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Comparison of the saturated salt and dynamic vapor sorption methods in obtaining the sorption properties of *Pinus pinea* L.

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Abstract Several methods are available for obtaining the sorption isotherms of wood. Among these, the saturated salt and dynamic vapor sorption methods are the most frequently used ones. For the first time, the hygroscopic response of wood obtained using these two methods is compared. This is done by determining the 35 and 50 °C adsorption isotherms of juvenile and mature wood of *Pinus pinea* L. The hygroscopic behavior of the two types of wood is different, as the mature wood has a higher moisture content than the juvenile wood in the isotherms studied. Comparison of the static saturated salt method and dynamic vapor sorption shows few significant differences between the equilibrium moisture content obtained by each method during the adsorption process, both in a point by point comparison and in the comparison of quadratic polynomial forms of the Guggenheim Anderson-de Boer model. Moreover, in both methods the point of relative humidity from which multilayer sorption predominates over monolayer sorption is similar.

1 Introduction

Numerous studies have been conducted on the hygroscopic behavior of wood. The sorption isotherms of various species have been determined (Popper et al. 2009; Hill et al. 2010; Hoffmeyer et al. 2011; Zaihan et al. 2011; Fernandez et al. 2014), also differentiating between sapwood and heartwood (Ball et al. 2001; Telkki et al. 2013; Song et al. 2014) and between juvenile and mature wood (Lenth and Kamke 2001; Militz et al. 2003; Neimsuwan et al. 2008; Hill et al. 2011; Esteban et al. 2015; Simon et al. 2015). Other authors obtained the isotherms of wood that was modified thermally (Engelund et al. 2010; Jalaludin et al. 2010; Hill et al. 2012; Murata et al. 2013; Pearson et al. 2013) or chemically (Cao and Kamdem 2004; Dieste et al. 2010; Engelund et al. 2010; Xie et al. 2011; Popescu et al. 2014), and also of old wood (Esteban et al. 2006, 2008a, 2010; Bratasz et al. 2012; Popescu and Hill 2013). This variety of studies confirms the importance of knowing the hygroscopic behavior of wood and its repercussion on the physical and mechanical properties of this material (Skaar 1988; Siau 1995; Almeida and Hernandez 2006; Hill 2006; Kretschmann 2010; Rautkari et al. 2014).

The literature includes various methods for obtaining the equilibrium moisture content (*EMC*) in wood. Among these, the static gravimetric method of saturated salts has been widely used (Cao and Kamdem 2004; Almeida and Hernandez 2006; Esteban et al. 2008b; Majka and Olek 2008; Thygesen et al. 2010; Hoffmeyer et al. 2011; Murata et al. 2013; Olek et al. 2013; Fernandez et al. 2014). This method, described in COST Action E8, consists of keeping the samples in a container with saline solutions that generate known relative humidities (*RH*) until the wood reaches a state of equilibrium with the ambient *RH*. Samples are weighed at regular intervals until they reach a constant value corresponding to the equilibrium state.

However, new studies conducted increasingly use dynamic vapor sorption (DVS) (Engelund et al. 2010; Hill et al. 2010, 2012; Jalaludin et al. 2010; Xie et al.

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2011; Zaihan et al. 2011; Popescu and Hill 2013; Popescu et al. 2014). This new technology generates the air relative humidity values by mixing dry nitrogen or air with saturated water vapor in automatically controlled proportions. The material is placed inside a small chamber where, as a result of a continuous flow of nitrogen and saturated water vapor over the sample, the equilibrium conditions of the material are reached in less time (Bingol et al. 2012). Changes in mass are constantly and automatically recorded.

The advantages of DVS over the saturated salt method are: (1) faster data acquisition (Engelund et al. 2011)—DVS technique requires a few days to determine a sorption isotherm whereas the salt method using desiccators takes months; (2) greater accuracy, as an automatic balance is used instead of a manual balance (Jalaludin et al. 2010); (3) continuous values for changes in mass are available as opposed to the discrete data of the static method (Zaihan et al. 2009), making it possible to monitor the process in real time and study changes over time; (4) the kinetic parameters of the sorption process that is related to the coefficients of diffusion, can be determined (Popescu et al. 2014) and (5) the possibility of obtaining all the values in the range of 0–96% *RH* (Engelund et al. 2011). The major disadvantage of DVS compared to the salt method is the high cost of the equipment (Arlabosse et al. 2003).

Very few authors have compared the adsorption behavior obtained using the saturated salt method and DVS. Levoguer and Williams (1999) and Surface Measurement Systems Ltd. (2012) determined the *EMC* in microcrystalline cellulose reference material (MCC RM 302) through DVS and compared the values with those obtained using the COST 90 procedure. The results showed similarities between the two methods for *RH* values above 33%. Below this value, the *EMC* values were higher when obtained by DVS than by the salt method. Arlabosse et al. (2003) determined this comparison in microcrystalline cellulose (MCC), pharmaceutical granules, PolyEtherBlocAmide (PEBA) membrane and sewage sludges. The *EMC* obtained showed small differences between the methods, which were more pronounced when the apparent diffusion coefficient in the material was higher than 10^{-9} m^2/s. Paes et al. (2010) studied the two methods in samples of ball milled cellulose and concluded that they give similar results. Bingol et al. (2012) obtained the sorption behavior in two varieties of rice using both methods and established that they have similar behavior. None of these studies used wood as the material.

The objective of this study was to compare the saturated salt and dynamic vapor sorption methods for determining the hygroscopic behavior of wood, using the adsorption isotherms of juvenile and mature wood of *Pinus pinea* L. to obtain the degree of similarity of the results.

2 Materials and methods

The samples of *Pinus pinea* L. were collected in the municipalities of Coca and Navas de Oro, in the province of Segovia (Spain). All the trees were adults more than 70 years old. A radial slice was taken from the basal disc, obtained 50 cm from the ground. Samples were taken from the juvenile and mature wood zones, defining the juvenile zone as the fraction between rings 10–20 and the mature wood zone as the area with rings older than 50 years. All the samples chosen were from the heartwood, both earlywood and latewood.

2.1 Saturated salt method

The isotherms were obtained at 35 and 50 °C following the methodology described by COST Action E8 (Themelin et al. 1997). The dimensions of the test pieces for both juvenile and mature wood were 15 mm long, 10 mm wide and 1 mm thick, with no specific anatomical orientation. The samples used in the tests had not been through a drying cycle.

The isotherms were plotted using the 10 equilibrium points corresponding to 10 different salts (Table 1). The relative humidity values generated by each salt for each temperature (35 and 50 °C) were taken from Stokes and Robinson (1949), Robinson and Stokes (1959) and Wexler and Wildhack (1965). Three replicates were performed per study sample.

The test pieces were then placed in a desiccator with phosphorous pentoxide for 40 days to anhydrous state. Then the adsorption isotherms were plotted. The samples were considered to have reached equilibrium in each salt when the difference in mass was no more than 0.1% when they were weighed in a 24 h interval. This process took 1 month.

2.2 Dynamic vapor sorption

The sorption isotherms were determined using the DVS-Advantage instrument. The wood was ground in a Retsch SM 2000 mill and sifted to improve air circulation. The size of the particles used in the experiment was 0.5–1.0 mm. The isotherms were determined at 35 and 50 °C. The *RH* used was the same as in the static saturated salt method. Because of the high reproducibility of the instrument (Jalaludin 2012), only one sample was used per measurement. The initial mass of the sample was 20 mg. The sample was placed in the DVS instrument and dried to obtain the dry mass, then hydrated to reach the corresponding *RH*. The sample was considered to have reached equilibrium when the change in mass (dm/dt) was less than 0.001% min^{-1} for 10 min. The change in mass was recorded every minute.

Table 1 Equilibrium moisture contents for 35 and 50 °C isotherms

Salt	35 °C Isotherm					50 °C Isotherm				
	RH	Juvenile		Mature		RH	Juvenile		Mature	
		Salt	DVS	Salt	DVS		Salt	DVS	Salt	DVS
LiCl	11.17	2.29 0.18[a]	2.16	2.54 0.12[a]	2.30	11.05	2.07 0.16[a]	2.09	2.24 0.12[a]	2.30
CH_3COOK	21.37	3.05 0.23[a]	3.07	3.22 0.16[a]	3.47	20.06	2.55 0.20[a]	3.02	3.01 0.18[a]	3.32
$MgCl_2$	32.00	4.11 0.42[a]	4.20	4.32 0.18[a]	4.72	30.54	3.47 0.16[a]	4.03	3.81 0.28[a]	4.47
K_2CO_3	42.55	4.82 0.23[a]	5.28	4.93 0.23[a]	5.93	40.91	4.68 0.21[a]	5.01	4.79 0.18[a]	5.53
$Mg(NO_3)_2$	49.72	6.11 0.09[a]	5.98	6.83 0.10[a]	6.69	45.44	5.24 0.16[a]	5.40	5.43 0.42[a]	5.94
$SrCl_2$	66.08	8.27 0.35[a]	8.00	9.41 0.42[a]	8.88	57.46	7.14 0.56[a]	6.62	7.65 0.12[a]	7.40
NaCl	75.11	10.10 0.28[a]	9.33	10.92 0.25[a]	10.39	74.84	8.89 0.27[a]	8.82	9.94 0.34[a]	9.87
KCl	82.95	11.60 0.45[a]	10.79	12.41 0.22[a]	12.00	81.20	10.38 0.32[a]	9.72	11.54 0.37[a]	10.98
$BaCl_2$	89.40	12.37 0.36[a]	12.35	14.23 0.62[a]	13.89	88.23	12.01 0.47[a]	11.19	13.08 0.75[a]	12.66
K_2SO_4	96.71	15.40 0.42[a]	15.15	18.08 1.08[a]	17.24	95.82	14.53 1.29[a]	13.42	16.11 0.47[a]	15.50

RH relative humidity

[a] Standard deviation

In both methods the equilibrium moisture content was determined using the following equation:

$$EMC(\%) = \frac{W_W - W_0}{W_0} \times 100 \qquad (1)$$

W_w: wet mass (g), W_0: anhydrous mass (g).

The isotherms were fitted using the Guggenheim Anderson-de Boer (GAB) model, which has been widely used to model the sorption isotherms of wood (Kelsey 1957; Themelin et al. 1997; Hartley 2000; Esteban et al. 2008a, 2010; Lesar et al. 2009; Todoruk and Hartley 2011; Bratasz et al. 2012; Lam et al. 2012; Olek et al. 2013). It also allows a type II sorption curve to be drawn in the whole *RH* range (Hartley 2000; Esteban et al. 2008a, 2010):

$$X = \frac{KC_g(RH/100)}{(1 - K(RH/100))\left(1 - K(RH/100) + C_gK(RH/100)\right)} X_m \qquad (2)$$

X: EMC (%), X_m: monolayer saturation moisture content (%), C_g: Guggenheim constant (dimensionless), *K*: constant (dimensionless), *RH*: relative humidity (%)

The isotherm fits were considered valid when the correlation coefficient (*R*) was greater than 0.990 and the root mean square error (*RMSE*) was less than 4% (Viollaz and Rovedo 1999; Esteban et al. 2006, 2009).

2.3 Comparison of methods

The methods were compared in two ways. Firstly, the existence of significant differences between the DVS measurement and the interval of variation of the measurement with the static saturated salt method was analyzed, using a two-tailed test (Miller and Miller 2002) with a confidence level of 95%.

Secondly, the quadratic polynomial forms of the GAB equations of the methods were compared using the MATLAB program® Version 7.5.0 Curve Fitting Toolbox Version 1.2, which enables the confidence intervals of the fitted curves to be obtained.

The GAB equation is expressed in quadratic polynomial form as follows:

$$\frac{RH/100}{X} = \frac{1}{X_m} \cdot \frac{(1 - K(RH/100))\left(1 - K(RH/100) + C_gK(RH/100)\right)}{KC_g}$$

$$y = A + Bx - Cx^2 \tag{3}$$

$$y = \frac{RH/100}{X};\ x = RH/100;\ A = \frac{1}{X_m K C_g};\ B = \frac{\left(C_g - 2\right)}{X_m C_g};$$

$$C = \frac{\left(C_g - 1\right)K}{X_m C_g}$$

This equation concurs with the polynomial form of the Hailwood–Horrobin model, which is also commonly used to model the isotherms of wood:

$$m = \frac{18}{W} \cdot \left[\frac{k_1 k_2 (RH/100)}{1 + k_1 k_2 (RH/100)} + \frac{k_2 (RH/100)}{1 - k_2 (RH/100)}\right]$$

$$y = A + Bx - Cx^2$$

$$y = \frac{RH/100}{X};\ x = RH/100;\ A = \frac{W}{18} \cdot \frac{1}{k_2\left(k_1 + 1\right)};$$

$$B = \frac{W}{18} \cdot \frac{k_1 - 1}{\left(k_1 + 1\right)};\ C = \frac{W}{18} \cdot \frac{k_1 k_2}{\left(k_1 + 1\right)}$$

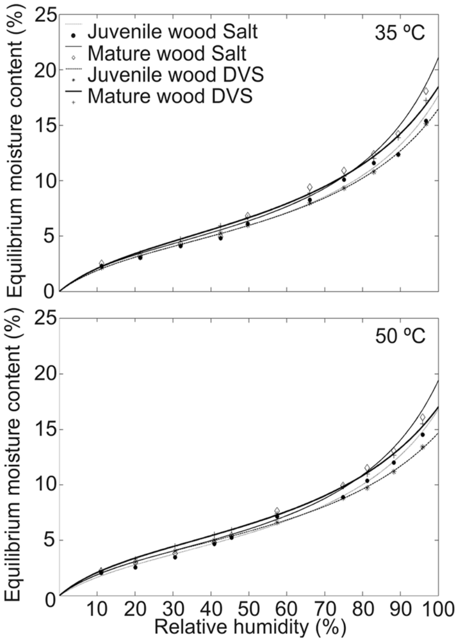

Fig. 1 35 and 50 °C sorption isotherms of juvenile and mature wood of *Pinus pinea*

Table 2 Results of the GAB fit for the 35 and 50 °C isotherms with the saturated salt method and DVS

Parameter	Juvenile		Mature	
	35 °C Isotherm	50 °C Isotherm	35 °C Isotherm	50 °C Isotherm
Salt				
X_m (%)	4.47 ± 0.25	4.40 ± 0.31	4.58 ± 0.33	4.41 ± 0.26
K	0.76 ± 0.39	0.75 ± 0.44	0.79 ± 0.53	0.78 ± 0.41
Cg	7.91 ± 0.06	6.57 ± 0.09	8.21 ± 0.08	7.72 ± 0.07
R	0.995	0.997	0.995	0.996
RMSE (%)	1.22	1.71	2.01	1.95
RH (%)[a]	33.00	32.80	31.70	31.90
EMC (%)[a]	4.32	3.99	4.47	4.22
EMC_f (%)	0.15	0.42	0.11	0.18
DVS				
X_m (%)	4.63 ± 0.10	4.63 ± 0.05	5.23 ± 0.06	5.03 ± 0.06
K	0.73 ± 0.15	0.70 ± 0.08	0.73 ± 0.09	0.72 ± 0.08
Cg	7.75 ± 0.02	8.21 ± 0.01	7.38 ± 0.02	8.15 ± 0.01
R	0.997	0.998	0.996	0.997
RMSE (%)	0.29	0.09	0.13	0.10
RH (%)[a]	34.10	35.70	34.10	34.80
EMC (%)[a]	4.44	4.52	4.95	4.90
EMC_f (%)	0.19	0.11	0.28	0.13

X_m monolayer saturation moisture content, *K* constant, C_g Guggenheim constant, *R* correlation factor, *RMSE* root medium square error, *RH* relative humidity, *EMC* equilibrium moisture content, EMC_f water taken up via monolayer sorption after the point of inflexion

[a] Point of inflexion of the isotherm

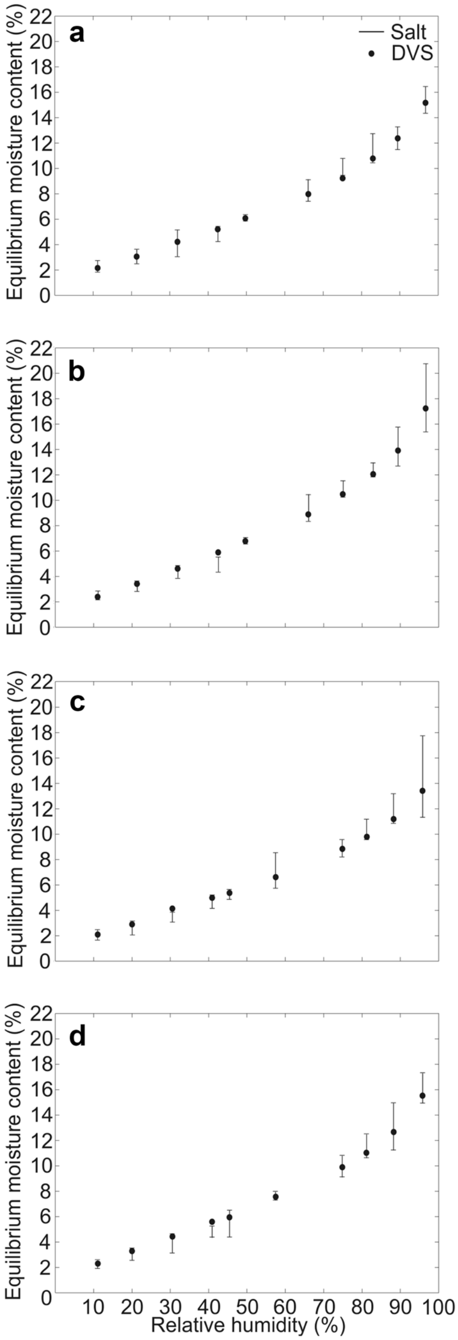

Fig. 2 Point by point comparison of the saturated salt method and DVS. **a** Juvenile wood at 35 °C. **b** Mature wood at 35 °C. **c** Juvenile wood at 50 °C. **d** Mature wood at 50 °C

3 Results and discussion

Table 1 shows the *EMC* values of juvenile and mature wood for the static saturated salt method and the dynamic method (DVS). In all cases the isotherms describe a type II sigmoid (Fig. 1) characteristic of cellulosic materials (Avramidis 1997; Zaihan et al. 2011; Engelund et al. 2013). *EMC* values are higher in salts than in DVS for high *RH* and lower for the remaining *RH*, except in the juvenile and mature wood at 11.17% *RH* and 35 °C (Table 1). The most likely explanation for this is that the ambient conditions for high *RH* are obtained with greater accuracy with DVS than with saturated salts.

Table 1 shows the relation between the sorption behavior of juvenile and mature wood. In all cases the *EMC* values are higher in the mature wood than in the juvenile wood and therefore there is a relation between growth ring location and sorption behavior. Other authors obtained similar results (Zobel et al. 1968; Militz et al. 2003; Neimsuwan et al. 2008; Esteban et al. 2015; Simon et al. 2015). In contrast, Lenth and Kamke (2001), Majka and Olek (2008) and Hill et al. (2015) obtained higher *EMC* values in juvenile wood than in mature wood. The difference in this behaviour is mainly due to the chemical composition of each type of wood (Esteban et al. 2015; Simon et al. 2015).

The isotherm fits with the GAB model are valid, as they have *R* values greater than 0.990 and *RMSE* values less than 4% for all cases (Table 2). The saturation moisture content of the monolayer (X_m) is higher in the mature wood than in the juvenile wood at both temperatures. The *RH* values where multilayer sorption starts to predominate over monolayer sorption are at around 30% (Table 2), supporting observations in other species (Esteban et al. 2009, 2010, 2015; Fernandez et al. 2014). The similar value using the saturated salt method and DVS indicates the good correlation between the methods for obtaining the *EMC*.

Figure 2 shows the experimental *EMC* of DVS and the intervals of variation of the measurements with the saturated salt method.

A good correlation between salts and DVS was obtained, confirming the findings of other studies on different materials (Levoguer and Williams 1999; Arlabosse et al. 2003; Paes et al. 2010; Bingol et al. 2012; Surface Measurement Systems Ltd. 2012). There is only one *RH* value for which the methods differ. In the mature wood, at both 35 and 50 °C, this difference occurs for *RH* at around 40%, and in the juvenile wood it depends on the temperature, as it is 75% *RH* at 35 °C and 30% at 50 °C. Bingol et al. (2012) compared the *EMC* obtained with salts and with DVS in various forms of two varieties of rice. The differences between the two methods occurred in different *RH* ranges depending on the form of rice—in some cases for 0 and 98% *RH* and in others for *RH* around 40–80%. Therefore, it is not possible to establish a specific range of differences.

Table 3 shows the values of the quadratic polynomials of the GAB model using the saturated salt method and DVS. It was observed that the values of the two methods are similar

Table 3 Values of the quadratic polynomials of the GAB model for the saturated salt method and DVS of *Pinus pinea* at 35 and 50 °C

	RH (%)	JUVENILE					MATURE				
		SALT		DVS		$x_{Salt} \neq x_{DVS}$	SALT		DVS		$x_{Salt} \neq x_{DVS}$
		RH/EMC (%)	x ($x_1 - x_2$)	RH/EMC (%)	x ($x_1 - x_2$)		RH/EMC (%)	x ($x_1 - x_2$)	RH/EMC (%)	x ($x_1 - x_2$)	
35 °C	11.17	4.88	5.42 (4.50–6.33)	5.17	5.43 (5.07–5.78)	–	4.40	5.03 (3.87–6.18)	4.86	4.95 (4.73–5.18)	–
	21.37	7.01	6.63 (6.03–7.23)	6.96	6.61 (6.37–6.84)	–	6.64	6.21 (5.45–6.97)	6.16	5.97 (5.83–6.12)	–
	32.00	7.79	7.57 (7.06–8.07)	7.62	7.53 (7.33–7.73)	–	7.41	7.11 (6.47–7.74)	6.78	6.77 (6.64–6.89)	–
	42.55	8.83	8.17 (7.62–8.71)	8.06	8.14 (7.93–8.35)	–	8.63	7.66 (6.97–8.34)	7.18	7.29 (7.15–7.42)	–
	49.72	8.14	8.38 (7.81–8.95)	8.31	8.38 (8.15–8.60)	–	7.28	7.84 (7.12–8.56)	7.43	7.49 (7.35–7.63)	–
	66.08	7.99	8.32 (7.78–8.85)	8.26	8.39 (8.18–8.60)	–	7.02	7.67 (6.99–8.34)	7.44	7.48 (7.35–7.61)	–
	75.11	7.44	7.94 (7.46–8.42)	8.05	8.08 (7.89–8.27)	–	6.88	7.23 (6.62–7.83)	7.23	7.20 (7.08–7.32)	–
	82.95	7.15	7.42 (6.93–7.90)	7.69	7.63 (7.44–7.82)	–	6.68	6.64 (6.03–7.26)	6.91	6.80 (6.68–6.92)	–
	89.40	7.23	6.85 (6.26–7.44)	7.24	7.13 (6.90–7.36)	–	6.28	6.02 (5.27–6.78)	6.44	6.36 (6.21–6.50)	–
	96.71	6.28	6.06 (5.23–6.88)	6.38	6.43 (6.11–6.75)	–	5.35	5.17 (4.13–6.21)	5.61	5.73 (5.53–5.94)	–
50 °C	11.05	5.34	6.16 (5.05–7.28)	5.29	5.40 (5.22–5.58)	–	4.93	5.44 (4.52–6.35)	4.80	4.90 (4.71–5.08)	–
	20.06	7.87	7.18 (6.43–7.93)	6.64	6.50 (6.38–6.62)	–	6.66	6.52 (5.90–7.14)	6.04	5.90 (5.77–6.02)	–
	30.54	8.80	8.07 (7.46–8.67)	7.58	7.51 (7.41–7.61)	–	8.02	7.47 (6.97–7.96)	6.83	6.81 (6.71–6.91)	*
	40.91	8.74	8.63 (7.98–9.29)	8.17	8.22 (8.11–8.32)	–	8.54	8.07 (7.53–8.61)	7.40	7.44 (7.33–7.55)	–
	45.44	8.67	8.78 (8.10–9.47)	8.41	8.44 (8.33–8.55)	–	8.37	8.22 (7.66–8.79)	7.65	7.63 (7.51–7.74)	–
	57.46	8.05	8.89 (8.19–9.60)	8.68	8.76 (8.64–8.87)	–	7.51	8.34 (7.76–8.92)	7.76	7.88 (7.76-8.00)	–
	74.84	8.42	8.31 (7.71–8.92)	8.49	8.54 (8.44–8.63)	–	7.53	7.71 (7.21–8.21)	7.58	7.61 (7.50–7.71)	–
	81.20	7.82	7.89 (7.27–8.50)	8.35	8.26 (8.16–8.35)	–	7.04	7.25 (6.74–7.75)	7.40	7.32 (7.21–7.42)	–
	88.23	7.35	7.27 (6.54–8.01)	7.88	7.82 (7.70–7.94)	–	6.75	6.59 (5.98–7.20)	6.97	6.88 (6.75-7.00)	–
	95.82	6.59	6.46 (5.43–7.48)	7.14	7.20 (7.04–7.37)	–	5.95	5.71 (4.86–6.55)	6.18	6.27 (6.09–6.44)	–

RH relative humidity (%), *RH/EMC* ratio of relative humidity to experimental equilibrium moisture content (%), *x RH/EMC* calculated, x_1 lower limit of the confidence interval of x with 95% probability, x_2 upper limit of the confidence interval of x with 95% probability, *Salt≠DVS* existence of significant differences between salts and DVS with 95% probability

*Yes, – no

(except in the mature wood at 50 °C and 30.54% *RH*), creating overlaps between their intervals of variation. This indicates that there are no significant differences between the methods.

No studies have compared the saturated salt method and DVS using the quadratic polynomials of the GAB model. However, this method can be considered valid, as the results obtained concur with those determined by comparing the *EMC* of DVS with the intervals of variation of the measurements using salts.

4 Conclusion

The isotherms of both juvenile and mature wood of *Pinus pinea* describe type II sigmoids and fit satisfactorily according to the GAB model. For any temperature and method, the juvenile wood has lower *EMC* than the mature wood.

The saturated salt and DVS methods show no significant differences when comparing the *EMC* points obtained with each one, both in the point-by-point comparison and using the quadratic polynomial form of the GAB model. This result is strengthened by the similar point of relative humidity from which multilayer sorption predominates over monolayer sorption in the two methods.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Almeida G, Hernandez RE (2006) Changes in physical properties of tropical and temperate hardwoods below and above the fiber saturation point. Wood Sci Technol 40(7):599–613

Arlabosse P, Rodier E, Ferrasse J, Chavez S, Lecomte D (2003) Comparison between static and dynamic methods for sorption isotherm measurements. Dry Technol 21(3):479–497

Avramidis S (1997) The basics of sorption. In: Hoffmeyer Preben (ed) Proceedings of International Conference on Wood-Water Relations. 16–17 June 1997, Copenhagen, Denmark. pp 1–16

Ball RD, Simpson IG, Pang S (2001) Measurement, modelling and prediction of equilibrium moisture content in *Pinus radiata* heartwood and sapwood. Holz Roh Werkst 59(6):457–462

Bingol G, Prakash B, Pan Z (2012) Dynamic vapor sorption isotherms of medium grain rice varieties. LWT-Food Sci Technol 48(2):156–163

Bratasz L, Kozlowska A, Kozlowski R (2012) Analysis of water adsorption by wood using the Guggenheim-Anderson-de Boer equation. Eur J Wood Prod 70(4):445–451

Cao JZ, Kamdem DP (2004) Moisture adsorption characteristics of copper-ethanolamine (Cu-EA) treated southern yellow pine (*Pinus* spp.). Holzforschung 58(1):32–38

Dieste A, Krause A, Mai C, Militz H (2010) The calculation of EMC for the analysis of wood/water relations in *Fagus sylvatica* L. modified with 1,3-dimethylol-4,5-dihydroxyethyleneurea. Wood Sci Technol 44(4):597–606

Engelund ET, Klamer M, Venas TM (2010) Acquisition of sorption isotherms for modified woods by the use of dynamic vapour sorption instrumentation. Principles and practice. IRG/WP 10-40518

Engelund ET, Klamer M, Venas TM (2011) Adsorption boundary curve influenced by step interval of relative humidity investigated by dynamic vapour sorption equipment. IRG/WP 11-40547

Engelund ET, Thygesen LG, Svensson S, Hill CAS (2013) A critical discussion of the physics of wood-water interactions. Wood Sci Technol 47(1):141–161

Esteban LG, Fernandez FG, Casasus AG, de Palacios P, Gril J (2006) Comparison of the hygroscopic behaviour of 205-year-old and recently cut juvenile wood from *Pinus sylvestris* L. Ann For Sci 63(3):309–317

Esteban LG, de Palacios P, Fernandez FG, Guindeo A, Conde M, Baonza V (2008a) Sorption and thermodynamic properties of juvenile *Pinus sylvestris* L. wood after 103 years of submersion. Holzforschung 62(6):745–751

Esteban LG, de Palacios P, Fernandez FG, Guindeo A, Cano NN (2008b) Sorption and thermodynamic properties of old and new *Pinus sylvestris* wood. Wood Fiber Sci 40(1):111–121

Esteban LG, de Palacios P, Fernandez FG, Martin JA, Genova M, Fernandez-Golfin JI (2009) Sorption and thermodynamic properties of buried juvenile *Pinus sylvestris* L. wood aged 1170 ± 40 BP. Wood Sci Technol 43(7–8):140–151

Esteban LG, de Palacios P, Fernandez FG, Garcia-Amorena I (2010) Effects of burial of *Quercus* spp. wood aged 5910 ± 250 BP on sorption and thermodynamic properties. Int Biodeter Biodegr 64(5):371–377

Esteban LG, Simon C, Fernandez FG, de Palacios P, Martin-Sampedro R, Eugenio ME, Hosseinpourpia R (2015) Juvenile and mature wood of *Abies pinsapo* Boissier: sorption and thermodynamic properties. Wood Sci Technol 49(4):725–738

Fernandez FG, Esteban LG, de Palacios P, Simon C, Garcia-Iruela A, de la Fuente J (2014) Sorption and thermodynamic properties of *Terminalia superba* Engl. and Diels. and *Triplochiton scleroxylon* K. Schum. through the 15, 35 and 50 °C sorption isotherms. Eur J Wood Prod 72(1):99–106

Hartley ID (2000) Application of the Guggenheim-Anderson-de Boer sorption isotherm model to klinki pine (*Araucaria klinkii* Lauterb.). Holzforschung 54(6):661–663

Hill C (2006) Wood modification. Chemical, thermal and other processes. Wiley, Chichester, UK

Hill C, Norton AJ, Newman G (2010) The water vapour sorption properties of sitka spruce determined using a dynamic vapour sorption apparatus. Wood Sci Technol 44(3):497–514

Hill C, Moore J, Jalaludin Z, Leveneu M, Mahrdt E (2011) Influence of earlywood/latewood and ring position upon water vapour sorption properties of sitka spruce. Int Wood Prod J 2(1):12–19

Hill C, Ramsay J, Keating B, Laine K, Rautkari L, Hughes M, Constant B (2012) The water vapour sorption properties of thermally modified and densified wood. J Mater Sci 47(7):3191–3197

Hill CAS, Ramsay J, Gardiner B (2015) Variability in water vapour sorption isotherm in Japanese larch (*Larix kaempferi* Lamb.)—earlywood and latewood influences. Int Wood Prod J 6(2):53–59

Hoffmeyer P, Engelund ET, Thygesen LG (2011) Equilibrium moisture content (EMC) in Norway spruce during the first and second desorptions. Holzforschung 65(6):875–882

Jalaludin Z (2012) The water vapour sorption behaviour of wood. Thesis, Edinburgh Napier University

Jalaludin Z, Hill CAS, Samsi HW, Husain H, Xie Y (2010) Analysis of water vapour sorption of oleo-thermal modified wood of *Acacia mangium* and *Endospermum malaccense* by a parallel exponential kinetics model and according to the Hailwood-Horrobin model. Holzforschung 64(6):763–770

Kelsey KE (1957) The sorption of water vapour by wood. Aust J Appl Sci 8:42–54

Kretschmann DE (2010) Mechanical properties of wood. In: Wood handbook, wood as an engineering material. General Technical Report FPL-GTR-190. US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison. pp 1–46

Lam PS, Sokhansanj S, Bi XT, Lim CJ, Larsson SH (2012) Drying characteristics and equilibrium moisture content of steam-treated Douglas fir (*Pseudotsuga menziesii* L.). Bioresour Technol 116:396–402

Lenth CA, Kamke FA (2001) Equilibrium moisture content of wood in high-temperature pressurized environments. Wood Fiber Sci 33(1):104–118

Lesar B, Gorisek Z, Humar M (2009) Sorption properties of wood impregnated with boron compounds, sodium chloride and glucose. Dry Technol 27(1):94–102

Levoguer CL, Williams DR (1999) The characterisation of pharmaceutical materials by dynamic vapour sorption. Dyn Vapour Sorp Appl Note 101:1–5

Majka J, Olek W (2008) Sorption properties of mature and juvenile lime wood (*Tilia* sp.). Folia Forestalia Polonica B 65–75

Militz H, Busetto D, Hapla F (2003) Investigation on natural durability and sorption properties of Italian chestnut (*Castanea sativa* Mill.) from coppice stands. Holz Roh Werkst 61(2):133–141

Miller JN, Miller JC (2002) Estadística y quimiometría para química analítica. Prentice Hall, Madrid

Murata K, Watanabe Y, Nakano T (2013) Effect of thermal treatment on fracture properties and adsorption properties of spruce wood. Materials 6(9):4186–4197

Neimsuwan T, Wang S, Taylor AM, Rials TG (2008) Statics and kinetics of water vapor sorption of small loblolly pine samples. Wood Sci Technol 42(6):493–506

Olek W, Majka J, Czajkowski L (2013) Sorption isotherms of thermally modified wood. Holzforschung 67(2):183–191

Paes SS, Sun SM, MacNaughtan W, Ibbett R, Ganster J, Foster TJ, Mitchell JR (2010) The glass transition and crystallization of ball milled cellulose. Cellulose 17(4):693–709

Pearson H, Gabbitas B, Ormarsson S (2013) Equilibrium moisture content of radiata pine at elevated temperature and pressure reveals measurement challenges. J Mater Sci 48(1):332–341

Popescu CM, Hill CAS (2013) The water vapour adsorption-desorption behaviour of naturally aged *Tilia cordata* Mill. wood. Polym Degrad Stab 98(9):1804–1813

Popescu CM, Hill CAS, Curling S, Ormondroyd G, Xie YJ (2014) The water vapour sorption behaviour of acetylated birch wood: how acetylation affects the sorption isotherm and accessible hydroxyl content. J Mater Sci 49(5):2362–2371

Popper R, Niemz P, Croptier S (2009) Adsorption and desorption measurements on selected exotic wood species. Analysis with the Hailwood-Horrobin model to describe the sorption hysteresis. Wood Res 54(4):43–55

Rautkari L, Honkanen J, Hill CAS, Ridley-Ellis D, Hughes M (2014) Mechanical and physical properties of thermally modified Scots pine wood in high pressure reactor under saturated steam at 120, 150 and 180 °C. Eur J Wood Prod 72(1):33–41

Robinson RA, Stokes RH (1959) Electrolyte solutions. Academic Press, New York

Siau JF (1995) Wood: influence of moisture on physical properties. Department of Wood Science and Forest Products, Virginia Polytechnic Institute and State University, Blacksburg, VA

Simon C, Esteban LG, de Palacios P, Fernandez FG, Martin-Sampedro R, Eugenio ME (2015) Thermodynamic analysis of water vapour sorption behaviour of juvenile and mature wood of *Abies alba* Mill. J Mater Sci 50(22):7282–7292

Skaar C (1988) Wood-water relations. Springer-Verlag, Berlin

Song KL, Yin YF, Salmen L, Xiao FM, Jiang XM (2014) Changes in the properties of wood cell walls during the transformation from sapwood to heartwood. J Mater Sci 49(4):1734–1742

Stokes RH, Robinson RA (1949) Standard solutions for humidity control at 25 °C. Ind Eng Chem 41:2013

Surface Measurement Systems Ltd. (2012) Moisture sorption of EC standard reference material RM 302 on a DVS instrument. Dynamic Vapour Sorption, Application Note 02

Telkki VV, Yliniemi M, Jokisaari J (2013) Moisture in softwoods: fiber saturation point, hydroxyl site content, and the amount of micropores as determined from NMR relaxation time distributions. Holzforschung 67(3):291–300

Themelin A, Rebollo J, Thibaut A (1997) Method for defining the behaviour of lignocellulosic produces at sorption: application to tropical wood species. In: Hoffmeyer Preben (ed) Proceedings of International Conference on Wood-Water Relations. 16–17 June 1997, Copenhagen, Denmark. pp 17–32

Thygesen LG, Engelund ET, Hoffmeyer P (2010) Water sorption in wood and modified wood at high values of relative humidity. Part I: Results for untreated, acetylated, and furfurylated Norway spruce. Holzforschung 64(3):315–323

Todoruk TM, Hartley ID (2011) Sorption isotherm of lodgepole pine (*Pinus contorta* Dougl. Ex Loud.) pulp chips affected by the mountain pine beetle (*Dendroctonus ponderosae*). Holzforschung 65(1):109–112

Viollaz PE, Rovedo CO (1999) Equilibrium sorption isotherms and thermodynamic properties of starch and gluten. J Food Eng 40(4):287–292

Wexler A, Wildhack WA (1965) Humidity and moisture: measurement and control in science and industry, vol 3. Fundamentals and standards. Reinhold Publishing Corporation, New York

Xie Y, Hill CAS, Xiao Z, Mai C, Militz H (2011) Dynamic water vapour sorption properties of wood treated with glutaraldehyde. Wood Sci Technol 45(1):49–61

Zaihan J, Hill CAS, Curling S, Hashim WS, Hamdan H (2009) Moisture adsorption isotherms of *Acacia mangium* and *Endospermum malaccense* using dynamic vapour sorption. J Trop For Sci 21(3):277–285

Zaihan J, Hill CAS, Hashim WS, Dahlan JM, Sun DY (2011) Analysis of the water vapour sorption isotherms of oil palm trunk and rubberwood. J Trop For Sci 23(1):97–105

Zobel B, Matthias M, Roberds JH, Kellison RC (1968) Moisture content of southern pine trees. Tech Rep No. 37. School For Res NC State Univ Raleigh