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THE PROCESS OF DRYING OF A CAPILLARY SPECIMEN SUBJECTED TO AN ACOUSTIC-CONVECTIVE EFFECT

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The process of drying of a model capillary specimen located in an intense acoustic field under the conditions of convective blowing is investigated. Video recording has registered a drop mechanism of water extraction from the capillaries of the specimen. It is shown that the driving force of this process is the difference between the acoustic pressure in the external flow and inside the cavity of the specimen. Measurements have demonstrated a certain increase in the temperature inside a capillary exposed to an acoustic field. The influence of the position of capillaries relative to the sonic wave front and of the flow velocity is investigated. It is shown that in the capillaries positioned horizontally the temperature in them is much lower than in those positioned vertically. Kinetic curves of drying of the specimen are obtained.

A survey of results of investigations into the phenomenon of acceleration of the process of drying capillary-porous materials in an intense acoustic field was made in [1]. In [2], visualization of a dehumidified field in transparent-model specimens consisting of a net placed between glass- or organic glass plates and filled with water was carried out. It was shown that the acoustic field substantially intensifies the dynamics of drying.

Since the structural unit of actual capillary-porous material consists of a "capillary-pore" element, it appears natural to study extraction of water at the level of individual capillaries and pores. In what follows, we present the results of such an investigation, using as an example a model specimen made from organic glass in the form of a parallelepiped of length 48 mm, width 27 mm, and height 33 mm, in which there are capillaries of diameter 0.3 mm and length 4 mm that on one side reach the surface of the specimen and on the other — the inner cavity (see Fig. 1a). The diameter of the cylindrical cavity was 18 mm and its length was 36 mm. The cavity could be filled with water by a syringe; from the opposite side it was closed by an LKh-610 pressure transducer. We hope that such a specimen models, for example, a tracheid (cavity) for wood with capillaries passing through its walls [3]. In the first (in the flow direction) capillary, near the outer surface of the specimen, at a depth of 0.5 mm the junction of a chromel-copel thermocouple was located with the diameter of the thermocouple wires being 0.05 mm. The junction of the second, similar thermocouple was brought out onto the surface of the inner cavity. A third thermocouple measured the main stream temperature and was put into the flow outside the specimen.

The schematic diagram of the experimental setup is given in Fig. 1b. The model capillary specimen was installed in the channel of a drying chamber of rectangular cross section 8. The inlet and exit of air from the setup are shown by arrows. As a source of sound we used a Hartmann oscillator 3. The operating conditions of the setup were determined by the working-gas stagnation pressure in the setting prechamber of a nozzle P_0 (pressure transducer 2) and by the position of pistons 1 and 6. The level of intensity of acoustic field in the drying chamber and in the inner cavity of the model was measured by pressure transducers 4 and 5, respectively. A light source (light diode) 7 illuminated the model specimen through optical windows 10. A video camera 9 was attached to the side of the setup, and it fixed the dynamics of the exit of water from capillaries when they were exposed to an acoustic-convective effect.

Experiments were run in two drying regimes: in the presence of an acoustic field of intensity 170 dB and frequency f = 470 Hz with a convective air flow treated in a Hartmann oscillator and without an acoustic field. The working-gas stagnation pressure in the prechamber of the nozzle and the mean air-flow velocity were approximately

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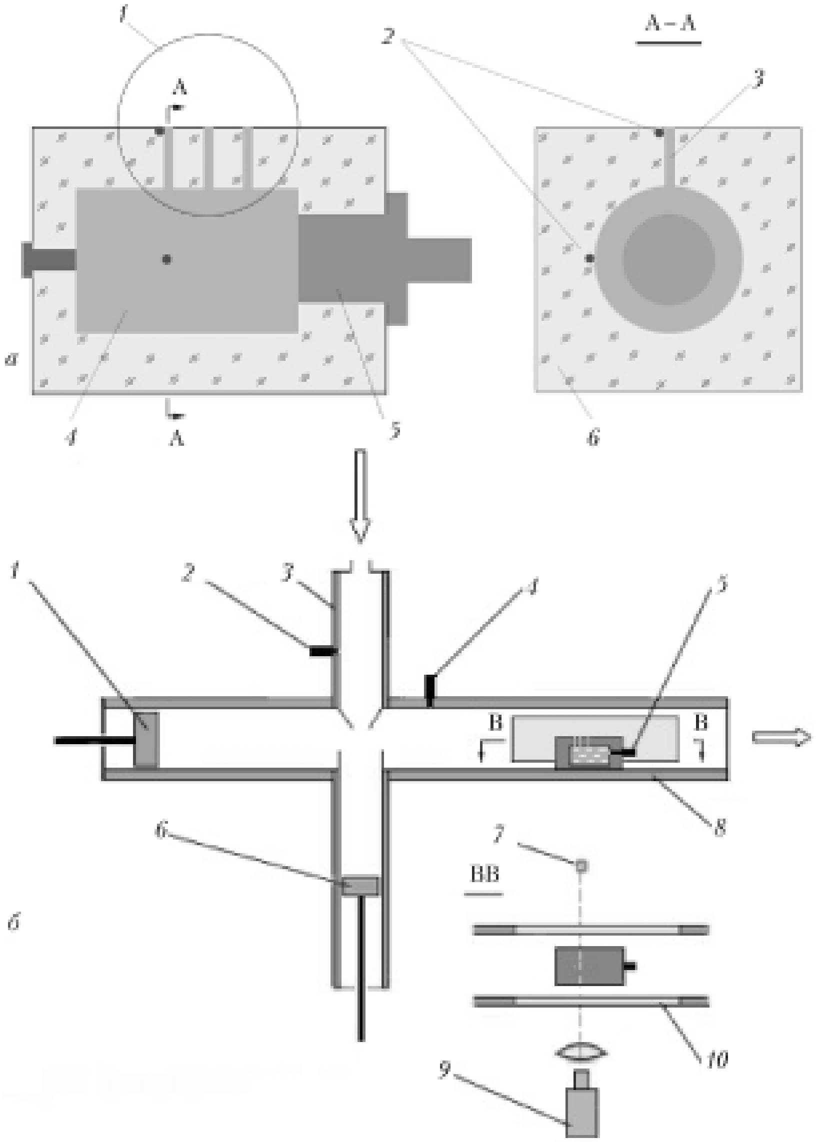

Fig. 1. Schematic diagram of experimental equipment: a) model capillary specimen [1) region of optical recording; 2) thermocouples; 3) capillaries; 4) water in the cavity of the specimen; 5) pressure transducer; 6) transparent casing of the model specimen]; b) experimental facility [1, 6) pistons of the oscillator; 2) transducer of pressure P_0 in the prechamber; 3) Hartmann oscillator; 4, 5) transducers of pressure in the drying chamber and in the internal cavity in the specimen; 7) light diode; 8) drying chamber of rectangular cross section; 9) video camera; 10) optical windows].

the same for both regimes. The capillaries emerged onto the upper face of the specimen perpendicularly to the air-flow direction.

Figure 2a presents video pictures of a capillary taken at a 1/30-sec interval at the time of onset of an acoustic-convective regime from left to right. The visible meniscus of the water level moves downward, and the capillary becomes opaque. When the capillary is filled with air, the latter acts as a strongly scattering cylindrical lens for a transmitted light.

A successive skeleton of pictures from the video recording of one of the experiments is presented in Fig. 2b. The arrow shows the direction of air flow.

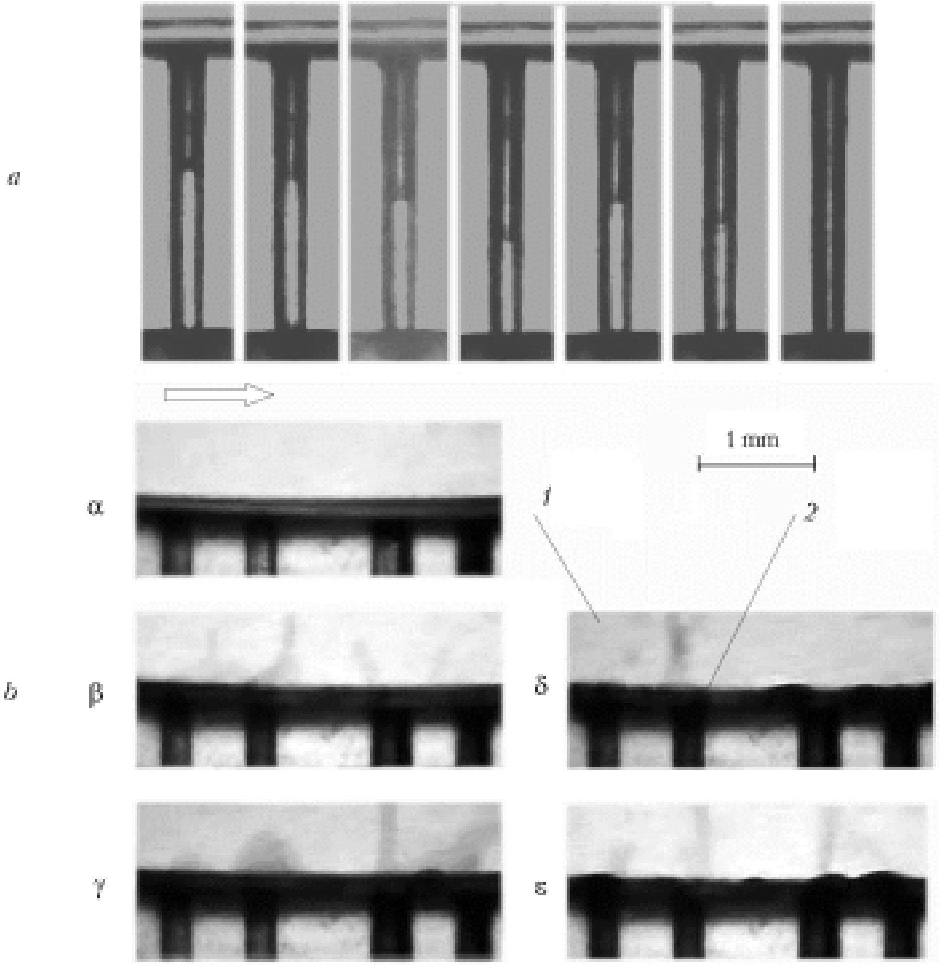

Fig. 2. Frame-by-frame depiction of the level of water in a capillary under acoustic action (a) and frames of video recording of water extraction from the specimen in the drying chamber (b) [1) trace of the drop escaped from the capillary; 2) water droplet on the surface of the specimen; α, convective regime; β, γ, δ, and ε, acoustic-convective regime].

Under acoustic-convective conditions (frames β, γ, δ, ε), dark prominences 2 are seen on the surface, which are displaced under the action of flow and which consist of the moisture extracted from the capillaries. The size of the drops is of the order of the diameter of the capillaries. Moreover, instantaneous dark ejections 1 from the capillaries into the coflow are recorded. It can be assumed that they result from ejections of one or, most likely, a multitude of finely dispersed water droplets under the action of an acoustic field. This phenomenon is not observed in the convective mode (frame α). The time intervals αβ, βγ, γδ, and δε between the frames are equal to $\Delta t_{\alpha\beta} = 30$ sec, $\Delta t_{\beta\gamma} = 0.13$ sec, $\Delta t_{\gamma\delta} = 0.47$ sec, and $\Delta_{\delta\varepsilon} = 0.9$ sec, respectively.

The results of measurements (of the temperatures of air flow, inside the water-filled capillary in the region close to the upper face of the specimen, and inside the cavity filled with water in the specimen) are presented in Fig. 3I. As is seen, the temperature in the capillary exceeds the temperature of the surrounding medium but remains lower than the evaporation temperature. This allows one to speak of the acoustic-convective drying as of the cold drying of materials. Similar results of measurements in the absence of water in the cavity and capillaries are presented in Fig. 3.II. It is seen that the acoustic field heats air in the capillary. A similar phenomenon of acoustic heating inside specimens made from a network is described in [4]. Air is heated as a result of acoustic-energy dissipation. As is seen from Fig. 3, the rate of heating depends weakly on the presence of water in capillaries.

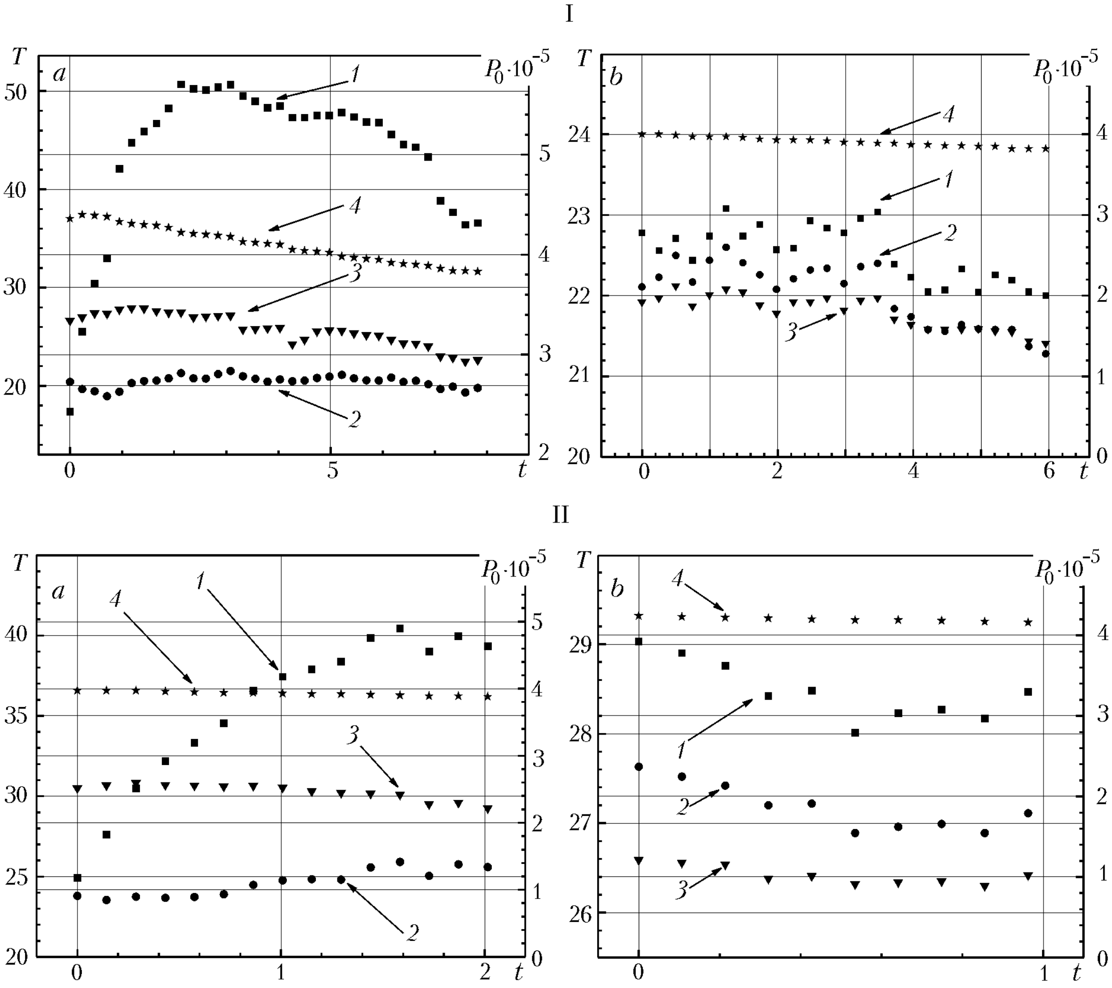

Fig. 3. Distribution of temperatures in the model with water (I) and without water (II) under acoustic (a) and convective (b) actions: 1) in the capillary; 2) in the cavity; 3) in the stream; 4) pressure in the prechamber. T, ^{o}C; P_0, Pa; t, min.

In another series of experiments, a model specimen was turned through 90^{o}, and the capillaries were located horizontally opposite to the sonic wave front and to the flow direction on the windward side. Air is heated noticeably less (Fig. 4). This is explained by the increase in the cooling effect of the air flow.

The kinetics of drying of a specimen in an acoustic-convective regime and without an acoustic field is presented in Fig. 5. The substantial increase in the rate of drying in the presence of an acoustic effect is associated for the most part with the drop mechanism of the extraction of water from a specimen.

The realization of the mechanism of droplet extraction of water from the capillaries of a specimen poses the question as to the driving force of this process. Obviously, for the drops to be precipitated out it is necessary to overcome the forces of surface tension. The capillary pressure is $p_c = 2\sigma/r = 9.7 \cdot 10^2$ Pa. It can be easily shown that the influence of water weight in the capillary can be neglected. The influence of the lowered static pressure of the convective flow of the worked-out air due to which the suction occurs is possible. At a flow velocity of 26 m/sec, the magnitude of the static pressure drop is $4 \cdot 10^2$ Pa. Thus, this drop is insufficient for overcoming the force of surface tension. This conclusion agrees with the result of video recording of the process of drying a specimen in the absence of an acoustic field, when the droplet mode of drying is not observed.

The most real driving force for separating-out droplets is the acoustic pressure drop due to the difference between the amplitudes of sonic pressure in a free air stream and inside the cavity of a specimen, where the pressure

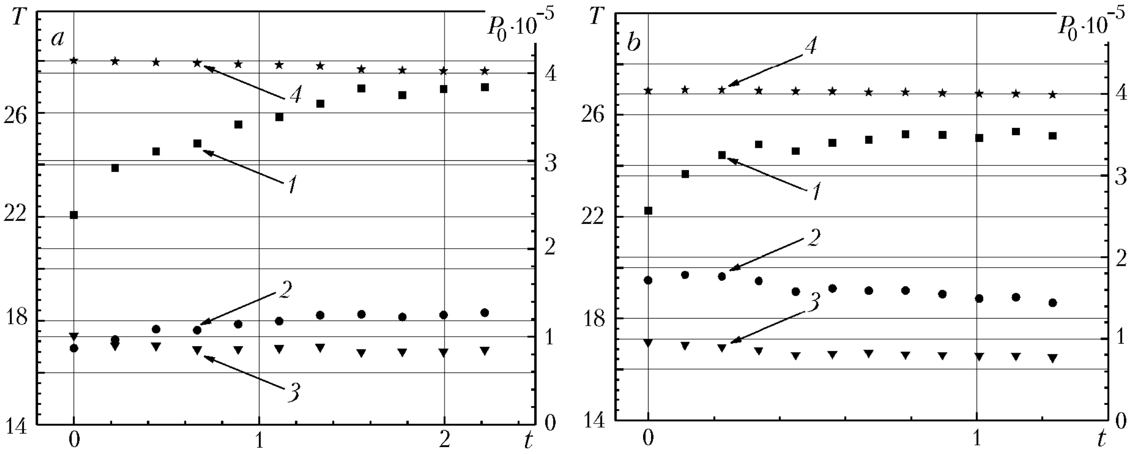

Fig. 4. Distribution of temperatures in the model with water and without water in the case of horizontal disposition on the windward side under acoustic-convective (a) and convective (b) actions: 1) in the capillary; 2) in the cavity; 3) in the stream; 4) pressure in the prechamber. T, °C; P_0, Pa; t, min.

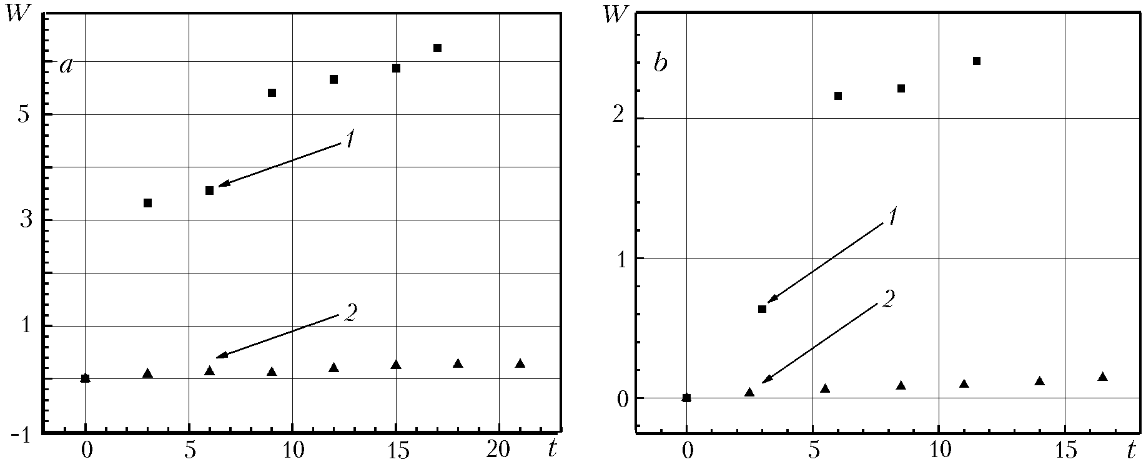

Fig. 5. Amount of extracted water depending on time on the lateral (a) and windward (b) side: 1) under acoustic-convective action; 2) under convective action. W, %; t, min.

amplitude must be smaller because of the weakening of sound by the specimen walls. Simultaneous measurement of the sonic pressure amplitudes in the channel of the facility and inside a specimen filled with water has shown that in the cavity this amplitude is two-to-three times smaller than in the channel. A shift of phases between pressure oscillations was not observed. For example, at a sound intensity in the channel of the facility of 170 dB, the intensity in the cavity of a specimen is 160 dB. This yields a difference in the acoustic pressure amplitudes of $6 \cdot 10^6$ Pa, which is much higher than the capillary pressure. Thus, the most probable is the following mechanism of extraction of water droplets from the capillaries of a specimen. In the phase of rarefaction, in an acoustic wave the liquid in the capillaries near the surface emerges from the capillaries under the action of the acoustic pressure drop and is entrained by the vibrational-convective air stream. In the phase of compression, the remaining part of the water recedes into the capillaries and then, with a decrease in the pressure drop under the action of constantly acting forces of surface tension, water is raised again to the specimen surface.

We will estimate the value of the displacement of the water meniscus in the capillary of a specimen under the action of the acoustic pressure drop. We will avail ourselves of the nonstationary linear Navier–Stokes equation of motion for the liquid velocity along the capillary:

$$\frac{\partial v}{\partial t} = -\frac{1}{\rho}\frac{dp}{dx} + \frac{\eta}{\rho}\frac{\partial^2 v}{\partial y^2}. \tag{1}$$

As a result of the reduction of Eq. (1) for processes with a characteristic circular frequency ω and radius of the capillary r to a dimensionless form, it can be easily seen that the second term on the right-hand side will be preceded by the dimensionless coefficient 1/Re, where Re = $\omega r^2/\nu$. For the conditions of the given experiments, the Re number is much higher than unity, therefore the influence of viscosity can be neglected, so that

$$\frac{\partial v}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x}. \tag{2}$$

Assuming the time dependence of the acoustic pressure to be harmonic and integrating Eq. (2), we obtain an expression for the liquid velocity in the capillary:

$$v(t) = -\frac{\sin(\omega t)}{\rho\omega}\frac{dp_a}{dx}. \tag{3}$$

Using Eq. (3), we determine the displacement of the water meniscus in the capillary in time t:

$$l(t) = -\frac{t\sin(\omega t)}{\rho\omega}\frac{dp_a}{dx}. \tag{4}$$

Substituting the values of the acoustic pressure drop, capillary length, and frequency of acoustic vibrations into Eq. (4), we obtain that the displacement in a quarter of the period is equal to 0.5 mm. This value is close to two diameters of the capillary, i.e., it is quite appreciable.

It is believed that at large amplitudes and frequencies of the acoustic field the meniscus in the capillary undergoes deformation without macroscopically noticeable slipping of the line of contact between water and capillary [5]. The results of the present experiments show that under the action of acoustic pressure drop the meniscus experiences such great deformations that there occurs the overcoming of the forces of surface tension with formation of liquid droplets.

The forces of surface tension strive to fill the liquid volume displaced by the acoustic pressure drop. Let us calculate the time needed to occupy this volume, proceeding from the Euler equation for the velocity of capillary motion v_c:

$$\frac{dv_c}{dt} = -\frac{1}{\rho}\frac{dp_c}{dx}. \tag{5}$$

Since a meniscus is absent on the lower end of the capillary, $dp_c/dx = -2\sigma/(rh)$. Substituting this expression into Eq. (5) and calculating the characteristic velocity for the time instant equal to half the period of vibrations, we find

$$v_c = \frac{\sigma}{\rho r h f}.$$

Having divided l by v_c, we write an expression for the time of filling τ:

$$\tau = \frac{l\rho r h f}{\sigma}. \tag{6}$$

Substituting the numerical values of all the quantities contained in it into Eq. (6), we obtain that τ = 1.9 msec. For comparison, the period of vibration is $1/f$ = 2.1 msec. Thus, it is seen that the forces of surface tension manage to rapidly fill the volume of water displaced by the acoustic pressure drop.

The most probable mechanism of extraction of water from the cylindrical capillary assembly, the open ends of which are under identical external conditions, is the dispersion of water into microdroplets [6]. The driving force of this process is the velocity of the acoustic-convective flow, which, due to viscous forces, sets the near-surface layers of liquid in the capillaries into motion. The mechanism of extraction of water from a model capillary-porous specimen in the present work has a different nature: it is extracted under the action of acoustic pressure drop in the phase of rarefaction with drops of the size of the capillary diameter.

In [7], for a polycapillary specimen immersed by its lower end into a water bath closed by an elastic lid, a drop-film mechanism of water extraction under acoustic action was fixed experimentally. It is evident that the main driving force in separation of droplets in this case was the forcing action of the lid — the membrane of the bath with water under the action of acoustic pulsations of pressure in the main gas stream. In real capillary-porous materials this mechanism of separation of water droplets seems to be hardly applicable.

Thus, under acoustic-convective action, various driving forces and mechanisms of water extraction can be realized, depending on the structure of the specimen being dried and the specific conditions in which it is located.

CONCLUSIONS

1. In a saturated capillary-porous specimen, extraction of water under the action of an intense acoustic field follows a drop mechanism, the main driving force of which is the acoustic pressure drop in the external medium and inside the specimen.
2. The capillary forces of surface tension ensure a virtually continuous supply of new portions of water to the specimen surface.
3. Because of the acoustic-energy dissipation in the boundary layer and at the exit of capillaries, both filled with water and without it, a certain near-surface heating of air occurs.

NOTATION

f, acoustic-field frequency, 1/sec; h, capillary height, m; l, value of displacement of a water meniscus in a capillary under the action of acoustic pressure drop, m; P_0, stagnation pressure in the prechamber of the nozzle, Pa; p and p_a, pressure amplitude, Pa; p_c, capillary pressure, Pa; r, radius of a capillary, m; Re, Reynolds number; T, temperature, ^{o}C; t, time, sec; v, velocity of water motion in the capillary under acoustic pressure drop, m/sec; v_c, velocity of water motion in the capillary under the action of surface-tension forces, m/sec; W, ratio of the weight of extracted water to the initial weight of water in the specimen, %; x and y, coordinates along and across the capillary, respectively, m; η, coefficient of dynamic viscosity, Pa·sec; ν, coefficient of kinematic viscosity, m^2/sec; ρ, water density, kg/m^3; σ, coefficient of surface tension, N/m; τ, characteristic time of displacement of a water meniscus in the capillary over a distance l under the action of the surface-tension forces, sec; ω, circular frequency of acoustic field, 1/sec. Subscripts: a, amplitude; c, capillary; 0, in the prechamber.

REFERENCES

1. Yu. Ya. Borisov and N. M. Gynkina, Acoustic drying, in: L. D. Rozenberg (Ed.), *Physical Principles of Ultrasonic Technology* [in Russian], Nauka, Moscow (1970), pp. 580–640.
2. Yu. G. Korobeinikov, A. P. Petrov, and A. V. Fedorov, Visualization of the process of water extraction from transparent model samples subjected to convective and acoustic drying, *Inzh.-Fiz. Zh.*, **77**, No. 2, 31–35 (2004).
3. B. N. Ugolev, *Science of Wood with Bases of the Science of Wood Commodities* [in Russian], Lesnaya Promyshlennost', Moscow (1975), pp. 41–51.
4. Yu. G. Korobeinikov, A. P. Petrov, G. A. Trubacheev, and A. V. Fedorov, Thermal effects in model specimens under acoustic and convective actions, *Inzh.-Fiz. Zh.*, **79**, No. 2, 168–173 (2006).
5. M. Hilpert, D. Stopper, and G. H. Jirka, Resonance of a liquid column in a capillary tube, *Z. angew. Math.Phys.*, **48**, 424–438 (1997).
6. Yu. G. Korobeinikov and A. V. Fedorov, On extraction of water from a capillary sample in an acoustic field, *Inzh.-Fiz. Zh.*, **76**, No. 1, 7–10 (2003).
7. V. N. Glaznev, Yu. G. Korobeinikov, and V. M. Fomin, Acoustic drying of porous materials, in: V. N. Parmon (Ed.), *Contemporary Approaches to Research and Description of the Processes of Drying of Porous Bodies* [in Russian], Izd. SO Ross. Akad. Nauk, Novosibirsk (2001), pp. 212–239.