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VISUALIZATION OF THE PROCESS OF WATER EXTRACTION FROM TRANSPARENT MODEL SAMPLES IN CONVECTIVE AND ACOUSTIC DRYING

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Visualization of a field being dried in a model saturated sample has been carried out. It has been shown that the process of moisture extraction under the acoustic action is faster compared to the convective action. Criteria dependences of the dimensionless relaxation time on the Biot criterion have been obtained. It has been found that the acoustic action decreases the coefficient in this dependence without changing the exponent.

The speeding-up of the drying of materials in a high-intensity acoustic field is associated with the processes proceeding both on the surface of the samples and in their bulk [1]. At the stage with a decreasing rate of drying, which is realized in practice, the processes in the bulk of the material are determining. To elucidate the physical mechanism of the increase in the rate of moisture extraction in a high-intensity acoustic field, it seems to be useful to visualize the processes proceeding in the bulk of the material being dried. One way of solving this problem is the drying of transparent model samples. The internal picture is observed in two regimes of drying — convective and acoustic ones, which permits gaining an insight into the mechanism of the influence of the acoustic field.

Figure 1 schematically represents the experimental facility in which transparent model samples were placed (AA and BB denote the cross sections of the sample and the model facility). As these samples, we used two glass plates 1 with a fine-mesh net 2 clamped between them by means of a plastic profile 3. The space between the plates was filled with distilled water through a medical needle 5 introduced into the internal cavity. The temperature was controlled by a thermocouple 4. Then the thus prepared sample was set in the drier channel with a rectangular cross section 6 so that the open edge of the net was on the leeward side of the flow. As a sound source, a Hartmann generator 8 was used. The operating conditions of the facility were determined by the brake pressure of the working gas in the settling chamber of the nozzle P and the position of pistons 9 and 10. The intensity level of the acoustic field was measured by a pressure transducer 7. The light source 11 illuminated the model sample through the optical window 12. The video camera 13 was mounted on one side of the facility and registered the dynamics of the moisture redistribution in the net in the drying process.

For the transparent samples to be able to model capillary-porous phenomena, the characteristic sizes of the meshes were selected so that water could rise, under the action of the capillary forces, in the meshes of a vertically positioned model sample.

A brass woven net with "window" sizes of 0.2 mm and a wire diameter of 0.1 mm proved to be suitable for investigations. Note that these sizes somewhat exceed the characteristic sizes of large pores, for example, in wood. The net thickness is 0.250 mm, and its length and width are, respectively, 51 and 18 mm.

The experiments were performed in two drying regimes — in an acoustic field of intensity 171 dB and frequency 520 Hz and by a convective method. The working-gas brake pressures in the settling chamber were approximately equal for these regimes. After three-minute acoustic-convective interactions the sample was weighed on an analytical balance to determine the quantity of extracted water.

The kinetic curves of drying for the two regimes (in the acoustic field and without it) are given in Fig. 2. On the Y-axis, the quantity of extracted water referred to the initial weight of water has been plotted. One can see a considerable increase in the drying rate and the total amount of extracted water under the acoustic action.

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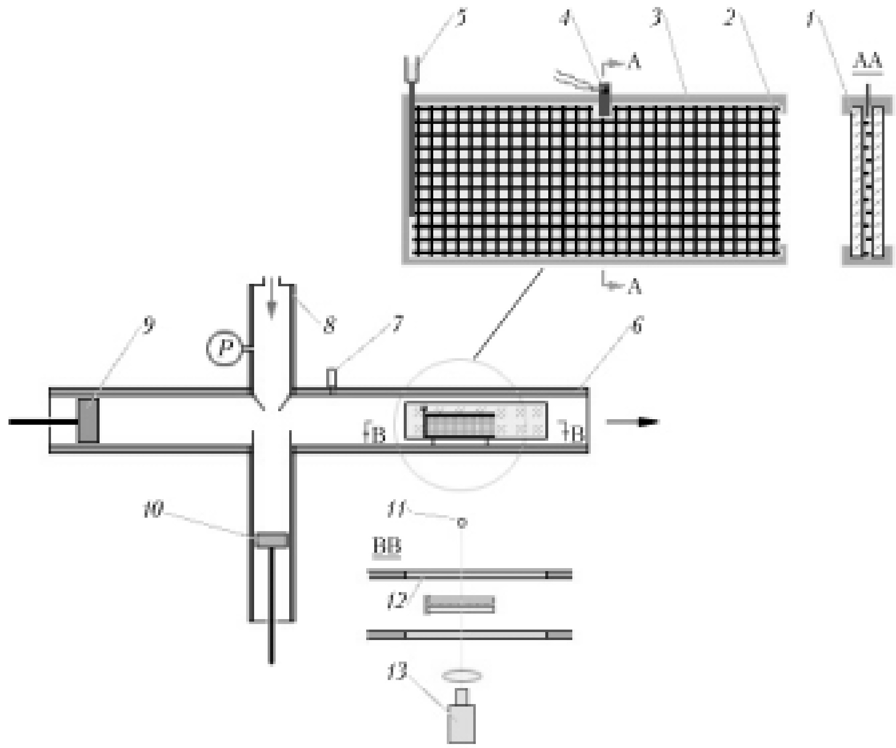

Fig. 1. Diagram of the experimental facility.

The video frames, two for each of the regimes (acoustic and convective), taken at 25-sec intervals in the drying process, show a more intensive dynamics of change in the moisture-content field in the acoustic regime (Fig. 3). It is thereby seen that the area of these changes is much larger under the acoustic action. In the figures, the light part corresponds to the meshes completely filled with water, the darkest part — to the meshes being dried (water is still present on the net wire), and the gray part — to the dried meshes. Analysis of the video information has revealed the presence of the mechanism of liquid "transfer" between meshes. It consists in the stage of a gradual decrease in the content of water in a mesh being followed by a stepwise flow of moisture under the action of the surface tension forces into one of the neighboring meshes. From the equation of motion of liquid between meshes under the action of the surface tension forces

$$\rho \frac{du}{dt} = -\nabla p$$

an estimate of the "jump" time can be obtained. Approximating the shape of water in the meshes in the form of spheres of radii r_1 and r_2, we obtain for the "jump" time

$$\Delta t \approx \frac{\rho u l}{2\sigma \left(\frac{1}{r_1} - \frac{1}{r_2} \right)} .$$

The velocity u can be found from the Bernoulli integral

$$\frac{p_1}{\rho} + \frac{v_1^2}{2} = \frac{p_2}{\rho} + \frac{v_2^2}{2} ,$$

where p_1 and v_1 and p_2 and v_2 are, respectively, the pressure and velocity in the first and second meshes. At the initial time of "jump" the liquid in the first mesh was at rest; therefore, we assume $v_1 \approx 0$. Let us estimate the pressures

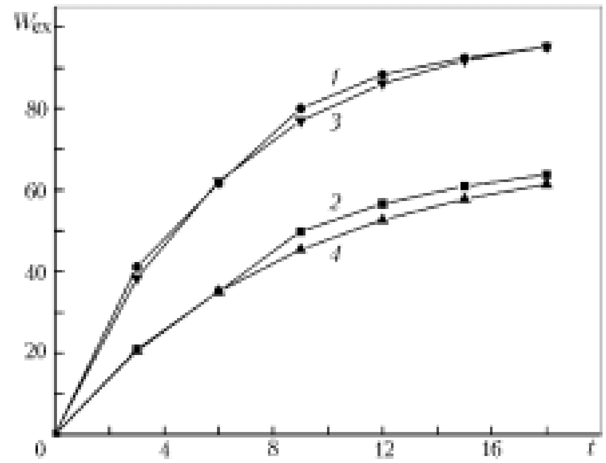

Fig. 2. Drying kinetics of the sample: 1 and 2) experiment with sound and without sound; 3 and 4) calculation with sound and without sound. W_{ex}, %; t, min.

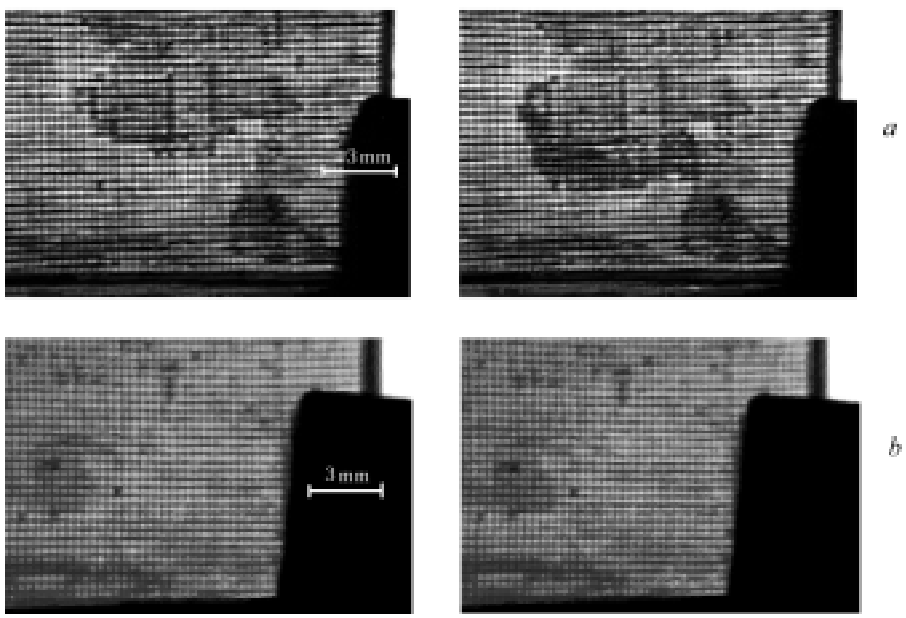

Fig. 3. Video frames of the drying process in the acoustic field (a) and without the acoustic field (b). Time between frames — 25 sec.

p_1 and p_2 by the formula for the internal pressure in liquid drops of radii r_1 and r_2. Then we find the fluid velocity in the second mesh:

$$u \approx v_2 \approx 2\sqrt{\frac{\sigma}{\rho}\left(\frac{1}{r_1}-\frac{1}{r_2}\right)}\ .$$

Substituting this relation into the formula for the "jump" time, we have

$$\Delta t \approx \frac{l}{\sqrt{\frac{\sigma}{\rho}\left(\frac{1}{r_1}-\frac{1}{r_2}\right)}}\ .$$

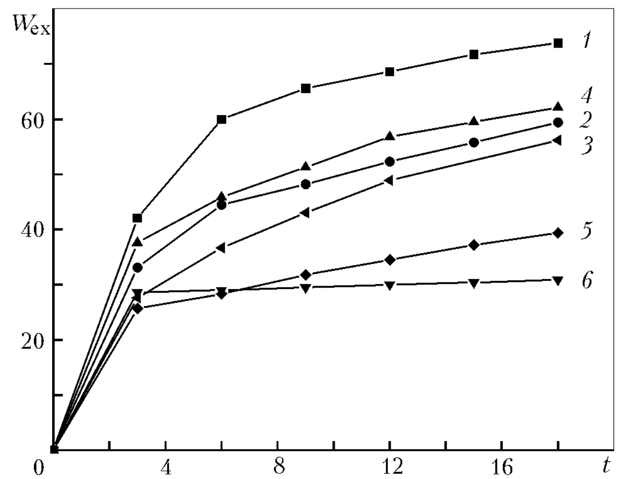

Fig. 4. Drying kinetics of samples with different materials of walls with sound [1) steel; 2) glass; 3) acrylic plastic] and without sound [4) steel; 5) glass; 6) acrylic plastic]. W_{ex}, %; t, min.

Using for the estimation $r_2 \approx 1/2$ and $r_1 \approx 1/4$, we obtain $\Delta t \approx 1.5 \cdot 10^{-5}$ sec.

The above observations and estimates indicate that under the acoustic action the role of the flow field increases. Restructuring of the flow pattern past the model occurs because of the influence of the vibrational speed of fluid particles, which at large sound intensities exceeds the velocity of the air used in the Hartmann generator. In this case, the leeward open end of the net finds itself during a half-period of vibrations on the windward side, which, naturally, increases the area of air flow past the net and the rate of water extraction.

In the two drying regimes, measurements of the flow temperature T_∞ and the mean temperature of the net with water and of the inner surface of the glasses T_m were taken. For the stationary heating stage of the glasses one can calculate the temperature of their outer surface T from the relation

$$\alpha (T_\infty - T) = \lambda \frac{T - T_m}{d} .$$

The heat-transfer coefficient can be calculated by the formula [2] $\alpha = 5.6 + 4v$.

Having determined the temperature of the outer surface of the glasses, one can estimate the quantity of heat supplied by the flow to this surface and compare it to the energy needed for the evaporation of a certain quantity of water, e.g., in 3 min of drying. For the acoustic drying conditions, we have $T_\infty = 21^oC$ and $T = 19^oC$. For extracted water to evaporate in 3 min, 48 J are needed, and the estimate of the quantity of heat supplied in the same time to the glasses gives 39 J. Under convective conditions about 150 J have been supplied, whereas water extraction by the evaporation mechanism requires 25 J. Thus, it is seen that the heat supplied suffices to extract water by the evaporation mechanism, especially under convective drying conditions. This does not mean, however, that only this mechanism is realized. In the presence of a free surface of water and at a fairly high rate of flow, the mechanism of breaking the liquid into microdroplets can also make its contribution [3].

In general, it can evidently be noted that the influence of acoustic vibrations under the given experimental conditions on the drying rate of the sample is due to both the increase in the area of moisture extraction and the intensification of the heat and moisture transfer because of the change in the flow field around the samples. The latter conclusion remains, perhaps, also applicable for practically important materials and samples (grain, wood, etc.).

Influence of the Material of Plates. Experiments to investigate the influence of the material from which the plates were made on the drying rate have been performed. We used plates made of steel, glass, and acrylic plastic. The meshes model the porous structure of internal layers of the real materials and the plates — the influence of the heat conductivity of external layers. Drying was carried out under acoustic and convective conditions. Comparison of the kinetic drying curves is given in Fig. 4. The increase in the drying rate of samples with steel and glass walls compared to the sample of acrylic plastic is explained by the large heat-conductivity coefficients of steel and glass as com-

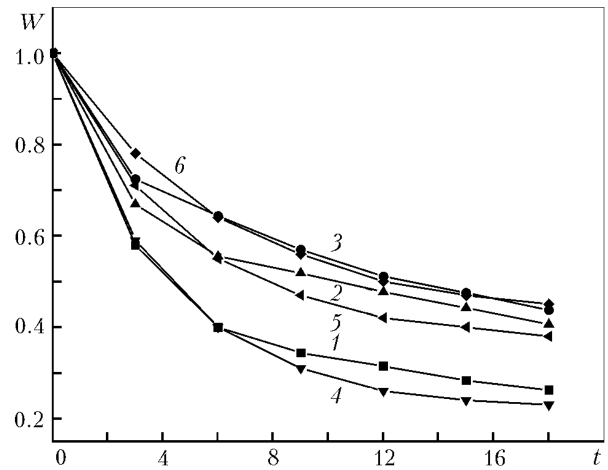

Fig. 5. Experimental [1) steel; 2) glass; 3) acrylic plastic] and calculated [4) steel; 5) glass; 6) acrylic plastic] data for drying in the acoustic field. *t*, min.

pared to acrylic plastic. The same also holds for the steel–glass pair. A large heat-conductivity coefficient leads to an increase in the net temperature and the rate of water extraction.

Mathematical Model of Moisture Extraction from Samples. The obtained experimental curves of the drying kinetics of the samples can be described by the solution of the linear kinetic equation for the current moisture of the samples

$$\frac{dW}{dt} = -\frac{W - W_e}{\tau} .$$

Here $W = m(t)/m(0)$; τ is the relaxation time found from the experimental data. This approach was used in [3] for another model sample. Examples of comparison of the calculated and experimental results for the regime of drying in an acoustic field are given in Figs. 2 and 5. A fairly good agreement of the results is seen.

One can determine the dependence of the relaxation time of the kinetic drying curve τ on the heat-conductivity coefficient of the wall material of the sample. For the acoustic and convective drying conditions, these dependences upon approximation of the exponents, respectively, are of the form

$$\tau_a = 5.25\lambda^{-0.07} , \quad \tau_0 = 6.79\lambda^{-0.07} .$$

Note that the exponents in these expressions are equal, which is due to the absence of the influence of the acoustic field on the heat-conductivity coefficients of the wall materials of the samples.

The latter relations can be reduced to the dimensionless form. Introducing the Fourier number $\text{Fo} = \lambda\tau/R^2$ and the Biot number $\text{Bi} = \alpha R/\lambda$, we obtain, respectively, for the acoustic and convective drying conditions

$$\text{Fo}^a = 6.47{\cdot}10^7\ \text{Bi}^{-0.93} , \quad \text{Fo} = 8.25{\cdot}10^7\ \text{Bi}^{-0.93} .$$

From this it is seen that the acoustic action decreases only the coefficient in the criteria dependence.

CONCLUSIONS

1. The visualization of the field in the model sample being dried and the weight measurements have shown that the process of moisture extraction is faster under the acoustic action than in the case of convective drying.

2. The process of spontaneous emptying of meshes from water, which follows the stage of slow extraction of water from the mesh, has been revealed. This process is more pronounced in the acoustic field.

3. A mathematical model of the relaxation type, which has enabled us to describe the obtained experimental time dependences of the moisture content for the model sample, is proposed. With allowance for the heat conductivity of the surrounding walls, criteria dependences of the dimensionless relaxation on the Biot criterion have been obtained. It has been shown that the acoustic action decreases the coefficient in this dependence without affecting the exponent.

NOTATION

ρ, fluid density, kg/m^3; u, fluid velocity, m/sec; v_1 and v_2, fluid velocities in the first and second meshes, m/sec; P, pressure in the nozzle settling chamber, Pa; p, pressure caused by the surface-tension forces, Pa; p_1 and p_2, pressures in the first and second meshes, Pa; l, characteristic size of the mesh, m; r_1 and r_2, radii of liquid droplets in two adjacent meshes, m; σ, surface-tension coefficient, N/m; t, time, sec; T_∞, $T_{\rm m}$, and T, temperatures of the flow, the net with water, and the outer surface of glasses, K: α, heat-transfer coefficient, W/(m^2·K); λ, heat-conductivity coefficient of the walls, W/(m·K); d, thickness of the walls, m; v, working-gas flow rate, m/sec; $m(t)$ and $m(0)$, current and initial weight of water in the sample, kg; W, relative quantity of water in the sample; $W_{\rm e}$, environment-equilibrium moisture of samples; $W_{\rm ex}$, relative quantity of extracted water, %; τ, relaxation time, sec; $\tau_{\rm a}$ and τ_0, relaxation time in the acoustic field and without it, sec; R, half-thickness of plates, m; Fo$^{\rm a}$ and Fo, Fourier numbers in the acoustic field and without it; Bi, Biot number. Subscripts: ∞, flow parameter; m, internal; e, equilibrium; a, acoustic; 0, convective; ex, extracted.

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