DRYING KINETICS OF CAPILLARY-POROUS MATERIALS FOR A CONDUCTIVE-CONVECTIVE HEAT SUPPLY IN AN ELECTROMAGNETIC FIELD

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An examination is made of the kinetics of drying capillary-porous materials by heat supplied by contact and by convection from ferromagnetic elements in an electromagnetic field; the drying regimes and regime parameters are given.

Heating and drying of capillary-porous materials by means of heat-generating ferromagnetic elements (meshes and grids) in the alternating electromagnetic field of a coil combines the merits of several methods of supplying heat [4].

The materials to be dried (e.g., wood) are stacked in a pile along with the heat-generating ferromagnetic elements, and placed in the alternating field of a coil (Fig. 1) installed in the drying chamber [3]. The ferromagnetic elements are heated by the electromagnetic field set up by commercial frequency current in the coil, and supply heat to the material by conduction, convection, or radiation.

Depending on the properties, form, and size of the material, the layout of the ferromagnetic elements relative to the material may be decided, allowing for a single method of heat supply or a combination of several methods, as desired. In wood drying practice, a contact-convective scheme of heat supply (Fig. 2) is used [4].

Transfer of heat in this scheme proceeds by conduction from the ferromagnetic elements to the material, and is discrete in nature, i.e., there is local contact heating. In contrast to pure contact heating, local contact heating is accompanied by convective heat transfer from the air to the material through the holes in the surface of the ferromagnetic element (grid). The local convective heat transfer is accompanied by external moisture transfer, i.e., by transfer of vapor from the surface of the material to the surrounding moist air.

In contact-convective heat transfer from the elements to the material, small temperature and moisture gradients occur, which are explained by partial migration and condensation of water vapor within the wood. This causes a large increase in the heat transfer coefficient, and transformation of osmotic bond moisture to mechanical bond moisture (capillary moisture). Thus, in conditions of asymmetric heat and mass transfer, there is continuous transformation of osmotic moisture into capillary moisture, due to slow migration of osmotic moisture towards the surface of the material, and also to its evaporation.

The drying of materials by contact-convective heat transfer from ferromagnetic elements in an alternating magnetic field permits uniform heating of the material throughout the whole drying chamber. The presence of the hot elements causes high air humidity locally near the surface (conditions similar to drying by superheated steam), and also greatly slows down vapor migration from the surface of a board to the surrounding medium.

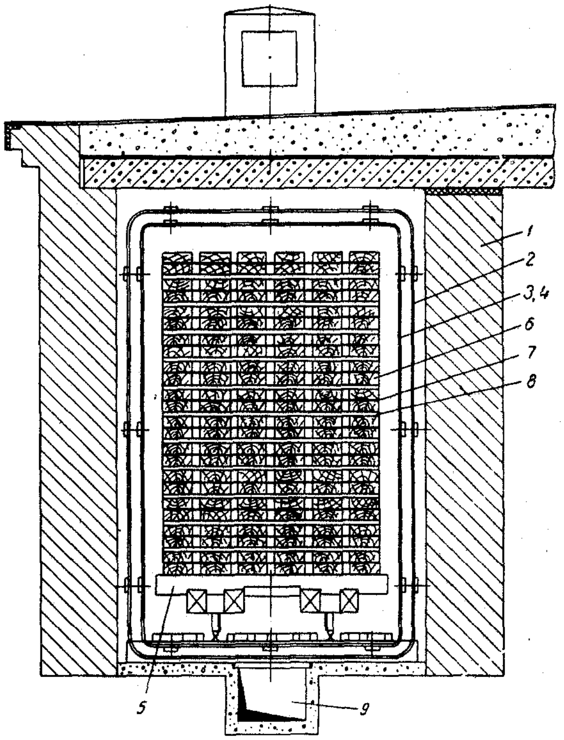

Fig. 1. The electromagnetic chamber with a stack of wood and ferromagnetic elements: 1) protective wall of the chamber; 2) main winding; 3) control winding; 4) supplementary winding; 5) track trolley; 6) wood stack; 7) ferromagnetic elements; 8) wooden spacer; 9) air duct.

To attain uniform heating of the material throughout the whole drying chamber by other means of drying (in particular, in intermittent convective drying chambers with ejection-reversal air circulation), a special ventilation and circulation plant is required, with devices for arranging the hydrodynamics of the air flow.

Experimental data [4] indicate that the temperature of the material decreases very little (by 3°–4°) from the place of contact to its free surface. In the periods of heating and of constant drying rate,

Table 1
Optimum Regimes of Wood Drying

Moisture content of the material U, %	Regime No. 1 for sawn timber 25-40 mm thick				Moisture content of the material, U, %	Regime No. 2 for sawn timber 50-80 mm thick			
	Temperature of the ferromagnetic elements, °K	Temperature of the surrounding medium, °K	Δt	Relative air humidity, φ, %		Temperature of the ferromagnetic elements, °K	Temperature of the surrounding medium, °K	Δt	Relative air humidity, φ, %
60 and above	383	358	3	88	60 and above	373	358	3	88
50—40	388	360	3	88	50—40	373	358	3	88
40—30	393	362	4	85	40—30	388	360	4	85
30—20	398	363	4	85	30—25	393	363	4	85
20—15	403	368	6	80	25—20	398	365	9	82
15—10	408	373	10	70	20—15	403	368	9	71
					15—10	408	370	10	69

Table 2
Basic Data on Drying of Sawn Timber

Size of the uncut timber	Drying in electromagnetic chambers						High-temperature drying and drying in superheated steam according to data of TsNIIMOD			
	Initial moisture content of wood, %	Final moisture content of wood, %	Drying regime	Duration of drying, hr	Standard duration of drying, hr.	Acceleration factor	TsNIIMOD regime;	Duration of drying, hr	Standard duration of drying, hr.	Acceleration factor
60×210–450×6500	78.0	8.0	2	72.5	230.4	3.2	1	98.5	230.4	2.3
60×210–450×6500	69.0	6.9	1	78.5	240.0	3.0	2	100.5	240.0	2.3
40×200–400×6500	110	6.8	2	60.1	211.2	3.5	1	97.5	211.2	2.1
50×200–400×6500	106	6.5	1	59.0	211.2	3.5	2	97.5	211.2	2.1
30×200–400×6500	63.4	6.8	2	38.0	120.0	3.2	1	53.0	120	2.2
30×200–400×6500	85	7.0	1	32.0	120.0	3.7	superheated steam, t_d = 384 °K, t_w = 372 °K	42.0	120	2.8

Table 3
Properties of Pine Wood for Tests

Property	For boards of thickness, mm;						Mean of the regimes allowing for numbers of observations	
	60		40		30			
	Regime 1	Regime 2	Regime 1	Regime 2	Regime 1	Regime 2	Regime 1	Regime 2
Volume weight	—1.78	0.8	—1.8	+1.81	0.0	1	2.0	0.0
Contraction along the grain	0.0	0.8	—6.3	—6.8	—4.5	+4.1	—2.6	—4.3
Specific work for impact bending	—10.1	—6.3	—5.1	+5.5	0.0	0.0	—6.3	0.0
Shearing along the grain	—8.0	—7.4	—1.0	—2.3	—8.6	—5.0	—6.6	—6.2

the drop in moisture content between the surface layers and the center of the material does not exceed 4–6 %/m. In the period of decreasing drying rate, the moisture content drop in the interior of the wood does not exceed 1.5–2.5 %/m. Temperature gradients in the material are similar in nature, and do not exceed 4°–6° in the constant drying rate period, and 2°–3° in the period of decreasing drying rate.

In the drying process large pressure gradients do not occur thus there are no hazardous distortions within the material. Therefore, even wood of considerable thickness (e.g., of thickness 60, 80, 100, or 120 mm) does not experience dangerous stresses and strains during drying and dries relatively free from warping and cracking.

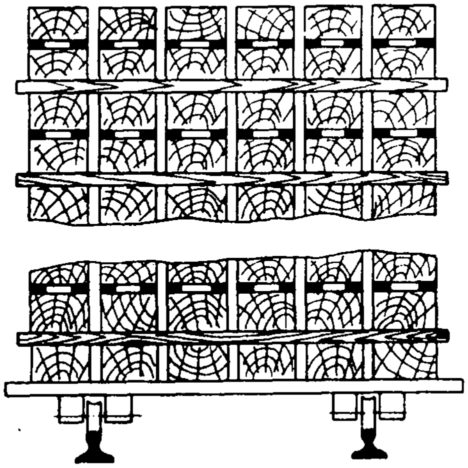

Fig. 2. Contact-convective scheme of supplying heat to wood from ferromagnetic element grids.

Drying kinetic curves show that with increase of the temperature of the ferromagnetic element temperature of 363° K, pine beads 50 mm thick and with an initial moisture content of 60%, dry to a final moisture content of 12% in 60 hr, and at 408° K in 42 hr.

The optimum parameters of the surrounding medium are temperature = 353–363° K and relative humidity = 70–88%. Under these conditions, gravity forces in the drying chambers achieve sufficiently good washing of all the elements of the material being dried, and artificial circulation is not required.

The drying kinetics data for soft wood under various drying regimes have been treated on the basis of the parmetric equation [2]

$$\bar{\Theta} = A\mathrm{Fo}^m \mathrm{Lu}^n (\mathrm{Bi}_m/\mathrm{Pn})^K. \qquad (1)$$

From (1) an equation of the dimensionless moisture content group is obtained

$$\bar{U} = 0.462\,\mathrm{Fo}\,\mathrm{Lu}^{0.62}. \qquad (2)$$

Equation (2) is valid for a range of the similarity parameter $0 < \mathrm{Fo} < 43$, and shows good agreement with the results of an experimental investigation [4].

From (2) a formula is obtained for calculating the duration of drying

$$\tau = \bar{U}R^2/0.462\,a^{0.38}a_m^{0.62}. \qquad (3)$$

This expression provides sufficiently accurate engineering calculations for the design of electromagnetic drying equipment for various regimes of drying softwood.

Table 4

Quality Indices of the Wood after Drying

Board thickness, mm	Moisture content, %			Drying category
	mean	within the board	on the board surface	
25	8	8.2	7.9	I
50	10	10.9	9.5	I
60	9.7	9.9	9.4	I
80	8.9	9.5	8.3	I
60	12	12.9	11.8	II

A thermal balance of the contact-convective drying process may be represented by an approximation equation of the form

$$-\lambda_{\mathrm{ef}}(\nabla t)_{\mathrm{fe}} = \left(C_0 + \frac{\bar{U}}{100}\right)\frac{M_{\mathrm{s}}}{S_{\mathrm{c}}}\frac{dt_{\mathrm{av}}}{d\tau} + \rho m + \alpha\frac{S_{\mathrm{op}}}{S_{\mathrm{c}}}(t_{\mathrm{op}} - t_{\mathrm{d}})_{\mathrm{av}}. \qquad (4)$$

The wood-drying regimes (Table 1) developed as a result of experiment and industrial verification make it possible, in a number of cases, to shorten the process by a factor of 2.5–3.5 in comparison with convective steam chambers [5–7].

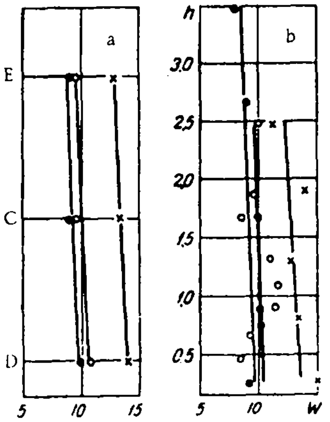

Fig. 3. Moisture content of the wood stack after drying: a) Moisture content along the chamber (D–door, C–center, E–end); b) moisture content over the height of the chamber.

The results of drying sawn timber in electromagnetic chambers are compared in Table 2 with

Table 5

Shrinkage of Pine Wood during Drying

Drying under room conditions					Drying in the electromagnetic chamber						
in the tangential direction		in the radial direction			in the tangential direction			in the radial direction			
K_t	n	K_r	n	$K_t.\ K_r$	K_t	n	N	K_r	n	N	$K_t.\ K_r$
0.239	18	0.214	18	1.11	0.145	21	61.0	0.146	21	67.8	1.00
0.268	26	0.189	26	1.41	0.204	21	78.0	1.151	21	80.0	1.35
0.272	21	0.133	21	0.05	0.191	26	70.0	0.120	26	90.5	1.59
Mean value											
0.259	—	0.178	—	1.52	180	—	69.6	0.139	—	79.4	1.31

those obtained in superheated steam and for high-temperature drying according to data of TsNIIMOD (Central Institute for Scientific Research on Mechanical Processing of Wood).

In order to appraise the quality of material dried according to regimes 1 and 2 in electromagnetic chambers for pine with properties given in Table 2, we carried out structural and mechanical tests according to the standard method recommended by GOST 6336-52. The tests results were treated statistically and are shown in Table 3. The structural and mechanical properties for (pine) wood assumed for the tests were close to the mean values for this wood given in GOST 4621-49. The accuracies are in the range 1–3%, i.e., a factor of 2.5 better than that assumed in investigations of the structural and mechanical properties of wood.

The drop in properties did not exceed 6–7% on the average for all thicknesses of material, which is of no practical significance for the majority of branches of industry requiring dried wood. The layered moisture content of dried wood with properties given in Table 2 is in the range 1.5–2% (Table 4).

The deviation of the moisture content of the wood from the mean over the whole volume of the stack did not exceed 2–4% (Fig. 3).

To determine the quality of the material after drying, 19 control boards were chosen from each stack, their defects were examined, and the final humidity through the thickness of the board was determined (Table 4).

The shrinkage was determined from the change in length of specimens during drying under room conditions ($t = 298°$ K) and in the electromagnetic chamber ($t_a = 378°$ K, $t_w = 358°$ K, $t_{fe} = 408°$ K) from the newly-felled state to equilibrium. The specimens were chosen with a view to the possibility of determining shrinkage of the wood through movement of moisture across the grain. The shrinkage coefficient for the drying of pine wood in specimens of section 50 × 50 mm under room conditions practically coincided with the GOST 4631-49 value, while those dried in the electromagnetic chamber gave a smaller shrinkage (Table 5).

Various methods and types of plant are used in contemporary practice for the drying and thermal treatment of materials. Their variety is justified by the difference in properties and dimensions, by specific requirements of drying technology, and by the nature of the bond between the moisture and the material, etc. For this reason, the electromagnetic drying method should not be regarded as universal and suitable for all production conditions. It may be used in specific conditions of production where it is more favorable in a technical sense and sufficiently economic.

NOTATION

λ_{ef}) effective (allowing for resulting mass transfer) thermal conductivity of moist material; $\bar{\Theta}$) dimensionless mass transfer potential; A) a constant, equal to 0.462; Fo, Lu, Bi_m, Pn) Fourier, Luikov, Biot, and Posnov numbers, respectively; $\bar{U}$) dimensionless moisture content group; a) thermal diffusivity; a_m) potential conduction mass transfer coefficient; C, γ) volume mean heat capacity and density, respectively; M_d) mass of absolutely dry material of body skelton; S_c) contact surface area of material contiguous to the ferromagnetic elements; $dt_{av}/d\tau$) rate of heating of moist material; ρ) specific heat of vaporization; m) intensity of drying, relative to the surface area in contact; α) heat transfer coefficient; τ) drying time; S_{op}) exposed surface area of material; t_{op}, t_s) temperature of the exposed surface of the material and of the surrounding medium, respectively; K_t, K_r) shrinkage coefficient in the tangential and radial directions, respectively; n) number of measurements; N) shrinkage as a percentage during drying in the electromagnetic chamber, relative to shrinkage under room conditions.

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