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INVESTIGATION OF THE PROCESS OF DRYING OF A SYSTEM OF CONNECTED CAPILLARIES IN AN ACOUSTIC-CONVECTIVE FIELD

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A study has been made of the process of drying of a model specimen with a system of capillaries connected via a slot space; the specimen is located in an intense acoustic-convective field. The film-dropwise mechanism of extraction of water from the specimen's system of capillaries has been video-recorded. It has been established that the difference of the acoustic pressures in the external flow and inside the cavity of the specimen is one motive force of this process. It has been shown that a vortex gas motion pulsating with the frequency of the acoustic field and under whose action the liquid breaks down into droplets is formed in the capillaries–slot space system in the acoustic-convective regime. Such phenomena have not been observed in the convective regime of drying. The influence of the frequency and amplitude of oscillations of the acoustic field on the rate of drying of the specimen has been studied.

Investigations of the acceleration of drying of capillary-porous materials in an intense acoustic field have been reviewed in [1]. Since the structural unit of actual capillary-porous materials is the "capillary–pore" element, it seems expedient to study the extraction of water at the level of individual capillaries and pores. In [2], we have given results of such investigation using the model acrylic-plastic specimen as an example; the model specimen had independent capillaries of diameter 0.3 mm and length 4 mm emerging on the specimen's surface on one side and extending into the internal cavity on the other. It was shown that the dropwise mechanism of extraction of moisture under the action of the difference of the acoustic pressures inside the specimen's cavity and in the external flow is realized in acoustic-convective drying. Since capillaries are not independent in actual capillary-porous materials, it is necessary to investigate an analogous system but with connected capillaries. In this work, the acrylic-plastic specimen (Fig. 1) had a water-filled cavity 16 whose lateral surface was covered with an acrylic-plastic plate 8 with milled square channels of depth 0.1 mm; the distance between the capillary channels was equal to 0.4 mm. This plate was pressed against the specimen's frame 4 by another plate with a much larger thickness 9. Thus, the lower part of the capillaries was located in the cavity, whereas the upper part emerged on the specimen's surface. A slot space of length 26 mm, height 20 mm, and thickness smaller than 0.05 mm limited by seal 12 was left between the plate with capillaries and the specimen's frame; this ensured the connection of the capillaries via this slot space.

To magnify the image we placed lens 10 in the groove in the pressing plate 9 in the immediate vicinity of the system of capillaries. The height of the cavity was equal to 8 mm, whereas its length and width were equal to 18 and 13 mm respectively. The cavity could be filled with water through orifice 15; the pressure transducer 5 (TDMA-0.4) was located in it on the opposite end. The junction of a Chromel-Alumel thermocouple 6 was placed on the upper surface of the specimen; the diameter of the thermocouple wires was 0.05 mm. The junction of the second identical thermocouple 7 was brought out to the surface of the internal cavity of the specimen. The third thermocouple measured the temperature of the incident flow 13 and was arranged in the flow outside the specimen.

The model capillary specimen was installed in the rectangular channel of a drying chamber [2]. The Hartmann generator 14 was used as the sound source. The intensity level of the acoustic field in the drying chamber was measured with an LKh-610 pressure transducer. The light source (light-emitting diode) 1 produced ray 2 and illuminated

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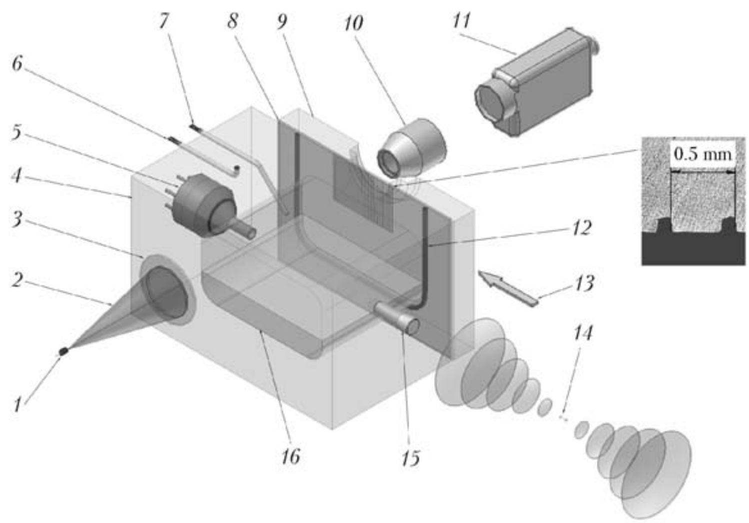


Fig. 1. Model capillary specimen.

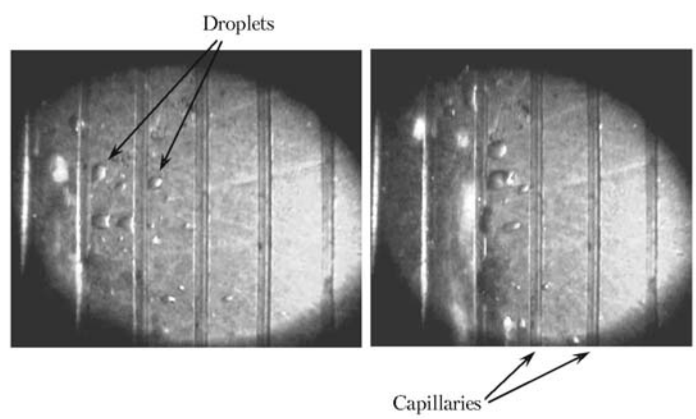
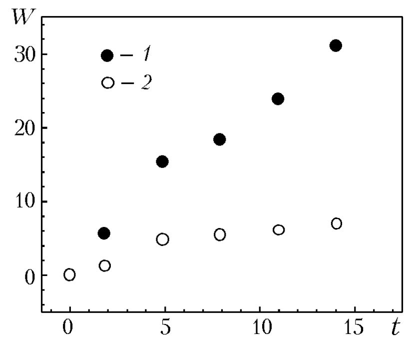


Fig. 2. Snapshots of the video-recorded process of acoustic-convective drying at different instants of time (after 0.44 sec).

the model specimen through an optical window 3. Video camera 11 was fixed on the side of the setup and recorded the dynamics of drying.

The experiments were carried out in two regimes: for the acoustic field with a convective flow of air spent in the Hartmann generator and without it. The stagnation pressure of the working gas in the nozzle prechamber and the average velocity of the air flow (equal to 26 m/sec) were nearly the same for these regimes. The sound-oscillation wavelength was much larger than the characteristic dimension of the specimen, whereas the oscillation amplitude was comparable to this dimension.

The intense movement of water from the cavity toward the thermocouple's surface both in the slot space between the capillaries and along the capillaries was video-recorded in the acoustic-convective regime of drying. This occurs under the action of the difference in acoustic pressures in the cavity and outside the specimen. The amplitude of the acoustic pressure in the flow for an intensity of, e.g., 170 dB is equal to $8.8 \cdot 10^3$ Pa (to $7.0 \cdot 10^3$ Pa in the cavity); the phase shift is equal to zero. Vortex gas motion pulsating with the frequency of the acoustic field and under whose action the liquid breaks down into droplets is formed in the capillaries–slot space system in the acoustic-convective regime (Fig. 2, the convective flow here is directed from left to right; the vortex motion of the gas in the slot space is clockwise). The pulsatory character of the vortex is caused by the addition of the velocity of particles in the acoustic field (the amplitude of the oscillatory velocity for the above-indicated intensity of the acoustic field is equal to 22.2 m/sec) and the average velocity of the flow. The character of motion of the liquid corresponds to the film-dropwise mechanism of extraction, when the liquid moves as a film in the slot space under the action of the difference in pres-



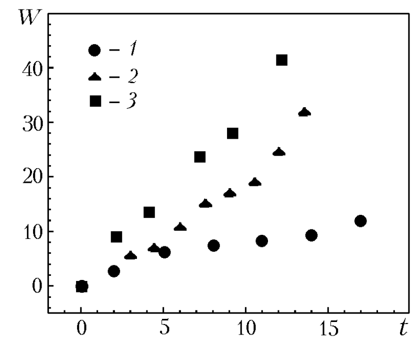


Fig. 3. Comparison of the relative quantity of the extracted water in the acoustic-convective regime (1) with an intensity of the acoustic field of 174 dB and a frequency of 415 Hz and in the convective regime (2). *W*, %; *t*, min.

Fig. 4. Quantity of the extracted water in acoustic-convective drying of the specimen with different frequencies of the acoustic field (intensity 167 dB): 1) f = 400, 2) 310, and 3) 293 Hz. *W*, %; *t*, min.

sures in the cavity and in the flow and disperses into droplets by the pulsating vortex. No visible motions and breaking down of the liquid are observed in convective drying; the drying goes through the mechanism of evaporation.

Let us evaluate the size of water particles produced by the dispersing action of the acoustic-convective vortex using the method of [3]. The density of the energy flux per unit surface of the slot space with an acoustic wave is equal to [4]

$$I = c\rho V_{\rm m}^2 \cos\frac{\theta}{2} . \tag{1}$$

Multiplying (1) by the cross section of the slot space S (with allowance for the cross section of the capillaries), we obtain the quantity of sound energy supplied in unit time. Dividing by the energy of formation of a droplet and multiplying by the dispersion efficiency K and by the mass of a droplet of radius r, we obtain an expression for the rate of extraction of water under the sound action:

$$\frac{\Delta m}{\Delta t} = \frac{\rho\rho_{\rm w} c V_{\rm m}^2 K r S \cos\theta}{6\sigma} . \tag{2}$$

For the water-particle size, from (2) we have

$$r = \frac{6\sigma \dfrac{\Delta m}{\Delta t}}{\rho\rho_{\rm w} c V_{\rm m}^2 K S \cos\theta} . \tag{3}$$

Using experimental data for the drying rate and taking $\theta \simeq 98^{\rm o}$ and $K \sim 0.01$ (from a comparison to experimental data on the dimension of water droplets), we obtain, from (3), an estimate for the particle size: $r \approx 10^2$ μm. This value is in good agreement with the data of video recording where water droplets of the order of the transverse dimension of the capillaries, which is equal to 10^2 μm, are seen on the walls confining the slot space. Thus, the dispersion efficiency is equal to nearly 1%.

Figure 3a gives results of measurement of the relative quantity of the extracted water in two regimes: the acoustic-convective and convective ones. The presence of the acoustic field substantially intensifies the process, which is in agreement with the data of video recording.

Change in the frequency of the acoustic field for a constant intensity influences the quantity of the extracted water (Fig. 4). The extraction efficiency increases with decrease in the frequency. This effect can, apparently, be explained from the well-known relation for the amplitudes of velocity, displacement, and frequency of acoustic oscillations:

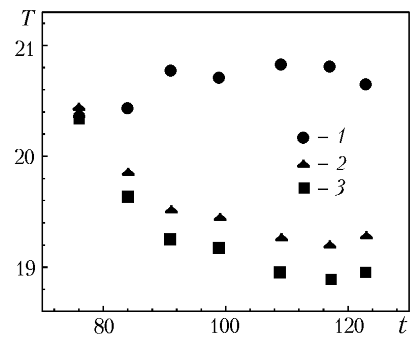


Fig. 5. Temperature distribution in acoustic-convective drying of the specimen: 1) on the specimen's surface; 2) in the cavity; 3) in the freestream. T, ^{o}C; t, sec.

$$V_m = 2\pi f A \ .$$

It is seen that, for a constant intensity of the acoustic field and consequently V_m, decrease in the frequency causes the amplitude of oscillatory motion of the gas in the freestream to increase: as the frequency varies from 400 to 293 Hz (for an intensity of 167 dB), the amplitude changes from 4.5 to 6.1 mm and the oscillatory process in the slot space is intensified, which causes the extraction of water to increase.

The values of the temperatures inside the cavity and on the surface of the specimen and of the temperature of the flow of air spent in the Hartmann generator are given in Fig. 5. These temperatures do not differ significantly. It has been shown in [5] that the temperature in the capillaries can increase markedly under the action of the acoustic field. In this work, using the thermocouple on the specimen's surface, we have recorded a slight growth in the temperature because of the dissipation of the acoustic field [4] (of $\approx 1.5^{o}$C compared to the flow temperature). The temperature in the cavity is close to the flow temperature and is lower than the temperature on the specimen's surface because of the absence of acoustic heating in the specimen's cavity and the cooling action of the gas flow.

CONCLUSIONS

1. The film-dropwise mechanism of extraction of water is realized in the system of capillaries which are in an intense acoustic-convective field and are connected via the slot space. The liquid in this system disperses, under the action of the vortex motion of the gas pulsating with the frequency of the acoustic field, into droplets which are subsequently removed to the external flow.

2. Neither visible motions of the liquid nor its breaking down are observed in convective drying; the mechanism of evaporation is realized.

3. The quantitative study of the kinetics of drying of the specimen has shown substantial intensification of the process in the acoustic-convective regime. Decrease in the frequency of the acoustic field for a constant intensify causes the oscillation amplitude to increase, which makes the drying rate much higher.

NOTATION

A, amplitude of acoustic oscillations of the gas in the freestream, m; c, velocity of sound in air, m/sec; I, density (intensity) of the sound-energy flux incident on the slot space, W/m^2; K, efficiency of the acoustic wave in the process of dispersion of water into droplets; f, frequency of the acoustic field, 1/sec; Δm, quantity of the extracted water, kg; r, characteristic radius of water droplets formed in dispersion, m; S, surface area of the entrance cross section of the slot space, m^2; T, temperature, ^{o}C; t, time, sec; Δt, period over which the quantity of water Δm is extracted, sec; V_m, amplitude of the acoustic oscillatory velocity in the freestream, m/sec; W, quantity of the extracted water, referred to the initial weight of water in the specimen, %; θ, angle of incidence of the acoustic wave, which is reckoned from the normal to the area of the entrance cross section of the slot space, deg; ρ, air density, kg/m^3; ρ_w, water density, kg/m^3; σ, coefficient of surface tension of water, N/m. Subscripts: w, water; m, maximum.

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