Nencho Deliiski[1]

Evaluation of Wood Sorption Models and Creation of Precision Diagrams for the Equilibrium Moisture Content

Ocjena sorpcijskih modela drva i izrada preciznih dijagrama za ravnotežni sadržaj vode u drvu

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ABSTRACT • *Precision has been evaluated of the 10 most often used wood sorption models, available in literature, for the calculation of the equilibrium moisture content of wood given a change in temperature within the range from 0 °C to 200 °C and in the relative humidity of the surrounding air environment from 0% to 100%. Based on the results of the critical analysis, an argumentative selection has been done of the models that can be purposefully used for the computer determination of wood equilibrium moisture content in contemporary systems for model-based or model predictive automatic control of different processes of hydrothermal treatment of wood and wood materials. With the help of these models, diagrams have been created for precise determination of wood equilibrium moisture content. The established high precision of both the Simpson and Ray et al. models and the Garsía model, which we have refined, makes them user friendly for model-based or predictive automatic systems and other engineering applications in the respective temperature ranges specified in the paper.*

Keywords: *wood sorption models, mathematical description, equilibrium moisture content, temperature, relative humidity, model-based control*

SAŽETAK • *U radu se ocjenjuje točnost deset u literaturi najčešće primjenjivanih sorpcijskih modela za izračun ravnotežnog sadržaja vode u drvu za raspon temperature od 0 do 200 ºC i relativne vlažnosti okolnog zraka od 0 do 100%. Na temelju kritičke analize napravljena je selekcija modela koji se mogu upotrijebiti za računalno određivanje ravnotežnog sadržaja vode u drvu u sklopu suvremenih sustava za automatsku kontrolu procesa hidrotermičke obrade drva i drvnih materijala. Uz pomoć odabranih modela napravljeni su dijagrami za prezicno određivanje ravnotežnog sadržaja vode u drvu. Dokazana visoka točnost Simpsonova i Rayeva te Garsíjeva modela, uz napravljene dorade modela, čine te modele jednostavnima za primjenu u automatskim sustavima za upravljanje i druge inženjerske primjene u rasponu temperatura specificiranih u radu.*

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Ključne riječi: *sorpcijski modeli drva, matematički opis, ravnotežni sadržaj vode, temperatura, relativna vlažnost, upravljanje na temelju modela*

1 INTRODUCTION
1. UVOD

In practice the most widely used method for the control of various processes of hydrothermal treatment of wood materials is based on ensuring scientifically based change during the time of wood equilibrium moisture content in a function of temperature t and relative humidity φ of the processing medium. In any combination of values t and φ after a certain time the wood reaches a state of stability and thus its moisture content is constant and it either receives, or emits moisture, i.e. it is in equilibrium with the surrounding environment. This moisture is defined as wood equilibrium moisture content U_{EMC}.

The instructions for exploitation of the systems for automatic control of the processes of convective drying and other kinds of hydrothermal treatment of wood materials, as a rule consist of empirical tables and/or diagrams for the dependency of U_{EMC} on t and φ. The implementation of modern control of technological processes with the help of programmable controllers or computers allows for the determination of U_{EMC} with the help of software. For this purpose, it is necessary to have a precise mathematical description of U_{EMC} depending on t and φ.

The effective control of U_{EMC} can ensure a significant reduction of the duration and specific energy expenses of the processes of hydro-thermal treatment of wood, as well as deviations in the final moisture content in the separated materials, subjected to such treatment.

The aim of the present paper is to analyze the precision of wood sorption models, found in reference literature and most often used, and to provide an argumentative choice of those most suitable for use as mathematical description of U_{EMC} in the systems of model-based and model predictive automatic control of various processes of hydrothermal treatment of wood and wood-composite materials (Deliiski, 2009b; Shubin, 1990; Trebula and Klement, 2002; Videlov, 2003).

2 MATERIAL AND METHODS
2. MATERIJAL I METODE

In the reference literature we found 10 most often used mathematical models of the sorption behavior of wood, with the help of which U_{EMC} can be calculated depending on temperature and relative humidity of the air. Chronologically, these models are published in the following way:

Model 1: Brunauer, Emmett, and Teller (1938);
Model 2: Hailwood and Horrobin (1946) – one hydrate model;
Model 3: Hailwood and Horrobin (1946) – two hydrate model;
Model 4: Malmquist (1958);
Model 5: King (1960);
Model 6: Day and Nelson (1965);
Model 7: Kaplan (1972);
Model 8: Simpson (1991);
Model 9: Garsía (2002);
Model 10: Ray *et al*. (2007).

Vidal and Cloutier (2005) make a relative assessment of the precision of the models 1, 2, 3, 4, 5, 6 and 9 in relation to experimental data published in the literature for U_{EMC} at five different values of relative humidity: 40, 52, 65, 75 and 85% for the temperature ranging between 0 °C and 160 °C. The authors determine, and our calculations also prove, that the models 1, 2 and 5 give the least accuracy. Because of this fact, these models are not evaluated below, and the calculations in the present paper at $0\% \le \varphi \le 100\%$ are limited to assessing the precision of the models 3, 4, 6, 7, 8, 9 and 10 within the range 0 °C $\le t \le$ 100 °C and of the model 3, 4, 6, 7 and 9 within the range 100 °C $\le t \le$ 200 °C. The models 8 and 10 represent regression equations, which indicate the change in U_{EMC} depending on t and φ only within the range from 0 °C to 100 °C and are not applicable in the range100 °C $\le t \le$ 200 °C (Deliiski *et al*, 2009a).

In the equations of the models below φ is labeled as the relative vapor pressure, which is the result of division by 100 so as to get the relative air humidity expressed in percentages. In the models 3, 4 and 6 thermo-dynamical temperature T (in K) is taken into account and in the models 7, 8, 9 and 10 – the temperature t (in °C).

The calculated values of wood equilibrium moisture content U_{EMC} of the models 3, 6, 7, 8 and 10 are expressed with dimension percentages, and in the models 5 (Malmquist, 1958) and 9 (Garsía, 2002) U_{EMC} is expressed in kg·kg^{-1} and in order to express this in percentage terms, the obtained results have to be multiplied by 100.

The models 3, 4, 6, 7, 8, 9 and 10 are presented through the following equations:

Model 3: Hailwood and Horrobin (1946) – two hydrate model

$$U_{\text{EMC}} = \frac{1800}{M_{\text{p}}}\left(\frac{K\varphi}{1-K\varphi} + \frac{K_1K\varphi + 2K_1K_2K^2\varphi^2}{1+K_1K\varphi + K_1K_2K^2\varphi^2}\right) \quad (1)$$

where 1800 is the molecular weight of water x 100, g·mol^{-1}; M_{p} - molecular weight of a polymer unit that forms a hydrate, g·mol^{-1}.

As a result of the parameterization procedure Vidal and Cloutier (2005) deduct the following equations for the calculation of the coefficients on the right side of equation (1):

$$M_{\text{p}} = -330.03 + 2.3468T + 0.00028368T^2, \quad (2)$$

$$K = 0.68405 + 0.00047238T - 3.3289.10^{-8}T^2, \quad (3)$$

$$K_1 = 19.641 - 0.0587818T + 4.05.10^{-5}T^2, \quad (4)$$

$$K_2 = 2.6172 + 0.0016795T - 0.000006414T^2. \quad (5)$$

Model 4: Malmquist (1958)

$$U_{\mathrm{EMC}} = \frac{K_1}{1 + K_2\left(\frac{1}{\varphi} - 1\right)^{\frac{K}{3}}}, \quad (6)$$

where, according to the author

$$K = 2.2885 - 0.0016742T + 2.0637.10^{-6}T^2. \quad (7)$$

$$K_1 = 0.40221 - 0.00009736T - 5.8964.10^{-7}T^2, \quad (8)$$

$$K_2 = 2.6939 + 0.018552T - 2.1825.10T^2. \quad (9)$$

Model 6: Day and Nelson (1965)

$$U_{\mathrm{EMC}} = \frac{K_1}{1 + K_2\left(\frac{1}{\varphi} - 1\right)^{\frac{K}{3}}}, \quad (10)$$

where K_1, K_2, K_3, K_4 are constants, for which Avramidis (1989) has determined the following values:

$K_1 = -3.4.10^{-17}$; $K_2 = 9.98$; $K_3 = 300$ and $K_4 = -0.93$.

Model 7: Kaplan (1972)

$$U_{\mathrm{EMC}} = 10{,}6^{\varphi}(3.27 - 0.015t), \quad (11)$$

Model 8: Simpson (1991)

$$U_{\mathrm{EMC}} = \frac{1800}{M_{\mathrm{p}}}\left(\frac{K_1\varphi}{1 - K_1\varphi} + \frac{K_2K_1\varphi + 2K_3K_2K_1^2\varphi^2}{1 + K_2K_1\varphi + K_3K_2K_1^2\varphi^2}\right) \quad (12)$$

where, according to the author:

$$M_{\mathrm{p}} = 349 + 1.29t + 1.35.10^{-2}t^2, \quad (13)$$

$$K_1 = 0.805 + 7.36.10^{-4}t - 2.73.10^{-6}t^2, \quad (14)$$

$$K_2 = 6.27 - 9.38.10^{-3}t - 3.03.10^{-4}t^2, \quad (15)$$

$$K_3 = 1.91 + 4.07.10^{-2}t - 2.93.10^{-4}t^2. \quad (16)$$

Model 9: Garsía (2002)

$$U_{\mathrm{EMC}} = K\left[\left(\frac{K_5}{\varphi}\right)^{K_7} - 1\right]^{-\frac{1}{K_6}}, \quad (17)$$

where, according to the author:

$$K = K_1 \exp\left[-\left(\frac{t + K_2}{K_3}\right)^{K_4}\right], \quad (18)$$

$K_1 = 1865.75.10^{-4}$; $K_2 = 1025$; $K_3 = 1163.31$; $K_4 = 12.7441$; $K_5 = 1.09603$; $K_6 = 2.36069$ and $K_7 = 1.84447$.

Model 10: Ray et al. (2007)

In 2007 Ray et al. (2007) published their results of research on the precision of the calculation of U_{EMC} with the help of the Simpson model, i.e. using the equations (12) ÷ (16). They came to the conclusion that the average square error, when determining U_{EMC} by these equations in the range 0 °C ≤ t ≤ 44 °C, is equal to ±0.5%, but in the range 44 °C < t ≤ 100 °C it increases to ±1.5%.

This inspired the authors to propose their regression equation for the computation of U_{EMC} depending on φ and t in the range 44 °C < t ≤ 100 °C. Ray *et al* (2007) present the equation for the determination of U_{EMC} depending on φ and on temperature t expressed in degrees Fahrenheit. After substituting t in the known relation from degrees Fahrenheit to degrees Celsius, namely: t[°F] = 1,8t [°C]+32 , we obtained the following equation for determining U_{EMC} for the range 0% ≤ φ ≤ 100% and 44 °C < t ≤ 100 °C:

$$U_{\mathrm{EMC}} = \begin{pmatrix} 7.30548 + 11.64339\varphi_{\mathrm{c}} - 0.00792t_{\mathrm{c}} \\ -0.37436K_1 - 0.39562K_3 + 0.06902K_2^2 \\ +0.00518K_3^2 + 0.00129K_1K_4 \\ -0.00048153K_2K_4 + 0.61135K_5 \end{pmatrix}^2 \quad (19)$$

where:

$$K_1 = 0.0001 + 0.0025t_{\mathrm{c}} + 0.0007t_{\mathrm{c}}^2, \quad (20)$$

$$K_2 = 0.2 + 0.06t_{\mathrm{c}} - 0.00004t_{\mathrm{c}}^2, \quad (21)$$

$$K_3 = 14.0 + 35.5\varphi_{\mathrm{c}} + 20.7\varphi_{\mathrm{c}}^2, \quad (22)$$

$$K_4 = 1.0 + 0.01\varphi_{\mathrm{c}}t_{\mathrm{c}} + 0.1\varphi_{\mathrm{c}}^2t_{\mathrm{c}}^2, \quad (23)$$

$$K_5 = \frac{1 + K_2 + K_3}{K_1^2 + K_3^2}, \quad (24)$$

$t_{\mathrm{c}} = 1.8t - 125.5$ - centered (named by the authors) value of t, °C (Ray *et al*, 2007),
$\varphi_{\mathrm{c}} = \varphi - 0.58537037$ - centered value of φ, (Ray *et al*, 2007).

The authors (Ray *et al*, 2007) prove that the error of the results obtained from the equations (19) ÷ (24), for the ranges 0% ≤ φ ≤ 100% and 44 °C < t ≤ 100 °C, is smaller by 44% than the error of the results obtained from the equations (12) ÷ (16).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

For the solution of the models 3, 4, 6, 7, 8, 9 and 10, which include the equations (1) ÷ (24), we created a program in the computing environment of VISUAL FORTRAN PROFESSIONAL supported by Windows.

With the help of the program, we calculated the values of U_{EMC} when t changes from 0 °C to 200 °C in steps of 0.1 °C and φ from 0% to 100% in steps of 0.1%. The results are compared with the corresponding experimental data from the literature (FPL 1999) and (Kubojima *et al*, 2003) related to the change of U_{EMC} depending on t and φ (Table 1, 2 and 3).

During the analysis of the results obtained, we did not take into consideration the sorption hysteresis, possible variations of the sorption isotherms due to different species of wood used for the determination of the sorption isotherms taken from the literature, and variations due to internal structures such as heartwood and sapwood (Ball *et al*, 2001; Pervan, 2000).

As the experimental data in FPL (1999) are temperatures expressed in degrees Fahrenheit, in the very first column of both Table 1 and 2, the values of t are given in degrees Celsius, which were assigned to t during the experiments. Since the experiments are conducted using different values of φ, not always corresponding to φ values in Table 1, 2 and 3, in the very last column of the tables the exact experimental values of U_{EMC} (when the experimental and computed values of φ coincide) are not marked with an asterix sign (*), while the interpolated experimental values of U_{EMC} (when the experimental and computed values of φ do not coincide) are shown with an asterix sign (*).

3.1 Change of U_{EMC} in the range $0 \le t \le 100$ °C
3.1. Promjena U_{EMC} u rasponu temperature $0 \le t \le 100$ °C

The computed values of U_{EMC} according to the models 3, 4, 6, 7, 8, 9 and 10 and their corresponding experimental values from FPL (1999) are given in Table 1 (for the range $0\% \le \varphi \le 50\%$) and in Table 2 (for the range $60\% \le \varphi \le 94\%$).

The analysis of the data from Table 1 and 2, and also of the others not given in these tables, shows that the experimentally established change in U_{EMC} depending on φ is described most accurately by the Simpson model within the range 0 °C ≤ t ≤ 50 °C and by the model of Ray et al. within the range 50 °C < t ≤ 100 °C. The absolute error of U_{EMC}, which is obtained from these models in the given temperature ranges, is within the limits of ±0.4% at $0\% \le \varphi \le 50\%$ and ±0.7% at 60% ≤ φ φ ≤ 94%. Figure 1 shows the isotherms of U_{EMC} derived using these two models when t = 0, 20, 40, 60, 80 and 100 °C with the change of φ from 0 to 100%.

The next most accurate model is that of Garsía with the absolute error within the limits of ± 0.7% at $0\% \le \varphi \le 50\%$ and 0.9% at $60\% \le \varphi \le 94\%$. The models of Hailwood and Horrobin–2 and of Malmquist give very close results with the absolute error within the limits of ±0.7% at $0\% \le \varphi \le 50\%$ and ±1.2% at $60\% \le \varphi \le 94\%$. The biggest inaccuracy is observed in the models of Day & Nelson and of Kaplan – they give the results of U_{EMC} higher than the experimental ones within the limits of 3.3%.

It should be noted that all of the examined models reflect very well the complicated character of change in U_{EMC} depending on t and φ as shown in Fig. 1. The indicated limits of change of the absolute error in determining U_{EMC} based on all the models refer to the relatively high values of φ. With smaller values of φ, the absolute error, as a rule, significantly decreases. Only for Kaplan's model the opposite dependency can be observed – the more the value of φ decreases, the more the absolute error increases and reaches +3.3% at t = 0 °C and φ = 0%.

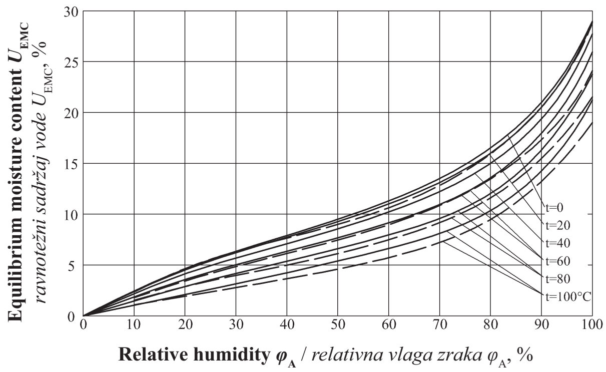

Figure 1 Isotherms of the change of U_{EMC} calculated based on the Simpson model (full lines), and based on a combination of both Simpson model – at t = 0, 20 and 40 °C and Ray *et al.* model – at t = 60, 80 and 100 °C (dotted lines)
Slika 1. Izoterme promjene ravnotežnog sadržaja vode izračunane na temelju Simpsonova modela (pune linije), i na temelju kombinacije Simpsonova modela za temperature t = 0, 20 i 40 °C te Rayeva modela za temperature t = 60, 80 i 100 °C (iscrtkane linije)

Figure 2 shows a precise diagram of the change of U_{EMC} depending on φ and t within the range 0% ≤ φ ≤ 100% and 0 °C < t ≤ 100 °C. The diagram curves are built based on the results obtained by the Simpson model at 0 °C ≤ t ≤ 50 °C, and with the help of Ray *et al*. model when 50 °C < t ≤ 100 °C. This diagram shows the experimentally established relations of U_{EMC} depending on t and φ with a higher precision in comparison with analogous diagrams, usually referred to in the literature (Shubin, 1990; Trebula and Klement, 2002; Videlov, 2003).

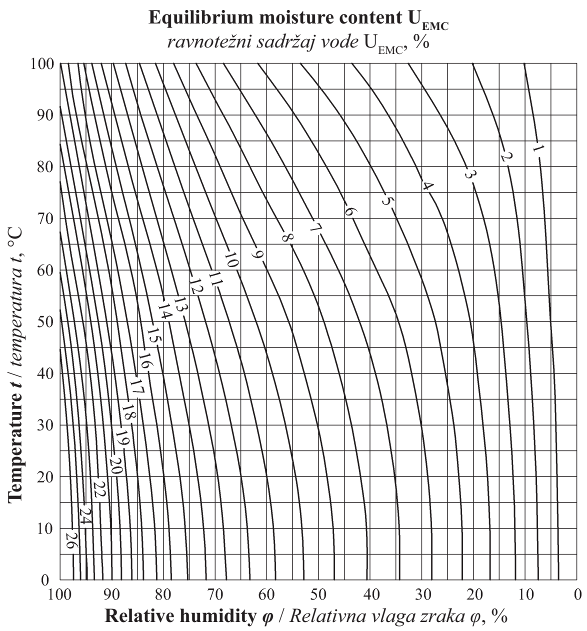

Figure 2 Change in U_{EMC} depending on φ and t, calculated according to the Simpson model at 0 °C ≤ t ≤ 50 °C and according the Ray et al. model at 50 °C < t ≤ 100 °C
Slika 2. Promjene ravnotežnog sadržaja vode u ovisnosti o temperaturi i vlažnosti zraka, izračunane na temelju Simpsonova modela za temperature 0 °C ≤ t ≤ 50 °C i Rayeva modela za temperature 50 °C < t ≤ 100 °C

Table 1 Change of the calculated and their corresponding experimentally established values of U_{EMC} depending on t and φ within the range $0 \leq t \leq 100$ °C and $0 \leq \varphi \leq 50\%$

Tablica 1. Razlike između izračunane i odgovarajuće eksperimentalno dobivene vrijednosti ravnotežnog sadržaja vode u ovisnosti o temperaturi i vlažnosti zraka u rasponu $0 \leq t \leq 100$ °C i $0 \leq \varphi \leq 50$ %

Temperature *Temperatura* t, °C	**Computed values of U_{EMC}, %** / *Izračunana vrijednost U_{EMC}, %*							**Experimental values** *Eksperimentalna vrijednost U_{EMC}, %*
	H & H-2 (1946)	M (1958)	D & N (1965)	K (1972)	S (1991)	G (2002)	R *et al.* (2007)	
	Relative air humidity φ = 0% / *Relativna vlažnost zraka φ = 0 %*							
0	0.0	0.0	0.0	3.27	0.0	0.0	126.2	0.0
25	0.0	0.0	0.0	2.89	0.0	0.0	7.23	0.0
50	0.0	0.0	0.0	2.52	0.0	0.0	0.02	0.0
100	0.0	0.0	0.0	1.77	0.0	0.0	0.33	0.0
Relative air humidity φ = 10% / *Relativna vlažnost zraka φ = 10 %*								
15.6	2.6	2.8	3.2	3.8	2.5	2.3	19.0	2.5*
26.7	2.3	2.6	2.8	3.6	2.4	2.2	7.0	2.4
35.0	2.1	2.4	2.6	3.5	2.3	2.1	3.6	2.3
48.9	1.9	2.2	2.3	3.2	2.1	2.0	2.1	2.3
65.6	1.6	2.0	1.9	2.9	1.8	1.9	2.6	2.2*
Relative air humidity φ = 20% / *Relativna vlažnost zraka φ = 20 %*								
26.7	4.2	4.2	4.7	4.6	4.4	3.8	8.0	4.5
35.0	3.9	4.0	4.4	4.4	4.2	3.7	5.5	4.0
46.1	3.6	3.7	4.0	4.1	4.0	3.6	4.0	3.9
60.0	3.2	3.4	3.5	3.8	3.6	3.3	3.4	3.5*
71.1	3.0	3.2	3.1	3.5	3.2	3.2	3.1	3.1*
Relative air humidity φ = 30% / *Relativna vlažnost zraka φ = 30 %*								
29.4	5.7	5.6	6.3	5.7	6.0	5.3	8.1	6.0
35.0	5.5	5.4	6.1	5.6	5.9	5.2	7.0	5.7
43.3	5.2	5.1	5.7	5.3	5.6	5.0	5.9	5.4
60.0	4.6	4.6	4.9	4.8	5.0	4.7	4.8	4.8
87.8	3.8	3.9	3.8	4.0	3.8	4.0	3.4	3.3
Relative air humidity φ = 40% / *Relativna vlažnost zraka φ = 40 %*								
35.0	6.9	6.8	7.8	7.1	7.3	6.7	8.2	7.2*
43.3	6.5	6.4	7.3	6.7	7.0	6.5	7.3	6.8
48.9	6.3	6.2	7.0	6.5	6.8	6.4	6.8	6.6
60.0	5.9	5.8	6.4	6.1	6.3	6.0	6.1	6.0
82.2	5.1	5.1	5.3	5.2	5.2	5.3	4.8	4.8
Relative air humidity φ = 50% / *Relativna vlažnost zraka φ = 50 %*								
40.6	8.0	8.0	9.2	8.7	8.6	8.2	9.0	8.7
46.1	7.8	7.8	8.9	8.4	8.3	8.0	8.5	8.2
60.0	7.2	7.2	8.0	7.7	7.7	7.5	7.5	7.5*
82.2	6.3	6.3	6.8	6.6	6.5	6.6	6.0	6.0
98.9	5.8	5.8	5.9	5.8	5.4	5.8	4.7	5.1

3.2 Change of U_{EMC} within the range $100 \leq t \leq 200$ °C

3.2. Promjene U_{EMC} u rasponu temperatura $100 \leq t \leq 200$ °C

The values of U_{EMC} calculated using the models 3, 4, 6, 7 and 9 and their corresponding experimental values from FPL (1999) and Kubojima *et al*. (2003) are given in Table 3 within the range 100 °C ≤ t ≤ 150 °C and 10% ≤ φ ≤ 85%.

The comparison of the calculated and experimental results, partly presented in Table 3, shows that the experimentally established change of U_{EMC} depending on t and φ is most accurately described by the Garsía model. Fig. 3 shows the isotherms of U_{EMC} built using this model when t = 100, 120, 140, 160, 180 and 200 °C with the change of φ ranging from 0% to 100%.

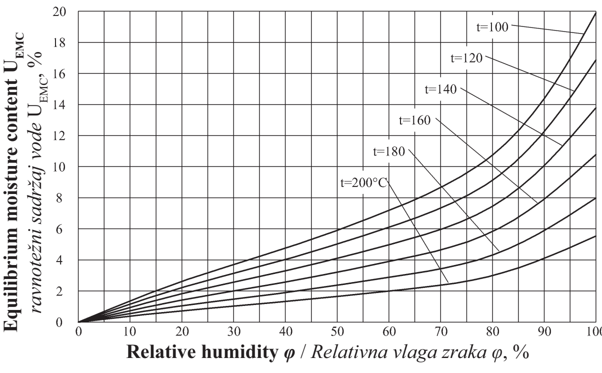

Figure 3 Change in U_{EMC} depending on φ and t, calculated based on Garsía model

Slika 3. Promjene ravnotežnog sadržaja vode u ovisnosti o temperaturi i vlažnosti zraka, izračunane na temelju Garsíjeva modela za temperature 0 °C ≤ t ≤ 50 °C

Table 2 Change of the calculated values and their corresponding experimentally established values of U_{EMC} depending on t and φ within the ranges $0 \le t \le 100$°C and $60 \le \varphi \le 94$%
Tablica 2. Razlike između izračunane i odgovarajuće eksperimentalno dobivene vrijednosti ravnotežnog sadržaja vode u ovisnosti o temperaturi i vlažnosti zraka u rasponu $0 \le t \le 100$ °C i $60 \le \varphi \le 94$ %

Temperature *Temperatura* t, °C	**Computed values of U_{EMC}, %** / *Izračunana vrijednost U_{EMC}, %*							**Experimental values** *Eksperimentalna vrijednost U_{EMC}, %*
	H & H-2 (1946)	M (1958)	D & N (1965)	K (1972)	S (1991)	G (2002)	R *et al.* (2007)	
	Relative air humidity φ = 60% / *Relativna vlažnost zraka φ = 60 %*							
12.8	11.5	11.4	13.1	12.7	11.2	10.9	14.5	11.0
40.6	9.6	9.7	11.2	11.0	10.2	10.0	10.6	10.3
54.4	8.9	9.0	10.3	10.1	9.5	9.4	9.4	9.4
71.1	8.1	8.2	9.1	9.1	8.5	8.6	8.1	8.2
87.8	7.4	7.5	8.0	8.0	7.5	7.8	6.8	7.0
98.9	7.0	7.1	7.4	7.4	6.7	7.2	5.9	6.3
110.0	6.7	6.7	6.7	6.7	5.8	6.6	4.7	5.7
Relative air humidity φ = 70% / *Relativna vlažnost zraka φ = 70 %*								
12.8	13.7	13.6	15.6	16.1	13.4	13.3	18.3	13.4
37.8	11.7	11.9	13.8	14.1	12.3	12.2	13.0	12.4
43.3	11.4	11.6	13.4	13.7	12.0	12.0	12.4	12.0
51.7	10.9	11.1	12.7	13.0	11.5	11.6	11.5	11.5
65.6	10.1	10.3	11.7	11.9	10.6	10.8	10.3	10.3
82.2	9.4	9.5	10.4	10.6	9.5	9.8	9.0	9.0
98.9	8.7	8.8	9.2	9.3	8.3	8.8	7.4	8.0
Relative air humidity φ = 80% / *Relativna vlažnost zraka φ = 80 %*								
10.0	17.0	16.8	19.0	20.6	16.4	16.6	28.0	16.3
37.8	14.4	14.6	16.9	17.9	15.1	15.0	16.3	15.0
48.9	13.6	13.9	15.9	16.8	14.4	14.4	14.6	14.1
65.6	12.6	12.8	14.5	15.1	13.1	13.3	12.9	13.0
87.8	11.5	11.6	12.6	12.9	11.4	11.7	10.8	10.9
98.9	11.0	11.0	11.7	11.8	10.4	10.8	9.6	10.3*
101.7	10.9	10.9	11.5	11.5	10.2	10.6	9.3	9.8
Relative air humidity φ = 90% / *Relativna vlažnost zraka φ = 90 %*								
43.3	18.2	18.4	21.1	21.9	19.1	18.9	20.1	19.0
51.7	17.6	17.8	20.3	20.9	18.4	18.2	18.6	18.3*
65.6	16.6	16.8	19.0	19.1	17.2	17.1	17.0	16.6
87.8	15.3	15.4	16.8	16.4	15.1	15.0	14.5	14.2
98.9	14.8	14.7	15.7	15.0	14.0	13.9	13.2	13.8
101.7	14.7	14.5	15.4	14.6	13.7	13.6	12.9	13.5
Relative air humidity φ = 94% / *Relativna vlažnost zraka φ = 94 %*								
48.9	20.3	20.6	23.8	23.3	21.2	20.9	21.4	21.3
54.4	19.9	20.2	23.2	22.6	20.7	20.4	20.5	21.0
82.2	18.0	18.3	20.3	18.7	18.0	17.6	17.2	17.3
87.8	17.8	17.9	19.7	18.0	17.4	17.0	16.5	16.9
92.3	17.5	17.6	19.2	17.4	17.0	16.5	16.0	16.4
98.9	17.2	17.2	18.5	16.4	16.2	15.7	15.3	16.0

In the contemporary model-based and model predictive systems for automatic control of high temperature processes for wood hydrothermal treatment (e.g. veneer drying), it is required to compute continuously the set values of U_{EMC} in the temperature range from 0 °C to 200 °C. For ensuring this requirement, the evaluation of the validity of the models has been extrapolated to 200°C in Fig. 3.

The comparison of the results calculated based on the Garsía model at t = 100 °C as shown in Table 3, with the precisely analogous results in Fig. 2 having the same temperature obtained based on the Ray *et al*. model, show that the Garsía model gives higher values of U_{EMC} within the whole range of change of φ. Table 3 clearly shows that the calculated values of U_{EMC} based on the Garsía model are higher than their corresponding values of U_{EMC} in all the examined values of $t \ge 100$ °C.

In order to increase the precision of the Garsía model and for a better qualitative and quantitative coordination of the calculated values of U_{EMC} when $t \ge 100$ °C with the values of U_{EMC} based on the Ray *et al*. model within the range 50 °C < $t \le 100$ °C, we suggest adding a power coefficient of 1.33 to the denominator on the right side of the equation (17). Then the equation (17) becomes:

$$U_{EMC} = K\left[\left(\frac{K_5}{\varphi^{1.33}}\right)^{K_7} - 1\right]^{-\frac{1}{K_6}} \tag{25}$$

Table 3 Change of the calculated values and their corresponding experimentally established values of U_{EMC} depending on t and φ within the range 100 °C ≤ t ≤ 150 °C and 0% ≤ φ ≤ 85%
Tablica 3. Razlike između izračunane i odgovarajuće eksperimentalno dobivene vrijednosti ravnotežnog sadržaja vode u ovisnosti o temperaturi i vlažnosti zraka u rasponu 100 °C ≤ t ≤ 150 °C i 0% ≤ φ ≤ 85%

Temperature *Temperatura* t, °C	**Computed values of U_{EMC}, %** / *Izračunana vrijednost U_{EMC}, %*						**Experimental values** *Eksperimentalna vrijednost U_{EMC}, %*
	Hailwood& Horrobin-2 (1946	Malmquist (1958)	Day&Nelson (1965)	Kaplan (1972)	Garsía (2002)	Garsía-Deliiski	
Relative air humidity φ = 10% / *Relativna vlažnost zraka φ = 10 %*							
100	1.21	1.63	1.23	2.24	1.50	0.83	1.0*
110	1.10	1.54	1.09	2.05	1.39	0.77	0.9*
120	1.01	1.45	0.95	1.86	1.28	0.70	0.8*
130	0.92	1.37	0.83	1.67	1.16	0.64	-
140	0.83	1.30	0.73	1.48	1.04	0.57	-
150	0.75	1.22	0.63	1.29	0.93	0.51	-
Relative air humidity φ = 20% / *Relativna vlažnost zraka φ = 20 %*							
100	2.4	2.7	2.3	2.8	2.6	1.7	2.3*
110	2.2	2.5	2.1	2.6	2.4	1.6	2.0*
120	2.1	2.4	1.8	2.4	2.2	1.4	1.7*
130	1.9	2.2	1.6	2.1	2.0	1.3	1.5*
140	1.7	2.1	1.4	1.9	1.8	1.2	-
150	1.6	2.0	1.3	1.6	1.6	1.1	-
Relative air humidity φ = 40% / *Relativna vlažnost zraka φ = 40 %*							
100	4.6	4.7	4.5	4.5	4.8	3.6	4.2*
110	4.3	4.4	4.1	4.2	4.4	3.4	3.6*
120	4.1	4.2	3.7	3.8	4.0	3.1	3.2*
130	3.8	4.0	3.4	3.4	3.7	2.8	2.9*
140	3.6	3.7	3.0	3.0	3.3	2.5	-
150	3.4	3.5	2.7	2.6	2.9	2.2	-
Relative air humidity φ = 60% / *Relativna vlažnost zraka φ = 60 %*							
100	7.0	7.1	7.3	7.3	7.2	6.0	6.3*
110	6.7	6.7	6.7	6.7	6.7	5.5	5.7*
120	6.4	6.4	6.2	6.1	6.1	5.1	-
130	6.1	6.1	5.6	5.4	5.5	4.6	-
140	5.8	5.8	5.1	4.8	5.0	4.1	-
150	5.5	5.5	4.7	4.2	4.4	3.7	-
Relative air humidity φ = 85% / *Relativna vlažnost zraka φ = 85 %*							
100	12.6	12.5	13.3	13.2	12.1	10.9	11.7*
110	12.1	12.0	12.4	12.1	11.2	10.1	9.9
120	11.7	11.5	11.5	10.9	10.3	9.2	7.8
125	11.5	11.2	11.1	11.5	9.8	8.8	7.5
130	11.3	11.0	10.7	9.8	9.3	8.4	6.9
135	11.2	10.7	10.3	9.3	8.8	8.0	5.9
140	11.0	10.5	9.9	8.7	8.4	7.5	5.2
145	10.8	10.3	9.5	8.1	7.9	7.1	4.5
150	10.7	10.1	9.1	7.6	7.5	6.7	4.4

The column before the last one in Table 3 presents the obtained results of the change of U_{EMC} based on the so-called Garsía–Deliiski model, which consists of both equations (25) and (18). The comparison of these results with the experimental data, presented on the right in Table 3, shows a significant reduction of the absolute errors of U_{EMC} when U_{EMC} is calculated according to the absolute errors obtained by Garsía model (17) and (18).

Fig. 4 shows isotherms of the change of U_{EMC}, with full lines, obtained based on the Garsía model, and their analogues, calculated based on the Garsía-Deliiski model, shown with dotted lines. In the present paper the proposed Garsía-Deliiski model, which consists of equation (25) and (18), precisely reflects qualitatively and quantitatively the relation of U_{EMC} depending on φ and t within the range from 100 °C to 200 °C. A future clarification of this model should be made when having extensive experimental data for the change in U_{EMC} depending on t and φ within this temperature range.

Fig. 5 shows for the first time the summarized diagram of the change in U_{EMC} depending on φ and t within the range 0% ≤ φ ≤ 100% and 0 °C < t ≤ 200 °C. The curves are built based on the results obtained by the Simpson model at temperatures 0 °C ≤ t ≤ 50 °C, by the Ray *et al*. model at 50 °C < t ≤ 100 °C and by the Garsía-Deliiski model at 100 °C < t ≤ 200 °C.

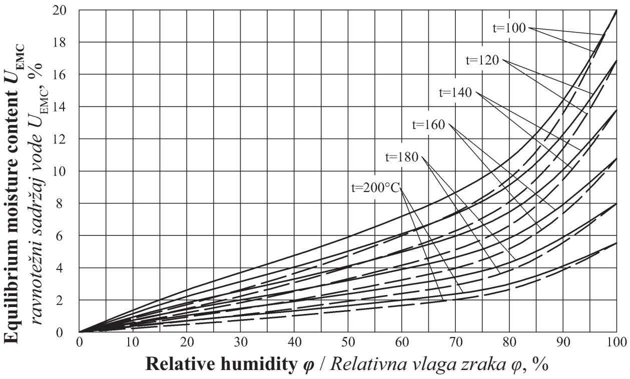

Figure 4 Change in U_{EMC} depending on both φ and t, calculated using the Garsía model – full lines, and using the Garsía-Deliiski model - dotted lines

Slika 4. Promjene ravnotežnog sadržaja vode u ovisnosti o temperaturi i vlažnosti zraka, izračunane na temelju Garsíjeva modela (pune linije) i Garsía-Deliiskijeva modela (iscrtkane linije)

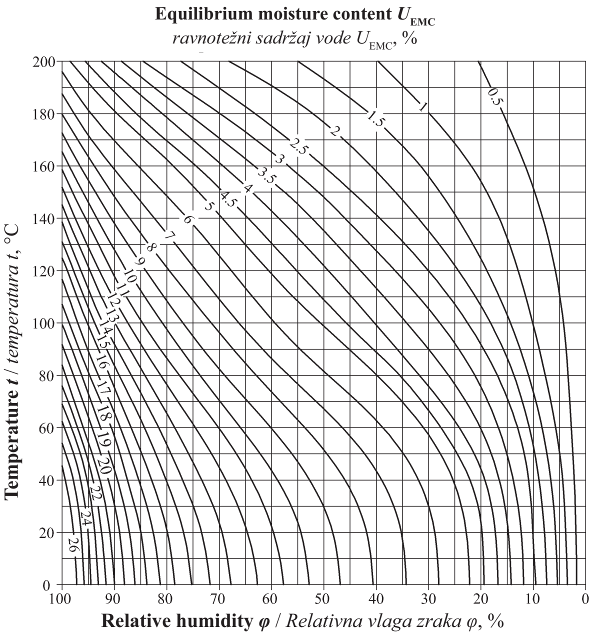

Figure 5 Change in U_{EMC} depending on φ and t, calculated by the Simpson model at 0 °C ≤ t ≤ 50 °C, by the Ray *et al*. model at 50 °C < t ≤ 100 °C and by the Garsía-Deliiski model at 100 °C < t ≤ 200 °C

Slika 5. Promjene ravnotežnog sadržaja vode u ovisnosti o temperaturi i vlažnosti zraka, izračunane na temelju Simpsonova modela za temperature 0 °C ≤ t ≤ 50 °C, Rayeva modela za temperature 50 °C < t ≤ 100 °C i Garsía-Deliiskijeva modela za temperature 100 °C < t ≤ 200 °C

4 CONCLUSIONS
4. ZAKLJUČCI

The present paper describes the evaluation of the precision of the 10 most often used wood sorption models, available in the literature, for the calculation of wood equilibrium moisture content U_{EMC} given a change in temperature within the range from 0 °C to 200 °C and in relative humidity φ of the surrounding air environment from 0% to 100%. The calculated results were compared to corresponding precise experimental data from the literature.

The obtained results show that the Simpson model gave the best fit to experimental data for the range 0 °C ≤ t ≤ 50 °C. The best precision within the range 50 °C < t ≤ 100 °C was provided by the Ray *et al*. model and within the range 100 °C < t ≤ 150 °C by the Garsía model.

In order to increase the precision of the Garsía model and for better qualitative and quantitative coordination of the calculated values, with the help of U_{EMC} at t ≥ 100 °C, with values of U_{EMC} based on the Ray *et al*. model within the range 50 °C < t ≤ 100 °C, we suggest the clarification of the Garsía model. The clarification means introduction of a power coefficient, equaling 1.33, to the denominator on the right side of the equation of the Garsía model.

With the results calculated from the Simpson and Ray et al. models, a diagram has been built for the change in U_{EMC} depending on φ and t within the ranges 0% ≤ φ ≤ 100% and 0 °C ≤ t ≤ 100 °C. This diagram reflects the experimentally established dependency of U_{EMC} on φ and t with better precision in comparison to analogous diagrams, usually found in the literature.

Using the results obtained by both the Simpson and Ray et al. models and the Garsía model, which we have refined, a summary diagram of the change in U_{EMC}, depending on φ and t within the range 0% ≤ φ ≤ 100% and 0 °C ≤ t ≤ 200 °C, has been created for the first time. This diagram can be used for the precise determination of U_{EMC} when having different temperature-humidity impacts on the wood.

The established high precision of both the Simpson and Ray et al. models and the Garsía model, which we have refined, makes them user friendly for contemporary systems for model-based and model predictive automatic control (Hadjiyski, 2003) of different processes of hydrothermal treatment of wood and wood materials. This way, for example, we have input the Simpson model into the software of the microprocessor programmable controller in order to control the temperature conditioning process of dried lumber (Fig. 6).

The long use of the implemented automated installation in the conditioning storage house (Deliiski, 2009b) confirmed completely the validity of the calculating and controlling algorithm used in the controller. It proved its high energy efficiency, reliable functioning and suitability to assure the temperature-humidity parameters of the air, corresponding completely to the U_{EMC} of the wood, required by the user.

5 REFERENCES
5. LITERATURA

1. Avramidis, S., 1989: Evaluation of “three-variable” models for the prediction of equilibrium moisture content wood. Wood Sci. Technol. 23: 251-258, http://dx.doi.org/10.1007/BF00367738
2. Ball, R.D.; Simpson, G.; Pang, S., 2001: Measurement, modelling and prediction of equilibrium moisture content in Pinus radiata heartwood and sapwood. Holz als Roh- und Werkstoff 59(6): 457-462, http://dx.doi.org/10.1007/s001070100242

Figure 6 Automated storage house for dried wood materials (on the left) and programmable controller for automatic computation and model-based control of its conditioning process (on the right)
Slika 6. Automatizirano skladište osušenoga drvnog materijala (lijevo) i programabilni kontroler za automatsko izračunavanje parametara i na modelu utemeljeno upravljanje procesom kondicioniranja u skladištu

3. Brunauer, S.; Emmett, P.H.; Teller, E., 1938: Adsorption of gases in multi molecular layers. J. Am.Chem. Soc. 60: 309-319, http://dx.doi.org/10.1021/ja01269a023
4. Day, D. L.; Nelson, G. L., 1965: Desorption isotherms for wheat. Trans. of the ASAE. 8: 293-297.
5. Deliiski, N. 2009a: Mathematical description of the equilibrium moisture content of the wood. International scientific conference “Automatic & Informatics”, Sofia, IV-33-36 (in Bulgarian).
6. Deliiski, N., 2009b: Model based control of storage house for conditioning of dried wood materials. Automatic & Informatics, 43 (1): 37-40 (in Bulgarian).
7. FPL. 1999: Wood Handbook. Chapter 3: Physical properties and moisture relations of wood. Forest Products Laboratory, Madison, United States, 463 p.
8. Garsía, P., 2002: Three-dimensional heat and mass transfer during oriented strand board hot-pressing. Ph.D. Thesis. University of British Columbia, Canada. 254 p.
9. Hadjiyski, M., 2003: Mathematical Models in Advanced Technological Control Systems. Automatic & Informatics, 37, (3): 7-12 (in Bulgarian).
10. Hailwood, A. J.; Horrobin, S., 1946: Absorption of water by polymers: Analysis in terms of a simple model. Trans. Faraday Soc. 42B: 84-102, http://dx.doi.org/10.1039/tf946420b084
11. Kaplan, V. Y., 1972: Investigation of the convective drying process of the wood. PhD. Thesis. Minsk, 155 p. (in Russian).
12. King, G., 1960: Theories of multi-layer adsorption. In J.W.S. Hearle and R. H. Peters, eds., Moisture in textiles. Textile Book Publ. Inst., Inc., New York, 203 p.
13. Kubojima, Y.; Suzuki, Y.; Tonosaki, M.; Ishikawa, A., 2003: Moisture content of green wood in high temperature water vapor. Holzforshung 57(6): 634-638, http://dx.doi.org/10.1515/HF.2003.095
14. Malmquist, L., 1958: Sorption a deformation of space. Svenska Träforskningsinstitutet. Träteknik. Meddelande. 983, Stockholm.
15. Pervan, S., 2000: Priručnik za tehničko sušenje drva. Sand, Zagreb.
16. Ray, Ch. D., et al, 2007: Identification on the Relationship between Equilibrium Moisture Content, Dry Bulb Temperature, and Relative Humidity Using Regression Analysis. Wood and Fiber Science, 39(2): 299-306.
17. Simpson, W. T. (ed.), 1991: Dry Kiln Operator’s Manual. Agricultural Handbook No.188, United States Department of Agriculture, Madison, WI, 274 p.
18. Shubin, G. S., 1990: Drying and Thermal Treatment of Wood, Publishing Company “Lesnaya promyshlennost”, Moskow, URSS (in Russian).
19. Trebula, P.; Klement, I., 2002: Drying and Thermal Treatment of Wood. TU Zvolen, Slovakia (in Slovakian).
20. Vidal, M.; Cloutier, A., 2005. Evaluation of wood sorption models for high temperatures. Clencia y tecnología 7 (2) 63: 145-158.
21. Videlov, H. 2003: Drying and Thermal Treatment of Wood. Publishing House of the LTU, Sofia, 335 p. (in Bulgarian).

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