus not a cautious estimation. The mean sorption curve, instead, gives an estimation of the risk similar to the one obtained with hysteresis. However, as shown in Figures 5 and 6, although the annual averages of the moisture content are similar between the calculations using the hysteretic and the average sorption curve, the periodic tendencies are different, i.e. during fall, the moisture contents are lowest with the hysteretic model, and highest during spring compared to the results when using the hysteretic model. Since late winter, early spring is typically the most critical period for wood moisture decay, the hysteretic model may give a more realistic representation of this critical situation, and the criterion we have applied in this paper to only discriminate between the number of

hours above/below 20% MC may be too simple. A more advanced wood decay model has been adopted in [15]. For similar boundary conditions, and using the same hysteresis model, these results are expected also for other material typologies with damage criteria based on moisture content (for example steel corrosion in concrete). Future work will be focused on the effects of moisture hysteresis on the hygrothermal behaviour of the entire building using also other hygrothermal models and on other material typologies [19, 20].

### Acknowledgments

The research leading to these results has received funding from the MIUR of Italy within the framework of the PRIN2017 project “The energy flexibility of enhanced heat pumps for the next generation of sustainable buildings (FLEXHEAT)”, grant 2017KAAECT.

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