Experimental determination of poplar (*Populus nigra* L.) wood drying curves

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Abstract

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Fresh plant material is degraded quickly and very easily. A possibility to avoid its degradation is drying. Drying is an energy-intensive operation and reducing of energy consumption means improving the energy balance and the economy of production. An important indicator of drying efficiency is the relative rate of drying. Curves of the relative drying rate for poplar (*Populus nigra* L.) wood were determined in an experimental oven. Freshly harvested samples were compared to samples of poplars that were stored between March and December on an outdoor uncovered area. The rate of stored wood drying was higher in comparison with fresh wood under comparable drying conditions.

Keywords: drying; biomass; bioenergy; energy consumption; poplar; energy wood

Poplar and willow present important bioenergy crops in Europe mainly due to rapid growth (Lenz et al. 2017). Jirjis (1995) reported that the main use of biofuels today is for heat production, which is mostly needed during the winter season. There are differences in the supply and the demand of the fuel occurs. This means that the fuel must be stored for a certain period. The storage, however, brings several problems and risks.

Plant biomass is a biological material, and it is subject to relatively rapid deterioration generally in fresh conditions. He et al. (2012) reported that the serious problems connected with the storage of fresh materials include gaseous emissions and dry matter losses. The reason is the high-water content which, in combination with a conventional range of temperature, presents suitable environment for the action of microorganisms (Pari et al. 2015). Reduc-

tion of water content is thus a means for damage prevention.

Wet material is determined by chemical composition, structure and shape of the particles. From the drying point of view, the material water content is a basic descriptive value. Water in the material is generally bound by chemical and physical forces. While drying removes only physically-bound water from material reduction of chemically-bound water is called dehydration.

Heat sharing and moisture transfer in the system of wet material and drying medium accompany the drying.

Kinetics of drying is determined by:
– internal conditions: heat and moisture transfer inside of the dried part,
– external conditions: heat and moisture transfer in the air and by desorption isotherm that

determines hygro-thermal relationship on the interface of the dried material and air.

Internal conditions of drying

In laboratory and technical practice, moisture content of the material (*W*) is frequently described by percentage water content, known as total water content:

$$W = \frac{m_{w}}{m_{s} + m_{w}} \times 100 \qquad (\%) \qquad (1)$$

where: m_{s} – weight of dry matter (kg); m_{w} – weight of water (kg)

Another way to express the water content, used mainly in industrial wood processing, is a value known as specific moisture (x_{m}):

$$x_{m} = \frac{m_{w}}{m_{s}} = \frac{W}{(100 - W)} \qquad (\text{kg/kg}) \qquad (2)$$

Therefore:

$$W = 100 \times \frac{x_{m}}{(x_{m} + 1)} \qquad (\%) \qquad (3)$$

External conditions

From physical point of view, drying medium is a mixture of vapour and the evaporation of moisture occur with a dry gas, usually air. Drying environment is characterized by state and transport properties. Conditions of the drying medium are set by thermodynamic variables: pressure, temperature and composition. Transport properties of the drying medium are described by e.g. viscosity, thermal conductivity and diffusion coefficient of the individual components. Transfer of heat and moisture in the drying medium creates the outer drying conditions. The kinetics of the process is determined by a mutual interaction of the drying environment and the dried material. This interaction is described by the flow of the drying medium over the dried material surface, by sharing of heat and humidity. Basic balance relationships were applied in each elementary volume and also in the whole.

The hygroscopicity threshold is important in terms of water sorption and desorption process-

es. The return water sorption does not take place above the limit of the hygroscopicity, but it occurs under this limit. The limit of the hygroscopicity for lignocellulosic material is approximately in the range from 23 to 29%.

Free water is stored in the cell cavities; there are no dimensional changes of wood during drying. The free water value is greater than the hygroscopicity limit. The bound water is stored in the cell walls between the individual fibres. Its moisture values are below the hygroscopicity limit.

Available data about the drying curves and properties in term of drying are usually focused on drying of the timber. However, these data cannot be used for the assessment of the course of drying of wood chips, sawdust or chopped straw.

Desorption isotherm of moisture is determined at the interface wood – air. Equilibrium moisture content is proportional to the relative humidity with which the wood is in balance. Specific values depend on the type, condition of the wood and the temperature at which the wood is in balance with the environment. Fig. 1 presents typical values of specific wood moisture of moisture desorption at different temperatures. Desorption isotherms determine the relationship on the interface of dried material – air. The courses of the isotherms for other lignocellulosic plant materials are very similar.

From the facts above, it is clear that in terms of the drying process, there is a difference between drying of fresh wood and wood, which has reached a lower water content than the hygroscopicity limit, during storage for example.

The aim of the measurement was to obtain generalized drying rate curves for wood of poplar (*Popu-*
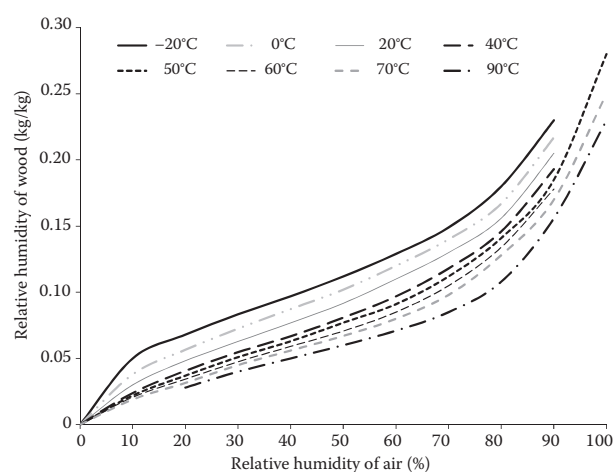

Fig. 1. Desorption isotherms at different temperatures

lus nigra) suitable for energy utilization. The drying parameters of fresh wood and wood that had been stored outdoors were compared.

MATERIAL AND METHODS

Preparation of the samples. For the measurement, samples were taken from an experimental plantation of energy poplar, in the Prosec (Vysočina Region, Czech Republic) locality. One part of samples was collected immediately after harvest (fresh poplar) and the second part of samples was collected from poplar that was stored from March to December on an outdoor uncovered area.

Measurements were carried out using an experimental oven (Fig. 2) (RIAE, Czech Republic) based on the ventilation circuit with radial fan, a controllable electric heating and an adjustable air flow rate.

The samples were dried individually. The experiments were carried out in four replicates. The size of the dried samples was determined by the size of the drying chamber and by the requirement of easy circulation of the drying air around the sample. Sample diameter was 12 mm and its length was 20 mm. The weight of the samples was 6.5 g ± 0.5 g. Thermocouple T was inserted into the centre of the sample and temperature of the material T_m was recorded. After weighing on laboratory analytical balance and preparation, the sample was hung on a hinge of a tensometric balance and placed in oven with predefined parameters (temperature, humidity, flow rate of air) immediately. Recording of temperature inside the sample started immediately after insertion into the oven. The measured temperature was recorded in a data logger. The sample was considered as dried if the drying air temperature and the temperature measured inside the sample for at least 10 min coincided accuracy of 0.5°C.

After the experiment the sample was weighed and then placed in a laboratory oven and was left for 4 hours. Sample was weighed again after cooling and stored in a desiccator. It verified that the sample was dried during the experiment.

Experimental oven. Weight of the sample was continuously measured by a tensometric balance RIAEng PV1. (RIAE, Czech Republic) during the measurement. Measuring range of the balance was 200 ± 0.01 g and the measured weight was recorded in data logger MS6D COMET (COMET system, s.r.o., Czech Republic).

The weight of the sample continuously decreased due to evaporation of water during drying and in a situation where the sample was dried (or its water content was in equilibrium with the ambient air), the weight remained constant.

Air velocity in the whole line was adjustable by regulating of fan rotation speed and by the throttle. The flow rate was measured using a Pitot tube and a differential pressure transducer Greisinger GMUD MP-F (Greisinger, Germany).

Air temperature could be continuously adjusted using a PID microprocessor controller TLK 39 (Ascon Tecnologic, Italy) and three heaters 500 W to 150°C with accuracy ± 1°C. The drying air temperature was measured by a thermocouple type T. All such measuring instruments were connected to data logger COMET MS6D as weight measurements.

Humidity of the drying air was measured during the drying and was measured in a stream of exhaust air by hygrometer Comet TR311 (COMET system, s.r.o., Czech Republic).

In addition to the sample weight, the air flow temperature T_v, relative humidity of exhaust air from the circuit x_v and air velocity v_v were monitored. All data were stored with preset interval to the control unit COMET MS6D. The data were processed

Fig. 2. Experimental oven (RIAE, Czech Republic)

using the standard user platforms MS Excel and were statistically evaluated in software Statistica 12 (Statsoft, USA).

Determination of drying curves. Drying curve characterizes the kinetics of drying. It is determined by the time dependence of integral mean specific humidity from whole sample x_m during drying under stable conditions – temperature, pressure, flow rate and humidity of the drying environment.

The rate of drying N is derived according to time (t) from the curves of drying:

$$N = dx_m/dt \qquad (-/s) \qquad (4)$$

where: x_m – the specific humidity of material (kg/kg); t – time (s)

The rate of drying changes during drying. After an initial period of heating of the material the rate of drying reaches the maximum and then decreases monotonically to zero i.e. the material passes into a steady (dried) state under given external conditions. The rate of drying depends on external conditions and the size, shape and type of material. For characterization of material properties in terms of the drying rate, it is therefore processed according to the specific humidity of the material. The drying rate may be additionally processed in dimensionless form N^*, i.e. in proportion to the rate of free water surface shape of the sample drying (i.e. completely wet sample):

$$N^* = N/N_e \qquad (-) \qquad (5)$$

where: N – rate of drying of the material (–/s); N_e – rate of free water surface drying(–/s)

The dependence of the relative drying rate on the specific humidity is theoretically independent on the external drying conditions (parameters of the drying medium). The impacts of drying conditions on wood properties were determined by Tukiainen and Hughes (2016). The generalized curve of drying of the material can be used for modelling and calculations of parameters of the drying device. The shape of the generalized drying curve is characterized besides the type of material also by its size and shape.

More detailed processes are necessary to be used in a more detailed assessment of the parameters during the drying, which requires determination and monitoring of the sample temperature T_m during the experiment. This allows determining of

the conditions under which the undesired heating of the dried material occurs and evaluating of the kinetics of heat transfer. That is the approximate determination of the coefficient of heat transfer *a*, and moisture transfer coefficient *b*.

When the heat supplied to the material is consumed only for the evaporation of moisture, then the following formula is valid:

$$\alpha \times S(T_v - T_m) = N \times m_s \times l_w \qquad (J/s) \qquad (6)$$

where: S – the surface area of the sample at which heat and moisture between the material and drying medium are exchanged (m^2); T_v – the air temperature (K); T_m – the material temperature (K); N – the rate of drying (–/s); m_s – dry weight (kg); l_w – the specific evaporation heat of water at the temperature of the material (J/kg)

Thereof:

$$\alpha = \frac{N \times m_s \times l_w}{S(T_v - T_m)} \qquad (W/m^2\ K) \qquad (7)$$

Similarly, the following formula is valid for moisture transfer coefficient β:

$$\beta = \frac{N \times m_s}{S(T_v - T_m)} \qquad (kg/m^2 s) \qquad (8)$$

where: x_v – the specific humidity of air (kg/kg); x_m – the specific humidity of the material (kg/kg)

The specific humidity of the drying medium on the surface of the sample can be derived from the sample temperature and moisture desorption isotherms.

In the case of evaporation from the free water surface the following equation then applies:

$$\alpha = \frac{N_e \times m_s \times l_w}{S(T_v - T_e)} \qquad (W/m^2\ K) \qquad (9)$$

where: T_e – the adiabatic temperature of the evaporation from the free water surface (determined only by the parameters of the drying air, in our case the temperature T_v and specific humidity x_a) (K)

according to the relationship:

$$T_e = \frac{T_v - l_w}{c_v(x_e - x_v)} \qquad (W/m^2\ K) \qquad (10)$$

where: x_e – the specific moisture content of the saturated drying medium at the surface temperature of the material (or adiabatic temperature T_e that approximately corresponds to the measured temperature in the constant drying section)

By comparing of Eqs (7) and (9), according to STRU-MILLO and KUDRA (1986), a formula can be derived for relative drying rate determination by measuring of the drying rate *N* and drying rate equivalent during evaporation from the free water level N_e:

$$\frac{N}{N_e} = \frac{T_v - T_m}{(T_v - T_e)} \qquad (-) \qquad (11)$$

Therefore, it is appropriate to add material temperature recordings to the drying curves. The generalized drying curves can be accompanied by the temperature T_m of the material processed in a dimensionless form i.e. as a relative temperature of the material:

$$T_m^* = \frac{T_m - T_e}{T_v - T_e} \qquad (-) \qquad (12)$$

where: T_v – the temperature of the drying medium (or the temperature of the material in the dry state) (K); T_e – the adiabatic temperature of evaporation of free water surface (K)

The resulting values of the dimensionless temperature are in the interval from 0 to 1, i.e. for

$T_m = T_e$ is $T_m^* = 0$ and for $T_m = T_a$ is $T_m^* = 1$

The obtained values of heat transfer coefficient *a* and humidity b represent the mean integrated values over the entire surface of the sample. Effective area of the dried material *S* and also the shape and the values of coefficients a and b are changed during the shrinkage of the material. Basic inaccuracies are the differences between the locally measured temperature T_m and a mean integrated temperature of the sample surface, for which the relations were derived.

RESULTS AND DISCUSSION

For comparative experiment drying air temperature of 90°C and air velocity 2.8 m/s were set. Sample temperature was increased from the temperature upon insertion into the device to a value equal to the temperature of the drying air (Fig. 3). The water content in the samples decreased from an initial value to a value of equilibrium with the drying air. The mean value of the input values of relative humidity of fresh poplar samples was 0.53 kg/kg.

In the same way, drying properties of the stored poplar wood were established (Fig. 4). For stored poplar samples, the input mean relative humidity of the samples was 0.42 kg/kg. Experimental drying and drying process parameters (temperature, humidity, flow velocity and flow rate of the drying air) were the same as in the drying samples of fresh poplar.

Fig. 5 shows progress of the generalized rate of the drying curves for fresh and stored poplar, recalculated according to Eqs (10) and (11).

This is evident from the curve that the progression rate of drying is increasing in the initial stage of drying, while the drying rate is decreasing after a peak attainment. With decreasing material humidity drying conditions for all samples are worsened and the drying rate decreases.

According to the obtained results it is possible to observe that the storage affects the drying rate. As BARONTINI et al. (2014) refer, free storage, which could be solved as uncovered heap on plastic sheets, presents the cheapest and suitable solution for renewable fuel market. NURMI (1999) also recommends storage before comminution as an effective measure against biomass degradation. On the other hand, long-term storage of the poplar wood leads to reduction of product quality, especially if
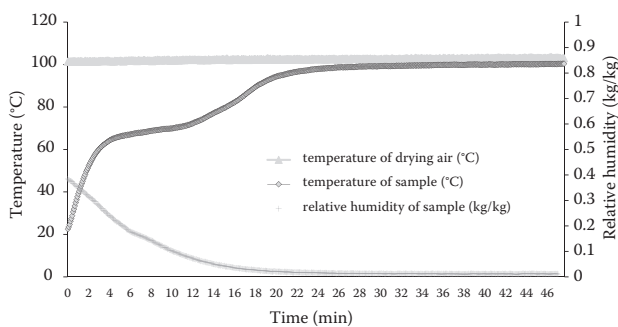

Fig. 3. Drying air temperature and relative humidity and temperature of the sample – poplar (*Populus nigra*), fresh sample, perpendicular section of branches, full profile
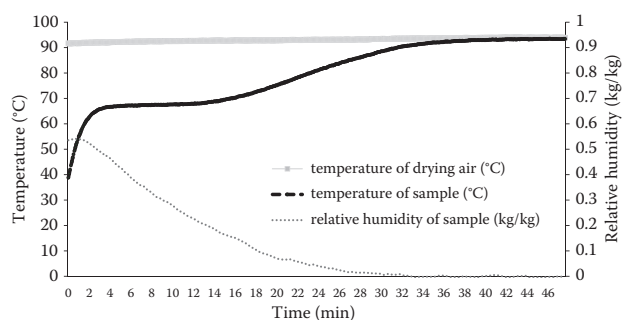

Fig. 4. Drying air temperature and relative humidity and temperature of the sample – poplar (*Populus nigra*), stored sample, perpendicular section of branches, full profile
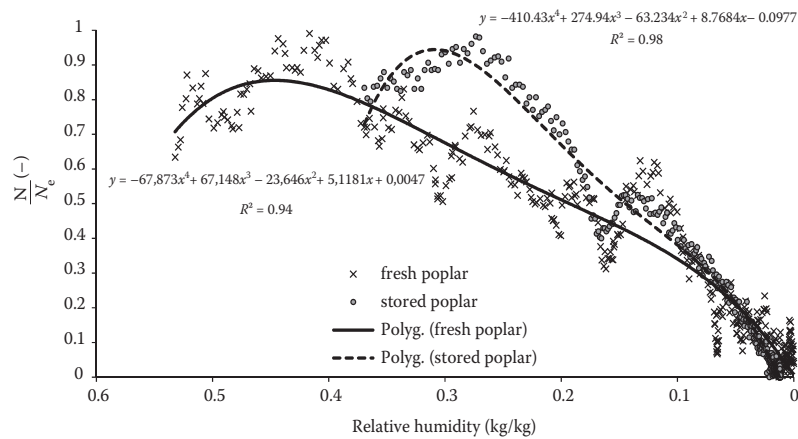
Fig. 5. The generalized rate of the drying curves for fresh and stored poplar (*Populus nigra*), perpendicular section of branches, full profile

the storage period exceeds few months (Pochi et al. 2015).

CONCLUSIONS

The drying parameters of poplar wood samples were determined by measuring in an experimental oven. The relative rate of drying was determined as the main parameter. Curves of the relative drying rate were determined in dependence on wood relative humidity of the. A higher drying rate was presented for the poplar that was stored in outdoor conditions. The partial conversion of water bonds in the material is the probable cause. This is caused by drying and re-moistening of wood with a change of equilibrium state of the stored wood and the surrounding environment.

The rate of drying was lower regardless of the relative humidity of material in case of the fresh material drying. From the energy consumption point of view it seems appropriate, based on the obtained results, to incorporate the material storage phase with sufficient aeration ensured between harvest and further processing.

In practice, the operation can be carried out in the form of temporary storage on the edge of the plantation or in the facility storage. Further studies should be also focused on the effect of the length of storage on the parameters of drying together with the quality evaluation of the product.

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