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NUMERICAL ANALYSIS OF THE MBV PARAMETER FOR PLYWOOD

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Abstract. *In this study, a mathematical model was developed to calculate the vapor mass transfer in 1-D geometry with the aim of analyzing the measurement of the MBV index of hygroscopic materials used mainly in civil construction. Plywood boards with a thickness of 15 mm were used. The mathematical model was developed on the Matlab R2015a platform and Domus - Eletrobras software was also used. This model has the objective of applying NORDTEST protocol conditions to the physical experiments done by Meissner (2008). As the protocol propose humidity variation in the time for a constant temperature the isothermal hypothesis is used to the model, considering only the mass transfer by diffusion. For all moisture isotherms a different value of MBV was obtained, the higher values for the hygroscopic properties of the material of Wu (2007), followed by Osanyintola and Simonson (2006) and the lowest value for Domus - Eletrobras. The value found by the numerical model was close to the test-cell for Meissner (2008). It was analyzed the different results obtained by Meissner (2008) (worked on experimental apparatus for mass transfer) for his test cell and sample for the same physical experiment.*

Keywords: *Hygroscopic, MBV, NORDTEST protocol, moisture isotherms.*

1. INTRODUCTION

Various building materials have porous structure, such as plaster, wood, brick, concrete, among others. The pore is a volume of voids, it allows that there is a moisture content inside. Thus, changes in the interface of the surface of these materials with the humidity of the environment leads to a diffusion of heat and humidity. These two properties (humidity and temperature) are coupled and control several factors, such as the durability of the construction, the air quality of the housing, the energy consumption of the building.

Moisture levels may vary in the air, on the surface of materials and internally. These levels depend on external factors such as: precipitation, diffusive transport of moisture in the wrappings, free transport of moisture in the air, and internal factors such as some human activities. In addition, the building may be located in a region that has large thermal amplitudes causing the diffusion of vapour both inside and out (Dedesko and Siegel, 2015).

The negligence of the control of the ambient air can trigger several problems to the occupants, one of them is the appearance of molds in the walls of the buildings that occurs when the level of the parameter A_w (water activity) reaches a critical value, when the fungus formation process occurs walls, ceilings, coatings. Thus, to avoid the pathology of these buildings, moisture levels must be reduced to below critical levels, minimizing fungal growth in the dwellings (Grant et al., 1989). If the environment is not in adequate psychrometric conditions, the problems of material degradation and poor air quality, also altering its mechanical properties and causing allergic and respiratory symptoms arise (Dedesko and Siegel, 2015).

Padfield (1998) suggests the use of hygroscopic materials in the control of humidity in museums, to help in the conservation of the works of the place, that is, to use these water properties (coupling of the properties of temperature and humidity) in the humidity control for the preservation of the local collection. For extreme values - such as low or high relative humidity level - they are detrimental to materials.

A large percentage of the energy consumed in the country is used to air-conditioning the environment. Since the 1980s, programs to reduce energy consumption have been created for the industrial and residential sectors. Within these programs, energy efficiency labeling was implemented in Brazil. Showing the positive effects of these initiatives / programs (for example Procel, Luz para Todos, Programa Brasileiro de Etiquetagem) (Nogueira et al., 2015). The experimental results Osanyintola and Simonson (2006) showed that it may be possible to reduce heating and cooling

energy consumption when applying hygroscopic materials with HVAC control systems, a hygroscopic material being one that has high moisture exchange capacity with the environment. In their work they simulated the climate in some European countries. At the level of Brazil, Nogueira *et al.* (2015) studied the efficiency of the control initiatives and the economic benefits that have been adopted in the current times. They showed a class of Products with a reduction of up to 36.7% of energy consumption.

Rode (2005) presented the parameter Moisture Buffer Value (MBV) being obtained experimentally. This parameter aims to predict the ability of a material to moderate the variations of humidity with the environment. In order to establish a more robust definition of the MBV, and to define a methodology for its obtaining, a work was done in conjunction with several institutions of researchers initiating the NORDTEST Protocol. Within this project the Robin Round Test was executed, and the participating institutes reproduced the same experimental test to verify if it was possible to obtain similar results, knowing that the Institutes had different equipment.

The *Laboratório de Sistemas Térmicos* (LST) of the *Pontifícia Universidade Católica do Paraná* (PUCPR) developed the software Domus - Eletrobras which simulates the hygromic energy conditions in environments (Manual Domus, 2012). This software – evolution of UMIDUS - was developed by the lack of computational tools for the national interest, since the computational models at the time did not take into account the coupling of temperature and humidity. Meissner (2008) developed a bench of tests for the psychrometric experimental measurements. Abe *et al.* (2010) numerical simulations with Domus to compare with the experimental results of Meissner (2008) and Meissner *et al.* (2010). Finally, the experimental results of Meissner (2008) were compared, he compared the mass vapour transfer measurements of a wooden box of large wooden boards with a small sample inside this Box and both presented discordant results, the reason for this will be investigated difference.

2. MATERIALS AND METHOD

A mathematical model was developed to calculate the vapor mass transfer for a 1-D geometry with the aim to analyzing the measurements of the MBV index for hygroscopic materials (for plywood in this work). For this analysis, the experimental results obtained by Meissner (2008) are used. Thus, the numerical work developed simulates the physical experiment carried out. The humidity and temperature conditions used by the NORDTEST protocol are simulated, and these are also applied in the experiments performed by Meissner (2008). He implemented a calorimeter, a control bench of the experimental parameters and a box of plywood as material for the tests, in the *Laboratório de Simulações Térmicas* (LST) at the *Pontifícia Universidade Católica do Paraná* (PUCPR).

This box is hygroscopically insulated on outside. Inside test-material is applying a charge to the hygroscopic for the vapor flow between a surface and airflow. As other boundary conditions are fixed: a volumetric air flow and constant temperature at 23°C, a box has an inlet and outlet for an air passageway and an outer surface for insulated to moisture. The time cycle is proposed by the NORDTEST protocol, constant airflow, 8 hours in high humidity (75%) and 16 hours at low humidity (33%). This cycle best represents human activities.

The mathematical model implemented simulates the protocol NORDTEST and the experimental parameters performed by Meissner (2008). He used a box of plywood, 15 mm thick wall (externally they were insulated with aluminum foil). The wood plates were fixed in a cubic structure (also hydraulically isolated). All this material was suspended in 0.50 m of the floor. Inside this cubic structure was placed a small sample inside a precision balance. The air flow is controlled by a psychrometric workbench comply with the conditions of the Nordtest protocol. The protocol proposed cyclic variations of 8 hours ambient air with relative humidity in 75% and 16 hours with relative humidity in 33%, in cycles of 24h. This air enters an orifice through one of the plates and exits through another hole in another plate. This article only makes use of numerical analysis and no physical experiments are performed.

2.1 Moisture buffer value (MBV)

The Moisture Buffer Value parameter measures the rate and capacity of a material to adsorption/desorption moisture in its environment (Rode, 2005). The determination of the MBV index depends on several parameters, such as cycle time, mass diffusivity, vapor permeability, moisture accumulation capacity, material thickness, surface finish, specific mass, roughness, air temperature, ventilation rate and flow velocity (Meissner, 2008). Moreover, the hygroscopic behavior of the environment is influenced by the equipment and furniture of the room, humidity load, air renovation among other factors (Rode, 2005).

The NORDTEST protocol proposes the use of psychrometric loads in cycles of 8 hours and 16 hours, varying the humidity. The test sample is exposed to a relative humidity of 75% for 8 hours and then exposed to 33% relative humidity for 16 hours. This cyclic variation from 8h ~ 16h best represents the human activities in one environment, being easier to control than in a cycle environment 12h ~ 12h, and the air velocity should be $0,10 \pm 0,05\text{m/s}$. This protocol proposed the Eq. (1) for the calculation of MBV, and the unit of measure is $(\text{kg}/(\text{m}^2\Delta\%RH))$ (Rode *et al.*, 2008).

$$MBV = \frac{\Delta m}{A \cdot \Delta \% RH} \quad (1)$$

m is the mass (kg), A is the area (m²) and Δ%RH is the relative humidity variation (%). Two mass variation results must be computed per cycle, one in water absorption (m_{8hour} – m_{0hour}) and desorption (m_{24 hour} – m_{8 hour}) in the drying of the material. The mean adsorption and desorption are calculated for each cycle, and the MBV is calculated by the average of the last three measurements. The Robin Round Test was fulfilled to check if it was possible for several institutes to do the same experiment for consistent results. They tested various materials such as concrete, gypsum, veneer, brick, concrete, and others. The synthesis of the Robin Round Test carried out by several institutes (Table 1), using plywood boards as test material in all laboratories.

Table 1. Mean values for MBV_{practical} for all cycles and all laboratories.

	DTU	LTH	NBI	UoS	VTT	Mean value
Mean of cycles	0.58	0.59	0.67	0.57	0.45	0.58
Stdv for cycle	0.03	0.03	0.03	0.06	-	0.07

2.2 Mathematical equations

In the mathematical model some moisture properties measured by Osanyintola and Simonson (2006) and Wu (2007) are used, the moisture content isotherm, the vapor permeability and the specific mass of the dry material. The thickness of the plywood boards is 15 mm. To simulate the mass transfer in a porous medium, a model based on the following hypotheses is used:

- Isothermal media;
- Transfer of moisture throughout the material is one-dimensional;
- Moisture transport is purely diffusive;
- Air and water vapor behave like ideal gases;
- Region of moisture only vapor content;
- Disregarded volume variation (retraction and swelling in wood) due to change in moisture content;
- Disregarded phase shift hysteresis and enthalpy;

For the isothermal problem the equations used in the model are the vapor transport Eq. (2) and the phase change rate Eq. (3) (Olutimayin and Simonson, 2005),

$$\frac{\partial(\varepsilon_g \rho_v)}{\partial t} - \dot{m} = \frac{\partial}{\partial x} \left(D_{eff} \frac{\partial \rho_v}{\partial x} \right) \quad (2)$$

$$\dot{m} = - \frac{\partial u}{\partial t} \rho_0 \quad (3)$$

\dot{m} is the phase change rate (kg/(m³ s)), ε_g is the volumetric fraction of the vapor in the material pore [-], ρ_v is the specific mass of the vapor (kg/m³), D_{eff} is the effective diffusion coefficient (m²/s), u is the moisture content (kg_{vapour}/kg_{dry}) and ρ_0 is the specific mass of the dry material (kg/m³). The value of the heat transfer coefficient by internal convection is 3 W/(m² K). This value is obtained from the formulation presented by Alamdari and Hammond (1983), which is a correlation, as a function of the temperature difference between the wall surface and the air outside the boundary layer (Mendes, 1997). Even using the isothermal problem hypothesis, the heat transfer coefficient is used to obtain the convection mass transfer coefficient - h_m (W/(m² K)) - through the analogy of the boundary layers, Eq. (4). In this work it is use the analogy method of the boundary layers to obtain them. Using the physical properties of the dry air mixture with water vapour, approximate Lewis number the unit, h_m is obtained as,

$$h_m = \frac{h}{\rho c_{air} Le^{2/3}} \quad (4)$$

ρ is the specific mass of the air (kg/m³), c_{air} is the specific heat capacity of air (J/(kg K)) and the Le is the dimensionless number of Lewis, this is the fraction between the dimensionless numbers of Schmidt and Prandtl.

2.3 Properties

In the period of the development of this work it was not possible to physically measure the moisture properties of the plywood, being this the test material, for this reason the results of measurements of two independent works published by Wu (2007) (provided the points) and Osanyintola and Simonson (2006) (provided the equation) are used. These values are applied in the mathematical model developed in this article and are expressed in Figure (1) and Eq. (5).

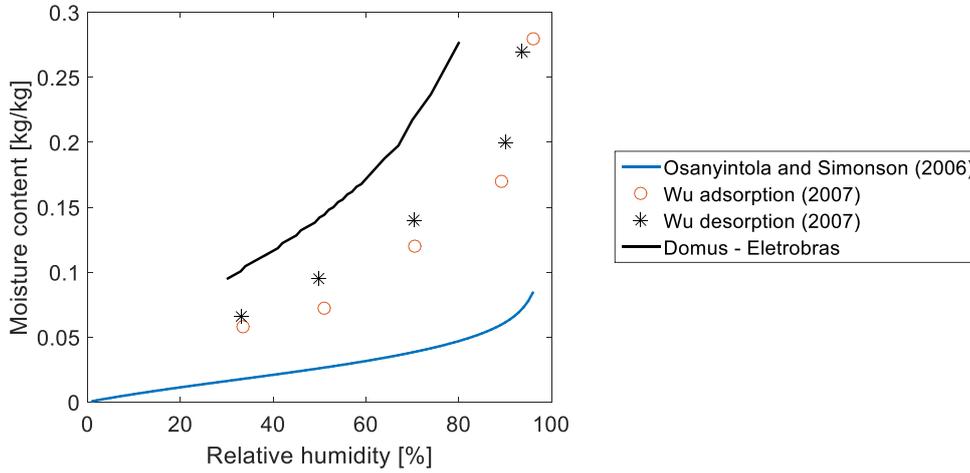


Figure 1. Moisture content for all Isotherm.

$$u = \frac{a + c\phi + e\phi^2}{1 + b\phi + d\phi^2 + f\phi^3} \quad (5)$$

Being u the moisture sorption isotherm in the plywood obtained by Osanyintola and Simonson (2006), ϕ is the relative humidity (in fraction), the constants are: $a=1.0147E-04$, $b=0.2339$, $c=0.06754$, $d=-2.3603$, $e = -0.06574$, $f = 1.1329$. Polynomial obtained and measured with $r^2 = 0.999$ (Osanyintola and Simonson, 2006). The coefficient of effective vapor diffusion - D_{eff} (m^2/s) – of wood can be calculated by Eq. (6) (Osanyintola and Simonson, 2006),

$$D_{eff} = \delta R_v T \quad (6)$$

Being δ the vapour permeability ($kg/(m \text{ s Pa})$), R_v is the vapour gas constant ($J/(kgK)$) and T is the temperature (K). The permeability of the vapour in the wood can be calculated by Eq. (7) provided by Osanyintola and Simonson (2006) and the measured points by Wu (2007), shown in Figure 2,

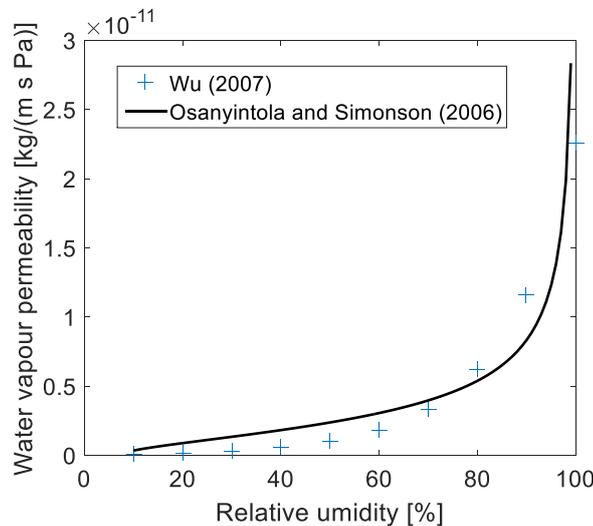


Figure 2. Water vapour permeability curve for plywood.

$$\delta = \left(a + \frac{b\phi}{\ln \phi} \right)^{1/2} \quad (7)$$

Being “a” and “b” the constants (a = -2,3573E-25; b= - 8,1601E-24) and ϕ is the relative humidity (in fraction).

2.4 Boundary conditions

To the inner side of the plate ($x = 0$ m) is exposed to the exchange of vapour between the porous surface and the air,

$$h_m (\rho_v|_{x=0} - \rho_{v,\infty}) = D_{eff} \frac{\partial \rho_v}{\partial x} \Big|_{x=0} \quad (8)$$

To the external side ($x = L$) the surface is isolated in mass flow, its boundary condition is expressed by,

$$\frac{\partial \rho_v}{\partial x} \Big|_{x=L} = 0 \quad (9)$$

As previously mentioned the model has the isothermal hypothesis. This consideration is only necessary in the initial obtaining of the parameters used, such as vapour saturation pressure, specific mass among others.

2.5 Analytical solution

The analytical solution for convective heat transfer in the wall to a semi-infinite medium can be used in a similar way to the problem of convection of humidity on the surface of a semi-infinite medium wall (Incropera *et al.*, 2008). Transient unidimensional conduction heat transfer for the boundary conditions with convection on the surface of a semi-infinite medium has analytical solution expressed by Eq. (10),

$$\frac{T - T_i}{T_\infty - T_i} = \operatorname{erfc} \left(\frac{x}{2\sqrt{\alpha t}} \right) - \left[\exp \left(\frac{h_a x}{k} + \frac{h_a^2 \alpha t}{k^2} \right) \right] \left[\operatorname{erfc} \left(\frac{x}{2\sqrt{\alpha t}} + \frac{h_a \sqrt{\alpha t}}{k} \right) \right] \quad (10)$$

Being the h_a the coefficient of heat transfer by convection of the air (W/(m² K)), α is the thermal diffusivity (m²/s) and k is the conductive thermal conductivity (W/(m K)). By making the analogies of heat transfer parameters for mass the analytical solution for the mass transfer problem to a semi-infinite medium with surface convection is expressed by (Olutimayin and Simonson, 2005),

$$\frac{\rho_v - \rho_{v,i}}{\rho_\infty - \rho_{v,i}} = \operatorname{erfc} \left(\frac{x}{2\sqrt{\alpha_{m,eff} t}} \right) - \left[\exp \left(\frac{h_m x}{D_{eff}} + \frac{h_m^2 \alpha_{m,eff} t}{D_{eff}^2} \right) \right] \left[\operatorname{erfc} \left(\frac{x}{2\sqrt{\alpha_{m,eff} t}} + \frac{h_m \sqrt{\alpha_{m,eff} t}}{D_{eff}} \right) \right] \quad (11)$$

$\rho_{v,i}$ is the initial mass specific vapour, erf the error function (Gaussian error function), and erfc the complementary error function (Incropera *et al.*, 2008). The moisture penetration depth (δ_m) is defined as the position in the porous medium when the specific mass of vapour is disturbed by 1% in the pores.

$$\frac{\rho_v - \rho_{v,i}}{\rho_\infty - \rho_{v,i}} = 0.01 \quad (12)$$

The depth of moisture penetration (δ_m) was calculated by Eq. (12) and compared with the mathematical model. Figure 3 shows the results obtained with the analytical solution and with the mathematical model for material thickness in 1 m. A time step of 60 seconds, the initial relative humidity of the material was used in 50%, the relative humidity of the air flowing on the plate is constant in the value of 75%, the diffusivity of the effective vapor of 3.2488E-07 m²/s, h_m is 2.70E-03 m/s and the constant temperature at 296.15 K. The plate length is 1.0 [m], the number of iterations is 7200 (5 days), and the number of nodes is 5000.

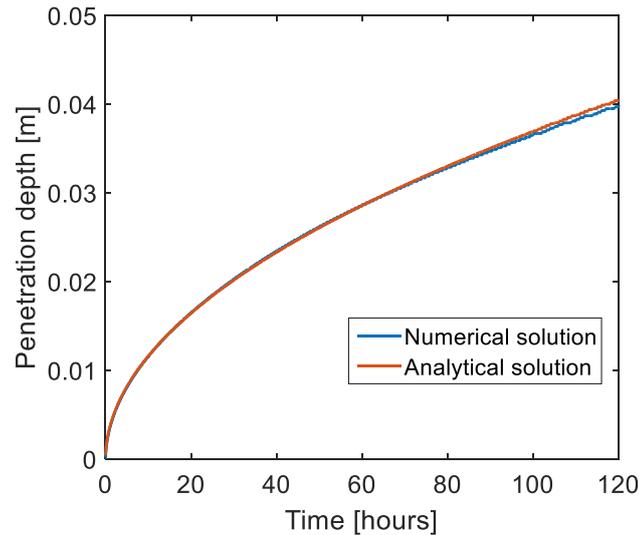


Figure 3. Penetration of moisture in time.

Observing Figure 3, it is noted that the analytical solution with the mathematical model is equivalent. The curves begin to move away in a region far from the surface (around 35 mm), being greater than the thickness of the material that will be analyzed, because the contour condition begins to influence the curve in the furthest region. For the 1-D model, assuming the isothermal hypothesis, we conclude that this result is satisfactory.

2.6 Mesh-refining

The mathematical model uses the discretized partial differential equations, by the finite volume method and explicit formulation. For its numerical solution, a mesh is defined for values with percentage differences less than 0.01% in the refining value of the vapour specific mass, varying the values of Δx and later for Δt . The chosen points of the wooden board are the positions $x = 4.5$ mm and $x = 9.5$ mm. Initially for Δx , the number of nodes for $\Delta t = 5$ seconds is tested. After this, a value for Δt is chosen. For mesh-refinement the simulation parameters are: The initial relative humidity of all materials is 50%, the length of the plate is 15 mm, the time step of 5 seconds during a 24-hour cycle, the relative humidity of the air constant is 75%, isothermal medium, transfer coefficient of mass h_m is $2.75E-03$ m/s, the properties of the material as Osanyintola and Simonson (2006) (Moisture content, vapor permeability, specific mass of the dry material). Fixed these data, complying the criterion of the percentage difference between the specific masses of steam varying Δx , is defined the number of nodes in 150, because the percentage difference between the vapor specific masses for 75 nodes and 150 nodes were 0.003%

3. RESULTS

For the isotherm of Osanyintola and Simonson (Fig. 4a)), the 3 curves tend to stabilize at the value of 0.66 $[g/(m^2\Delta\%RH)]$, the curves for the initial relative humidity condition of the material by 33% and 75% have not yet reached this value because the system has not yet come into equilibrium with moist air. Evaluating the percentage difference (Figure 4b)), from the third cycle, all curves present a percentage difference of less than 5% (parameter defined by the NORDTEST protocol). The 50% curve achieves the equilibrium faster because it begins in a moisture condition closer to the moisture stabilization than the other two curves. The curves of 50% and 75% RH show a peak in the second cycle, due to the vapor sorption equilibrium in the material, and the highest sorption (adsorption and desorption) in the second cycle.

For the isotherm of Wu (2007) - the 3 curves tend to stabilize at 0.96 $[g/(m^2\Delta\%RH)]$, the curves for the initial relative humidity condition of the material in 33% and 75% have not yet reached this value because the system still it did not come into balance with the moist air. Analyzing Figure 4d), from the third cycle, all curves present a percentage difference of less than 5% (parameter defined by the NORDTEST protocol). The 50% curve reaches equilibrium faster because it starts at a moisture condition closer to stabilization in moisture than the other two curves. The 75% RH curve shows a peak in the second cycle, this occurs because of the vapor sorption equilibrium in the material, and the highest sorption (adsorption and desorption) average occurs in the second cycle.

In the case of the Domus-Eletrabras, it is shown the lowest value of MBV among the mathematical models. The system tends to the value of 0.090 $[g/(m^2\Delta\%RH)]$. The system is in equilibrium in the third cycle because the percentage difference of MBV is less than 5% (Figure 4f)).

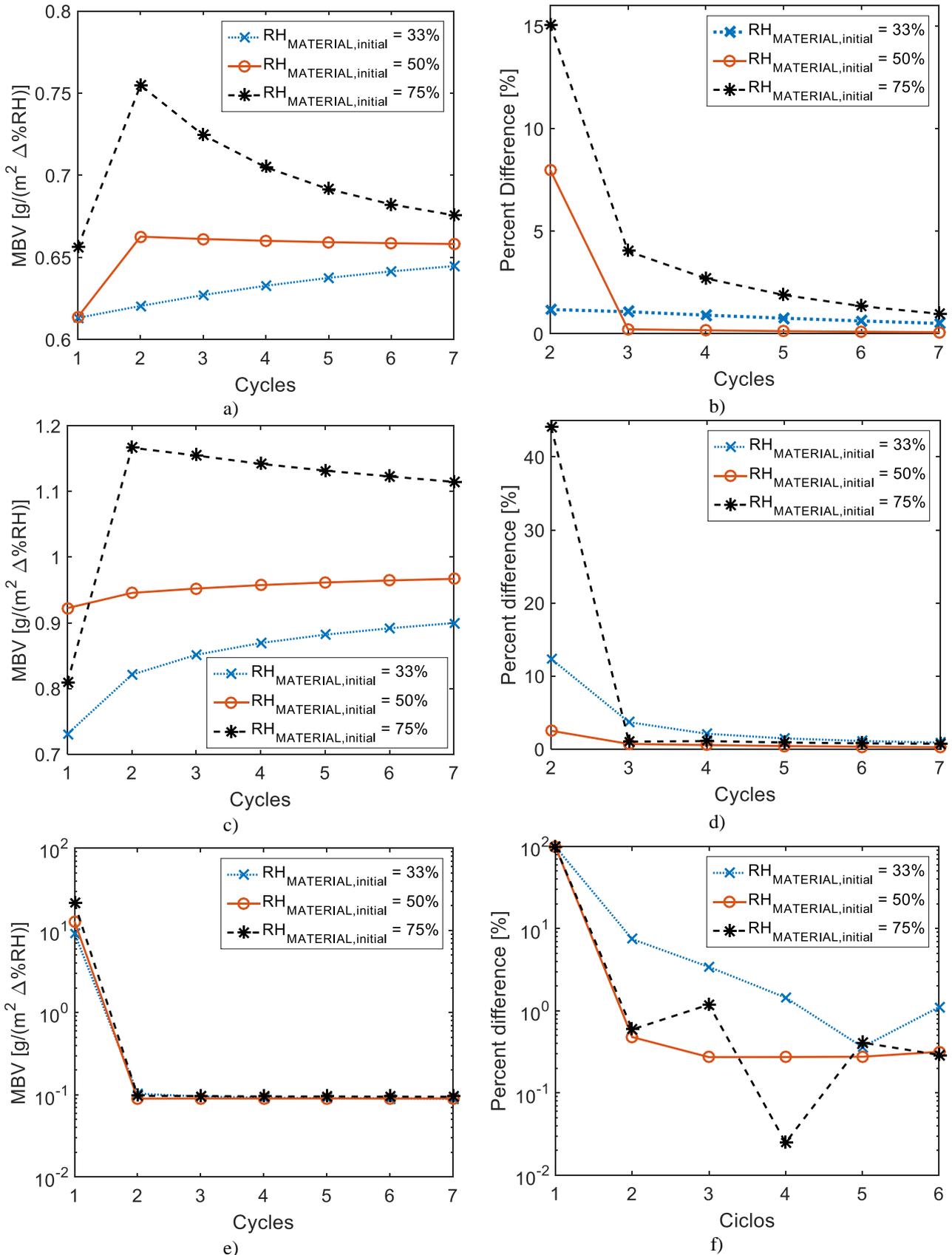


Figure 4. Numerical results of MBV. a) Isotherm of Osanyntola and Simonson (2006). b) The percentage difference for Isotherm of Osanyntola and Simonson (2006). c) Isotherm of Wu (2007) d) The percentage difference for Isotherm of Wu (2007). e) Isotherm Domus. f) The percentage difference for the Domus Isotherm.

The three moisture isotherms presented different results because each had a different sorption, the highest MBV value is from Wu (2007) followed by Osanyintola and Simonson (2006) and the lowest value for moisture isotherm of Domus - Eletrobras. These results evidenced the influence of the permeability property of the material on the hygroscopic inertia. By varying the initial relative humidity of the material at 33%, 50% and 75% for all moisture isotherms, the MBV mean for the isotherm of Osanyintola and Simonson ($\text{g}/(\text{m}^2 \Delta\%RH)$), for Wu (2007) 0.9928 ($\text{g}/(\text{m}^2 \Delta\%RH)$) and for Domus 0.0918 ($\text{g}/(\text{m}^2 \Delta\%RH)$).

Now it is analyzed the results of Meissner (2008), he did the first experimental work on the LST apparatus. Constructed a test cell of internal dimensions of 2020 x 2020 x 2005 mm, totaling a total internal surface area of 24.3516 m^2 and an internal volume of 9.76468 m^3 , for details of the experimental apparatus see reference of Meissner (2008). In addition to the wooden box was used for comparison a small sample that was located inside this box a precision balance for data acquisition. The internal sample area is $7.82 \times 10^{-2} \text{ m}^2$. This sample was positioned internally to compare the result of every test cell with the small sample inside it. The measured values of relative humidity of the experiment are presented in Figure 5.

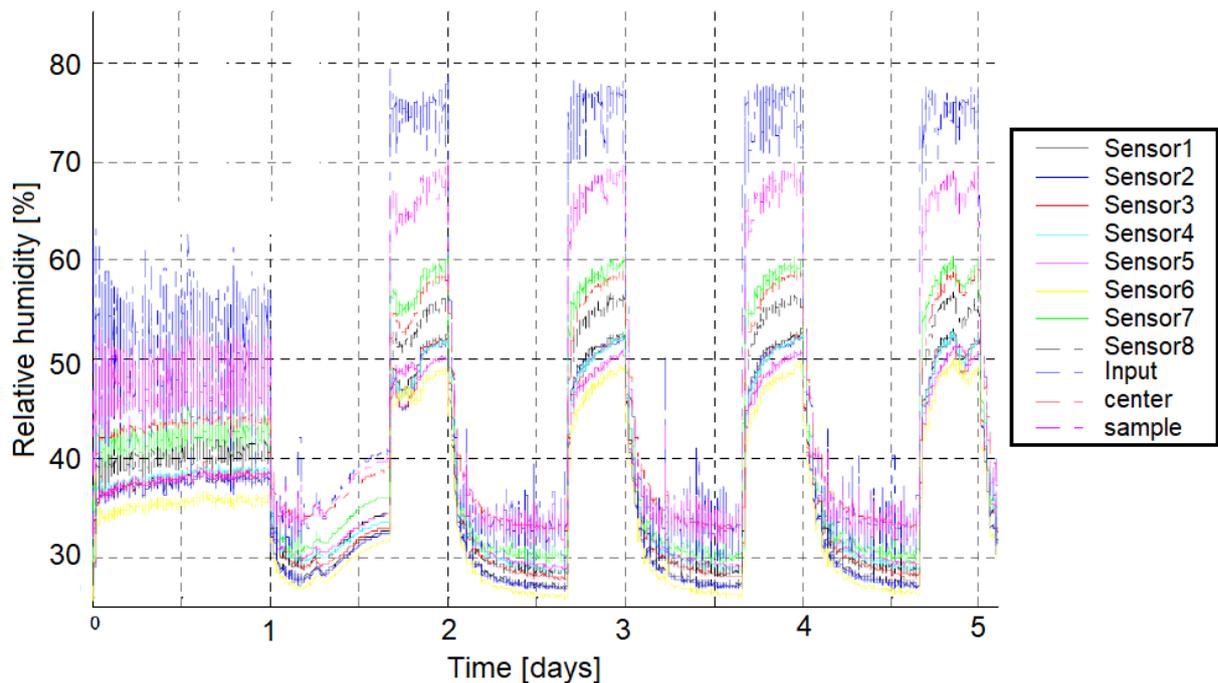


Figure 5. Measurement of relative humidity variation of all sensors in the experimental apparatus (Meissner, 2008).

Meissner (2008) obtained different MBV values between the test cell and sample. Sample MBV is 5.5 times smaller than the Test-Cell (with external moisture insulation). The result of the sample obtained was 0.106 ($\text{g}/(\text{m}^2 \Delta\%RH)$) and for the test cell 0.58 ($\text{g}/(\text{m}^2 \Delta\%RH)$). For the same experiment the sample MBV 5.5 times smaller. The experimental data provided by Meissner (2008) are simulated to analyze this difference. The data of Figure 5 were used to calculate the MBV values for each moisture sensor, these values are presented in Figure 6.

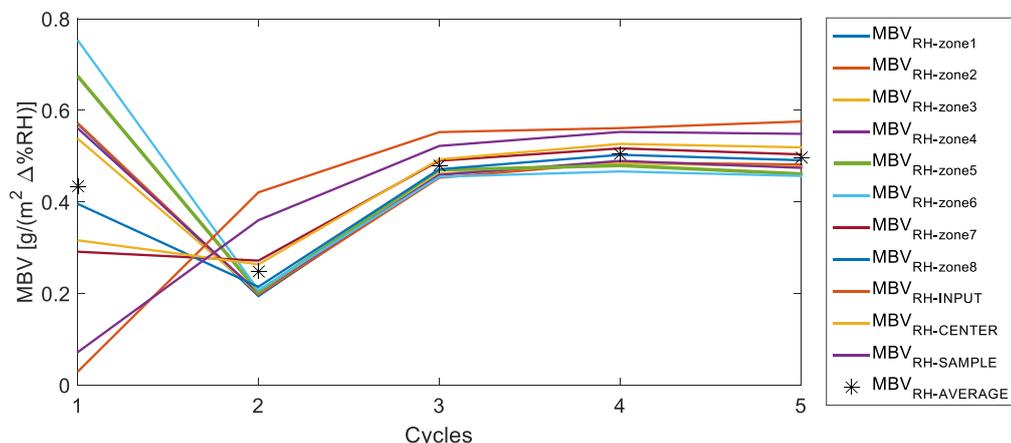


Figure 6. Results of simulation of experimental data.

MBV values tend to stabilize from the 3rd cycle. Each sensor in the apparatus measured different values of relative humidity at the same instant of time, this affects the MBV. Most of the results showing the Hygroscopic classification is the Limited. Comparing the MBV of the test-cell from Meissner (2008) with the numerical results, the percentage difference is 14.8% being a close value and both consistent with the Round Robin Test results.

The values obtained for the sample sensor were close to all others. This happened in the mathematical model because of the calculation made for parameter h_m (mass transfer coefficient by convection), because by the analogy of the boundary layers, while the surfaces of the wooden plates have free flow, the volumetric space of the precision balance is protected by the sides by a small protection wall, this reduces the value of the coefficient h_m . These protective walls are standard on the precision balance to prevent that the airflow interfering the mass measurements. Simulations are repeated for the experimental moisture variation of the sample, but altering the values of h_m to study its influence, the results obtained are presented in Figure 7.

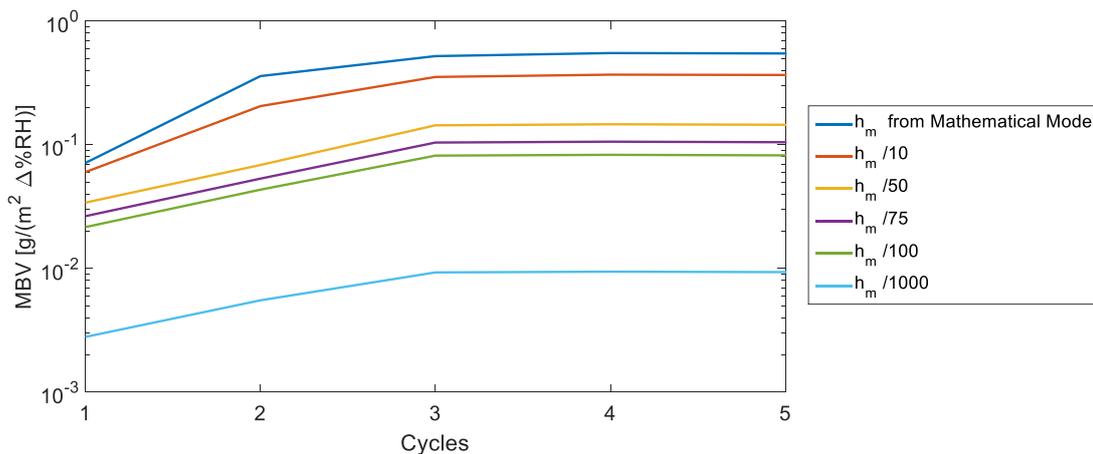


Figure 7. Results of the MBV simulation of the sample varying the values of h_m .

It was found that dividing the h_m by 75 times gives the expected result, proving that the side walls of the balance influenced the experiment, affecting the value of h_m and finally changing the value of the MBV of the sample. The pooled results are presented in Table 2.

Table 2. Main results of MBV.

MBV [g/(m ² %RH)]	Experimental results Meissner (2008)	Mathematical Model MBV médio	MBV for reduction h_m by 75
Sample	0.106	0.494	0.1053
Test-Cell	0.58	0.494	-

The MBV calculated for the mathematical model approached the MBV obtained for the test-cell in the experiment, and reducing the h_m in 75 times the MBV of the sample was close to the experimental MBV, the percentage difference between these two values being 0.66% only.

4. CONCLUSIONS

A mathematical model was developed to analyze the mass transfer to porous materials (plywood) of 1-D geometry, analyzing specifying the MBV experiment, following the NORDTEST protocol. Meissner's experimental work measurements (2008) are implemented in this model. It was used two moisture isotherms in the mathematical model (in MATLAB) and the humidity isotherm in the Domus - Eletrobras software for comparisons, all these isotherms refer to the plywood material, but all were measured by samples, jobs, different people, and all of different origins.

The Domus - Eletrobras isotherm allows a greater amount of water, but has a higher resistance to vapor flow, and the Wu (2007) isotherm showed higher values of MBV and a mean amount of moisture in the material. For all cases from the third cycle the MBV was in stability condition of 5% difference from the previous cycle, carrying out the requirements of the NORDTEST protocol.

It was discovered why the MBV of the Meissner work sample (2008) is 5.5 times smaller than that obtained by the test-cell, because the walls of the precision balance in which the sample was positioned interfered in the internal flow, thus drastically reducing the coefficient of mass transfer by convection. The MBV result obtained by the mathematical model was close to the Meissner experimental MBV (2008). For a more complete analysis it is recommended to measure the hygrothermal properties of the material for comparison with the numerical results.

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