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MOISTURE CONDUCTIVITY AND DENSITY OF INDUSTRIAL WOODS: A STUDY FOR EFFECTIVE DRYING

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ABSTRACT

An analysis of the physical properties of the main industrial tree species revealed significant variation across growing regions with different climatic conditions. For drying sawn timber products, convection chambers equipped with automatic systems with pre-set schedules designed for tree species native to the countries where dryers are manufactured are most widely used. It does not always lead to positive results. Adjusting the parameters of the modes requires the density and moisture-conductivity coefficients for industrial tree species. The dependence of moisture conductivity coefficients in the transverse directions of moisture movement on temperatures in the 25 °C – 80 °C range was determined. Adequate regression equations for the dependence of moisture conductivity coefficients on temperature in the tangential and radial directions were obtained. The values of the average basic density of these tree species originating from different regions and its dispersion determined experimentally were as follows: pine 414 kg·m^{-3} ± 11%; alder 448 kg·m^{-3} ± 9%; oak 569 kg·m^{-3} ± 10%; ash 640 kg·m^{-3} ± 6%; hornbeam 667 kg·m^{-3} ± 7%. These values were used to determine the analytical dependence of the moisture conductivity coefficients on the basic density and its dissipation, which is necessary for developing optimal schedules of drying sawn timber by adequately modelling convection drying and predicting process quality.

Keywords: lumber; convection drying; processing temperature; moisture conductivity coefficient; basic density.

INTRODUCTION

Drying sawn timber is the most time-consuming and energy-intensive process in wood processing. Today, convection chambers are mainly used for their implementation, in which the drying agent, i.e., air, is heated by contact with heaters filled with hot water. Using hot water as a heat source prevents temperatures from rising above 70-80 °C. This is because wood is increasingly being used as a construction material. The use of wood as a structural material requires compliance with mechanical property requirements, particularly strength (Toba *et al*., 2022; Perre *et al*., 2014).

Such 'low-temperature' dryers are used by many woodworking companies. They all have virtually the same design and differ only slightly in the automation system and drying schedules. The latter is designed to account for the characteristics of tree species grown in the countries where the chambers are manufactured, so the operating parameters often need to be adjusted to achieve a high-quality result (Simpson, 2007; Chen *et al*., 2020; Tomad *et al*., 2023).

Meanwhile, it is known that even within the same country, both the physical and mechanical properties of wood depend on the region of growth. For example, the central regions where pine grows include Chernihiv, Volyn, and Zhytomyr, which have different soils and humidity. In a more humid region, raw wood materials will be less dense and, accordingly, will have worse mechanical properties. However, the process of drying sawn timber products will be easier.

In Ukraine, industrial tree species such as pine, oak, ash, hornbeam, and alder are popular for manufacturing solid wood products. The most widespread areas of oak distribution are the Forest-Steppe and Polissya regions, with average fundamental density values of 554 $kg{\cdot}m^{-3}$ and 600 $kg{\cdot}m^{-3}$ (Lakyda *et al*., 2011). The distribution of hornbeam (with average fundamental density values of 620 $kg{\cdot}m^{-3}$ and 710 $kg{\cdot}m^{-3}$) and ash (with average fundamental density values of 600 $kg{\cdot}m^{-3}$ and 680 $kg{\cdot}m^{-3}$) is dominated by the Forest-Steppe zone, mainly Vinnytsia and Sumy regions, and alder (with average fundamental density values of 410 $kg{\cdot}m^{-3}$ and 490 $kg{\cdot}m^{-3}$) by Polissia (Zhytomyr and Volyn regions) (Lakyda *et al*., 2020). The Polissia region is characterized by higher air and soil humidity, while the Forest-Steppe region is drier. Therefore, the properties of timber from the different areas require an individual approach to drying sawn timber products. It is known that hardwood lumber with a high basic density is difficult to dry (Denig *et al*., 2000; Walker, 2006).

Unlike other wood processing processes, such as sawmilling, joinery, and furniture production, where the result is evident during the process, the drying result is only visible afterward, and it is impossible to mitigate potential negative consequences. For example, if the movement of moisture is too fast under the influence of heat, which, on the one hand, reduces the processing time and, on the other hand, contributes to the occurrence of drying defects in the form of cracks due to high drying stresses. To understand and properly develop wood drying technology, it is of primary importance to study the entire complex of numerous elementary heat and moisture transfer phenomena. The theoretical study of these phenomena led to the creation of a mathematical model of interconnected heat and mass transfer, which enabled the description of non-isothermal drying, sorption, and two-phase filtration from a single perspective (Elustondo, 2021; Dzurenda and Deliiski, 2010). The theoretical studies developed to date on various approaches to solving the problems of wood drying focus on the need to consider individually the phenomena that limit the drying mechanism and the material's quality. The moisture conductivity coefficient is the key to calculating the drying time in any process model. Its value depends on many factors, such as the anatomical structure of wood, anisotropy, basic density, which characterizes the mass of dry wood per unit volume of green wood, and the processing temperature (Lykov, 1968; Pinchevska *et al*., 2023).

Given that both wood and energy prices are rising, poor-quality drying of domestic tree species can result in significant losses due to incorrect processing time calculations. Therefore, to build adequate models for drying sawn timber products that allow calculating the expected drying time and predicting the achievement of the required process quality, it is necessary to have quantitative values for the physical quantities that affect the moisture-removal process in wood. Therefore, it is important to determine the moisture-conductivity coefficients for different types of wood.

The aim of the research is to determine the coefficients of moisture conductivity and basic density for pine, alder, oak, ash, and hornbeam as key parameters for modelling and the development of rational drying schedules.

MATERIALS AND METHODS

Radially and tangentially sawn timber made of pine (*Pinus sylvestris* L.), oak (*Quercus robur* L.), ash (*Fraxinus excelsior* L.), hornbeam (*Carpinus betulus* L.), and alder (*Alnus glutinosa* L.) wood were selected to determine the moisture conductivity and basic density. Test samples were cut to determine the moisture conductivity coefficients, and samples measuring 20×20×30 mm were used to determine the basic density. The number of samples was 27 per tree species, for a total of 300 samples examined.

The procedure for determining the coefficient of moisture conductivity includes auxiliary experiments to determine the limit of hygroscopicity of wood, *Whl*, and main experiments (Pinchevska *et al*., 2018). For the auxiliary experiments, wood samples measuring 3×30×50 mm were first dried in a thermostat at a temperature of t = 103 ± 2 °C to a completely dry state, m_0. Then they were humidified in hygroscopic covers placed in a water-charged desiccator (Figure 1a) at 25, 40, 60, 80 °C. The weight of the samples was monitored hourly, and the experiment was completed when the samples reached a constant weight, m_{hl}. The formula determines the moisture content of the hygroscopic limit:

$$W_{hl} = \frac{m_{hl} - m_0}{m_0} 100\% \quad (1)$$

The main experiments used tangential and radial sawn wood samples with dimensions of 5×50×70 mm and 10×50×70 mm, respectively. The samples, dried to a completely dry state, were placed in the desiccator charged with a sulfuric acid solution with a density of ρ = 1260 kg·m^{-3} to achieve a uniformly distributed initial moisture content W_{in} across the cross-section, which corresponds to the equilibrium moisture content W_{emc} = 12% (Figure 1b).

a b

Fig. 1 Location of the samples: a - samples in hygroscopic covers placed in a water-charged desiccator; b - samples in a sulfuric acid-charged desiccator.

The samples were then wrapped in hygroscopic covers and left in a water-charged desiccator to achieve a steady-state value of dimensionless humidity $\overline{E}$, (Pinchevska *et al*., 2023):

$$\overline{E} = \frac{W_{hl} - W_f}{W_{hl} - W_{in}} \quad (2)$$

Where: W_{hl} – moisture content of the hygroscopic limit, %, which is determined by moisture sorption in a saturated medium at a certain temperature;
W_{in} – initial moisture content of the sample, %;
W_f – final moisture content of the sample, %.

The conditional moisture conductivity coefficients for samples of each thickness are calculated by the formula (Pinchevska *et al.*, 2023):

$$a'' = \frac{\pi S^2}{16\tau}\left(1 - \overline{\text{E}}\right)^2 \quad (3)$$

Where: S – sample thickness, mm;
τ – duration of the experiment, h.

The actual coefficient of moisture conductivity is calculated by the formula (Pinchevska *et al.*, 2023):

$$a' = \frac{(S_2 - S_1)\cdot\overline{a_2''}\cdot\overline{a_1''}}{S_2\cdot\overline{a_1''} - S_1\cdot\overline{a_2''}} \quad (4)$$

Where: $\overline{a_1''}$ i $\overline{a_2''}$ – average values of conditional moisture conductivity coefficients for samples of two different thicknesses $S_1 = 5$ *mm* and $S_2 = 10$ *mm*.

Determination of the basic density, ρ_b, $kg{\cdot}m^{-3}$, as an important indicator widely used for calculations of the processes of heating, drying, and impregnation of wood is determined by the formula:

$$\rho_b = \frac{m_0}{V_{max}} \quad (5)$$

Where: m_0 – the weight of the absolutely dry sample, kg;
V_{max} – sample volume at humidity above the saturation of cell walls, m^3.

RESULTS AND DISCUSSION

The results of determining the moisture conductivity coefficients for the researched tree species are shown in Figure 2.

In all studied tree species, an increase in the values of moisture conductivity coefficients with increasing temperature was observed, which is associated with a decrease in moisture viscosity (Lykov, 1968; Pinchevska *et al.,* 2018). The nature of the dependence of the moisture conductivity coefficients on temperature for each species is determined by the peculiarities of its structure and density. It was found that this process is adequately described by quadratic equations for such as pine and alder, which may be assocoiated with lower density compared to hardwood species. The adequacy testing was performed using Fisher's, *Fi*, and Student's, *St*, criteria. It can be seen that the calculated values of the criteria, Fi_{calc}, St_{calc}, are lower than the tabulated ones, Fi_{tab}, St_{tab}, $0.93 \leq Fi_{calc} \geq 1.05$; $2.5 \leq Fi_{tab} \geq 2.97$; $0.03 \leq St_{calc} \geq 0.05$; $St_{tab} = 2.770$:

Pine:

Tangential direction $\quad a^{`} = 0.0013t^2 - 0.0114t + 2.2915 \quad (6)$

Radial direction $\quad a^{`} = 0.0015t^2 - 0.0146t + 3.3267 \quad (7)$

Alder:

Tangential direction $\quad a^{`} = 0.0011t^2 + 0.0213t + 0.0794 \quad (8)$

Radial direction $\quad a^{`} = 0.0012t^2 + 0.0235t + 0.1599 \quad (9)$

For hardwoods, the obtained equations correspond to the adequately described polynomial dependence $(0.33 \leq Fi_{calc} \geq 6.84;\ 8.89 \leq Fi_{tab} \geq 6.09;\ 0.19 \leq St_{calc} \geq 1.99;\ St_{tab} = 2.77)$

Oak:

Tangential direction $$a^{`} = 0.00006t^3 - 0.0079t^2 + 0.4042t - 5.0758 \quad (10)$$

Radial direction $$a^{`} = 0.00005t^3 - 0.0076t^2 + 0.4040t - 5.0920 \quad (11)$$

Ash:

Tangential direction $$a^{`} = 0.00004t^3 - 0.0066t^2 + 0.3543t - 4.7747 \quad (12)$$

Radial direction $$a^{`} = 0.00003t^3 - 0.0047t^2 + 0.2743t - 3.5418 \quad (13)$$

Hornbeam:

Tangential direction $$a^{`} = 0.00003t^3 - 0.0051t^2 + 0.2641t - 3.5553 \quad (14)$$

Radial direction $$a^{`} = 0.00003t^3 - 0.0047t^2 + 0.2555t - 3.2712 \quad (15)$$

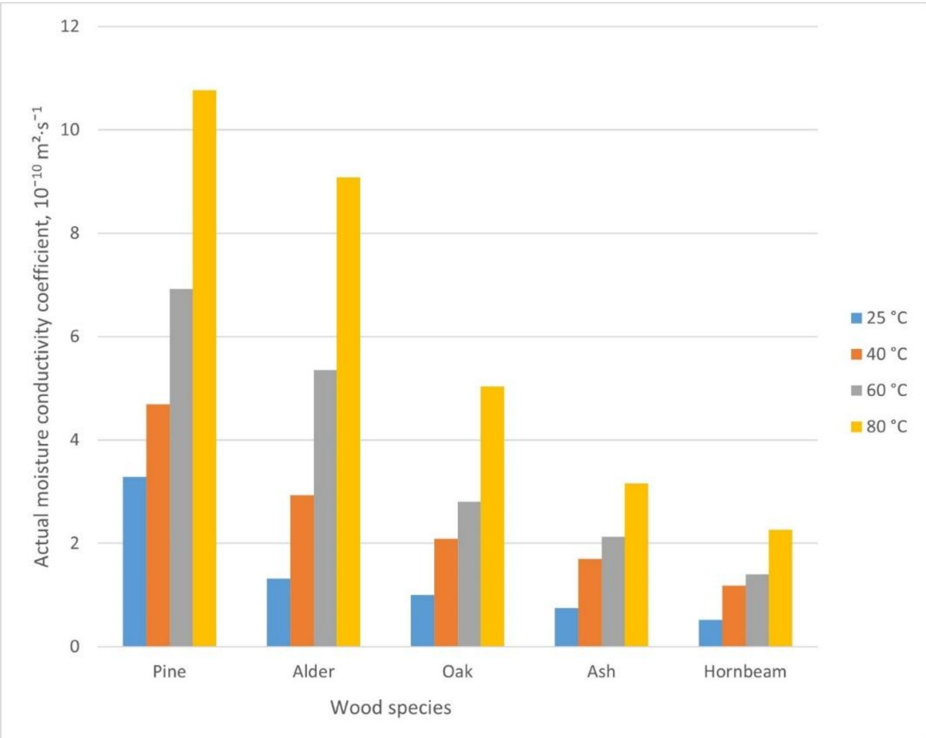

Fig. 2 Effects of tree species on the actual moisture conductivity coefficient at different processing temperatures.

The correlation between moisture flow values in the radial and tangential directions across different species was established, ranging from 1.1 to 1.6. It is due to the significant influence of the ray cells, in which the anatomical elements of wood are arranged longitudinally. In addition, the ray cells' width varies from 0.005 mm to 1 mm, and their percentage of the total trunk volume can inhibit or accelerate moisture removal from the wood (Vintoniv *et al*., 2007). Even though oak has the widest ray cells and the percentage of its content in the trunk is 36%, most of the studied species (Ugolev, 2007; Vintoniv *et al*., 2007), the value of the coefficient of moisture conductivity is almost two times lower than that of pine.

The results of the basic density study are shown in Figure 3.

Comparison of the average fundamental density values for the studied species with those reported by previous researchers showed that the results are ambiguous. The results of large-scale studies conducted by Lakyda *et al*. (2020) show a similar trend. However, according to Biley *et al*. (2008), the basic density of ash wood is 13% lower and close to values obtained for wood from the Russian Far East, which is most likely explained not by their own experiments but by reference data.

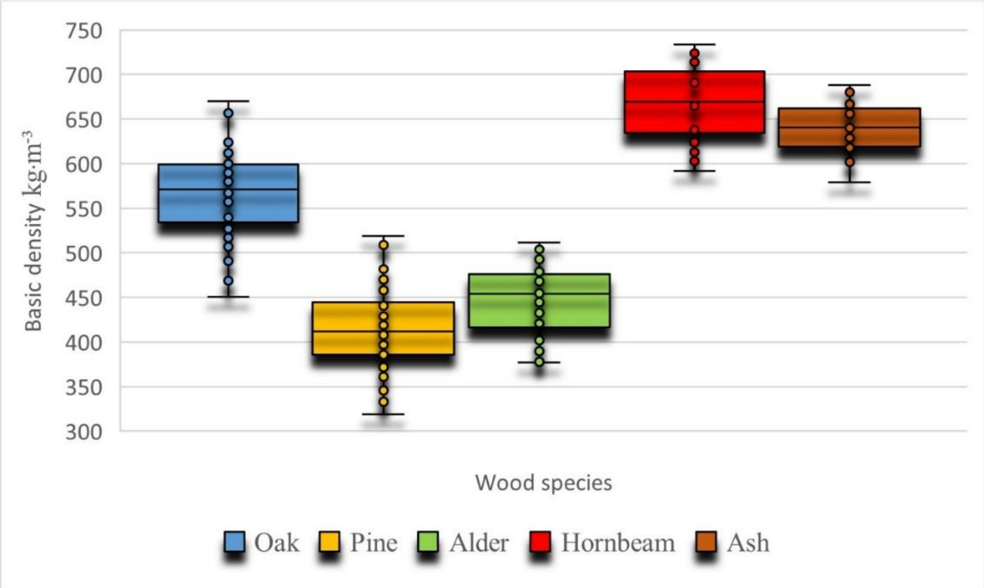

Fig. 3 Average values of the basic density of different species.

The basic density of wood shows a relatively large dispersion due to the wide distribution of tree species across the country. Since such a physical quantity as wood basic density is fundamental in determining many physical and mechanical properties, its dependence on the place of growth of wood raw materials has a direct impact on their variability (Majka *et al*., 2023).

The dependence of the moisture conductivity coefficients on the basic density at different temperatures is shown in Figure 4.

Given the complex dependence of the moisture conductivity coefficients on temperature and basic density of wood, the next step was to establish their analytical description. In addition, for the further development of rational drying schedules and the determination of processing time, it will be necessary to consider the dispersion of the basic density, which will certainly affect the dispersion of the moisture conductivity coefficients.

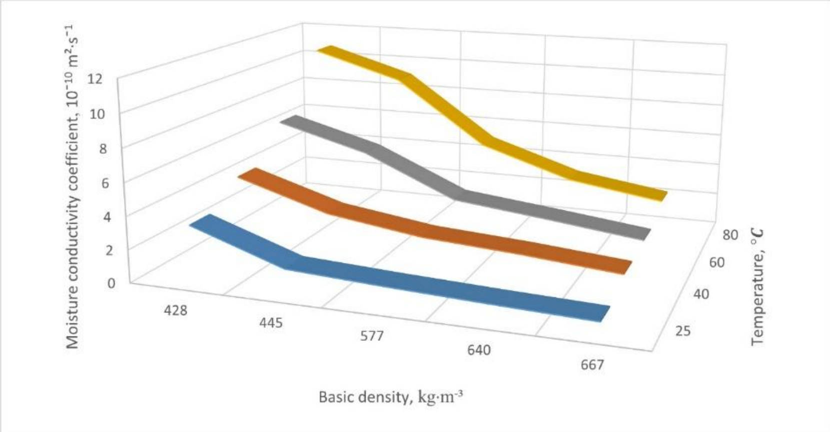

Fig. 4 Visualization of the dependence of the moisture conductivity coefficients in the transverse direction on the average values of the basic density.

Since the drying of sawn timber is a stochastic process (Pinchevska *et al*., 2016), accounting for the dispersion of the moisture conductivity coefficient, which drives moisture movement within the material, will allow predicting the drying quality of different types of wood when applying different drying schedules. In addition, the creation of databases of the properties of various tree species will facilitate the use of artificial intelligence to model and control the drying process (Elustondo *et al*., 2023).

CONCLUSION

Analysis of the properties of industrial tree species in Ukraine showed that they depend on the region of origin. This affects achieving the desired results when modelling the process of drying sawn wood products. The scientific novelty lies in determining the moisture-conductivity coefficients of industrial tree species, which are necessary for developing rational drying schedules and determining the objective time of the process. Adequate equations for the dependence of moisture conductivity coefficients on the processing temperature have been obtained. The dispersion of fundamental density values for the studied tree species, which affects the variability of moisture conductivity coefficients, was quantified.

Further research is needed to determine the relationship between the moisture conductivity coefficients depending on the basic density of wood and temperature, the result of which will allow us to select rational drying schedules, even with the use of artificial intelligence, for each case, taking into account the dispersion of the basic density of wood.

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