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PHYSICAL FEATURES OF ACOUSTIC DRYING OF WOOD

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We present results on acoustic drying of wood (pine). By use of a tomograph, we obtained the distribution of moisture in the cross section of a specimen before and after acoustic action exerted on it. It is found that in the direction of the normal to the annual rings this action is not monotonic, but rather it varies periodically. Affected by an acoustic field, moisture flows intensely from the early to the late zone of an annual ring.

Extraction of moisture from dried material under the action of sound (acoustic drying) as a physical phenomenon has been known for more than 40 years [1]. Over this period of time, research workers mainly obtained kinetic curves of drying for a number of materials. On the basis of these experiments a variety of hypotheses were advanced about the mechanism of the phenomenon, and evaluations of energy expenditures were made.

Drying of wood is of interest to investigators because of its great practical importance. In monograph [2] virtually the whole range of subjects concerned with the use of the classical (thermal) technique of drying is covered. In describing heat and mass exchange processes in drying of wood, the classical approaches are based on representation of wood as a homogeneous solid body endowed with certain physical and mechanical properties. From this, in particular, a monotonic parabolic distribution of moisture content over the thickness of the specimen in the process of drying with a maximum at the center follows [2, p. 145]. Below we present some results of an experiment on acoustic drying of specimens of pine.

Experiments were carried out with specimens of pine in the form of rectangular parallelepipeds measuring $(51 \times 17 \times 17)\cdot 10^{-3}$ m. The initial moisture content of the specimens was equal to $w_0 = (140-150)\%$. A photographic picture of one of them (end view) is presented in Fig. 1. According to well-known concepts [3], the light band of an annual ring is the early zone of this ring, while the dark band is the late zone of it. The former is characterized by the presence of large capillaries separated by thin walls, the latter contains fine capillaries separated by thick walls. According to [3], the characteristic transverse dimensions of large capillaries exceed the transverse dimensions of fine ones by a factor of 2-3.

The experiments were conducted in the channel of a model drying chamber. As the source of sound in the regime of acoustic drying we used a Hartmann jet generator with the following charactersitics of the acoustic field: frequency 160 Hz, intensity of sound 166 dB with respect to $p_0 = 2\cdot 10^{-5}$ N/m^2. The average velocity of waste air over the channel cross section and the speed of blowing of a test specimen in acoustic and convective drying were 15 m/sec, which was dictated by the parameters of the source of sound and the design of the drying chamber. In all the regimes the air temperature was equal to 23 ^{o}C. To measure the frequency and intensity of sound (first tone) we used LKh-610-type piezoelectric transducers, an S5-3 spectrum analyzer, and an oscillograph.

By weighing the specimen we found that in a time of acoustic drying of 30 min the change in the initial moisture content was equal to 33%.

To diagnoze the moisture distribution in the specimens investigated, we used a Bruker MSL-300 NMR spectrometer with an attachment for NMR tomography. The test specimen was inserted in the saddle-shaped radio-frequency (rf) coil, with inner diameter $> 2.5\cdot 10^{-2}$ m, of the NMR-spectrometer sensor in such a way that

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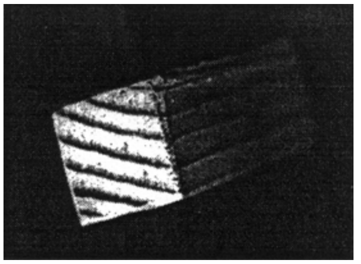

Fig. 1. A specimen of pine.

the orientation of the long axis of the test specimen coincided with the orientation of the magnetic field of the superconducting magnet of the spectrometer (the z axis). In the experiments we recorded the NMR signal of protons at a frequency of 300 MHz. To obtain two-dimensional images in the plane perpendicular to the z axis, we used a standard two-pulse sequence of spin echo with frequency coding of the signal along the x axis and position coding along the y axis (spin-warp) [4]. The value of the magnetic-field gradient along the x axis was $7.625 \cdot 10^{-2}$ T/m, and the number of recorded points of the signal of the echo was 128, which was doubled before Fourier transformation by a supplement with zeroes. The initial gradient along the y axis was equal to $-4.8 \cdot 10^{-2}$ T/m, its increment was equal to $7.5 \cdot 10^{-4}$ T/m, and the number of phase increments was 128. The entire experiment was repeated twice with a shift in the phase of the first pulse and the phase of recording by 180°, and the results obtained were summed.

In our experiments we did not use selection of a layer along the z axis, and therefore after two-dimensional Fourier transformation and calculation of the square root of the power spectrum we obtained two-dimensional images that represent an integral projection of the specimen on the xy plane with a spatial resolution of $1.5 \cdot 10^{-4}$ m $\times$ $3 \cdot 10^{-4}$ m in this plane.

Since the duration of the echo τ_e was $1.6 \cdot 10^{-3}$ sec, only free water gave a contribution to the observed signal, since the times of spin-spin relaxation (T_2) of protons of bound water and solid wood are much shorter than this value [5]. As a result the two-dimensional image obtained represents the spatial distribution of free water in the test specimen. One-dimensional profiles of moisture content were obtained by selecting the corresponding one-dimensional cross sections of the two-dimensional projections.

It should be noted that because of the different sizes of the pores the values of T_2 can differ for late and early layers of an annual ring and for different annual rings. To make a qualitative interpretation of the results, this is not important, since in the specimens investigated the average time of spin-spin relaxation T_2 is about an order of magnitude longer than the time τ_e used. Therefore, in a first approximation the amplitude of the NMR signal in the images obtained was proportional to the content of free moisture.

The main results of the experiment are presented in Fig. 2, which shows the qualitative distribution of moisture in the cross section of a specimen (the photograph) and the quantitative distribution (the graph) along a line normal to the edge of the annual rings. In the photographs the degree of blackening is proportional to the content of moisture. The duration of drying was 10 min.

The data of Fig. 2 indicate that the distribution of moisture in the cross section of the specimen before its drying is determined by the presence of the annual rings. It has a pronounced nonmonotonic (oscillating along the above-indicated line) character. Almost all the moisture is concentrated in large capillaries of the early zone (light band in Fig. 1) of an annual ring. The result obtained differs in principle from the concept, well-known in the literature [2, p. 145], of a monotonic parabolic distribution of moisture over the thickness of the specimen with a maximum in its axial plane.

A comparison of the results presented in Fig. 2 shows that acoustic and convective drying differ fundamentally in their effect on the distribution of moisture in a specimen in the process of drying. From the photographs and graphs of Fig. 2b it follows that in convective drying the character of the distribution of moisture in the bulk of the specimen does not change in the process of drying. Moisture is retained mainly in large capillaries (the early zone of an annual ring). Drying amounts to motion of moisture from surface layers of the specimen to its surface and its subsequent removal. A different picture is observed in the regime of acoustic drying (Fig. 2a).

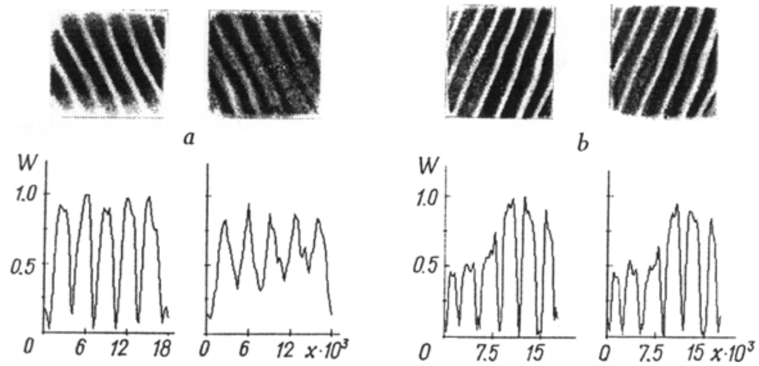

Fig. 2. Results on the distribution of moisture in a specimen before (on the left) and after (on the right) drying in an acoustic field (a) and by the convective method (b). The units for measuring moisture are arbitrary. x, m.

Along with removal of moisture from the surface of the specimen, its distribution within the specimen changes substantially. Under the effect of alternating pressures brought to the surface of the specimen by the acoustic wave, elastic vibrations develop in its volume. As a result, moisture flows from large capillaries of the early zone of an annual ring to fine capillaries of the late zone. As a consequence, the area of the specimen surface with a high moisture content increases. This fact causes an increase in the rate of drying of the material by the acoustic method in comparison with the traditional convective one. Moreover, as a result of periodic deformation of wood under the effect of acoustic vibrations a certain heating of it and, as a consequence, acceleration of the process of drying are possible.

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NOTATION

p_0, threshold sound pressure; τ_e, time for formation of the signal of the echo after the first pulse; T_2, time of spin-spin relaxation of protons of bound water and solid wood; W, distribution of moisture averaged over the length of the specimen; x, coordinate along a line normal to the edge of the annual rings.

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