Modelling of Drying Curves of Spruce, Beech, Willow and Alder Particles

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ABSTRACT • Drying behaviour of spruce (Picea abies (L.) H. Karst.), beech (Fagus sylvatica L.), willow (Salix alba L.), and alder (Alnus glutinosa (L.) Gaertn.) particles was investigated in a convective dryer at constant air velocity of 0.01 m/s and at the drying air temperature of 25, 60, 80, and 130 °C. The results of the experiments have shown that the wood species and drying air temperature influence the drying behaviour. The experimental drying data of wood particles obtained were fitted to six empirical models. The effects of wood species and drying air temperature on the drying model parameters were determined. The accuracy of the models was measured using the determination coefficient (R²), root mean square error (RMSE), and reduced chi-square (χ²). The results showed that Lewis model, Henderson and Pabis model, and modified Page model, with the model parameters determined taking into account the effect of wood species and of drying air temperature, were found to satisfactorily describe the drying curves of spruce, beech, willow, and alder particles.

Key words: wood species, particles, drying kinetics, drying temperature, modelling

SAŽETAK • U radu su prikazani rezultati istraživanja procesa sušenja iverja od drva smreke (Picea abies (L.) H. Karst.), bukve (Fagus sylvatica L.), vrbe (Salix alba L.) i johe (Alnus glutinosa (L.) Gaertn.) u konvekcijskoj sušionici pri konstantnoj brzini zraka od 0,01 m/s i pri temperaturi zraka 25, 60, 80 i 150 °C. Rezultati pokusa pokazali su da vrsta drva i temperatura zraka utječu na tijek procesa sušenja drvnog iverja. Podaci dobiveni sušenjem iverja analizirani su s pomoću šest empirijskih modela. Određen je učinak vrste drva i temperature zraka na parametre modela sušenja. Točnost modela mjeren je veličinom koeficijenta determinacije (R²), korijena srednje vrijednosti kvadrata pogreške (RMSE) i reduciranog hi-kvadrata (χ²). Rezultati su pokazali da se krivulje sušenja iverja od drva smreke, bukve, vrbe i johe na zadovoljavajući način mogu opisati primjenom Lewisova modela, Hendersonova i Pabisova modela, te modificiranoga Pageova modela s parametrima određenima tako da se uzmu u obzir utjecaj vrste drva i temperature zraka pri sušenju iverja.

Ključne riječi: vrsta drva, iverje, kinetika sušenja, temperatura sušenja, modeliranje

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1 INTRODUCTION

1. UVOD

Drying of wood particles is one of the main steps not only in a particleboard production process but also in biofuel (pellets and briquettes) production process. For pellet production, the wood must be dried to the range 0.09-0.14 kg H₂O/kg d.m. (dry matter) moisture content (Stähl et al., 2004). Consumption of high amount of energy, apart from environmental impacts, makes drying one of the most energy intensive operations with a great importance in particleboard, pellet and briquette manufacturing. Hence, reducing energy consumption, besides product quality, would be highly important for drying the raw materials used in industry (Zarea Hosseinabadi et al., 2012). Improvements in the wood drying process are accompanied by better understanding of the drying process (Kohantorabi et al., 2015).

Wood drying is a complex process of heat and mass transfer, which is conditioned by some phenomena, such as heat/moisture exchange between wood and environment, and heat/moisture movement in wood (Kajalavičius, 2008). It can be stated that this technological process is based on considerably complicated hydro-thermal processes and, despite the noticeable effort of scientists and technologists, it has not yet been fully clarified (Dzurenda and Delsiikki, 2012).

Investigation of drying kinetics is one of the best methods to get sufficient information about drying performance. Experimental data from the drying curves can be used in simulation of wood particle drying to optimize the particleboard and biofuel production processes (Zarea Hosseinabadi et al., 2012).

An important aspect of drying technology is the mathematical modelling of the drying process. Mathematical modelling provides a tool to enable drying rate and efficiency to be predicted under a range of conditions. Scientists developed various mathematical models on the basis of which it would be possible to predict wood moisture content under changing conditions and moisture movement in wood (Turner, 1996; Gigler et al., 2000; Truscott and Turner, 2005; Deliiski and Syulemanov, 2006; Zarea Hosseinabadi et al., 2012). To account for the effect of drying variables on the drying model constants and coefficients, the predicted values were also correlated as a function of drying air temperature and air flow velocity (Zarea Hosseinabadi et al., 2012) or initial material load, particle shape and size (Kaleta and Górnicki, 2010). There is, however, no information on the investigation of the effect of wood species on the drying models constants and coefficients. Therefore, the aim of the present study was to investigate the effect of wood species and of drying air temperature on the drying model parameters.

2 MATERIALS AND METHODS

2. MATERIJALI I METODE

2.1 Raw material

2.1. Sirovina

In this research, sawdust of spruce (Picea abies (L.) H. Karst.), beech (Fagus sylvatica L.), willow (Salix alba L.), and alder (Alnus glutinosa (L.) Gaertn.) was used in the drying experiments. Sawdust was obtained from a sawmill. The size distribution of raw material determined through screen analysis was as follows: the size of 86 % of all particles for spruce, 82 % for beech, 84 % for willow, and 77 % for alder was less than 10 mm and bigger than 0.5 mm. Sawdust particles totalling 14 % for spruce, 18 % for beech, 16 % for willow, and 23 % for alder passed through the 0.5 mm screen. The initial moisture content of samples ranged from: 0.45 to 0.49 kg H₂O/kg d.m. for spruce, 0.85 to 0.90 kg H₂O/kg d.m. for beech, 0.77 to 0.82 kg H₂O/kg d.m. for willow, 1.07 to 1.16 kg H₂O/kg d.m. for alder.

2.2 Drying procedure

2.2. Postupak sušenja

The drying experiments were carried out using Memmert UFP400 (MEMMERT GmbH+Co. KG, Schwabach, Germany) laboratory dryer. The drying experiments were conducted at the drying air temperature of 25, 60, 80, and 150 °C and airflow velocity of 0.01 m/s. Measurements of the moisture content changes carried out in the laboratory dryer were conducted in the following way. The sample was put on the tulle stretched on the metal frame (scale) and hung up to the electronic scales WPX 650 (RADWAG, Radom, Poland). The accuracy of the weighing was ±1 mg. Computer connected to the scales was an additional equipment of experimental stand. It recorded the mass of dried sample at regular intervals of 60 s. Measurements of mass changes were recorded up to the moment, when the mass changes of the sample were not observed. Experiments were replicated three times.

Air temperature inside the dryer was measured with ±0.1 °C accuracy using thermocouple TP-01b-W3 (NiCr–NiAl, CZAKI THERMO–PRODUCT, Raszyn, Poland), placed at the central part of dryer chamber. Temperature reading was done with EMT–08 meter (CZAKI THERMO–PRODUCT, Raszyn, Poland). The velocity of drying air was measured with ±3 % accuracy using Kestrel®4000 Packet WeatherTM TrackerTM (Nielsen–Kellerman Company, Boothwyn, PA, USA).

The initial and final moisture contents of sawdust were determined using the oven method (ASAE, 1994).

2.3 Mathematical modelling of drying and data analysis

2.3. Matematičko modeliranje procesa sušenja i analiza podataka

Table 1 indicates the models used to describe the drying kinetics of wood particles, where a, b, k, n are constants of the models and t is the time. The dimensionless moisture ratio MR is given by

\[ MR = \frac{M_t - M_e}{M_0 - M_e} \]  

(1)

Where \( M_t \) is the moisture content at \( t \), \( M_0 \) is the equilibrium moisture content, and \( M_e \) is the initial moisture content. Moisture contents are on dry basis.

The models applied are empirical models. From the practical point of view, the simple models having...
The drying of wood particles was affected by drying air temperature (Fig. 1). Each of the drying curves $M(t)$ represents an empirical formula, which approximates the results of three measurement replications of the moisture content changes with time. Each of the drying rate curves $dM/dt$ was obtained by differentiation of the drying curves.

Fig. 1 shows that the higher the air temperature, the shorter was the drying time and the higher was the drying rate. The following explanation of the obtained experimental results can be presented. Heat transfer rate increases with increasing of drying temperature and, therefore, the water molecules move faster. Moreover, the moisture diffusion coefficient increases with increasing of discussed temperature. Consequently, the water migration inside the product accelerates with increasing of drying temperature (Kaleemullah and Kailappan, 2005; Kashaninejad et al., 2007; Zielinski and Markowski, 2007; Zarea Hosseiniabadi et al., 2012). The same trends as discussed for alder (Fig. 1) were obtained for spruce, beech, and willow particles. The decrease in drying time and increase in drying rate with the increase in drying air temperature have been also observed for particles of Scots pine (Bauer, 2003) and poplar particles (Zarea Hosseiniabadi et al., 2012).

The initial moisture content of the investigated wood species was different. Therefore, in order to compare the course of their drying, the moisture ratio vs. time chart is presented in Fig. 2. It can be stated that the drying of wood particles was affected by wood species. Fig. 2 shows that the shortest drying time was observed for spruce particles and the longest for beech ones. This can be explained by different densities of beech, alder, spruce, and willow. Such an explanation,
taking into account different densities of wood species, was given by Albrektas and Ukvalbergiené (2015) for the course of moistening process of oak, ash, and aspen wood. The explanation is as follows. In case of wood with lower density, cell cavities whose holes contain bound moisture have a relatively large internal surface. Consequently, such wood desorbs more moisture at the beginning of the drying. In present study, this can be noticed for spruce and alder. On the other hand, there is a smaller number of microcapillaries in low density wood and for this reason water migration from deeper layers becomes slower with drying duration. Desorption of moisture from wood of high density is slower and steadier. In the present study, such a situation was observed for beech particles. The same trends as discussed for drying at 80 °C were obtained at the air temperature of 25, 60, and 150 °C.

3.2 Evaluation of the models

3.2 Ocjena modela

The evaluation of the considered empirical models was conducted in the following way. The moisture content data obtained for different drying air temperatures were converted to the dimensionless moisture content expression and then curve fitting computations with the drying time were carried out using the six drying models considered above. Then the regressions were undertaken to account for the effect of wood species and drying air temperature on the drying model parameters of the six models. The effects of wood species and drying air temperature on the drying model parameters were also included in the models. The summation, subtraction, multiplication, and division dependences were tested. Regarding the air drying temperature, the following types of equation were used: linear, rational, logarithmic (natural), logarithmic (common), and square. The multiple combinations of the parameters that gave the highest $R^2$-values were included in the final model. The considered equations with the determined coefficients were then used to estimate the moisture content of spruce, beech, willow, and alder particles at any time during the process. Validation of the established models was made by comparing the computed moisture content with the measured ones in any particular drying run under certain conditions.

It turned out from the statistical analyses that the models 1, 2, and 4 (Table 2) with the model parameters determined with the following type of equations: 1) summation (or subtraction) and linear, rational or logarithmic (common), 2) multiplication and square, 3) division and linear or rational can be considered as appropriate for spruce, beech, willow, and alder particles. To determine which models can be recommended for practical applications the results for drying characteristics of spruce, beech, willow, and alder particles. Models 1, 2, 4, and 5 with division and square model parameters seemed to be appropriate for the examined wood particles. Taking into account values of $R^2$, RMSE, and $\chi^2$, however, it can be stated that the best results of the above cases were obtained by model 1, 2, and 4 with the model parameters determined by summation (or subtraction) and linear, rational, logarithmic (common) or square type of equations.

It can be concluded from the analysis that the effect of wood species and of drying air temperature on the drying model parameters can be considered individually (Table 3).

By substituting the coefficients given in Table 3 into parameter equations and then substituting the discussed equations into tested models, the course of drying curve can be predicted for spruce, beech, willow, and alder particles in the temperature range of 25 – 150 °C. Obtained results can be used in practice. From the practical point of view, the used drying models need to be accurate and simple in application. Therefore, models 1 and 2 can be recommended for practical applications. The results of statistical analysis for the recommended models are as follows: model 1 (Newman model): $R^2 = 0.8347 – 0.9998$, RMSE = 0.0203 – 0.3529, $\chi^2 = 0.0002 – 0.1250$ and model 2 (Henderson and Pabis model): $R^2 = 0.8287 – 0.9998$, RMSE = 0.0200 – 0.3229, $\chi^2 = 0.0004 – 0.1044$.

4 CONCLUSIONS

4. ZAKLJUČAK

Drying behaviour of spruce, beech, willow, and alder particles was investigated in a convective dryer. The effect of wood species and air drying temperature on the drying model parameters was investigated. Six empirical models were considered. The determination coefficient ($R^2$), root mean square error (RMSE), and
Table 2 Type of parameter equation and comparison of results of statistical analysis of modelling of drying of spruce, beech, willow, and alder particles

| Type of parameter equation | Models No. | Broj modela | $R^2$ | RMSE | $\chi^2$ |
|----------------------------|------------|-------------|-------|------|---------|
| Summation (or subtraction) and linear zbrajanje (ili odzamanje) i linerna $Y = A_y \pm (A + B \cdot T)$ | 1 | 0.9511-0.9998 | 0.0203-0.1059 | 0.0002-0.0112 |
| | 2 | 0.9364-0.9991 | 0.0200-0.1072 | 0.0004-0.0115 |
| | 4 | 0.8962-0.9920 | 0.0515-0.1213 | 0.0025-0.0148 |
| Summation (or subtraction) and rational zbrajanje (ili odzamanje) i racionalna $Y = A_y \pm (A + B \cdot T^{'})$ | 1 | 0.9277-0.9980 | 0.0203-0.1270 | 0.0004-0.0161 |
| | 2 | 0.9101-0.9990 | 0.0202-0.1287 | 0.0004-0.0166 |
| | 4 | 0.8731-0.9631 | 0.0596-0.1421 | 0.0035-0.0203 |
| Summation (or subtraction) and logarithmic (common) $Y = A_y \pm (A + B \cdot \log(T))$ | 1 | 0.9402-0.9988 | 0.0240-0.1163 | 0.0003-0.0135 |
| | 2 | 0.9242-0.9929 | 0.0248-0.1179 | 0.0004-0.0159 |
| | 4 | 0.8903-0.9782 | 0.0529-0.1316 | 0.0028-0.0174 |
| Multiplication square $Y = A_y \cdot (A + B \cdot T^{'})$ | 1 | 0.8870-0.9992 | 0.0273-0.3529 | 0.0007-0.1250 |
| | 2 | 0.8612-0.9986 | 0.0214-0.3183 | 0.0005-0.1014 |
| | 4 | 0.8629-0.9750 | 0.0569-0.2753 | 0.0032-0.0763 |
| Division and linear dijeljenje i linearna $Y = A_y / (A + B \cdot T)$ | 1 | 0.9202-0.9991 | 0.0271-0.2839 | 0.0007-0.0809 |
| | 2 | 0.9292-0.9992 | 0.0202-0.2361 | 0.0004-0.0559 |
| | 4 | 0.8198-0.9693 | 0.0694-0.3082 | 0.0048-0.0956 |
| Division and rational dijeljenje i racionalna $Y = A_y / (A + B \cdot T^{'})$ | 1 | 0.8450-0.9992 | 0.0271-0.2706 | 0.0007-0.0733 |
| | 2 | 0.8287-0.9987 | 0.0201-0.2203 | 0.0004-0.0486 |
| | 4 | 0.8195-0.9692 | 0.0605-0.3012 | 0.0036-0.0913 |
| Division and logarithmic (common) dijeljenje i logaritamska $Y = A_y / [A + B \cdot \log(T)]$ | 1 | 0.9203-0.9992 | 0.0271-0.2763 | 0.0007-0.0766 |
| Division and square dijeljenje i kvadratna $Y = A_y / (A + B \cdot T^{'})$ | 1 | 0.8347-0.9992 | 0.0276-0.3353 | 0.0007-0.1043 |
| | 2 | 0.9288-0.9986 | 0.0217-0.3229 | 0.0005-0.1044 |
| | 4 | 0.8303-0.9754 | 0.0481-0.2642 | 0.0023-0.0735 |
| | 5 | 0.8569-0.9743 | 0.0945-0.3444 | 0.0053-0.1122 |

$R^2$: determination coefficient / koeficijent determinantacije; RMSE: root mean square error / korijen srednje vrijednosti kvadrata pogreške; $\chi^2$: reduced chi-square / reducirani hi-kvadrat

Table 3 Coefficients of parameter equations for chosen models of drying of spruce, beech, willow, and alder particles

| Model No. | Broj modela | Type of parameter equation | Vrsta parametarske jednadžbe | $A_y$ | Spruce Smreka | Beech Bukva | Willow Vrbe | Alder Joha | $A$ | $B$ | $C$ |
|-----------|-------------|-----------------------------|--------------------------------|-------|--------------|-------------|-------------|-----------|-----|-----|-----|
| 1 | 1 | Summation (or subtraction) and logarithmic (common) zbrajanje (ili odzamanje) i logaritamska $Y = A_y \pm [A + B \cdot \log(T)]$ | $k$ | 0.000929 | 0.001394 | 0.001858 | 0.000465 | -0.420312 | 0.169434 | - |
| 2 | 2 | Summation (or subtraction) and linear zbrajanje (ili odzamanje) i linearna $Y = A_y \pm (A + B \cdot T)$ | $k$ | 0.001319 | 0.001979 | 0.002639 | 0.000660 | -0.066479 | 0.000220 | - |
| 4 | 4 | Multiplication and square množenje i kvadratna $Y = A_y \pm (A + B \cdot T^{'})$ | $n$ | -0.000018 | -0.000026 | -0.000035 | -0.000009 | -2078.24 | 17.07 | -0.03 |
| 5 | 5 | Division and square dijeljenje i kvadratna $Y = A_y / (A + B \cdot T^{'})$ | $a$ | -16.711 | -25.066 | -33.421 | -8.355358 | 220998.8 | -1103.3 | 1.4 |

$A_y$: Coeficients of parameter equations for chosen models of drying of spruce, beech, willow, and alder particles

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reduced chi-square ($\chi^2$) were examined for the applied models to compare their goodness of fit to the experimental drying data. It turned out that the effect of wood species and of drying air temperature on the drying model parameters can be considered individually (separated from one another). The following models: Lewis, Henderson and Pabis, and modified Page with the model parameters determined taking into account the effect of wood species and of drying air temperature were quite suitable for predicting the drying curve behaviour of spruce, beech, willow, and alder particles at the drying air temperature of 25, 60, 80, and 150 °C. For practical applications, Lewis model and Henderson and Pabis model can be recommended. Their goodness of fit to the experimental drying data is as follows:

Lewis model: $R^2 = 0.8347 - 0.9998$, RMSE = 0.0203 – 0.3529, $\chi^2 = 0.0002 - 0.1250$ and Henderson and Pabis model: $R^2 = 0.8287 - 0.9998$, RMSE = 0.0200 – 0.3229, $\chi^2 = 0.0004 – 0.1044$.

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