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Natural drying of fruit trees wood

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Abstract: *Natural drying of fruit trees wood*. The aim of this study was to evaluate the fit of mathematical models for drying wet wood chunks with a length of 60 ±1 mm and a diameter of 10 ±2 mm and dry wood chips size of 40 ±10 mm obtained from the branches of fruit trees stored for a 6-months period under natural conditions. Biomass moisture was measured on a monthly basis. For moisture ratio the parameters of nine mathematical models and their statistical evaluation were developed. It was found that wet wood chunks had a large shrinkage (15%) which was probably due to the high content of soft wood tissue in the branches. During the storage of wet wood chunks the moisture decreased significantly, from 47.57 to 10.84%, and the dry chips only slightly (from 11.85 to 8.04%), and in both cases at the end of drying the biomass reached an equilibrium moisture. The best model reflecting changes moisture ratio of wet wood chunks is the Page's model, but the Wang's, Singh's and logarithmic models, may also be used for drying a moist biomass under natural conditions. Drying of dry wood chips is best represented by the logarithmic model, but for this kind of material a Page's, Wang's and Singh's, two term and Midilli's et al. models can be used. Modeling in natural conditions requires consideration of ambient conditions, especially air temperature and relative humidity.

Key words: natural drying, wood, fruit trees, particle size, mathematical model

INTRODUCTION

To gain more insight into the drying of wood, the drying characteristics of the biomass were investigated. The basic parameter is biomass moisture content. Moisture is a feature strongly associated with the development of the plant phase and their type and varies along the height of the plant [Kasprzycka 2010, Lisowski et al. 2012, Chlebowski 2012, Nowakowski 2012]. Several studies have been undertaken on the drying and storage of wood fuels [Mitchell et al. 1988, Gislerud 1990, Gigler et al. 1996, Kofman and Spinelli 1997]. Drying is advantageous with respect to the conversion efficiency and gaseous emissions of the energy plant [Riley and Drechsel 1983, Lyons et al. 1988, Van den Brock et al. 1995, Liang et al. 1996]. Forced convective drying of chips was described by Gigler et al. [2000a, c] and natural wind drying of willow stems was considered by Gigler et al. [2000b].

The advantage of stems is their suitability for long term storage with low microbial activity, and thus, low dry matter losses. The moisture content of steams in a pile can be reduced at very low cost by natural wind drying [Jirjis 1995, Nurmi 1995]. Several experimental studies have been reported on storage and drying of willow stems [Lyons et al. 1989, Nurmi 1995, Kofman and Spinelli 1997, Gigler et al. 2000a]. These studies describe overall initial, final, and, occasionally, intermediate moisture contents. However, for chunks and chips the drying process as such has not been described in detail yet.

The aim of the present study is to fit the mathematical models for describing the drying behaviour of chunks and chips fruit trees wood by long period storage time under natural conditions.

MATERIAL AND METHODS

The study was conducted in the period from 12.19.2012 to 07.25.2013 for two forms of wood by cut of the tree apple branches of Idared variety. A wood with a moisture content of the initial 47.57 ±0.26% was obtained directly from the trees in winter at a temperature of 2–4°C and after cutting the branches into pieces of 60 ±1 mm. Wood B with initial moisture content of 11.85 ±0.16%, which was achieved after pre-stored in a dry, was in the form of size chips 40 ±10 mm. For planned research, the wet wood chunks and dry wood chips were stored in the shed without heating the natural flow of air through the material stored in cardboard containers. The thickness of the stored biomass layer was equal to the dimension of the chunks or chips. Material samples were taken to determine the moisture content in monthly cycle for half a year. Before randomly taking out of samples of each type of material, the chunks and chips were mixed.

From biomass in chunks were randomly selected 100 pieces. Each piece was weighed on an electronic balance Radwag WPS 600/C with an accuracy of 0.01 g and using an electronic calliper with an accuracy of 0.01 mm at the marked locations were measured of the length and diameter in the mid-piece and two planes perpendicular to each other. Measurements were performed before and after drying of biomass in a drying chamber 115 SLW at 103 ±2°C for 24 h. On the basis of the measurements the shrinkage of wood chunks was determined.

Material moisture content was determined by drying-weighing method according to requirements of the standard S358.2 ASABE [ASABE Standards 2011].

$$w = 100\frac{m_w - m_s}{m_w} \tag{1}$$

where:
w – moisture content [% w.b.];
m_w – initial weight of sample [g];
m_s – dry matter content of sample [g].

On the basis of moisture content the water content and the moisture ratio were calculated:

$$u = \frac{w}{100 - w} \tag{2}$$

where:
u – wood water content [kgH_2O/kg DM];
w – wood moisture content [% w.b.].

$$MR = \frac{u - u_e}{u_i - u_e} \tag{3}$$

where:
MR – moisture ratio;
u – wood water content [kg H_2O/kg DM];
u_e – equilibrium water content of the wood [kg H_2O/kg DM];
u_i – initial water content of the wood [kg H_2O/kg DM].

DATA ANALYSIS

Nine empirical and semi-empirical thin-layer drying models given in Table 1 have been taken into account in this study. Non-linear regression analyses of these equations [Eq. (3)–Eq. (24)] were made by using Statistica v.10 software and Solver in Microsoft Excel. Non-linear regression analysis was performed to estimate the parameters a, b, c, k, k_1, k_2, and n of empirical and semi empirical equations in Table 1. To adjust the mathematical models analyses non-linear regressions were performed using the Quasi-Newton method. To check the fit degree of each model was evaluated the significance of the regression coefficient by t-tests, adopting the 5% level of probability, the magnitude of the coefficient of determination (R^2), the global relative average error values (δ_g) and the root mean square error (RMSE), and the reduced chi-square (χ^2), and verified by the behaviour of the distribution of residuals [Midilli et al. 2002].

$$R^2 = \frac{\sum_{i=1}^{N}\left(MR_i - MR_{pi}\right)\sum_{i=1}^{N}\left(MR_i - MR_{ei}\right)}{\sqrt{\left(\sum_{i=1}^{N}\left(MR_i - MR_{pi}\right)^2\right)\left(\sum_{i=1}^{N}\left(MR_i - MR_{ei}\right)^2\right)}} \tag{4}$$

Chi square (χ^2) is the mean square of the deviations between the experimental and predicted moisture levels. The lower are the values of the reduced χ^2, the better is the goodness of fit.

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{ei} - MR_{pi}\right)^2}{N - z} \tag{5}$$

The root mean square error (RMSE) may be computed from the following equation which provides information on the short-term performance.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{pi} - MR_{ei}\right)^2}{N}} \tag{6}$$

TABLE 1. The models used for modelling drying process

Model	Analytical expression	Equation number	References
Lewis	$MR = \exp(-kt)$	(9)	Lewis 1921
Page	$MR = \exp(-kt^n)$	(10)	Page 1949
Henderson and Pabis	$MR = a\exp(-kt)$	(11)	Henderson and Pabis 1961
Wang and Singh	$MR = 1 + at + bt^2$	(12)	Wang and Singh 1978
Yagcioglu et al. (Logarithmic)	$MR = a\exp(-kt) + c$	(13)	Yagcioglu et al. 1999
Two term	$MR = a\exp(-k_1t) + b\exp(k_2t)$	(14)	Henderson 1974
Midilli et al.	$MR = a\exp(-kt^n) + bt$	(15)	Midilli et al. 2002
Two term exponential	$MR = a\exp(-kt) + (1 - a)\exp(-kat)$	(16)	Sharaf-Elden et al. 1980
Logistic	$MR = \frac{b}{1 + a\exp(-kt)}$	(17)	Chandra and Singh 1995

MR – moisture ratio [–]; a, b, c, k, k_1, k_2 and n – drying constants; t – drying time [days].

The global relative average error values (δ_g) is given as

$$\delta_g = \frac{\sqrt{\sum_{i=1}^{N}\left(MR_{ei} - MR_{pi}\right)^2}}{\sqrt{\sum_{i=1}^{N}\left(MR_{ei}\right)^2}}100 \qquad (7)$$

Basing on the Solver mod, each iteration of algorithms provided a new set of values of the coefficients of the selected operating model. Their usefulness decided on value of the objective function, defined as follows

$$S = \sum_{i=1}^{N}\left(MR_{ei} - MR_{pi}\right)^2 \qquad (8)$$

where:
MR_{ei} – the i^{th} experimentally observed moisture ratio;
MR_{pi} – the i^{th} predicted moisture ratio;
z – number of constants;
N – number of observation.

The model to be selected must show the highest value of R^2 and lowest values χ^2, RMSE and δ_g and ease of use in practice [Midilli et al. 2002].

RESULTS AND DISCUSSION

Chunks of biomass having an initial moisture content of 36.03% and diameter of 10.29 mm and length of 60.03 mm, after drying decreased in diameter to 8.75 mm and only slightly shortened to 60.01 mm (Table 2). Drying shrinkage of wet wood chunks in the radial direction amounted to 15% due to wood soft tissue contained in the branches. At the available literature lacks information on the drying shrinkage of the wood pieces from the branches of deciduous fruit trees. For example, the shrinkage of fresh pine wood (*Pinus sylvestris* L.) along the fiber is very small (0.1–0.6%) and has no practical importance [Krzysiak 1978]. Shrinkage in the radial direction is much higher and is 2.6–5.1%. The wood of large diameter, for example logs shrinks also in the tangential direction in the range of 6.1–9.8%, which results in the fracture of the wood in the direction from edge to the core in accordance with a radial cross-sectional wood. In the literature [Babiński 2007] can be also found higher wood drying shrinkage values. In conjunction with the non-uniform wood structure and response in different ways

TABLE 2. The characteristics of wood chunks before and after drying

Parameter	Wet chunks			Dried chunks			Mass of chunks [g]	
	Diameter, d_1, d_2 [mm]		Length, l [mm]	Diameter, d_1, d_2 [mm]		Length, l [mm]	wet	dried
Average	10.22	10.36	60.03	8.78	8.71	60.01	4.5	2.9
Average diameter, d [mm]	10.29		×	8.75		×	×	×
Mass of sample, m_s [g]	×		×	×		×	447.7	286.4
Standard deviation, *SD*	2.08	2.06	13.18	1.77	1.79	12.26	2.0	1.3
Coefficient of variation, c_v [%]	20.4	19.9	22.0	20.2	20.5	20.3	44.4	44.8

in different directions, due to the anisotropy, can be observed warping, gales, twisting, buckling and other curvature of the wood. Because the test chunks of biomass are relatively short and small diameter, it was not observed such phenomenon.

During the 6-month storage biomass the dynamics of drying the wet wood chunks having an initial moisture content of 47.57% was considerably higher than the dry wood chips with an initial moisture content of 11.85% (Fig. 1). Although the initial difference in moisture content between biomass was 35.72 percentage points (p.p.), after 5 months of storage the biomass reached the state of equilibrium moisture content and the difference in moisture content decreased to 2.71 p.p. (average). In winter the biomass drying dynamics of wet wood chunks was very small. Starting from April 2013 to reduce the moisture content in the wood was the fastest and stabilized in June, reaching a state of equilibrium moisture. The mositure content of the wood was finally in equilibrium with the drying air as the wood reached its equilibrium moisture content. The relation between the relative humidity and equilibrium moisture content at constant temprature is given by th sorption isotherm. The drying results are in agreement with the trends reported by Lyons et al. [1988], Nurmi [1995], Kofman and Spinelli [1997] and Gigler et al. [2000b].

During a drying processes of wet wood chunks, two periods can be distinguished. In the first so-called constant drying rate period, the water activity at the surface of the wood is equal to one (i.e. the water vapour concentration at

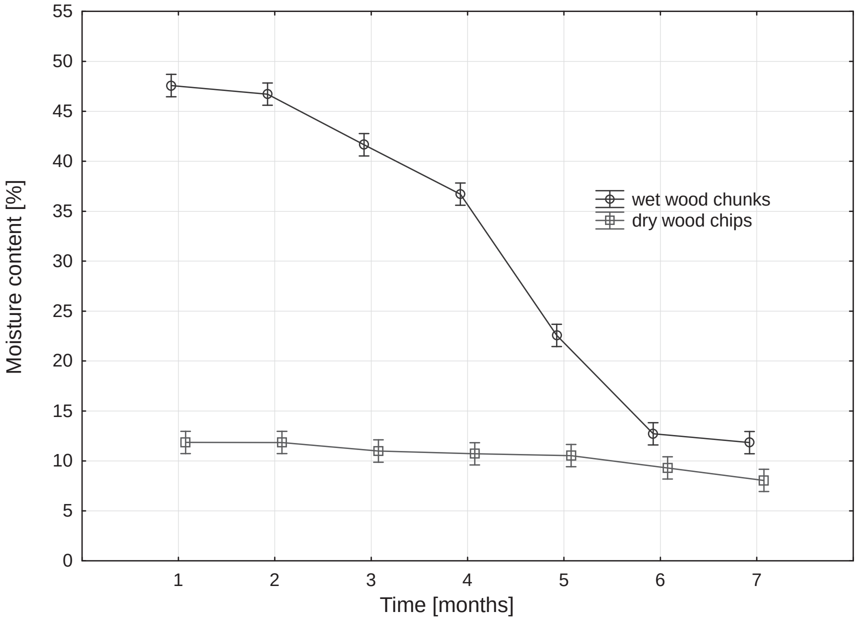

FIGURE 1. The average moisture content of biomass changes with error bars, during its 6-month storage in natural conditions

the surface equals the saturated concentration at surface temperature, which was changed during drying period). Thus at constant temperature (in the moment), the drying force for mass transfer is constant which results in a constant water flux. The energy necessary for evaporation is supplied by the drying air. After some times, the moisture concentration at the surface of the wet wood chunks was lower than the corresponding saturated moisture concentration. In this case, moisture diffusion in the wood chunks become the limiting factor. This drying stage is called the falling drying rate period (Fig. 1). The same processes were at dry wood chips, but they were very slow.

The estimated parameters of 9th mathematical models of changes of moisture ratio over time and their statistical evaluation (SD – standard deviation, t-Student, p-value) for the drying of wet wood chunks shown in Table 3, while the dry wood chips in Table 4. The degree of fitness of 9 models was compared on the basis of R^2, F – Fisher-Sendecor, p-value, χ^2, RMSE, δ_g described in the research method.

Generally, better fit mathematical models reflecting the biomass drying process under natural conditions was obtained for wet wood chunks than for dry wood chips. The best mathematical model for wet wood chunks proved the model of Page [1949], for with $R^2 = 0.967$ and $F = 830$ are high, $p < 0.0001$ and $\chi^2 = 0.0048$, RMSE = 0.066 and global error $\delta_g = 10.64$ are the lowest (Table 3, Fig. 2).

$$MR = \exp(-0.0072t^{1.0058})$$

For wet wood chunks drying good evaluation also received models developed by Wang and Singh [1978], and Yagcioglu et al. [1999] (logarithmic model):

$$MR = 1 - 0.003t - 0.00001t^2$$

$$MR = 15.42 \exp(-0.0003\mathrm{t}) - 14.42$$

For two term Midilli et al. [2002] and logistic models received poor evaluation of parameters and its cannot be used for discribed drying process of wet wood chunks.

Drying of dry wood chips is best represented by logarithmic model developed by Yagcioglu et al. [1999] because $R^2 = 0.834$, $F = 399$, $p < 0.0001$ and $\chi^2 = 0.0067$, RMSE = 0.076 and global error $\delta_g = 11.38$ are the lowest (Table 4, Fig. 3).

$$MR = 50.64 \exp(-0.00006t) - 49.69$$

For Page's [1949], Wang's and Singh's [1978], two term and Midilli's et al. [2002] models received poor evaluation of parameters and its cannot be used for discribed drying process of dry wood chips.

The drying of dry wood chips at initial moisture content of 11.85% (w.b.) was no effective, because moisture content was decreased very slowly. During 6-months drying period the moisture content of dry wood chips dropped by 3.81%, up to 8.04%.

Drying of wet wood chunks was more effective and was successfully described by three of drying mathematical models.

These models were described for average ambient conditions of 18°C and relative humidity of 60%. The air temperature during the drying experiment has changed from 14 to 22°C and air relative humidity from 52 to 78%. Future

TABLE 3. Statistical results of modeling criteria and drying constants, and coefficients (parameters) of wet wood chunks

Model	Drying parameters and its estimation				Estimation of model					
	parameter	SD	t	p	R^2	F	p	χ^2	RMSE	δ_g
Lewis	$k = 0.0079$	0.0008	10.2	<0.0001	0.875	454	<0.0001	0.0170	0.127	20.54
Page	$k = 0.0072$ $n = 1.0058$	0.0028 0.0807	2.6 12.5	0.0184 <0.0001	0.967	830	<0.0001	0.0048	0.066	10.64
Henderson and Pabis	$k = 0.0082$ $a = 1.0416$	0.0009 0.0594	8.7 17.5	<0.0001 <0.0001	0.878	222	<0.0001	0.0174	0.126	20.26
Wang and Singh	$a = -0.0030$ $b = -0.00001$	0.0006 0.000001	–4.9 –2.5	0.0001 0.0195	0.950	670	<0.0001	0.0059	0.073	11.83
Yagcioglu et al. (Logarithmic)	$k = 0.0003$ $a = 15.42$ $c = -14.42$	0.00003 1.2436 1.2353	12.0 12.4 –11.7	<0.0001 <0.0001 <0.0001	0.955	399	<0.0001	0.0063	0.074	11.88
Two term	$k_1 = 0.0091$ $k_2 = 0.0680$ $a = 1.1561$ $b = -0.2310$	0.0013 0.0540 0.1610 0.1933	7.0 1.3 7.2 –1.2	<0.0001 0.2256 <0.0001 0.24863	0.878	99	<0.0001	0.0195	0.126	20.26
Midilli et al.	$k = -0.0561$ $n = 0.5729$ $a = 0.9018$ $b = -0.0141$	0.0480 0.0905 0.0725 0.0059	–1.2 6.3 12.4 –2.4	0.2589 0.0001 <0.0001 0.0283	0.965	352	<0.0001	0.0064	0.072	11.60
Two term exponential	$k = -0.0036$ $a = -0.4642$	0.0016 0.2119	–2.3 –2.2	0.0336 0.0412	0.957	649	<0.0001	0.0189	0.127	20.54
Logistic	$k = -0.0337$ $a = 0.0158$ $b = 0.9402$	0.0036 0.0082 0.0272	–9.3 1.9 34.5	<0.0001 0.0692 <0.0001	0.980	904	<0.0001	0.0183	0.125	20.21

TABLE 4. Statistical results of modeling criteria and drying constants, and coefficients of dry wood chips

Model	Drying parameters and its estimation				Estimation of model					
	parameter	SD	t	p	R^2	F	p	χ^2	RMSE	δ_g
Lewis	$k = 0.0048$	0.0005	10.1	<0.0001	0.753	551	<0.0001	0.0164	0.125	18.72
Page	$k = 0.0002$ $n = 1.6627$	0.0003 0.3449	0.6 4.8	0.5771 0.0001	0.786	304	<0.0001	0.0149	0.116	17.41
Henderson and Pabis	$k = 0.0044$ $a = 0.9469$	0.0006 0.0539	7.0 17.6	<0.0001 <0.0001	0.765	276	<0.0001	0.0164	0.122	18.25
Wang and Singh	$a = -0.0017$ $b = -0.00001$	0.0008 0.000001	–2.1 –2.3	0.0514 0.0353	0.824	398	<0.0001	0.0115	0.102	15.26
Yagcioglu et al. (Logarithmic)	$k = 0.00006$ $a = 50.64$ $c = -49.69$	0.000009 1.2436 1.2353	12.0 7.4 7.4	<0.0001 <0.0001 <0.0001	0.834	399	<0.0001	0.0067	0.076	11.38
Two term	$k_1 = 0.0276$ $k_2 = 0.0059$ $a = -0.3667$ $b = 1.2406$	0.0235 0.0017 0.3841 0.3747	1.2 3.5 –0.9 3.2	0.2560 0.0029 0.3531 0.0041	0.878	99	<0.0001	0.0183	0.122	18.25
Midilli et al.	$k = 0.6862$ $n = -1.7226$ $a = 1.2304$ $b = -0.0038$	0.2818 11.6152 0.2158 0.0013	2.4 –0.1 5.7 –2.9	0.0262 0.8838 <0.0001 0.0095	0.846	37	<0.0001	0.0119	0.098	14.73
Two term exponential	$k = -0.0070$ $a = -0.1400$	0.0008 0.0248	–8.2 –5.6	<0.0001 <0.0001	0.870	215	<0.0001	0.0181	0.125	18.67
Logistic	$k = -0.0002$ $a = -0.9610$ $b = 0.0368$	0.00006 0.0010 0.0034	4.1 –709.6 10.9	0.0007 <0.0001 <0.0001	0.705	18	<0.0001	0.0173	0.122	18.23

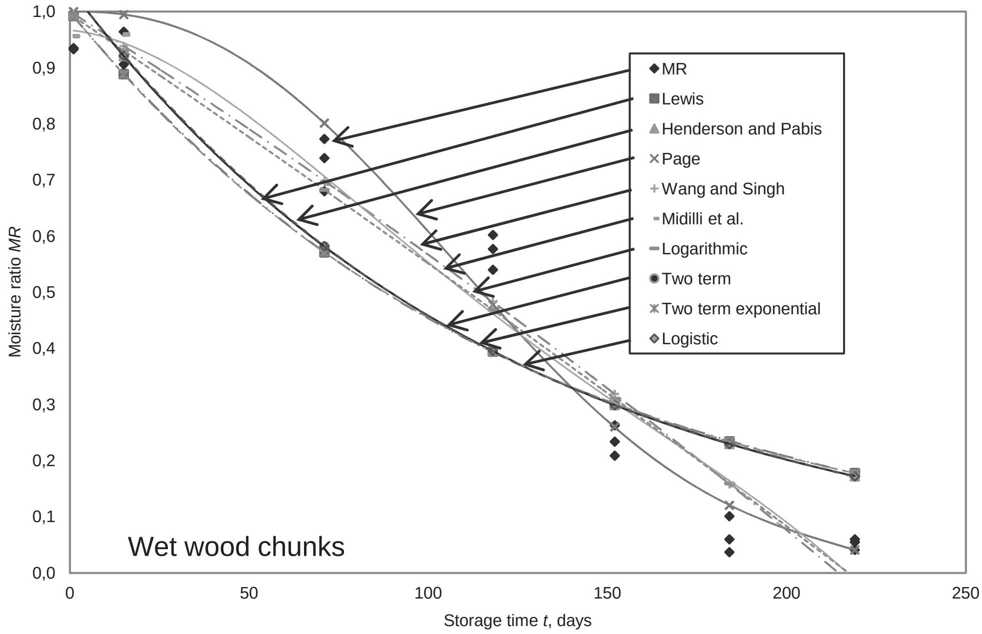

FIGURE 2. Curves of the moisture ratio determined on the basis of analyzed mathematical models against measurement points for wet wood chunks (material A)

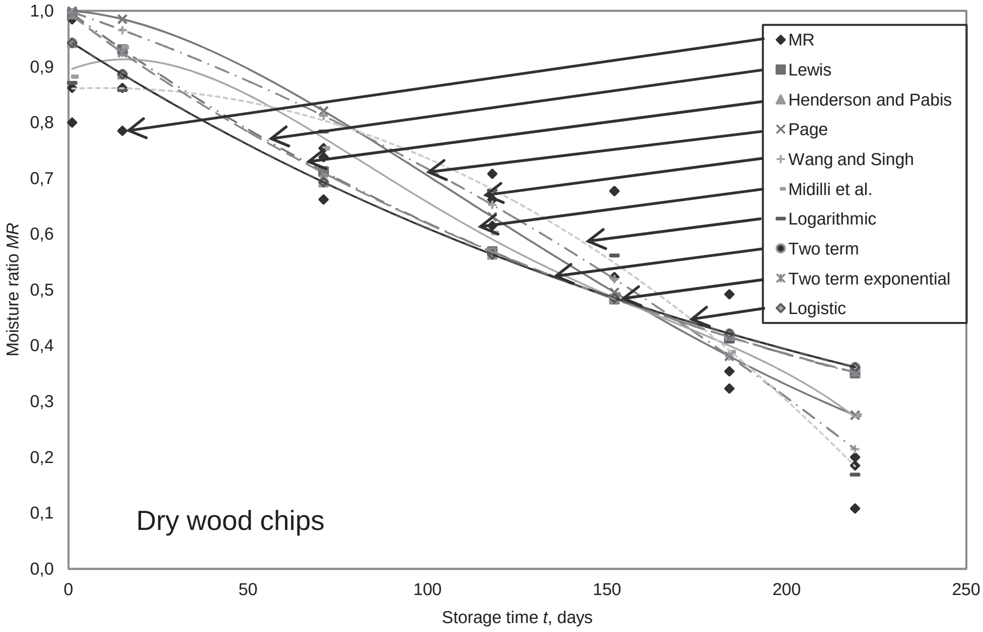

FIGURE 3. Curves of the moisture ratio determined on the basis of analyzed mathematical models against measurement points for dry wood chips (material B)

work will focus on validation of current diffusion model at a range of relative humidities and at ambient temperature for wood chunks or chips.

CONCLUSIONS

1. Drying shrinkage of wet wood chunks in the radial direction amounted to 15% due to wood soft tissue contained in the branches.
2. After cutting the tree fruit branches on the chunks, during 6-months storage until August the average chunks moisture content can be reduced from 47.57 to 10.84% (w.b.).
3. The storage of dry wood chips was less effective because during this period the wood moisture content was decreased from 11.85 to 8.04% (w.b.) and it was probably close to the equilibrium moisture content.
4. Of the nine analyzed mathematical models the Page's model proved to be the best to describe drying process of wet wood chunks. For this kind of biomass can be used Wang's and Singh's, and logarithmic models too. Drying of dry wood chips are the best represented by logarithmic model, but for this material can be used also Page's, Wang's and Singh's, and two term, and Midilli's et al. models.
5. Moisture diffusion within the wet wood chunks is a long-term process which is governed by the relative air humidity and ambient temperature and for modelling drying process these parameters should be taken into consideration.

REFERENCES

ASABE STANDARDS. 2011: Moisture measurement – forages ASABE S358.2 (R2008). In: ASABE Standards 2011, American Society of Agricultural and Biological Engineers, St. Joseph, MI, USA.

BABIŃSKI L. 2007: Influence of pretreatment on shrinkage of freeze-dried archaeological pine-wood. Folia For. Pol., B 38: 3–12.

CHANDRA P.K., SINGH R.P. 1995: Applied numerical methods for food and agricultural engineers. Boca Raton, FL: CRC Press: 163–167.

CHLEBOWSKI J. 2012: Simulation investigations of energetic loads of the headers for long-stem plants harvesting. Annals of Warsaw University of Life Sciences – SGGW, Agriculture (Agricultural and Forest Engineering) 59: 59–69.

GIGLER J.K., CURVERS A.P.W.M., ANNEVELINK E. 1996: Input and output characteristics of biomass pretreatment techniques. Report P96-23, IMAG, Wageningen, The Netherlands.

GIGLER J.K., Van LOON W.K.P., SERES I., MEERDINK G., COUMANS W.J. 2000a: Drying characteristics of willow chips and stems. J. Agric. Engng Res. 77(4): 391–400.

GIGLER J.K., Van LOON W.K.P., Van Den BERG J.V., SONNEVELD C., MEERDINK G. 2000b: Natural wind drying of willow stems. Biomass and Bioenergy 19: 153–163.

GIGLER J.K., Van LOON W.K.P., VISSERS M.M., BOT G.P.A. 2000c: Forced convective drying of willow chips. Biomass and Bioenergy 19(4): 259–270.

GISLERUD O. 1990: Drying and storing of comminuted Wood Fuels. Biomass 22: 229–244.

HENDERSON S.M., PABIS S. 1961: Grain drying theory. II. Temperature effects on drying coefficients. Journal of Agricultural Engineering Research 6: 169–174.

HENDERSON S.M. 1974: Progress in developing the thin layer drying equation. Transection of ASAC, 17: 1167–1172.

JIRJIS R. 1995: Storage and drying of wood fuel. Biomass and Bioenergy 9: 181–190.

KASPRZYCKA A. 2010: Przyczyny zakłóceń procesu fermentacji metanowej. Autobusy, Technika, Eksploatacja, Systemy Transportowe 10: 224–228.

KOFMAN P.D., SPINELLI R. 1997: Storage and handling of willow from short rotation coppice. Elsam Projekt-Report, Elsam Projekt, Fredericia, Denmark.

KRZYSIAK F. 1978: Nauka o drewnie. PWN, Warszawa.

LEWIS W.K. 1921: The rate of drying of solid materials. Industrial Engineering Chemistry 13: 427–432.

LIANG T., KHAN M., MENG Q. 1996: Spatial and temporal effects in drying biomass for energy. Biomass and Bioenergy 10: 353–360.

LISOWSKI A., STASIAK P., POWAŁKA M., WIŚNIEWSKI G., KLONOWSKI J., SYPUŁA M., SZCZESNY W., CHLEBOWSKI J., NOWAKOWSKI T., KOSTYRA K., STRUŻYK A., KAMIŃSKI J. 2012: Charakterystyki rozdrobnionej biomasy przeznaczonej na biogaz. Autobusy, Technika, Eksploatacja, Systemy Transportowe 10: 111–120.

LYONS G., RICE B., O'DONNEL B. 1988: Storage and drying of forest biomass. Proceedings of the Third Contractors' Meeting, Paestum, Italy, 25–27 May, London, UK, Elsevier Applied Science 240–247.

MIDILLI A., KUCUK H., YAPAR Z. 2002: A new model for single layer drying. Drying Technology 20(7): 1503–1513.

MITCHELL C.P., HUDSON J.B., GARDNER D.N.A., STORRY P. 1988: A comparative study of storage and drying of chips and chunks in the UK. In: Production, Storage and Utilization of Wood Fuels, Proceeding of IEA/BA Conference Task III/Activity 6 and 7, Vol II. Uppsala (Sweden), 6–7 December: 72–89.

NOWAKOWSKI T., ŚLESIŃSKI K. 2012: Morphometric characteristics of the energetic plants chaff. Annals of Warsaw University of Life Sciences – SGGW, Agriculture (Agricultural and Forest Engineering) 60: 51–57.

NURMI J. 1995: The effect of whole-tree storage on the fuelwood properties of short-rotation Salix crops. Biomass and Bioenergy 8: 245–249.

PAGE G. 1949: Factors influencing the maximum rates of air-drying shelled corn in thin layer. M.Sc. Thesis. Department of Mechanical Engineering, Purdue University, West Lafayette, IN, USA.

RILEY J.G., DRECHSEL C.S. 1983: Drying and storage of woody biomass fuels. Presentation at the 1983 Winter Meeting of the ASAE, December 13–16, Chicago, IL, USA, ASA Paper 83-3560.

SHARAF-ELDEEN Y.I., BLAISDELL J.L., HAMDY M.Y. 1980: A model for ear corn drying. Transactions of the ASAE 23: 1261–1271.

Van Den BROCK R., FAAIJ A., Van WIJK A. 1995: Biomass combustion power generation technologies. Report 95029, Department of Science, Technology and Society, Utrecht University, Utrecht, the Netherlands.

WANG C.Y., SINGH R.P. 1978: A single layer drying equation for rough rice. ASAE Paper No. 78-3001, ASAE, St. Joseph, MI.

YAGCIOGLU A., DEGIRMENCIOGLU A., CAGATAY F. 1999: Drying characteristic of laurel leaves under different conditions of conditions. In: Proceeding of the 7th International Congress of Agricultural Mechanization and Energy (Ed. A. Bascetincelik) Cukurova University, Adana, Turkey, 26–27 May: 565–569.

Streszczenie: *Naturalne suszenie drewna drzew owocowych.* Celem pracy była ocena dopasowania matematycznych modeli suszenia dla wilgotnych kawałków drewna o długości 60 ±1 mm i średnicy 10 ±2 mm oraz podsuszonych zrębków o wymiarze 40 ±10 mm uzyskanych z gałęzi drzew owocowych przechowywanych przez okres

6 miesięcy w warunkach naturalnych. Wilgotność biomasy zmierzono w okresach miesięcznych. Dla zredukowanej zawartości opracowano parametry dziewięciu modeli matematycznych oraz ich oceny statystyczne. Stwierdzono, że wilgotne kawałki drewna miały duży skurcz suszarniczy (15%), który prawdopodobnie wynikał z dużej zawartości tkanki miękkiej w gałęziach. W okresie przechowywania wilgotność wilgotnych kawałków drewna zmniejszyła się istotnie, z 47,57 do 10,84% a suchych zrębków tylko nieznacznie (z 11,85 do 8,04%) i w obu przypadkach pod koniec suszenia biomasa osiągnęła wilgotność równowagową. Najlepszym modelem odzwierciedlającym zmiany zredukowanej zawartości wody w wilgotnych kawałkach drewna okazał się model Page'a, ale modele Wanga i Singha oraz logarytmiczny mogą być również wykorzystane do suszenia biomasy wilgotnej w warunkach naturalnych. Suszenie podsuszonych zrębków jest najlepiej reprezentowane przez model logarytmiczny, ale do tego rodzaju materiału mogą być użyte modele Page'a, Wanga i Singha, dwuwyrażeniowy oraz Midilliego i innych. Modelowanie w warunkach naturalnych wymaga uwzględnienia warunków otoczenia, a zwłaszcza temperatury i wilgotności względnej powietrza.

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