2. **Belyankin, F., Yatsenko, V.** (1960) *Prochnost i deformativnost derevyannykh sterzhney pri tsentralnom, vnetsentralnom szhatii i chistom izgibe* [Strength and deformability of wooden rods at the central, eccentric compression and pure bending]. Kyiv: USSR Academy of Sciences (in Russian).

3. **Belyankin, F., Yatsenko, V., Dybenko, G.** (1964) *Prochnost i deformativnost sloistykh plastikov*. [Strength and deformability of laminated plastics]. Kyiv: Naukova dumka (in Russian).

4. **Gayda S.V., Voronovich V.V.** (2011) Investigation of the features of bending of post-consumer wood // Proceedings of the Conference, Mari State University, 190-192 (in Russian).

5. **Gayda S.V., Voronovich V.V.** (2011) Comparative analysis of bending particularities for various post-consumer wood species and age categories // Forestry, Forest, Paper and Woodworking Industry, 37.1:84-88. (in Ukrainian).

6. **Gayda S.V., Maksymiv V.M., Tunytsya T.Yu.** (2008) Elaboration of post-consumer wood classifier // Forestry, Forest, Paper and Woodworking Industry, 34:55-68. (in Ukrainian).

7. **Gayda S.V.** (2009) Potential of post-consumer recovered wood and possible ways of it using in Ukraine // Forestry, Forest, Paper and Woodworking Industry, 35:63-83.

8. **Gayda S.V.** (2008) Chemical compound and degree of its contamination as the basis to systematization of post-consumer wood / Forestry, Forest, Paper and Woodworking Industry, 34:68-79. (in Ukrainian).

9. Gayda S.V. (2009) The effective use of post-consumer wood is basis for diminishing of CO_2-emission // Scientific Herald, 19.14:72-89. (in Ukrainian).

10. **Gayda, S.** (2011) Recycled of post-consumer wood is for the production of particleboard in Ukraine. Proceedings of the XXI International symposium Adhesives in Woodworking Industry (Slovakia, Zvolen Juve 29 – July 01. 2012). TU Zvolen, 108-121.

11. **Gayda, S.** (2013) The technological solutions for recycling of post-consumer wood. Proceedings of I International Interdisciplinary Scientific Conference Formation of stable outlook as the basis of sustainable development (Ukraine, Lviv, 14-16 March 2013) UNFU: Lviv, 5-11.

12. **Gayda, S.** (2013) Techniques for utilization of post-consumer wood in the production of fuel pellets and briquettes. Proceedings of the XXI International symposium Adhesives in Woodworking Industry (Slovakia, Zvolen Juve 23-26. 2013). TU Zvolen, 119-130.

13. **Gayda, S.** (2014) The theoretical rationale for the approach on the prediction the strength of particleboard from recycled wood. Collection of scientific works, BGITA, 38, 212-216.

14. **Gayda S.V.** (2013) Resource-saving technologies of recycling of post-consumer wood. Scientific Bulletin of NULES of Ukraine: Technology and Energy of agroindustrial complex 185(2):271-280, (in Ukrainian).

15. **Gayda S.V.** (2013) Bases of secondary wood resources classifier formation. Scientific Works of the Forestry Academy of Sciences of Ukraine 11:208-215 (in Ukrainian).

16. **Gayda S.V.** (2000) Матеріали для виготовлення виробів з деревини / Materials for the Productsion of wood Productss, 160 p. (in Ukrainian).

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Побудова математичних моделей залежності радіусу вигину ДВП стосовно її товщини та часу зволоження

Представлено обробке експериментальних досліджень, необхідних для виробництва вигнутих предметів меблів з ДВП. Знайдено математичну залежність, яка вивчає процеси, використовуючи методи інтерполяція і наближення. Представлено мінімальний радіус вигину предметів меблів залежно від товщині пластин при різних умовах вологості клею.

Ключові слова: різьблені елементи меблів, ДВП, мінімальний радіус, інтерполяція, апроксимація.

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ANALYSIS OF PHYSICAL FACTORS AFFECTING THE DRYING PROCESS OF LUMBER

An analysis of physical factors affecting the drying process of lumber has been done. Considered is their influence upon the drying rate and qualitative characteristics of the dried wood material. Also methods of moisture removal from wood have been examined. Described are equations for heat-

moisture conduction. Also an analysis of these equations has been carried out. The characteristic patterns of moisture movement within wood have been considered.

Keywords: wood, lumber, humidity, pressure, gradient, temperature, heat conduction, evaporation, moisture, moisture transfer, moisture content.

Introduction. Green lumber that has not been properly dried is not suitable for further use. To facilitate effective use of wood material, excess water should be removed from the wood, that is, a drying process is to take place the purpose of which is changes in the lumber's physical and service properties due to its moisture content change. Drying of lumber is a physical process of moisture removal based on the process of heat-moisture exchange. When warm air comes into contact with moist wood material, the thermal energy is transmitted to the wood and the moisture is changed into water vapour for evaporation process to take place. As a result of this process, the performance figures of lumber change making this lumber suitable for furniture making and construction purposes [5-13].

Dry lumber has higher mechanical strength, it is more resistant to the attack of fungi and insects, and wood products have good shape and dimensional stability.

Drying of lumber is a complex physical process whose peculiarities and characteristics are conditioned by a number of physical phenomena. Drying of lumber requires energy to evaporate the moisture from the lumber and the environment which would be capable of absorbing the water vapour, also it is necessary to ensure air circulation for transferring the vapour. Free water is the first to evaporate during the process of lumber drying. All the free water having been evaporated, the lumber reaches the so-called the fiber saturation point (FSP). The moisture content at FSP ranges from 20 to 35% depending on wood species. The moisture remaining in wood below FSP is called bound water. The removal of bound water from lumber requires much higher consumption of energy than evaporation of free water.

Discussion and results. Lumber drying results from moisture movement from the inner layers towards the surface layers. Drying of lumber consists of the following processes:

- evaporation of water from the surface of the lumber into the environment;
- moisture movement from the inner layers towards the surface layers.

The drying process starts with the surface moisture evaporation immediately after the wood comes to be exposed to the ambient air. The surface evaporation creates moisture gradient that increases in the direction towards the centre.

Green wood, in addition to hygroscopic water which is chemically and physically bound with the cell walls, normally contains free water which is held in the cell cavities (Lumina) and intercellular spaces [2]. Heartwood of conifers has a moderate moisture content (W=31-35%), sapwood is noted for its high moisture content (W=120-160%). Lumber of hardwood has higher moisture content (W=80-90%, for example poplar wood has W=212%), while there is no pronounced difference in moisture content between sapwood and heartwood [3]. Moisture content in lumber of softwoods is higher for upper parts of the tree due to a predominance of sapwood there, while lumber of hardwoods does not exhibit essential distinction in moisture content in this respect. Normally, the moisture content in wood is lower as the tree grows older, that is why lumber produced from young trees has higher moisture content than that produced from mature trees. As a rule, uneven-aged forests yield lumber of higher moisture content than even-aged forests do, while lumber from coppice forests is of higher moisture content than that of high forests [4].

Anisotropic nature and anatomic structure of wood influence the moisture movement in different directions relative to the wood grain. Moisture conduction is the least in the tangential-to-the grain direction. Moisture conduction in the parallel-to-the grain direction is 15-20 times higher than in the tangential-to-the grain direction [1].

By using expression (1), it is possible to determine the relationship between water conduction in the tangential (a_T) and radial (a_r) directions:

$$\frac{a_r^{'}}{a_T^{'}} = 1 + \frac{2L}{100\%} , \tag{1}$$

where L is the volume of woodrays voids.

For water evaporation to take place, it is necessary that the surrounding air should be unsaturated, while to ensure internal moisture movement toward the surface layers, as well as toward the inner layers moisture gradient should be maintained. The evaporation process occurs by Dalton's Law according to which vapour (like all gases) moves in the air in the direction toward the region of minimum pressure, and the evaporation rate is proportional to the pressure difference of water vapour at the surface zone [5]. The law (2) for the total pressure of gas mixture

$$P = \sum_{i-1}^{n} p_i = p_1 + p_2 + ... + p_n . \tag{2}$$

The law (3) for solubility of gas mixture components $m_i = \frac{p_i}{P}$, (3)

where P is the pressure.

But Dalton's formula for determining the amount of evaporated (condensed) moisture in capillars is unsuitable to use due to considerable difficulties associated with determination of mass-transfer coefficient and mass-exchanger area.

The moisture gradient ensures the movement of water and water vapour within lumber from zones of higher to zones of lower moisture content. The patterns (4) of such movement are called moisture conduction

$$i_H = -a^{'} \rho_0 \frac{dU}{dX} , \tag{4}$$

where $a^{'}$ is the coefficient of moisture conduction; ρ_0 is the density of oven dry wood.

Moreover, the moisture conduction inside lumber can be caused by temperature gradient due to which moisture moves from warmer towards cooler layers of wood. The movement rate grows up as the temperature gradient increases.

The rate of internal moisture movement is controlled by the moisture and temperature gradients inside the lumber. In most cases, this rate, except for wood with very high moisture content, is conditioned by moisture gradient, wood density, temperature. On the other hand, elevated temperatures lead to lower mechanical strength and counter stresses that occur in lumber during the drying process, these are minimal at moisture content above the FSP. The movement of moisture inside lumber depends on its permeability for moisture and vapour, that is, the structure of wood. Moisture can be transported through cell lumina, through vessels of hardwoods and also through intervessel pitting with opening in the membranes [3].

The driving force for moisture movement is due to the presence of force gradient of surface tension in wood capillary meniscus and, at time, this mechanism is due to manifestation of liquid osmosis, as well as gas diffusion in the direction of vapour pressure gradient in the cavities of the surrounding cells.

The presence of pressure gradient inside lumber is responsible for molar vapour movement. This pressure gradient causes no uniform distribution of the movement rate. The occurrence of such pressure is attributed to moisture evaporation from capillary and vessel voids at elevated temperatures [5]. The capillary and vessel voids present rather a confined (sealed) space and, therefore, the water vapour is not easy to get into the atmosphere, which result in pressure build-up. The movement (5) of water vapour and liquid water due to the pressure inside the capillars and vessels as well as the movement intensity can be described by the following equation:

$$i_p = -b\frac{dP}{dX},\qquad (5)$$

where: b is the coefficient of moisture molar transfer; $\frac{dP}{dX}$ is the pressure gradient in wood material.

Provided that all the three driving forces (6) are involved, the expression will take the following form:

$$i_\Sigma = -a'\rho_0\left(\frac{dU}{dX} + \delta\frac{dT}{dX}\right) - b\frac{dP}{dX}\ .\qquad (6)$$

The diffusion rate of vapour through cell lumina, open vessels and pores is thousands times greater than that for other types of flow, thus ensuring a very high rate of drying green lumber, this is especially true when interior boiling occurs.

Moisture movement is going on as long as free water is present in the surrounding cells [4]. After the removal of free water, the cell walls will contain only bound water (hygroscopic water) the movement of which occurs at the expense of water molecules transfer through the cell walls in the direction of moisture concentration gradient as well as due to water vapour diffusion through cell lumina in the direction of vapour pressure gradient [2]. Free water and vapour contained in cell lumina and intercellular spaces also move in accordance with the mechanism for molecular movement through cell walls. Permeability of wood by gases and liquid decreases with wood's higher density, increased number of growth rings, with presence of secreting gums and resins [4].

The increase in diffusion rate at the expense of moisture concentration gradient is somewhat limited due to reduced wet ability of oven dry wood, which might block the moisture permeability, that is, occurrence of casehardening and formation of water pockets. Diffusion rate increases with temperature rise, while lower temperatures slow down the diffusion rate. The evaporation rate is a function of the ambient temperature and relative humidity. The evaporation rate increases with increasing temperature and decreased atmospheric relative humidity [3]. The evaporation rate remains steady provided that the temperature and moisture conditions are constant. The heat-moisture conduction is a complex physical process. The moisture movement occurs in the liquid and gaseous states and the driving forces are vapour partial pressure as well as the liquid pressure in capillars.

The equation for heat-moisture conduction (7) takes the following form:

$$i_t = -a'\rho_0\delta\frac{dT}{dX},\qquad (7)$$

where δ is the coefficient of heat – moisture conduction; dT/dX is the temperature gradient in wood.

Heat-moisture conduction in capillary-porous substances consists of capillary heat-moisture permeability, relative thermal diffusion of liquid and vapour.

The coefficient of heat-moisture conduction is linearly proportional to temperature rise. The absolute value of the heat-moisture coefficient decreases with increased moisture diffusivity or molecular diffusion. The moisture gradient, which is produced by heat-moisture conduction, varies proportionally with the temperature gradient [5]. The water flow caused by heat-moisture conduction will also take in additional amount of heat to move in the direction of the main heat flux.

Conclusions. Based on the literature source, the analysis of the drying process of lumber has shown that moisture movement within lumber is due to the presence of three driving forces: moisture content gradient, temperature gradient, internal pressure.

References

1. **Vintoniv, I., Sopushynskyy, I., Tayshinher, A.** (2007) *Derevynoznavstvo* [Wood Science]. Lviv: Apriori (in Ukrainian).

2. **Biley, P., Sokolovskyy, I., Pavlyust, V., Kunynets, Ye.** (2010) *Kerivni tekhnichni materialy z tekhnolohiyi kamernoho sushinnya pylomaterialiv* [Guiding technical materials from lumber drying technology]. Uzhgorod: Karpaty (in Ukrainian).
3. **Biley, P., Pavlyus, V.** (2008) *Sushinnya ta zakhyst derevyny* [Drying and protection of wood]. Lviv (in Ukrainian).
4. **Sergovskyy, P., Rasev, A.** (1987) *Gidrotermicheskaya obrabotka i konservirovanie drevesiny* [Hydrothermal treatment and preservation wood]. Moscow: Lesnaya promyshlennost (in Russian).
5. **Biley, P.** (2005) *Teoretychni osnovy teplovoyi obrobky i sushinnya derevyny* [Theoretical foundations heat treatment and drying of wood]. Kolomyia: Vik (in Ukrainian).
6. **Gayda S.V.** (2009) The effective use of post-consumer wood is basis for diminishing of CO_2-emission // Scientific Herald, 19.14:72-89. (in Ukrainian).
7. **Gayda, S.** (2011) Recycled of post-consumer wood is for the production of particleboard in Ukraine. Proceedings of the XXI International symposium Adhesives in Woodworking Industry (Slovakia, Zvolen Juve 29 – July 01. 2012). TU Zvolen, 108-121.
8. **Gayda, S.** (2014) The theoretical rationale for the approach on the prediction the strength of particleboard from recycled wood. Collection of scientific works, BGITA, 38, 212-216.
9. **Gayda S.V.** (2012) Production techniques and properties of fuel pellets produced from post-consumer wood // Forestry, Forest, Paper and Woodworking Industry, 38: 112-150.
10. **Gayda S.V.** (2013) Resource-saving technologies of recycling of post-consumer wood. Scientific Bulletin of NULES of Ukraine: Technology and Energy of agroindustrial complex 185(2):271-280, (in Ukrainian).
11. **Gayda S.V.** (2013) Bases of secondary wood resources classifier formation. Scientific Works of the Forestry Academy of Sciences of Ukraine 11:208-215 (in Ukrainian).
12. **Gayda S.V.** (2000) Матеріали для виготовлення виробів з деревини / Materials for the Productsion of wood Productss, 160 p. (in Ukrainian).
13. **Gayda, S.** (2013) Technologies and recommendations on the utilization of post-consumer wood in woodworking industry. Forestry, Forest, Paper and Woodworking Industry, 39.1:48-67.

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Аналіз фізичних закономірностей процесу сушіння пиломатеріалів

Проведено аналіз фізичних закономірностей, які впливають на процес сушіння пиломатеріалів. Розглянуто їх вплив на швидкість на якість висушеного матеріалу. Розглянуто методи видалення вологи з деревини. Описано рівняння вологопровідності та термовологопровідності. Проведено аналіз цих рівнянь. Розглянуто принципи руху вологи в середині вологої деревини.
Ключові слова: деревина, пиломатеріал, вологість, тиск, градієнт, температура, теплопровідність, випаровування, волога, вологоперенесення, вологовміст.

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SOFTWARE DEVELOPMENT FOR DETERMINATION OF STRESS FIELDS IN THE WOOD WITH A PARABOLIC DISTRIBUTION OF MOISTURE

The task of determination of the flat tense consisting is in-process decided of radiality-tangentiality plane of anisotropy of wood with the uneven distributing of moisture. On the basis of method of Ritca an algorithm and software is developed for the calculation of components of tensor of tensions in saw-timbers with the parabolic distributing of moisture. The algorithm of description is given in it is given in a verbal form. The program is realized in the environment C++ with the use of visual components.
Keywords: Ritz method, the stress field.

At the stage of constant rate drying saw in the plain stress state is flat , the value of the axial component of the stress tensor is almost negligible. Therefore, to determine