

2. ТЕПЛОМАСООБМІННІ ПРОЦЕСИ В ДЕРЕВООБРОБНІЙ ГАЛУЗІ

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НАПРУЖЕННЯ І ДЕФОРМАЦІЇ У ДЕРЕВИНІ В ПРОЦЕСІ СУШІННЯ

Розроблено методи синтезу та аналізу напружено-деформівним станом деревини у процесі сушіння з урахуванням її реологічної поведінки, які дозволили встановити та кількісно описати закономірності впливу гігроскопічної вологи, її градієнту і форми зв'язку вологи з матеріалом, структурної анізотропії, геометричних розмірів та густини на розподіл в'язкопружних і залишкових напружень для періодів падаючої та сталої швидкостей сушіння деревини зі сталими і змінними потенціалами тепломасоперенесення.

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Stresses and Strains of Wood in the Drying Process

Developed methods of synthesis and analysis of stressed-strained state of wood in drying process with taking account of its rheological behaviour, which allowed to set and quantitatively to describe influence conformities of hygroscopic moisture, its gradient and form of connection with material, structural anisotropy, geometrical dimensions and density on distribution of viscous-elastic and residual strains for falling and constant speeds of wood drying with constant speeds of wood drying with constant and changeable potentials of mass heat transfer.

Key words: wood, drying, stressed, strained, viscous-elastic, heat-mass-exchange.

Introduction

For rational directing of wood drying process provided with necessary quality indexes is an important problem to make physical-mathematical model of rheological state of wood taking into account mechanism of regenerating strains in time, and also to develop methods of synthesis and analysis of strain relaxational processes in these materials taking into account changeable potentials of mass heat transfer, interrelation between stresses and parameters of external and internal mass heat transfer, anisotropy of properties, structure transformations. Limitation of these researches is one of the basic suppressing factors for rational choice and basing of technological regime of wood drying processes with simultaneous improving of its mechanical properties.

Thermodynamical approach and mathematical model

In base of synthesis and analysis of offered physical-mathematical model of strains and stresses development in technological wood drying processes is laid methodology of system-structural approach, that stipulated basing of parameters choice of phenomenological model description and setting of suitable heat, mass, energy and impulse laws. On base of thermodynamical analysis was described structure of relations, set mutual influence of different phenomena and factors specifically creeping processes, relaxation and shrinkage on deformation of arboreal

materials. There was described generalised function of free energy (thermodynamical potential of researching system), as material state function with changeable potentials of mass heat transfer, that determines by components of summary (elastic, viscous-elastic and residual) strains tensors or stresses, chemical potential or moisture content and temperature T, and entropies. State function is expressed through invariants from determining parameters, specifically strains tensors.

There was synthesized physical-mathematical model of strain-relaxational processes in wood during process in general case directed in form of differential equations system [1, 2]: balance and motion equations

$$\sigma_{ij,i} = \rho \partial^2 U_i / \partial \tau^2; \sigma_{ij} = \sigma_{ji}; \quad (1)$$

$$\frac{\partial t}{\partial \tau} = \text{div}(\lambda_{tt} \text{grad} t) + \text{div}(\lambda_{tu} \text{grad} U) + \text{div}(\lambda_{tp} \text{grad} P) + t \frac{\partial}{\partial \tau} \left(\epsilon_{kk} \frac{\partial G(t, U, P)}{\partial t} \right); \quad (2)$$

$$\frac{\partial U}{\partial \tau} = \text{div}(\lambda_{ut} \text{grad} t) + \text{div}(\lambda_{uu} \text{grad} U) + \text{div}(\lambda_{up} \text{grad} P) + U \frac{\partial}{\partial \tau} \left(\epsilon_{kk} \frac{\partial G(t, U, P)}{\partial U} \right); \quad (3)$$

$$\frac{\partial P}{\partial \tau} = \text{div}(\lambda_{pt} \text{grad} t) + \text{div}(\lambda_{pu} \text{grad} U) + \text{div}(\lambda_{pp} \text{grad} P) + P_0 \frac{\partial \epsilon_{kk}}{\partial \tau}; \quad (4)$$

$$G(t, U, P) = \frac{dV}{V_0} (3\lambda + 2\mu) - \xi P;$$

state equations:

$$\sigma_{ij} = 2\mu(1 - \omega) \epsilon_{ij} + \left(\epsilon_{ij} \left(\lambda + \frac{2}{3} \mu \omega \right) - \frac{dV}{V_0} (3\lambda + 2\mu) + \xi P \right) \delta_{ij}; \quad (5)$$

$$\mu = \epsilon_{\phi} \gamma - \epsilon_{ij} \frac{\partial}{\partial U} G(t, U, P) + \epsilon_{ij} \epsilon_{ij} \frac{\partial}{\partial U} \mu(1 - \omega) + \epsilon_{ij}^2 \frac{\partial}{\partial U} (\lambda/2 + \mu \omega/3); \quad (6)$$

$$S = \int_{t_0}^t \frac{C_v}{t} dt + \epsilon_{ij} \frac{\partial}{\partial t} G(t, U, P) - \epsilon_{ij} \epsilon_{ij} \frac{\partial}{\partial T} \mu(1 - \omega) + \epsilon_{ij}^2 \frac{\partial}{\partial T} (\lambda/2 - \mu \omega/3). \quad (7)$$

For enclosing of equation system (1)–(7) were used conditions of strains compatibility, kinematical equations of mass heat transfer potentials, and also initial and boundary conditions which are typical for different drying process stages.

Was obtained equations system (1)–(7) which allows to describe temperature-moisture and stress-strained fields in wood drying process with taking into account viscous-elastic properties of material and strains regeneration mechanism in time.

On basis of relation setting between balance equations (2)–(4) and generalized law of Hooke for viscous-elastic materials was obtained law of rheological wood behaviour with changeable temperature-moisture fields as viscous-elastic material, for which transformation in time one kind of strains into another is typical. Inasmuch for determination of characteristics of rheological wood behaviour in suitable change diapasons u and t were developed methods of experimental research on creeping and relaxation with use of integral functions (creeping and relaxation nucleus), then rheological regularity of wood straining can be given in form (8).

$$\varepsilon(\tau, U, t) = \frac{1}{E(U, t)} \left(\sigma(\tau) + \int_0^\tau \left(\frac{\partial K_1(\tau - \tau'_1 U_1 t)}{\partial \tau} + R_2(\tau - \tau'_1 U_1 t) \frac{dU(\tau')}{d\tau'} \right) \sigma(\tau') d\tau' \right) - \alpha U. \quad (8)$$

Offered rheological equation (8) was endorsed by experimental results for cases of creeping and reverse creeping strains for different levels of temperature and moisture.

Experimental researches of rheological wood properties

Taking into account experimental researches referring to studies of stress-strained wood state in drying process, were determined tasks of rheological researches: to inquire into rheological behaviour of wood on creeping, relaxation and reverse creeping with taking into account anisotropy in range of change of moisture (8 %, 15 %, 20 % Wrr) and temperature (20°C, 40°C, 80°C, 95°C); to set regularities of development of elastic, viscous-elastic and residual strains and to describe quantitatively function of creeping and relaxation, which are necessary for computation of stress-strained state of drying wood; to substantiate application of speed up methods of temporal analogies, which allow by results of short-time researches to forecast rheological properties of wood along fibres for long-time term. Each experiment was carried out on separately taken sample of pine-tree, fir-tree, birch and oak for constant loading tension and compression, that does not exceed limits of long-time resistance.

Results of experimental senses of creeping function $\psi(\tau, w, t=20^\circ\text{C})$ of pine-wood for tangential direction of deformation directed in table 1, where $\psi(t=0)=E_n^{-1}$; $\psi(t=\infty)=E_t^{-1}$; E_m, E_t – momentary and continuous modulus of elasticity, ϕ_1 – characteristic, that allows to estimate degree of wood creeping.

On analysis base of experimental data of strains creeping, obtained for constant and changeable senses of moisture content and temperature, was studied strains mechanism and displayed different types of interaction of given above factors on wood deformation [34]. Considerable growth of strains components of experimental wood species irrespective of loading method is observed with augmentation of moisture from 8 % to Wrr. Further change of strain ε changes insignificantly, that qualitatively agree with experimental data for elastic component. Augmentation of viscous-elastic and residual components caused by acceleration of kinetic energy dissipation at the expense of intermolecular interactions of lignin and cellulose molecules in wood and by their conformation changes. For wood with moisture $w \geq w_{rr}$ dependently on temperature change is observed a insignificant distinction between sense of strains of creeping and reverse creeping in radial and tangential directions is observed an influence of initial moisture content of material on full strain and its components.

Creeping of strains of moisture samples under loading is greater than visco-elastic component in unloading process, that is during loading goes accumulation of residual strain, which is absent in elastic loading regime. Was set, that elastic and viscous-elastic components of strain for tension across fibers do not depend on initial loading, and its augmentation causes strains augmentation, in the same time

when decrease of temperature for creeping process does lead to essential change of strains. Were set dependencies of elastic characteristics (Young's modulus and Poisson coefficient) of pine-wood for orthotropic scheme of anisotropy dependent on temperature and moisture changes.

Table 1. Deformation indexes of pine-wood

$\Psi, 10^{-3} \text{ MPa}$	time of deformation $\tau \cdot 10^3$, Ψ' – tension, Ψ'' – compression									
	0.05	12	24	36	48	60	78	90	120	
Ψ' W=8 %	1.07	1.21	1.33	1.43	1.50	1.54	1.58	1.63	1.68	
Ψ''	1.04	1.22	1.32	1.40	1.53	1.56	1.60	1.62	1.69	
ϕ	419	478	517	561	599	612	619	639	662	
Ψ' W=15 %	0.92	1.09	1.21	1.34	1.40	1.44	1.47	1.50	1.52	
Ψ''	0.97	1.07	1.26	1.36	1.42	1.44	1.46	1.50	1.54	
ϕ	346	378	432	483	503	510	520	533	545	
Ψ' W=20 %	0.86	1.05	1.18	1.27	1.36	1.37	1.40	1.42	1.43	
Ψ''	0.85	1.06	1.19	1.28	1.34	1.36	1.39	1.43	1.43	
ϕ	266	333	372	401	420	426	435	448	448	
Ψ' W=Wrr	0.64	0.82	0.93	0.99	1.03	1.06	1.06	1.07	1.07	
Ψ''	0.64	0.81	0.93	1.01	1.03	1.05	1.05	1.06	1.08	
ϕ	167	212	242	259	268	272	273	275	280	

Were set regularities of temperature and moisture influence on important index of rheological wood behaviour, as time of anisotropy dependent on temperature and moisture changes.

Were set regularities of temperature and moisture influence on important index of rheological wood behaviour, as time of relaxation $\tau_p(w, t)$. Is observed that moisture change influences more essentially on $\tau_p(w, t)$ for wood straining along fibres. Specifically, for pine-wood ($t=20^\circ\text{C}$), moisture from 20 % to 10 % stipulates decreasing $\tau_p(w, t)$ almost in 42 times. For tangential direction for the same condition $\tau_p(w, t)$ decreases in 2.5 times. Temperature growth causes decreasing of $\tau_p(w, t)$. However speed of τ_p falling with t growth is smaller than speed of change $\tau_p(w, t)$ dependently on w . By measuring results in identical temperature-moisture conditions was obtained a dependency $\tau_p(w, t) = A(t) \exp(-BW)$, and coefficient A, B determined for each wood specie.

Results of strains researches of creeping and reverse creeping of wood across fibres allowed to build necessary for synthesis and analysis of stress-strained lumber state (8) of creeping functions with taking into account accumulation of residual strains:

$$K_1(\tau - \tau'; U, t) = \psi_0 + \sum_{k=1}^N a_k \exp(-\alpha_k(\tau - \tau')); \quad K_2(\tau - \tau'; U, t) = \beta \exp(-L(\tau - \tau')). \quad (9)$$

Was developed an algorithm of determining parameters $\psi_0, a_k, \alpha_k, \beta$ and substantiated a choice of their amount from minimum of quadratic deviation of approximation of experimental curves $\varepsilon(t, w, \tau)$. Application of more complicated function of creeping because of high changeability of strain properties of wood essentially complicates mathematical apparatus and it is inconvenient for practice.

For research of rheological behaviour of wood along fibres and generalization of existing experimental data was offered an approach with use of fixed scale function, which provide invariance of strain process concerning temperature and moisture changes. Were built generalized curves of creeping for researched species of wood in half-logarithmical coordinates $(\varepsilon, \ln \tau)$ and determined scale function $\ln a(t, w)$, that characterizes creeping curves dependency on generalized, directed for base senses of temperature $t_0=40^\circ$ and moisture $W_0=8\%$. Was set that function is unlinear for each from arguments and is stipulated by their mutual influence. In general case $\ln a(t, w)$ is described by polynomial and coefficients are determined by method of minimum squares.

On base of observed peculiarities of wood straining along fibres for different temperature and moisture senses was offered rheological equation

$$\varepsilon(\tau) = \varepsilon_0(\sigma, t, W) + \frac{1}{n} \sum_{i=1}^n b_i (1 - \exp(-a(t, W)/\tau_{oi})). \quad (10)$$

Were set spectrums of relaxation times and function $a(t, w)$. Specifically, for $t=40^\circ\text{C}$:

$$a(W) = (W_0/W)^b \frac{\ln 50(1 - (E_T(W_0)/E_M(W_0)))}{\ln 50(1 - (E_T(W)/E_M(W)))}; \tau_{oi} = \tau_p(W_0)(W_0/W)^b \quad (11)$$

Senses of coefficient b for different species of wood and method of loading are directed in table 2.

Table 2. Senses of coefficients b for determining of relaxation time

b		pine-tree	fir-tree	birch	oak
	compression	0.63	0.51	0.42	0.7
	tension	4.73	4.3	3.85	4.8

Computation of flat stress-strained state of wood in drying process

With use of elastic theory methods was researched flat (two-dimensional) stress-strained wood state in drying process with taking into account anisotropy of mechanical and heat physical properties, stipulated by structural construction of wood [5,6]. Was considered an orthotropic plate of wood, which in two mutual perpendicular direction is characterized by anisotropy of mechanical and moisture properties, and a plane of orthotropy coincides with co-ordinates system planes, beginning of which is situated in the center of transversal section (fig. 1).

Task of determining of moisture stresses in drying wood by integration of equilibrium equations (1) turns into decision of differential equation with boundary conditions:

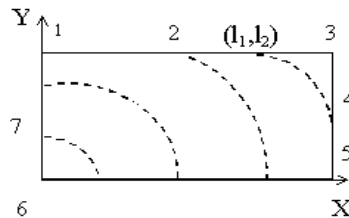


Fig. 1. Scheme of task organization of determining of stress-strained state of drying wood

$$\bar{\nabla} F = -\partial^2(\beta_y \Delta U)/\partial x^2 - \partial^2(\beta_x \Delta U)/\partial y^2, \quad (12)$$

$$\bar{\nabla} = E_y \partial^4 / \partial x^4 + (G_{xy}^{-1} - 2\nu_{xy}/E_y) \partial^4 / \partial x^2 \partial y^2 + E_x \partial^4 / \partial y^4;$$

$$\sigma_x = 0, X = \pm l_1 = L_1/2; \sigma_y = 0, Y = \pm l_2 = L_2/2;$$

$$\beta_y = \left((\beta_{y0} - \beta_{x0}) \sqrt{(x^2 + y^2)/(l_1^2 + l_2^2)} + \beta_{x0} \right) (30 - W)/30; \beta_x = \beta_{x0} (30 - W)/30;$$

$\beta_{x0}(W, t)$, $\beta_{y0}(W, t)$ – tangential and radial coefficients of shrinkage, $\Delta U = U^* - U(x, y, \tau)$ – function of change of hygroscopic moisture content. For $U > U^*$ was taken $\Delta U = 0$, that accords with lack of shrinkage in moisture zone. Because change of inflexibility in wood starts from 25...30 % then $U^* = 0.25$.

Function of stresses F is related with components of stresses by formulae

$$\sigma_x = \partial^2 F / \partial y^2; \sigma_y = \partial^2 F / \partial x^2; \tau_{xy} = -\partial^2 F / \partial x \partial y. \quad (13)$$

Numerical decision was obtained with use of conjugate with distribution of temperature-moisture field designed function φ_i that provide a minimum of potential energy of drying wood by dint of determination of unknown coefficients a and k from fixed system of equations

$$\sum_{i=1}^3 \sum_{k=1}^3 (\bar{\nabla} \varphi_i, \varphi_k)_{ik} = \left(-\partial^2(\beta_y \Delta U)/\partial x^2 - \partial^2(\beta_x \Delta U)/\partial y^2, \varphi_n \right), \quad (14)$$

where $(\Delta \varphi, \varphi)$ and right part (14) are scalar. Residual strains, stipulated by dependence between modules of elasticity E_x, E_y, ν_{xy} and moisture (effect of regeneration) are defined for formulas:

$$\sigma_{x3ал} = \sigma_x - \sigma_{x\max}/3; \sigma_{y3ал} = \sigma_y - \sigma_{y\max}/3. \quad (15)$$

Numerical decision of written in criterional form of mass heat transfer equations (2),(3) and boundary conditions was obtained by intheratical locally one-dimensional method. On fig.2 and 3 are presented the modeling results of stress-strained state of drying wood.

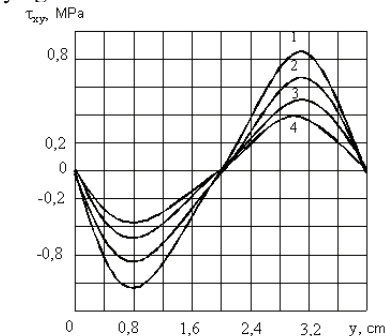


Fig. 2. Distribution of tangential stresses τ_{xy} (τ): $y=2$; $l_1=4$ cm; $l_2=8$ cm, 1 – $F_0 \approx 2.47$; 2 – $F_0 \approx 3.63$; 3 – $F_0 \approx 4.02$; 4 – $F_0 \approx 6.32$; $t_c=84^\circ\text{C}$; $\varphi=0.62$; $\alpha=22.5$ W/(m² t); $\beta=3 \cdot 10^{-6}$ m/c; $\beta_{y0}=7.1\%$; $\beta_{x0}=3.4\%$; $\rho_0=460$ kg/m³

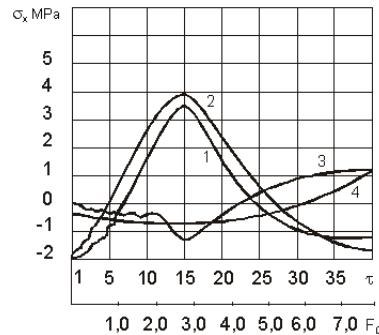


Fig.3. Change of normal stresses σ_x : 1 – 1, Fig 1; 2 – 2, Fig 2; 3 – 6; 4 – 7; $t_c = 84^\circ\text{C}$; $\varphi = 0,62$; $\alpha = 22,5 \text{ Wm/(m}^2\text{t)}$; $\beta = 3 \cdot 10^{-6} \text{ m/c}$; $\beta_0 = 7,1 \%$; $\beta_{c0} = 3,01 \%$; $\rho_0 = 460 \text{ kg/m}^3$

On basis of offered single approach was solved practically important for wood drying process class of task of stress-strained state determining. Was set a distribution of moisture and residual strains for parabolic distribution $\Delta W = W \dots$ Was observed influence of distribution of properties and geometrical size of lumber on normal and tangential stresses. Maximum senses normal stresses reach in the medium layer of drying wood, and tangential—in undersurface zones, and on the surface and in the center of the board they are insignificant.

Were found components of stresses for case, when initial moisture of lumber is higher than transition moisture content in the first period (bound moisture stands of from surface zones, and in central $-W > W_m$). Was obtained distribution of tangential and normal stresses of zone of lumber in drying process, which essentially depends on modulus of elasticity of wood along fibres. Was estimated influence on normal stress of відношення change of hygroscopic zone to board thickness were found coefficients of stress intensivities on possible cracking surface dependently on even and quadratic distribution of hygroscopic moisture. Was observed influence of intensive drying (moisturing) on components of stresses, for example, in shrinkage process of thin layer (veneer) glued on massive base.

Research of stress-strained wood state in drying process with taking into account of viscous-elastic properties and peculiarities of strain regeneration in time. Developed methods of synthesis and analysis, which are formalized with the aim of using of obtained experimental data of rheological wood behaviour allow quantitatively to set important in technology of wood drying regularities of distribution influence of hygroscopic moisture, its gradient, anisotropion of constant and changeable coefficients and internal sources of mass heat transfer, geometrical size of lumber on development of viscous-elastic and residual stresses in wood on different drying process stages.

Obtained dependences for determination of stress-strained state of drying wood are represented in structural form [7,8]. For irregular drying process regime we have:

$$\sigma_B(X, F_0) = K^{t, \mu} \beta(U, X) \left(\frac{1}{2} K I_m \left(1 + \varepsilon K_0 P n L u \left(\frac{1}{3} - X^2 \right) \right) \right)$$

$$- \frac{1}{\varepsilon K_0} \sum_{n=1}^{\infty} \sum_{l=1}^2 C_m (1 - \nu_l^2) \cos \nu_l \mu_n X - \frac{\sin \nu_l \mu_n}{\nu_l \mu_n} \exp(-\mu_n^2 F_0) (U_0 - U_p); \quad (16)$$

$$\sigma_3(X, F_0) = K^{t, \mu} \beta(U, X) \int_0^{\tau} \left(\partial U(X, F_0) / \partial \tau - \partial \bar{U}(\tau) / \partial \tau \right) \sum_{i=1}^2 S_i(U, t) K^0(\tau - \tau', U, t) d\tau' \quad (16)$$

Developed methods of synthesis and analysis allowed to set regularities of distribution of moistural and residual stresses in wood with constant and changeable coefficients of mass heat transfer for period of falling velocity of drying. Were considered cases of initial parabolic and cosinusoidal distribution of moisture content. For drying process of hardwood species moisture content in which can be described by cosinusoidal law, stress-strained state determines by correlations [9]:

$$\sigma_B(Y, \tau) = f(U, t) g(U_0, U_p, B_i) \exp(-\pi^2 B_i F / (4 B_i + \pi^2)) \quad (17)$$

$$\sigma_3(Y, \tau) = - \left(\exp(\tau / \tau_{\text{pell}}) / h(\tau_{\text{pell}}, B_i, a') \right) f(U, t) g(U_0, U_p, B_i) * \\ * (E(U, t) - E_T(U, t)) / E_T(U, t) \tau_{\text{pell}} (\exp(h(\tau_{\text{pell}}, B_i, a')) - 1),$$

where

$$f(U, t) = F(U, t) / (1 + \beta_0 U_0) \beta(U, t);$$

$$g(U_0, U_p, B_i) = 4(U_0 - U_p) B_i (\pi \cos X \pi / 2 - 1) / \pi (\pi^2 + 4 B_i);$$

$$h(\tau_{\text{pell}}, B_i, a') = 1 / \tau_{\text{pell}} - \pi^2 a' B_i / R^2 (4 B_i + \pi^2).$$

Was observed influence of maximum stresses on cracking criterion. K_{Tp} , accepted as concerning gradient between local and mean moisture content and initial moisture content [7]. For determining of maximum-admissible senses K_{Tp} in case of parabolic distribution of moisture content (regular regime) was obtained integral equation

$$\int_0^{\tau} K(\tau - \tau', U, t) K'_{\text{Tp}} d\tau' + K' = \frac{2 \sigma_{\text{max}}(X, F_0) (1 + \beta_0 U_0)}{3 E(U, t) U_0 \beta(U, t) K} - \\ - \frac{\Delta t}{t_c - t_M} G u P n (1 + \tau_{\text{pell}} (1 - \tau_{\text{pell}} \exp(\tau / \tau_{\text{pell}}))). \quad (18)$$

Was learned stress-strained state of wood with taking into account deepening of moisture evaporation zone in period of falling drying velocity [10]. In connection with complication of temperature-moistural fields determining was accepted an assumption, that moisture content of moisture zone is constant, and in evaporation zone is equal to equilibrium sense. On base of analysis of results was showed presence of turners in stresses for different heat physical senses of deepening zone of moisture evaporation, and also augmentation of size of compression stresses for some senses of evaporation zone in dry region of wood plate (without taking into account zone of tensional stresses).

On base of carried out researches were studied basic regularities of development of viscous-elastic and residual stresses in wood during drying process with taking into account distribution of hygroscopic moisture, forms of moisture connection with material, physical and mechanical characteristics, conventional density (species) and geometrical size of lumber. Character of dynamics of residual

stresses is stipulated by uneven development of moistural strains and creeping strains and reverse creeping dependently on forms of connection of moisture with material, and velocity of their development for constant change of moisture content is proportional to moisture gradient change. Peculiarity of forming of stresses in visco-elastic region of straining is displacement of spectrum of maximum senses on lumber surfaces concerning maximum senses in central layers, caused by uneven distribution of level-by-level moisture and by dependence of time of maximum senses $\tau_{\max}$ reaching from relaxation time which for fixed senses of E_t and E_m are associated by correlation $\tau_{\max}(x) = 1,38\tau_p^2 / \sigma_{\max} \gamma$ – velocity of changing of moisture strains. Augmentation of conventional density sense causes growth of maximum stresses, especially on surface and in under surface lumber zones, and also retardation of velocity of stresses relaxation. Specifically, for parameters of drying agent t, t, W % for wood with $\rho_0 = 550 \text{ kg/m}^3$ $\sigma(\tau=10) - \sigma(\tau=20)$, is 0.18 MPa to $XL_2=0$, and for $\rho_0=450 \text{ kg/m}^3$ analogic size is 1.37 MPa was set considerable influence of structural anisotropy on stress-strained state of logs under action of uneven distributed moisture. In this case unlike isotropic, where components of stresses are insignificant, even distribution of moisture causes growth of stresses. Was shown compressional character of radial stresses for $r/R < 0,53$ (R – radius) and tensional in under surface zones. Was observed change the sign of tangential stresses (tensional character for $R/r \leq 0,42$ and for central zone), if coefficient of shrinkage in tangential direction is greater than in radial direction.

Connection of components of stressed-strained state of drying wood with parameters of internal and external mass heat transfer

For quantitative description of connection was analyzed and described interacting mass heat transfer flows on border of drying wood and moisture environment with taking into account behaviour peculiarities of bound moisture with material. Was taken into account that process of mass heat transfer in drying wood simultaneously goes in liquid, airvaporous and hard phases. With aim of concretization of thermodynamical components were made researches of them dependently on hygroscopic moisture of material, its structural properties with following normalization of sum of the flows, on general geometrical surface. Integral components of surfaces are determined from equality of volumetric and surface heterogeneities component of surface skeleton is a constant, and component of surface of liquid and gas-vaporous phases depend on moisture content of material.

Was synthesized model of connection of stress-strained state of drying wood with parameters of external and internal mass heat transfer processes [12], and also dependences of heat-physical and mechanical characteristics of material with parameters of moistural air allow to determine maximum senses of parameters of drying agent directly at the expense of stresses, that do not exceed bound durability and provide integrity of material. Were obtained engineering correlations for φ and t_0 choice with taking into account constant and changeable coefficients of mass heat transfer dependently on rheological properties of wood. Specifically, for parabolic distribution of moisture content in wood (period of constant velocity of drying):

$$t_c = \frac{0,13(238+t)\ln B}{1 + \frac{238+t}{1785}\ln B}, \quad \ln B = \frac{2a_m \rho_0 (1 + \beta_n U_0) \sigma_B}{E_m(U, t) K N u_D p_{nc}}. \quad (19)$$

For cosinusoidal distribution of moisture content in wood (period of falling-drying velocity) was set:

$$\varphi = 0,018 * \frac{H_{os}^2 H_o^{4,8} U_{ost}}{V_s (1 - 3,1 \ln t/t_0)} * \left(\frac{\sigma_B(X, Fo)(1 + \beta_0 U_0)(U_n + (U_n - U_n) \cos X\pi/2)}{4(U_0 - U_p)(H(U, t) + K(U, t)) \frac{B_i \cos X\pi/2 - 2B_i/\pi}{4B_i + \pi^2} \exp\left(-\frac{4BiFo}{4B_i + \pi^2}\right)} + 1 \right) * \left(\frac{\lambda_u \varphi}{\rho_0} - \rho_s \frac{\alpha U_l}{N u_u} \left(\frac{1}{\rho_0} - \frac{1}{\rho_T} (U_n + (U_n - U_n) \cos X\pi/2) \right) \right)^{-1}. \quad (20)$$

Was researched influence of parameters of moistural air on stress-strained state of wood in drying process with taking into account mechanical-sorptional creeping of material, caused by decreasing of moisture content in drying wood. Was observed a greater deformation change of wood in case of growth of relative moisture of air φ in compare of its decreasing. Influence of temperature of moistural environment is more essential on development of residual strains and strains, caused by wood shrinkage.

Due to researches results was developed a system of automatic regulation of drying agent parameters with taking into account stress-strained state of wood.

Symbols: ρ – density; u – moving; τ – time; u_0, u_p, u_n, u_y – moisture content: initial, equilibrium on surface, in the center; c – thermal capacity; λ, ϑ, x – coefficients of mass heat transfer: Poisson, Lamé, filtration, kinematic viscosity, thermal conductions of dry wood; ε, r – criterion and heat of phase transition; $K^{t,u}$, E_i , G_{xy} – volumetric modulus of elasticity, modules of shift elasticity; $R(\tau - \tau', U, t)$, $K(\tau - \tau', U, t)$, S_1, S_2 – functions of rheological behaviour (functions of relaxation, creeping and functionals of relaxation times); δ – temperature gradients; $K_i, K_0, P_n, W, F_0, B_i, R_b$ – criteria of Kirpichov, Kosovich, Posnov, Lykova, Fourier, Bio, Rebinder; c_m, ν, μ – characteristic number; A, B – parameters of approximation; δ_i – Kronecker symbol.

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АНАЛІЗ ОСНОВНИХ СПОСОБІВ СУШІННЯ КАПІЛЯРНОПОРИСТИХ КОЛОЇДНИХ МАТЕРІАЛІВ

Розглянуто фізичні особливості та ефективність кондуктивного, радіаційного, електричного та конвективного способів сушіння капілярнопористих колоїдних матеріалів.

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Analysis of basic of colloid materials drying methods

Considered the physical peculiarities and effectiveness conduction, radiation, electric and convection drying methods of colloid materials.

Капілярнопористі колоїдні матеріали охоплюють широкий спектр речовин, в основному, органічного походження. Деревина, яка входить до цього класу матеріалів, має складну анатомічну будову і фізико-механічні властивості. Особливість будови деревини полягає в тому, що при початковому зволоженні вона має явно виражені колоїдні властивості, а в подальшій полімолекулярній конденсації – властивості капілярнопористого тіла.

Процес видалення вологи з капілярнопористих колоїдних матеріалів супроводжується порушенням її зв'язку з тілом, на що потрібно витрачати значну кількість енергії. Тому, класифікація форм зв'язку тіл з вологою побудована за принципом інтенсивності цього зв'язку. У цьому ж напрямку доцільно провести аналіз ефективності різних способів сушіння та їх комбіна-

цій. За особливостями передачі тепла до висушуваного матеріалу сформульовано чотири основні способи сушіння: кондуктивний (контактний), електричний, радіаційний (тепловим випромінюванням) та конвективний. Кожний з цих способів можна розділити на види та підвиди, яких найбільше має конвективний. Можлива комбінація окремих способів, видів та підвидів, якщо одночасно використовуються різні способи передачі тепла або суміщаються інші ознаки. У чистому виді названі вище основні способи зустрічаються рідко, частіше переважаючим є той чи інший метод передачі тепла, який доповнюється іншим. Таким чином, аналіз ефективності способів сушіння є актуальною і різноплановою задачею.

Кондуктивне сушіння характеризується передачею тепла на нагрівання вологого матеріалу і випаровування з нього вологи від нагрітої поверхні. Кондуктивний спосіб сушіння широко використовується в промисловості для сушіння паперу та інших тонких листових матеріалів. Основними параметрами, які визначають кінетику процесу кондуктивного сушіння, є температура гріючої поверхні, ступінь притискання матеріалу до гріючої поверхні, параметри оточуючого середовища.

Основним технологічним параметром є товщина матеріалу. Названі параметри впливають не тільки на швидкість сушіння і на критичний вологовміст, але і на технологічні властивості та якість матеріалу.

Температура гріючої поверхні є основним параметром, який впливає на тривалість контактного сушіння. З підвищенням температури гріючої поверхні тривалість сушіння різко скорочується. Вплив температури гріючої поверхні є істотним протягом всього процесу сушіння, лише в кінці процесу цей вплив зменшується. Температура гріючої поверхні впливає також і на якість висушуваного матеріалу. На тривалість процесу великий вплив має товщина матеріалу. Наприклад, збільшення товщини шпону від 0.22 мм до 0.44 мм веде до збільшення тривалості сушіння майже у три рази. Наступне збільшення товщини веде до ще більшого зростання (на два-три порядки) загальної тривалості сушіння. Сила притискання матеріалу до контактуючої поверхні має незначний вплив на теплофізичну суть процесу, але значною мірою впливає на формування поверхні матеріалу і його загальну якість.

Для практичних розрахунків загальної тривалості контактного сушіння використовують [1] наближену залежність:

$$\tau = \frac{W_0}{N} - \frac{1}{XN} [1 + 2.3lg XW_n], \quad (1)$$

де: N – швидкість сушіння в першому періоді, %/с; X – відносний коефіцієнт сушіння, 1/%; W_0 і W_n – початкова і кінцева вологість матеріалу, %.

Кількість тепла, яка отримана від гріючої поверхні в першому періоді процесу сушіння, витрачається на випаровування та втрати тепла на випромінювання відкритою поверхнею матеріалу в середовищі і на конвективні втрати. Але ці втрати є невеликими (3...5 %) і ними можна знехтувати. Отже,

$$q = r_0 j, \quad (2)$$