Modeling Pine and Birch Whole Tree Drying in Bunches in the Cutting Area

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Abstract

Natural drying is practiced to improve the quality of fuel wood. The purpose of this study is to obtain the mathematical model of natural drying of whole trees stacked in bunches in the cutting area. To do this, an experimental study of natural drying of whole trees with different diameter was carried out from March to October 2015. Whole pine and birch trees were sorted according to their diameter and placed in bunches in the cutting area. During the next 7 months, the moisture content of wood and ambient parameters were constantly measured. As a result, the mathematical model describing the change in moisture content of the trees in bunches in the cutting area in the process of natural drying was developed. The resulting mathematical model makes it possible to determine the change in the average moisture content of wood depending on the following factors: diameter of a tree trunk, cumulative precipitation, relative humidity and ambient temperature, average wind speed and duration of natural drying. The developed mathematical model allows to predict changes in moisture content of wood in the process of natural drying. During the experiment, in the process of natural drying from March to October, it decreased from 52% to 27% on average. The results can be used to improve the efficiency of fuel wood production. The proposed mathematical model can be used in practice for predicting the outdoor wood moisture content change of whole trees packed in stacks for natural drying, and therefore, to determine the optimum drying time.

Keywords: natural drying, drying modeling, moisture content, fuel wood drying, energy forest

1. Introduction

It is a known fact that high moisture content of fuel reduces its calorific value (Erber et al. 2014) and the efficiency of power equipment (Anisimov and Onuchin 2013). This also applies to the direct burning of fuel wood, combustion technology of wood from the intermediate gasification (Rajvanshi 1986), and to the production of wood technology for liquid fuel (Fagernäs et al. 2010). In order to improve the quality of fuel wood, that is to improve the calorific value and decrease the moisture content, natural atmospheric drying is practiced. Logging residues (Pettersson and Nordfjell 2007), as well as fuel wood in the form of whole trees (Kundas 2008) are placed in bunches or stacks for summer drying and shedding greenery. An important issue is to determine the optimal duration of natural drying of fuel wood (Kim and Murphy 2013). To this end, mathematical drying models are developed to predict changes in the moisture content of wood (Erber et al. 2014). In studies (Routa et al. 2014, Kim and Murphy 2013, Röser et al. 2010, Pettersson and Nordfjell 2007), it is noted that the dynamics of round wood moisture content change under natural atmospheric drying in the stack depends on the following factors: average diameter of the tree trunk, ambient temperature and relative humidity, cumulative precipitation, presence of bark, geometrical dimensions of the pile and the density of packing in the stack, wind velocity, as well as the availability of the stack protection from precipitation. Numerous studies indicate increased moisture content (rewetting) when timber is stored in the open air in autumn and spring, during rain and during snowmelt (Routa et al. 2014, Gigler et al. 2000, Röser et al. 2010). While some studies (Raitila et al. 2015, Kim and Murphy 2013) report no rewetting in summer, other studies indicate that there was a slight rewetting of wood in covered and non-covered stacks during heavy rains in summer (Filbakk et al. 2011, Erber et al. 2014, Gigler et al. 2000). It should be mentioned that all papers report about the reduction of moisture content of wood after summer natural drying. By the end of experiments, the moisture of wood was 1.5–2 times lower than the moisture of freshly felled trees despite the periodic rewetting of wood due to rains (Filbakk et al. 2011, Erber et al. 2014, Gigler et al. 2000).

In order to determine the timing and duration of the natural drying of fuel wood, its logistics should be taken into account. The consumption of fuel wood chips for heat and electric power has a distinct seasonal pattern with peak consumption in winter months. At the same time, the grinding of frozen wood chips requires higher energy consumption, as it has high hardness (Golovkov et al. 1987, Shelgunov 1982). Therefore, the bulk of production of fuel wood chips is economically feasible to implement in the warmer months before the start of the heating season and (or) before the onset of freezing temperatures of the outside air. Forestry also often has seasonal character, as weak and waterlogged soils (Poršinsky et al. 2006), for example, in Russia, occupy a large part of the forest area. Due to the weak soil on the territory of Russia, the bulk of wood is harvested in the winter months (Suhanov 2008). Thus, the laws governing natural drying of fuel wood that was cut down in winter during the spring – summer – early autumn are of greatest practical interest.

Mathematical models of natural drying of round wood are based on empirical data. Raitila et al. (2015) note that it is essential to complete the database models for specific drying conditions as soon as possible. The majority of papers are devoted to the natural drying of logs and logging waste in stockpiles. However, it is necessary to conduct further research of natural drying of whole trees of various diameters in bunches in the cutting area.

Therefore, the aim of this study is to get a mathematical model based on the experimental data that describes the change in the moisture content of whole pine and birch trees during their natural drying in the stack in the cutting area. The resulting regression equation should determine the dependence of the average moisture content of wood in a bunch from the diameter of wood, monthly sum of precipitation and evaporation.

2. Materials and methods

2.1 Mathematical modeling

In order to predict the change in the average moisture content of the wood exposed to the natural atmospheric drying, we propose eq. (1), which is a modification of the equations proposed in other works (Raitila et al. 2015, Kim and Murphy 2013). Eq. (1) takes into account the effects of temperature, relative humidity, and rainfall on the natural drying of wood:

$$w_{i+1} = w_i + k_1 \times \sum P + k_2 \times \sum E \qquad (1)$$

Where:

- w_{i+1} target relative humidity during natural wood drying at time τ_{i+1}, %
- i unit of time, for example, one week, two weeks or one month
- w_i average relative humidity of timber at time τ_i, %
- ΣP the total amount of liquid precipitation for the period $(\tau_{i+1} - \tau_i)$, mm
- ΣE the total direct evaporation of water from the surface for the period $(\tau_{i+1} - \tau_i)$, mm
- k_1, k_2 coefficients obtained experimentally

The total direct evaporation of water from the surface ΣE for the period $(\tau_{i+1} - \tau_i)$, mm, is given by (2), which is based on the equation for determining the amount of evaporated water per hour from an open water surface of the proposed drying laboratory – All-Russian Thermal Engineering Institute (Moscow) and is given in reference (Bogoslovskij et al. 1992):

$$\sum E = h \times (7.4 \times (0.022 + 0.017\upsilon) \times (p_s - p_n)) \times 101 \frac{3}{P_{bar}} \qquad (2)$$

Where:

- h the number of hours in the period under review $(\tau_{i+1} - \tau_i)$
- υ average wind speed measured at stack mid-height level
- p_s pressure of saturated water vapor in air at a temperature equal to that of water (in this case, the water temperature is equal to ambient temperature), kPa
- p_n partial pressure of water vapor in the air, kPa
- p_{bar} barometric pressure, kPa

Saturated water vapor pressure over pure water surface (in the temperature range 0–83 °C) can be found in the tables or by the equation proposed in (Fil'nej 1966):

$$p_s = 0.001 \times 10^{\frac{658+10.2\times t}{236+t}}, psi \qquad (3)$$

Where:

- t ambient temperature for a period of time $(\tau_{i+1} - \tau_i)$, °C

The partial pressure of water vapor in the air is found by equation:

$$p_n = p_s \times \frac{\varphi}{100}, kPa \qquad (4)$$

Where:

- φ average relative humidity of ambient air for a period of time $(\tau_{i+1} - \tau_i)$, %

The coefficients k_1, k_2 have been obtained by experiment. They take into account other parameters influencing the process of natural drying of wood, such as the average diameter of a tree trunk in a pack of trees, wood species, type of fuel wood (whole trees, forest residues, non-debarked, partially debarked, etc.). Additionally, the coefficients k_1, k_2 consider storage conditions (dimensions of the pack or stack, the density of stacking packs or stacks, cover of a stack from above against rain, etc.).

2.2 Experimental layout

In order to estimate values of k_1, k_2 coefficients of eq. (1) and to determine the regression equations defining the dependence of the coefficients k_1, k_2 from the average diameter of the tree trunk in a stack, an experiment was conducted with natural drying of whole trees of pine and birch (Fig. 1) arranged in a specific way in the cutting area. The study was conducted in the territory of Training and Experimental Forestry »Volga State University of Technology« in Medvedev's district of the Republic of Mari El (56.477°N; 47.861°E).

From whole trees felled at the logging site, 4 bunches (3 bunches of pine trees, sorted by diameter, and 1 bunch of birch trees, not sorted by diameter) were formed. The volume of a bunch and method of stacking bunches of trees is determined by the employed timber harvesting technology for energy use, which consists of two stages. In the first stage, the trees are cut and stacked in bunches using a feller-buncher. The number of trees in the stack is determined by the reach of the boom. In the second stage, after summer natural drying, stacks of whole trees are ground into chips in the cutting area by using a mobile wood chipper with a storage container.

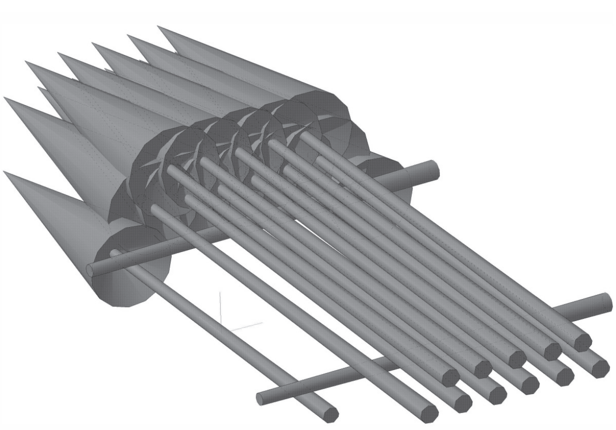

Fig. 1 Way of laying the stacks of whole trees (fuel wood) for natural drying in a cutting area

Table 1 Parameters of stacks of the whole trees of pine laid in a cutting area for natural drying

Parameter\N° bunch of tree	1 (pine)	2 (pine)	3 (pine)	4 (birch)
Average diameter of tree trunks in a bunch, cm	7	11	15	14
Average height of a tree, m	8	10.5	14.5	13
Number of trees in a bunch, pcs.	21	18	15	25
Wood volume in a bunch, density, m^3	0.65	1.9	3.7	5
Average height of a bunch, m	1	1.1	1.1	1.3

Trees of approximately the same diameter were placed in one pack. Parameters of tree packs are shown in Table 1. The diameter mentioned is the diameter at half tree height. The trees were entirely placed in stacks. Stacks were not covered.

Each stack of trees was placed on a pad on the ground directly in the cutting area, as shown in Fig. 1.

Pine trees and birch trees were felled with feller-buncher and stacked in bunches at the logging site in early March 2015 in the open area after cutting. The bunches were left in the cutting area for natural drying of wood and shedding of pine needles and part of the bark till the end of September. During the experiment, on the 1st or on the 2nd day of each month from April to October 2015, moisture content of the wood was measured in accordance with GOST 17231-78 and ISO 4470-81.

The moisture content of green wood was determined by weight method in early March and at the end of the experiment on October 1st. The minimum amount of samples for determining wood moisture is chosen in accordance with GOST 16483.0-89. The minimum amount of samples providing 5% relative accuracy of the sample mean with confidence coefficient 0.95 is 6 pieces. Consequently, it was necessary to take 6 trees from each bunch for measuring the moisture. In accordance with GOST P 54217-2010, each bunch of trees had 3 levels of height, and 2 trees were taken from each level for the experiment.

The samples were round cross sections of 10–15 mm along fiber. Four cross sections were made from each tree. A total of 24 samples were made from each bunch. Samples were repeatedly weighed at an accuracy of less than 0.1 grams before and after drying in an electric muffle at 103 °C. The drying was practiced in electric muffle until the constant mass of samples was reached. Thus the mass of moisture in samples was determined by measuring it before and after drying.

Moisture content of wood in the process of natural drying in the experiment on the 1st or the 2nd day of each month from April to September was measured using an electrical moisture meter »GANN Hydromette HT 85 T«. The following electrodes were used: Drive-in Electrode M 20 with measuring pins 23 mm long, Ram-in Electrode M 18 with pins 60 mm long and Deep Electrod M 21–100 with pins 100 mm long. There were 6 samples. There were 4 sections for the determination on each tree in accordance with ISO 4470-81. The sections were determined in a random manner at the distance no less than 0.5 m from the butt end. The measuring at each section was conducted at different depth. In each stack, there were 24 sections. The first measurement was taken at the surface of the body. Bark and cambium were taken away and electrodes were placed into the timber. For the second measurement, the blind hole for electrodes was bored out at the depth of 1/4 of body diameter. And for the third measurement, the blind hole was 2/5 of body diameter. After measuring, the blind holes were filled to prevent water penetration. The arithmetical mean of 3 measurements was accepted as moisture content of the section at the local depth. As a result, 216 measurements were taken.

In the course of the experiment, the environmental conditions, affecting the drying process at the experimental site, were recorded. These included the amount of precipitation in the form of rain, relative humidity, air temperature and wind speed. Rainfall was measured using a M-99 field rain gauge. The average relative air humidity was recorded using the thermal hygrometer. Wind speed was measured using an anemometer placed at mid stack height level.

3. Results

The recorded environmental parameters were reduced to monthly averages, while all the other parameters were calculated according to the eq. (2–4). All environmental parameters are presented in Table 2. The cumulative precipitation ΣP, in mm, for the period of time ($\tau_{i+1} - \tau_i$) in the experiment is the total amount of rain fallen for i^{th} month of trees drying. The total direct evaporation of water from the surface for the i^{th} month was taken as ΣE both in the experiment and simulation. In the experiment and in the mathematical model, *t* was the average ambient temperature measured near the stacks of trees. Wind speed was measured at mid-height of the stack, at 0.55 meters height from the ground. The results of measuring of moisture content of wood w_i in the process of air seasoning are shown in charts 1–4 of Fig. 2. Individual points on the graphs, indicating experimental values of moisture content, were calculated using eq. (1).

Deviation of the theoretical values calculated by the eq. (1) from the experimental values was less than 5%. Fig. 4 includes an additional dotted line. It represents the estimated birch moisture content calculated by eq. (1) with coefficients k_1, k_2 (eq. 5, 6) for pine. Substitution of experimental coefficients k_1, k_2 by those obtained from pine experiments leads to an increased deviation of up to 10%, which confirms the influence of tree species on the drying process.

Regression coefficients k_1, k_2 in eq. (1) were determined by the method of least squares, i.e. by minimizing the sum of squared timber moisture deviations from the measured values calculated using the regres-

Table 2 Environmental parameters in the process of natural drying

i	Month	Average air temperature t, °C	Average relative humidity of ambient air φ, %	Total amount of liquid precipitation ΣP, mm	Saturated pressure ps, kPa	Partial pressure of water vapor in the air υn, kPa	Average speed of movement of air, blowing a stack of trees J, mps	Total direct evaporation of water from the surface ΣE, mm
0	March	–2.1	–	–	–	–	–	–
1	April	3.95	74	66	0.81	0.6	1.2	47.9
2	May	16	57	22.1	1.82	1.04	1	169.3
3	June	18.75	66.5	54.2	2.17	1.44	0.8	139
4	July	17.1	90	138.7	1.95	1.76	1.3	48
5	August	15.35	75.4	64.1	1.74	1.32	1	9.3
6	September	14.5	65	30.8	1.65	1.07	0.9	115.9
	Total	–	–	375.8	–	–	–	613.5

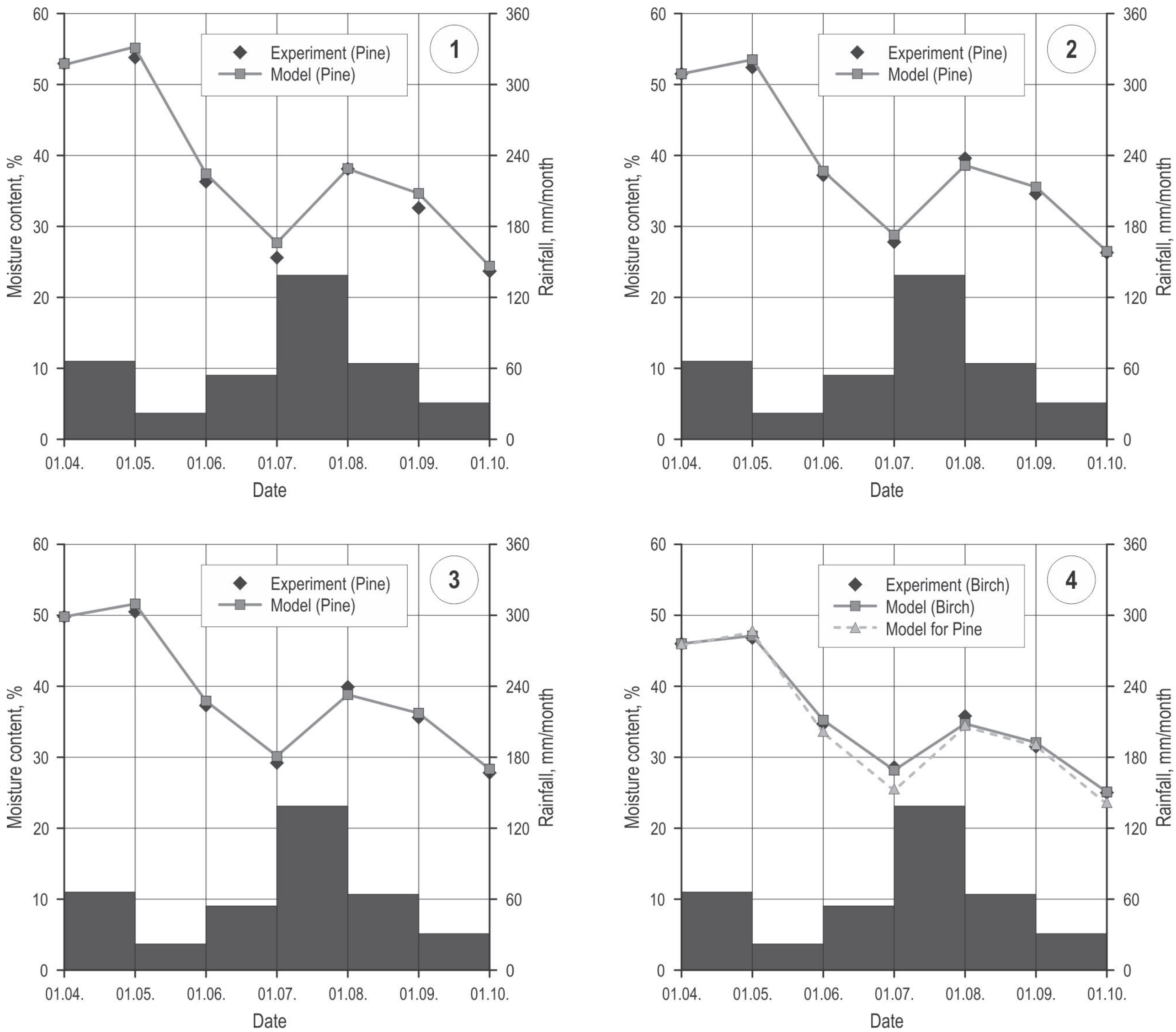

Fig. 2 Experimental and theoretical (eq. 1) values of moisture content of wood

sion model (1). The experimental values of the coefficients k_1, k_2 of the mathematical model (1) are shown in Table 3.

Table 3 Experimental coefficients k_1, k_2 of mathematical model (1)

N° bunches of trees	k_1	k_2
1	0.1226	–0.1219
2	0.113	–0.1092
3	0.1012	–0.0966
4 (birch)	0.076	–0.0802

As it can be seen from the graphs in Fig. 2, natural drying process is greatly influenced by the average diameter of the tree trunk. Approximation of the values of the coefficients k_1, k_2 for drying pine obtained experimentally were obtained by eq. (5, 6) and determine the dependence of the coefficients k_1, k_2 from wood diameter:

$$k_1 = -0.00275 \times D + 0.1426 \quad (5)$$
$$R^2 = (0.98)$$

$$k_2 = -0.003125 \times D + 0.1437 \quad (6)$$
$$R^2 = (0.98)$$

Where:

D average diameter of tree trunks in a bunch, cm

R^2 reliability of approximation

4. Discussion

The maximum decrease in wood moisture for all stored timber was observed in the first stack with medium-diameter timber of 7 cm. From March to September, the relative humidity decreased from 53.5% to 23.7%. The larger the diameter of trees, the less the moisture content decreased. The third stack of wood with a diameter of 0.15 m dried to a moisture content of 27.8% from the initial 50.1%. Rewetting of all stacks was observed in July, when precipitation ΣR mm is significantly (3 times) higher than the theoretical total evaporation from the surface of water ΣE, mm. In July 2015, precipitation was up to 190% of the monthly norm. In other months, there was a decrease of moisture content. Thus, for freely stacked stacks in the environment, where ΣP does not exceed ΣE, it is not necessary to cover the trees.

After 7 months from the start of the experiment, the bark loss was insignificant and it was about 6%. Pine trees lost 95% of needles and the bark became crisp and started to peel.

Since tree stacks were placed directly on the ground, the two trees at the bottom are a kind of basis. Thus their moisture content was not taken into account when determining the average moisture content of stacks.

The proposed mathematical model can be used in practice to predict the changes in the moisture content of whole trees, stacked in bunches for natural drying in the open air. Predicting the moisture content, the optimal duration of natural drying can be determined. For predicting the moisture content of round logs and whole trees in natural drying process on the basis of the proposed mathematical model, statistical data on the climate of a particular region can be used, for example from the Scientific and Applied Reference Book on the USSR Climate, long-term data, 1992.

Naturally, there are limitations and conditions for the correct use of the research results. The proposed mathematical model to determine the moisture content of wood during drying whole trees stacked in a stack outdoors is only valid for the warm season with positive average daily temperature of the ambient air, when evapotranspiration ΣE for the entire drying period exceeds the total precipitation in the form of rain ΣR. Regression dependence (5, 6) for the determination of the coefficients k_1, k_2 is applicable to pine trees, whole or sawn in half, with a height of 7–16 meters stacked in the open air in a stack as shown in Fig. 1, with no protection from the weather. For the estimation of k_1 and k_2 coefficients, the average diameter at half tree height should be used. The mathematical model can be used for natural drying of trees with an average diameter between 5 and 18 cm, an average monthly ambient temperature between +3 and +35 °C and an average wind speed of 0.1 to 3.5 mps.

Concerning the optimum drying period, for the climatic conditions of this experiment, it can be concluded that it ends either at the end of June or in late September (Fig. 2).

5. Conclusions

A mathematical model was developed describing the moisture content change of the pine and birch trees during natural drying in a stack in the cutting area. The alteration of the average moisture content of trees stacked in a bunch depends on the diameter of the trunk, the amount of liquid precipitation, relative humidity and ambient temperature, average wind speed and length of the drying period.

Deviation of the theoretical values, calculated using the proposed mathematical model, from the experimental data was less than 5%, confirming the adequacy of the proposed regression model (1) and of the experimental coefficients k_1, k_2 (Table 3, and Eq. 5, 6).

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