Effects of Different Moisture Sorption Curves on Hygrothermal Simulations of Timber Buildings

Michele Libralato – University of Udine, Italy – michele.libralato@uniud.it
Maja Danovska – Free University of Bozen-Bolzano, Italy – maja.danovska@natec.unibz.it
Giovanni Pernigotto – Free University of Bozen-Bolzano, Italy – giovanni.pernigotto@unibz.it
Andrea Gasparella – Free University of Bozen-Bolzano, Italy – andrea.gasparella@unibz.it
Paolo Baggio – University of Trento, Italy – paolo.baggio@unitn.it
Paola D'Agaro – University of Udine, Italy – paola.dagaro@uniud.it
Giovanni Cortella – University of Udine, Italy– giovanni.cortella@uniud.it

Abstract

Building energy simulations are a key tool in designing high performance buildings capable of facing the future challenges and in helping emission reduction targets to be met. Currently, thermal properties of materials used in most building energy simulations are assumed to be constant and not dependent on moisture content and temperature. Heat and moisture dynamic transfer models allow a simulation of building envelope performance considering thermal resistance reduction due to moisture effects. These models are generally considered more accurate than the heat transfer models, and they could be used to simulate the heat transfer (increased by water vapor storage) and the moisture buffering effect on the indoor environment. For the simulation to be performed, hygrothermal material properties should be known as functions of moisture content. Nevertheless, hygrothermal material properties are rarely available and correlations from the literature have to be used. In this study, the moisture storage curves of CLT, OSB and two types of wood fibre insulation have been measured with a dynamic vapor sorption analyser. The other hygrothermal properties are estimated from values measured in previous studies or taken from the literature. The simulations of two small single room buildings in four Italian locations are performed with the software EnergyPlus, considering an ideal HVAC system, to calculate the heating and cooling needs of the building. The HAMT (heat and moisture transfer) module of EnergyPlus is used. With the results presented in this study, it is possible to evaluate how an approximated curve affects the results of a whole-building simulation in terms of wall average water content, indoor air relative humidity and heating/cooling loads.

1. Introduction

The energy required for heating and cooling buildings is a large fraction of the total consumption and therefore of greenhouse gas emissions. These emissions need to be reduced as soon as possible and Building Energy Simulation (*BES*) methods are essential for designing high performance buildings and predicting their energy needs. Researchers and practitioners are using dynamic detailed building energy models that consider the transient behavior of the building envelope and of the *HVAC* systems to minimize the carbon emissions and reduce the energy demands during both heating and cooling seasons. When the building envelopes are composed of porous materials, water vapor diffusion plays a significant role in heat transfer. The main effect on the materials is the increase of the value of thermal conductivity, which results in larger heat losses during the heating season and larger heat gains during the cooling one (Danovska et al., 2020a and 2020b). Using the appropriate software, it is possible to model whole buildings using heat, air and moisture transfer models (*HAMT*) for the building envelope, calculating the effects of moisture diffusion and storage in building materials (Libralato et al., 2021a and 2021b), as well as the moisture buffering effect on the air conditions of the thermal zones (Zu et al., 2020). 17 *BES* tools based on *HAMT* models (including EnergyPlus) are presented in Woloszyn and Rode (2008), defining a benchmarking process included in IEA ECBCS Annex 41. All these models require advanced

Part of
Pernigotto, G., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). 2023. Building simulation applications BSA 2022. bu,press.
https://doi.org/10.13124/9788860461919

hygrothermal material characterizations, which are possible with time-consuming testing activities. The thermal and hygroscopic properties of the materials have to be tested at different temperatures and moisture contents, often requiring months of conditioning in climatic chambers (depending on the size of the samples).

This research is focused on the comparison between Moisture Sorption Curves (*MSCs*) interpolation models (Fig. 1), commonly used for timber materials when few Equilibrium Moisture Content (*EMC*) values are available. The study is based on the *MSCs* of four wood-based materials, measured at the Thermal Systems Laboratory of the University of Udine, and the thermal conductivity of three of the same set of materials, previously measured at different moisture contents and temperatures at the Building Physics Laboratory of the Free University of Bozen-Bolzano (Danovska et al., 2020a and 2020b).

First, the points of the moisture curve are measured using a Dynamic Vapor Sorption (*DVS*) analyser. Then, a piece-wise linear curve is developed to represent a *MSC* starting from the measured points. At this stage, using only three *EMC* points from the measured ones, three commonly used *MSC* models are adopted to interpolate the values. Finally, two small single-zone buildings are simulated in four locations, using the 4 *MSC* modeling approaches and comparing the results. The simulation tool used is EnergyPlus (version 9.5).

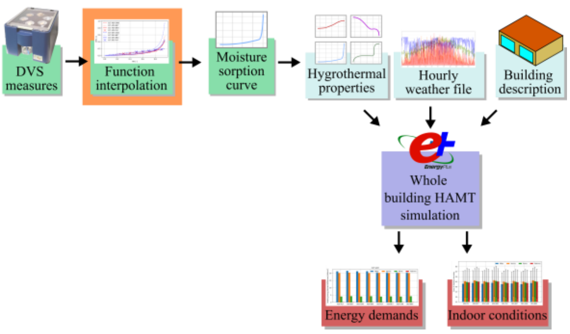

Fig. 1 – Study procedure scheme. In this study the effects of the choice of the function interpolation of *MSC* are quantified in terms of energy demands and indoor air conditions

The effect of *HAMT* models on *BES* energy consumption results has been already studied in the literature (Yang et al., 2015), finding differences of 5-10 % from the thermal simulations. The aim of this comparison is to assess to what extent an approximated sorption curve can alter the results of a whole-building hygrothermal simulation. Indeed, little information exists in the literature on the influence of different *MSCs* on *BES*.

The topic of the effects of *MSC* has been mainly tackled when considering moisture hysteresis in *HAMT* wall simulations for moisture-related risk analysis or for moisture buffering evaluations (Berger et al., 2020; Libralato et al., 2021a; Scheffler, 2008), comparing the effects of including hysteresis sorption models in the material sorption process. In this paper, hysteresis will not be considered, since EnergyPlus cannot model moisture hysteresis, but the adsorption and desorption curves of the materials will be taken into account separately.

2. Material Characterization

To perform heat and moisture transfer transient simulations, knowledge of several hygro-thermal material properties is required. In this study, the *MSCs* and thermal conductivities are obtained from measurements, while heat capacity and vapor permeability is taken from the literature. The study is limited to the hygroscopic range (under 95 % *RH*).

The *MSCs* of four materials were measured using the Proumid VSORP basic *DVS* analyser (Fig. 2). The instrument was set to perform gravimetric tests of the five samples every 20 minutes in a small climatic chamber with controlled dry bulb air temperature (*T*) and relative humidity (*RH*). *T* and *RH* being kept constant, and the samples are weighed until they reach equilibrium conditions. This procedure is performed automatically for every point of the *MSCs*. The environment was set to 23 °C and the relative humidity was set sequentially to 0 %, 30 %, 40 %, 50 %, 60 %, 70 %, 80 %, 90 %, 80 %, 70 %, 60 % and 50 % *RH*. The air *RH* is kept constant until the equilibrium condition is met by all the samples. The equilibrium condition is set to a mass change lower than 0.01 % in 350 minutes. The balance resolution is 0.1 mg. The whole test lasted approximately 42 days for a total of 12 *EMC* points.

The measurement procedure used differs from the standard ISO 12571 (CEN, 2021) on the following points:

- the sample's mass shall be at least of 10 g, and 100 mm x 100 mm if the material has a density lower than 300 kg/m³. Smaller samples can be used but it should be demonstrated that the result will not be affected;
- three samples shall be tested for each material;
- the equilibrium is reached when three consecutive weights, made 24 h apart, differ less than 0.1 % of the total mass;
- the starting point for the desorption curve should be at least 95 % *RH*.

Using the *DVS* analyser in place of the standard procedure removes the error caused by moving the sample from the controlled air environment to the scale, and reduces the time required by the test.

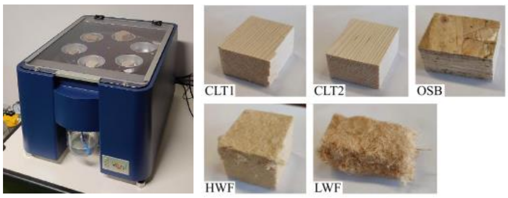

Fig. 2 – Experimental device (Vsorp Basic dynamic vapor sorption analyser) and studied samples of wood-based materials

The materials studied (Fig. 2) are spruce timber (used for Crossed Laminated Timber (*CLT*) panels), Orientated Standard Board (*OSB*), Low-density Wood Fibre (*LWF*) and High-density Wood Fibre (*HWF*). Since the instrument can measure 5 samples at the same time, two samples of *CLT* are tested and the *MSCs* used in the simulations is obtained averaging the two values.

The dry weight, volume, and free saturation moisture content of the samples are presented in Table 1. The dry weight is obtained after conditioning the samples at 0 % *RH* at 23 °C. The free saturation moisture contents of the five samples are obtained from the weight of the samples submerged in water until the weight variation is under the 0.1 %. A scale with 0.01 g resolution is used. The results of the sorption analysis are presented in Fig. 3. The *EMCs* of the five samples for the adsorption process are measured starting from the dry state up to the 90 % *RH*, and for the desorption process, starting at 90 % *RH* and back to 50 % *RH*.

Table 1 – Sample description

Sample ID	Dry weight [mg]	Volume [mm³]	Sat. M.C. [mg]
CLT1	7577.0	14570	13270
CLT2	7094.2	15850	14740
OSB	8632.1	18045	19890
LWF	2449.5	47740	41410
HWF	8654.5	80686	46390

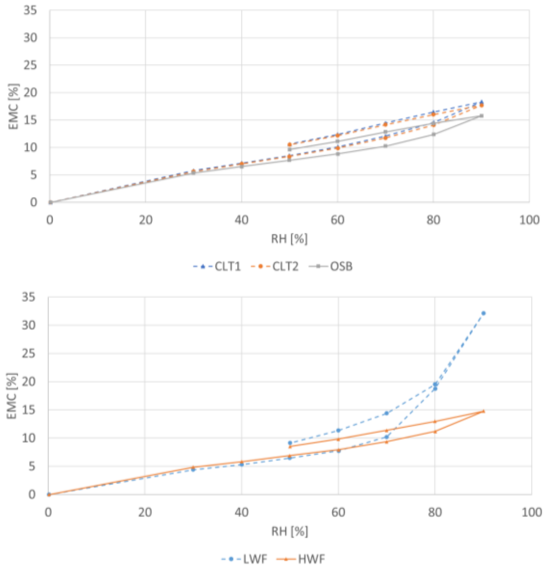

Fig. 3 – Adsorption and desorption curves measured for the five samples

2.1 Other Hygrothermal Properties

The thermal conductivity and specific heat values of the materials are taken from (Danovska et al., 2022), except for the *OSB* values which are obtained from the correlation reported in (Vololonorina et al., 2014) at 25 °C. The values of thermal conductivity are measured at different moisture contents and temperatures, but for this paper only the values at 20 °C with different moisture contents are considered. As an overall description of the materials, the hygrothermal properties are presented in Table 2. The values of permeability μ_{dry} and specific heat c_{dry} of the dry materials are taken from (Carbonari, 2010), except for *OSB*, which is from (Igaz et al., 2017).

Table 2 – Hygrothermal properties of the materials

Material	λ_{dry} [W m^{-1}K^{-1}]	ρ_{bulk} [kg m^{-3}]	c_{dry} [J kg^{-1} K^{-1}]	μ_{dry} [-]
CLT	0.104	467	1380	34
OSB	0.096	478	1287	46
LWF	0.039	51	2100	6
HWF	0.048	107	1380	6

The values of density ρ_{bulk} are calculated from Table 1. The values of μ used in the models are dependent on the moisture content and are described by linear piecewise functions connecting the values presented in (Vololonorina et al., 2014). The values of the vapor resistance factor at 0 % *RH*, μ_{dry} are presented in Table 2.

2.2 Moisture Sorption Curve Functions

In this study, four types of *MSC* interpolation are compared:

1 - Piecewise linear function (*PLF*)
2 - Brunauer–Emmett–Teller model (*BET*)
3 - Guggenheim-Anderson-de Boer model (*GAB*)
4 - Modified BET (*B80*)

The *PLF* case is obtained from the list of measured points. The interpolated *EMC* are calculated between the known points with a linear interpolation. The *BET* and the *GAB* model isotherm functions are considered in the form described in (Thybring et al., 2021) and they are used to obtain a correlation for the *MSC*s from three points of the measured *EMC* values series using the parabolic form presented also in (Thybring et al., 2021). The *B80* modified *BET* model is presented in (Künzel, 1995) and it is used in the WUFI software family to define the unknown *MSCs*. The parameters of the *B80* curve are defined by the *EMC* at 80 % *RH* and by the free water saturation point, set at 100 % *RH*, therefore it is the only function in this study that includes information on the over-hygroscopic range. The analytical curves obtained are used to define the sorption curve in EnergyPlus in the hygroscopic range for both adsorption and desorption curves. Fitting the values of *EMC* is commonly done when only few measured *EMC* are available. Therefore, to perform this situation, 3 *EMC* values are used to calculate the functions' parameters. The *GAB* and *BET* adsorption curves are fitted to the *EMC* values of 30 %, 50 % and 80 % *RH*, while the desorption curves are fitted to the 50 %, 70 % and 80 % *RH* points.

3. Simulations

To perform a simple comparison a modified version of the BESTEST Common Exercise 600 (Fig. 4) is used as test building (ANSI/ASHRAE, 2017).

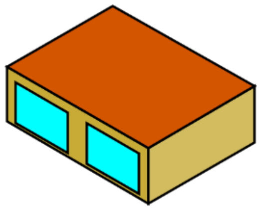

Fig. 4 – The BESTEST 600 geometrical model is used for the simulations. The model is a single room building with two large windows facing South

To evaluate the effects of the variation of the *MSC*s, the Heat Balance Algorithm is set to the Combined Heat and Moisture Finite Element model. Then the materials' *MSCs* are defined with 22 points (EnergyPlus allows a maximum of 25 points). The 22-point definition of the *MSCs GAB*, *BET* and *B80* is obtained from this subdivision of the *RH* range: every 10 % *RH* up to the 70 % *RH*, while from 72 % *RH* to 96 % every 2 %; the last point of the moisture curve is set at 100 % *RH* to the free water saturation point. The liquid conduction coefficients are set to 0 to avoid the over-hygroscopic moisture transport. Constant infiltration is set to 0.5 ACH and the internal sensible heat gains are set (as the BESTEST case) constantly to 200 W (60 % radiative, 40 % convective, 0 % latent). The weather files used are the ASHRAE IWEC (International Weather for Energy Calculation) files for the locations of Milan, Rome, Palermo and Venice. Annual average *T*, *RH* and total solar horizontal irradiation I_G of the weather files are presented in Table 3. The initial water content for every material is set to the *EMC* value correspondent to the 50 % *RH* value of the adsorption *PLF MSC*.

Table 3 – Weather files: average temperature and relative humidity, and total solar horizontal irradiation

Location	*T* [°C]	*RH* [%]	I_G [MWh/m²]
Milan	11.8	75	1.29
Palermo	18.8	74	1.69
Rome	15.8	78	1.46
Venice	13.2	77	1.15

Two construction types are set as external vertical walls (yellow walls in Fig.4): a *CLT* wall and a frame wall, while the floor and the roof constructions are the same for both cases. The build-ups of the two walls are described in Table 4.

Table 4 – Wall types

Wall type	Material layers	d [cm]
CLT wall *U* = 0.26 W/(m²K)	*OSB* (external layer)	2
	LWF	10
	CLT	10
Frame wall *U* = 0.37 W/(m²K)	*OSB* (external layer)	2
	HWF	10
	OSB	2
Floor and Roof *U* = 0.31 W/(m²K)	Barrier (external layer)	-
	HWF	10
	LT	10

A vapor barrier (S_d = 1500 m), not defined in the BESTEST, is added on the external side of the floor and of the roof, to remove the influence of the ground and of the roof. The floor external surface is set as adiabatic. An ideal heating and cooling system is set to maintain the internal temperatures between 20 °C and 27 °C, without air humidity control, and the heating and cooling demand is calculated. There are six warmup days required by EnergyPlus to reach convergence not reported in the results.

4. Results

In this section, first the *MSC* fitted curves are compared with the measured *PLF* curves, then the effects of using different *MSCs* in EnergyPlus *HAMT* whole building simulations are presented.

4.1 Fitting Evaluation

The curves fit the experimental points differently: from Fig. 5 it could be observed that the *GAB* model tends to follow the measured points, but it does not increase the *EMC* values after 90 % *RH*. Differently, the *BET* and *B80* curves always have lower *EMC* for values of *RH* lower than 80 %.

On one hand, the *B80* function is constrained at the *EMC* for 80 % *RH* and at 100 % *RH* and overestimates the values at 90 % *RH*. On the other hand, the *BET* curves overestimate also the 80 % *RH*. It should be also noted that the *LWF* adsorption *GAB* curve is above the desorption curve after the 80 % *RH*, being the only case where the *GAB* curve shows high moisture contents in the higher *RH* values.

Depending on the *RH* range used in the simulations, the material will have different moisture contents. In the cases studied, the room air *RH* is calculated to be between 30 % and 60 %, therefore, the representativeness is evaluated only up to 70 %. To evaluate the goodness-of-fit, the difference (in terms of moisture content) between the curves (*BES*, *GAB* and *B80*) and the *EMC* measured points (*PLF*) is calculated for each measured point of the desorption and adsorption curves, up to 70 %. The average of the differences is presented in Fig. 6. The *GAB* curves are the closest to the measured points, except for the *LWF* curve. The *BET* and *B80* curves have higher differences, therefore larger differences are expected in the simulation results. Despite the constraint at 80 % *RH*, the *B80* curves have larger average distances from the measured points.

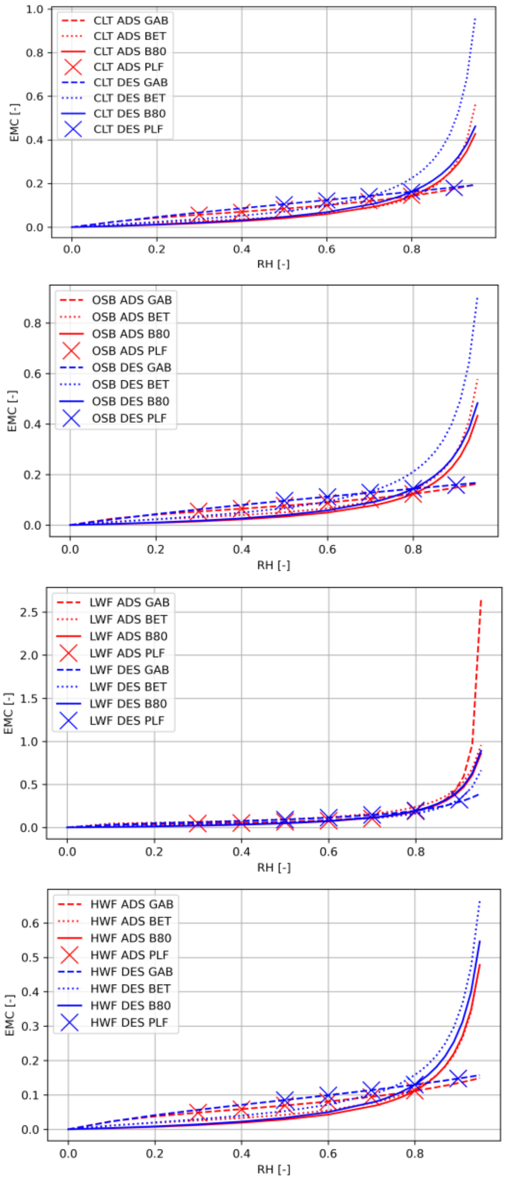

Fig. 5 – Measured (*PLF*) adsorption and desorption curves, *BET*, *GAB* and *B80* (adsorption and desorption) curves for the four considered materials

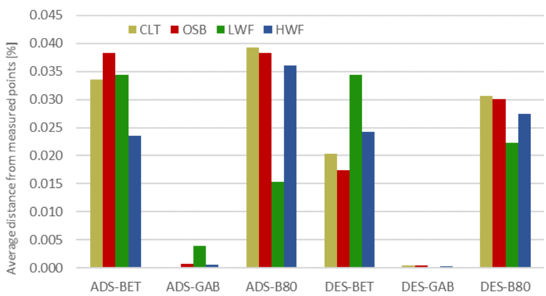

Fig. 6 –Absolute average distance from measured points of the *MSCs* considered. The differences are expressed in percentage mass/mass and the points from 0 % to 70 % *RH* are considered

4.2 Simulations

The results of the simulations follow the expectations of the differences presented in Fig. 6. The hourly values (Fig. 7) show that the moisture contents calculated with the measured curves are almost overlapping the values obtained using the *GAB* curve for both adsorption and desorption. The other results follow the order of the *CLT* sorption curves: *ADS-B80*, *DES-B80*, then *ADS-BET* and *DES-BET*, *ADS-GAB* and *ADS-PLF* (whose line is covered by the *ADS-GAB*), and, finally, *DES-GAB* and *DES-PLF*.

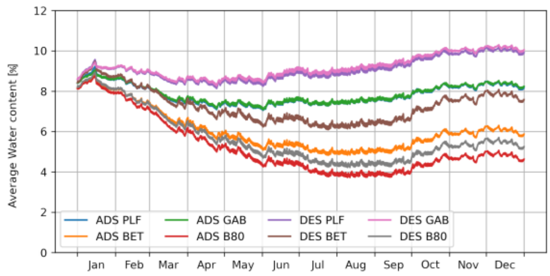

Fig. 7 – Hourly average water content of 1 m² of the North-facing wall for the *CLT* wall building simulation in the Milan weather file. The visualised values start after the 6-day warm-up period and are expressed in $\%kg_{water}/kg_{dry}$

In Fig. 8, the annual mean values are reported for both wall typologies and for all the other climates considered. The relative positions of the *MSCs* seen in Fig. 6 are confirmed. Similar results with similar values are obtained for the Frame wall case (not reported here). When considering the heating and cooling demands, the simulations with *MSCs* with higher *EMC* values are expected to have larger values of energy needs, and lower energy needs for lower *EMC*, since the thermal conductivity is dependent on the moisture content of materials. Moreover, also the effects of latent heat transfer should be expected, especially when the effect of initial moisture content is present.

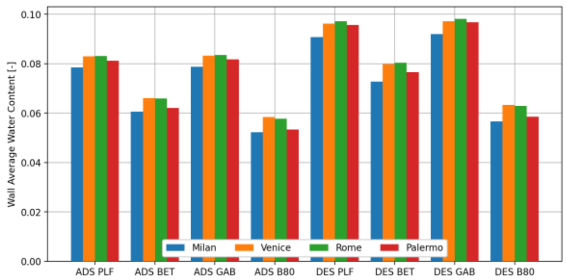

Fig. 8 – Annual mean water content of 1 m² of the North-facing wall for the *CLT* wall building simulation in the Milan weather file

Heating and cooling demands are also influenced by the latent loads due to the walls drying or adsorbing air moisture to reach *EMC*; this resulted in larger heating loads for the simulations with *MSCs* with lower *EMC* values and vice versa. The differences among the loads of the studied cases are the combination of the effect of the conductivity reduction and the effect of latent loads provided by the moisture migration from the walls. The results for the adsorption and desorption curves are presented as annual energy demands in Table 4 (*CLT* wall) and Table 5 (frame wall). In most of the cases, the energy demands values are higher for the adsorption curve results, except for the *CLT* cooling demands of Venice, Rome and Palermo, and the heating demands in Milan.

Table 4 – Annual heating and cooling demands calculated for the *CLT* wall with the adsorption and desorption *PLF MSC*

Location	Heating demand [kWh/(m² yr)]		Cooling demand [kWh/(m² yr)]	
	ADS	*DES*	*ADS*	*DES*
Milan	21.77	21.80	32.40	32.32
Venice	20.98	20.75	27.75	27.77
Rome	4.19	4.05	40.16	40.19
Palermo	0.17	0.16	56.45	56.61

Table 5 – Annual heating and cooling demands calculated for the frame wall with the adsorption and desorption *PLF MSC*

Location	Heating demand [kWh/(m² yr)]		Cooling demand [kWh/(m² yr)]	
	ADS	*DES*	*ADS*	*DES*
Milan	28.22	27.95	33.54	33.28
Venice	26.05	25.80	28.11	27.89
Rome	7.52	7.34	40.48	40.19
Palermo	0.69	0.65	56.03	55.90

The desorption curves have higher moisture contents, and this is expected to lead to higher demands, caused by higher thermal conductivity values of the envelope materials. However, when the loads due to the drying process are larger, the resulting effect is the opposite. The charts in Fig. 9 show the deviation from the adsorption and desorption results obtained using *MSC* fitting curves. In these charts the difference for the adsorption and desorption fitting curves is calculated from the results of the adsorption and desorption *PLF* curves, respectively. The calculated differences for the heating demands are all below 1.2 kWh/m², with Milan *CLT ADS-BET* having the highest corresponding to a deviation of 5 % from the *PLF* values. The higher relative deviations are found for Palermo *CLT DES-B80* (38 % of 0.16 kWh/(m² yr)) due to the very low heating loads. The cooling loads differences are below 1 kWh/m² (e.g., for Milan frame wall *DES-B80*), which is also the maximum relative difference (2.5 %). As expected, in every case, the *GAB* model produces the lowest differences, while the *B80* the largest. The negative values of the *CLT* wall cooling demands are caused by the drying process due to the initial moisture contents of the walls. To verify this, multi-year simulations have been performed (removing the dependence on the initial moisture content), obtaining positive differences in the last year of the simulations.

The effect of the *MSCs* on the internal environment for the *CLT* wall case is presented in Fig. 10. While the internal temperature values are controlled by the ideal heating and cooling system, the relative humidity is influenced by the constant air infiltration and by the moisture buffering effect of the building materials on the internal environment. The results show that the *MSCs* compared can also have an influence on the annual average moisture content. The variation due to the *MSC* of the average value is less than 2 % *RH*, while the maximum values have variations up to 4 % *RH*. The minimum annual average values are found for the *CLT ADS-B80* case (e.g., 41.3 % *RH* in Milan), while the maximum is found for *CLT DES-GAB* (e.g., 43.0 % *RH* in Milan). The *ADS* simulations have 1 % *RH* higher values than the respective *DES* simulations, and the *BET* and *B80* have higher values than *PLF* and *GAB*. Sorption curves with lower *EMC* obtained lower wall moisture contents (Fig. 8) and higher air *RH* values.

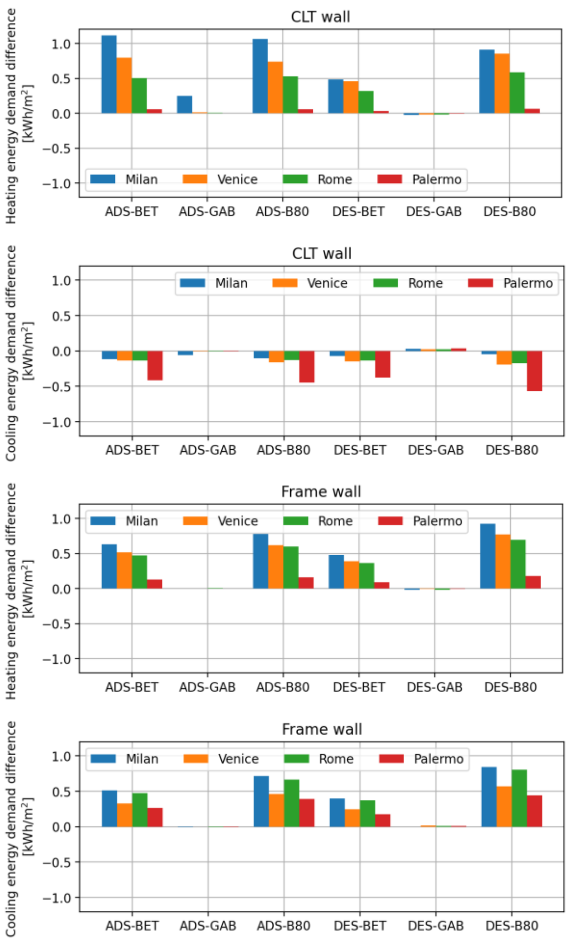

Fig. 9 Annual heating and cooling demands deviations. The differences of the *ADS* and *DES* fitting curves are calculated from the respective *ADS* and *DES PLF* curves (Table 5)

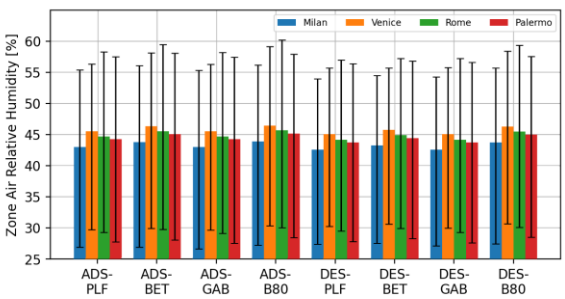

Fig. 10 – Annual average indoor air *RH* calculated with different *MSCs* at different locations. The error bars indicate the annual hourly maximum and minimum *RH* values

5. Conclusions

In this preliminary research the moisture adsorption and desorption curves of four wood-based building materials have been measured with a *DVS* analyser. The measured values have been compared with three commonly used fitting functions based on different *MSC* models. 64 simulations of a small building have been performed, with two different envelopes composed of the materials analysed, in four Italian locations, for four *MSC* fitting curves, for both adsorption and desorption curves. The simulations have been performed with the software EnergyPlus considering moisture dependent hygrothermal material properties.

The effects of every fitting function on the results of the simulation have been quantified in terms of heating and cooling annual demands, moisture content in walls and air relative humidity. The main findings are:

- The *GAB* function represents better the measured *EMC* in the hygroscopic range.
- For the studied cases, using the *BET* and *B80* functions in hygrothermal building energy simulations caused errors in the heating demand up to 1.2 kWh/(m² yr) (case of *CLT* simulation in Milan, with 5 % difference from the same *PLF* case) and 1 kWh/(m² yr) in cooling demands (Milan frame wall *DES-B80*, with 5 % difference from the same *PLF* case).
- When considering the internal annual average air relative humidity, the influence of the fitting function is found to be of 2 % *RH*, and of 4 % *RH* on the annual maximum values.

In conclusion, the differences are of a small order, and could be of interest when high precision results are required (for example, with high performance buildings, in risk evaluations, or in model calibration procedures). The desorption curves, as expected, led to the calculation of higher moisture contents and internal relative humidity values, and should be preferred to adsorption curves when conservative simulations are needed.

Further research is required to increase the accessibility of hygrothermal simulations. Future work will focus on extending the analysis on the other hygrothermal material properties and on the over-hygroscopic range, considering the effects of rain and extreme weather conditions. Occupants' comfort parameters and multi-year results will also be considered.

Acknowledgement

The research leading to these results has also 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.

Libralato M. acknowledges fellowship funding from MUR (Ministero dell'Università e della Ricerca) under PON "Ricerca e Innovazione" 2014-2020 (D.M. 1062/2021).

This research was partially funded by the project "Klimahouse and Energy Production", in the framework of the programmatic-financial agreement with the Autonomous Province of Bozen-Bolzano of Research Capacity Building.

Nomenclature

Symbols

c_{dry}	Specific heat capacity (J·kg^{-1} K^{-1})
λ_{dry}	Thermal conductivity (W·m^{-1} K^{-1})
μ_{dry}	Water vapor resistance factor (-)
ρ_{bulk}	Density (kg·m^{-3})
U	Air-to-air thermal transmittance (W·m^{-2}K^{-1})

Abbreviations

ADS	Adsorption
B80	BET model with 80 % *RH* constraint
BES	Building Energy Simulation
BET	Brunauer–Emmett–Teller model
CLT	Cross-Laminated Timber
DES	Desorption
DVS	Dynamic Vapor Sorption analyser
EMC	Equilibrium Moisture Content
GAB	Guggenheim-Anderson-deBoer model
HAMT	Heat Air and Moisture Transfer
HWF	High-density Wood Fibre
LWF	Low-density Wood Fibre
MSC	Moisture Sorption curve
OSB	Oriented Strand Board
PLF	Piecewise Linear Function
RH	Relative Humidity

References

ANSI/ASHRAE. 2017. "Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs (ANSI/ASHRAE Standard 140)."

Berger J., T. Busser, T. Colinart, and D. Dutykh. 2020. "Critical assessment of a new mathematical model for hysteresis effects on heat and mass transfer in porous building material." *International Journal of Thermal Sciences* 151: 106275. doi: https://doi.org/10.1016/j.ijthermalsci.2020.106275

Carbonari, A. 2010. "Proprietà materiali edilizi." Lecture notes. Accessed on December 1, 2021 http://www.iuav.it/Ateneo1/docenti/architettu/docenti-st/Carbonari-/materiali-1/claSA-06-0/proprmat.pdf

CEN. 2021. EN ISO 12571:2021 – *Hygrothermal performance of building materials and products - Determination of hygroscopic sorption properties*. European Committee for Standardization.

Danovska, M., G. Pernigotto, P. Baggio, and A. Gasparella. 2022. "Simulation uncertainty in heat transfer across timber building components in the Italian climates: the role of thermal conductivity". *Energy and Buildings* 268: 112190. doi: https://doi.org/10.1016/j.enbuild.2022.112190

Danovska, M., G. Pernigotto, M. Baratieri, P. Baggio, and G. Gasparella. 2020a. "Influence of moisture content, temperature and absorbed solar radiation on the thermal performance of a spruce XLAM wall in the Italian climates." *Journal of Physics: Conference Series, 37th UIT Heat Transfer Conference*. doi: https://doi.org/10.1088/1742-6596/1599/1/012028

Danovska, M, M. Libralato, G. Pernigotto, A. De Angelis, O. Saro, P. Baggio, and A. Gasparella. 2020b. "Numerical and experimental study on the impact of humidity on the thermal behavior of insulated timber walls." *Proceedings of Building Simulation Applications BSA 2019*. doi: https://doi.org/10.13124/9788860461766

EnergyPlus. 2021. "Weather Data." National Renewable Energy Laboratory (NREL). Accessed Dec 1, https://energyplus.net/weather

Igaz, R., L. Krišťák, L. Ružiak, M. Gajtanska and M. Kučerka. 2017. “Thermophysical properties of OSB boards versus equilibrium moisture content.” *BioResources* 12(4): 8106-8118.

Künzel, H.M. 1995. “Simultaneous heat and moisture transport in building components: One- and two-dimensional calculation using simple parameters.” Fraunhofer-Institut für Bauphysik

Libralato, M., A. De Angelis, O. Saro, M. Qin, and C. Rode. 2021a. “Effects of considering moisture hysteresis on wood decay risk simulations of building envelopes.” *Journal of Building Engineering* 42: 102444 doi: https://doi.org/10.1016/j.jobe.2021.102444

Libralato, M., A. De Angelis, G. Tornello, O. Saro, P. D’Agaro, and G. Cortella. 2021b. “Evaluation of Multiyear Weather Data Effects on Hygrothermal Building Energy Simulations Using WUFI Plus.“ *Energies.* doi: https://doi.org/10.3390/en14217157

Scheffler, G. A. 2008. “Validation of hygrothermal material modelling under consideration of the hysteresis of moisture storage.” PhD Thesis. Dresden University of Technology.

Thybring, E. E., C. R. Boardman, S. L. Zelinka, and S. V. Glass. 2021 “Common sorption isotherm models are not physically valid for water in wood.” *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 627: 127214. doi: https://doi.org/10.1016/j.colsurfa.2021.127214

Vololonorina, O., M. Coutand, and B.Perrin. 2014. “Characterization of hygrothermal properties of wood–based products – Impact of moisture content and temperature.” *Construction and Building Materials* 63: 223–233. doi: https://doi.org/10.1016/j.conbuildmat.2014.04.014

Woloszyn, M., and C. Rode. 2008. “Tools for performance simulation of heat, air and moisture conditions of whole buildings.” *Building Simulation* 1: 5–24. doi: https://doi.org/10.1007/s12273-008-8106-z

Yang, J., H. Fu, and M. Qin. 2015. “Evaluation of Different Thermal Models in EnergyPlus for Calculating Moisture Effects on Building Energy Consumption in Different Climate Conditions” *Procedia Engineering* 121: 1635-1641 doi: https://doi.org/10.1016/j.proeng.2015.09.194

Zu, K., M. Qin, C. Rode, and M. Libralato. 2020. “Development of a moisture buffer value model (MBM) for indoor moisture prediction.“ *Applied Thermal Engineering* 171: 115096 doi: https://doi.org/10.1016/j.applthermaleng.2020.115096