EFFECT OF ACOUSTIC OSCILLATIONS ON THE DRYING OF CAPILLARY-POROUS MATERIALS

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Inzhenerno-Fizicheskii Zhurnal, Vol. 13, No. 5, pp. 735–742, 1967

UDC 534.23:66.047

We present the experimental results which make possible an evaluation of the effect of sound on the processes of internal and external mass transfer.

The possibility of intensifying the processes of mass transfer by means of acoustic oscillations of high intensity has been demonstrated in a number of references [1, 2]. Since with the acoustic method the kinetics of the drying process does not differ from the kinetics involved in traditional methods [3], with indications to the effect that acceleration takes place both during the period of constant and declining drying rates, it became of interest to ascertain the effect of acoustic oscillations on each of these stages and to verify the existing hypotheses relative to the mechanism of acoustic drying. These hypotheses reduce to the fact that the external mass transfer is accelerated as a result of a periodic reduction in pressure at the surface of the material on passage of the sonic wave through the expansion phase and as a result of a change in the hydrodynamic conditions at the surface resulting from the appearance of acoustic flows [1]. During the second drying period the sound may make itself felt through a reduction in the viscosity of the liquid and through pulsating bubbles trapped in the capillaries [2].

Our research [4, 5] enabled us to establish that the sonic pressure—as a physical factor—exerts no effect on the drying process, but that the accelerating action of the sound is a strong function of the energy density, with the relationship between the dimension of the body, the wavelength, and the displacement amplitude of no mean importance. In studying the effect of sound on the processes of liquid evaporation and diffusion in a capillary porous material, we investigated the case in which $L < \lambda$ and $A < L$.

In view of the fact that in a sound field, even at comparatively low intensities (120 dB), liquids begin to gush and spray, the investigations were carried out on the evaporation of liquids from a plate of a fireclay ceramic with an average capillary dimension of 2–3 μm. The plate was positioned in a diffuse sound field (with a frequency of 6.2 kc) produced by means of a gas-jet GSI-4 emitter [6] positioned in the upper portion of a vertical tube 20 cm in diameter and 100 cm long. The level of the sound pressure was kept constant in all of the experiments and equal to 148 dB, so that the hydrodynamic and acoustic conditions remained constant. It was the rate of evaporation in a sound field as a function of the physical properties of the vapor-gas mixture that was being investigated. The experiments were carried out on 7 liquids whose molecular weight, vapor pressure, and coefficients of diffusion varied within wide limits (see table).

The evaporating liquid was removed from the chamber by means of a stream of air whose velocity was approximately 15 cm/sec and kept constant through all of the experiments. The temperature of the incoming air was 22° C and the humidity was φ = = 30%. The vapor pressure p_m of the liquid removed to the ambient medium (with the exception of water) was assumed to the equal to zero in the calculations. After the plate was soaked in the test liquid it was placed into the sound field, perpendicular to the direction of wave propagation. The initial mass content and the quantity of the evaporated liquid were determined gravimetrically, the error not exceeding ±7%.

The coefficient of mass transfer was determined from the expression

$$\alpha_m = \frac{q_m}{p_s - p_{me}}.$$

The Effect of Sound on the Mass-Transfer Coefficient

Liquid	Molecular weight μ, kg/mole	Diffusion coefficient D, cm²/sec	Vapor pressure at t = 20° C, mm Hg	Without sound (v = 15 cm/sec)				With sound (f = 6.2 kc, P = = 148 dB, v = 15 cm/sec)				$\frac{\alpha_{ma}}{\alpha_{m0}}$
				q_{m0}, kg/(m²·hr)	t_s, °C	p_s, mm Hg	α_{m0}, kg/(m²·hr·mm Hg)	q_{ma}, kg/(m²·hr)	t_s, °C	p_s, mm Hg	α_{ma}, kg/(m²·hr·mm Hg)	
Carbon tetrachloride	153.8	0.07	90.7	8.9	13	65	0.137	12.6	15	72	0.176	1.28
Acetone	58.1	0.109	185	7.2	6	92	0.078	10.1	7	97	0.103	1.32
Methyl alcohol	32.0	0.13	95.7	1.87	11.5	61	0.03	3.4	12	66	0.052	1.73
Isopropyl alcohol	60.1	0.099	32	1.1	14	26	0.043	2.4	14	26	0.092	2.14
Water	18	0.198	17.5	0.32	17	8.5	0.038	0.73	17	8.5	0.086	2.26
Butyl acetate	116.2	9.059	8	0.84	19	7.5	0.112	2.06	20	7.9	0.260	2.31
n-butyl alcohol	74.1	0.068	6	0.34	20	6	0.056	0.84	22	6.1	0.137	2.44

The initial volume of the liquid in the ceramic was kept constant and amounted to 4.72 cm^3 so that the degree of capillary filling was kept constant to an accuracy of ±5%. This is an extremely essential condition from the standpoint of eliminating the effect of temperature which increases as a result of sound absorption in capillaries free of liquid. The surface temperature of the ceramic specimen was recorded with an accuracy of ±1° C by means of a copper-constantan thermocouple.

Two series of measurements were carried out with each liquid (with and without sound), with each experimentally derived quantity representing the average value from three measurements. The experimental data are processed to determine the mass-transfer coefficient (during the first drying period) by constructing the drying curves and determining the vapor pressure at the surface [7], with the latter assumed to be equal to the saturated vapor pressures of the liquids at the surface temperature.

The results of the experiments are presented in Table 1. We can see from the cited data that the surface temperature of the specimen in a sound field is 1–2° C higher than under identical conditions, but in the absence of sound. However, the increase in the transfer potential cannot serve to explain the substantial variation in drying intensity (from 40 to 150%), since the maximum change in vapor pressure (in carbon tetrachloride) amounted to only 10%.

Since the physical properties of the vapor-gas mixture for a given liquid in the evaporation of that liquid in a sound field remain the same as in the absence of sound, the acceleration of mass transfer may be associated only with the variation in the hydrodynamic conditions at the evaporation surface and, mainly, with the appearance of acoustic flows at the test surface, whose magnitude is a function of the sound intensity which may reach several meters per

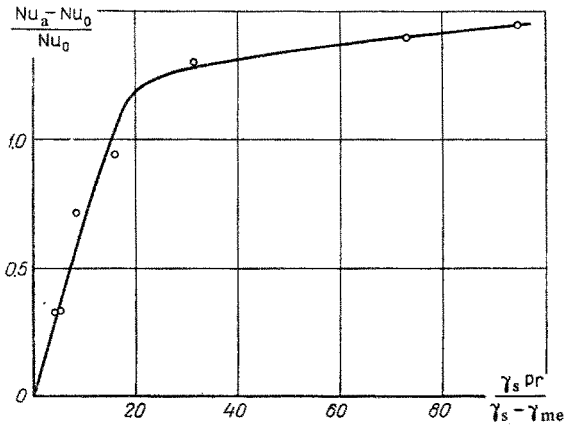

Fig. 1. Relative change in dimensionless mass transfer coefficient in a sound field.

second. The process of evaporation in a sound field is therefore subject to the same quantitative relationships as prevail in the absence of sound in the case of forced convection, while the dimensionless coefficient of mass transfer in the acoustic field should be sought in the form

$$Nu_a = f(Pr, Re).$$

The Reynolds number in this case is defined on the basis of the velocities of the acoustic flows and is therefore a function of sound frequency and intensity,

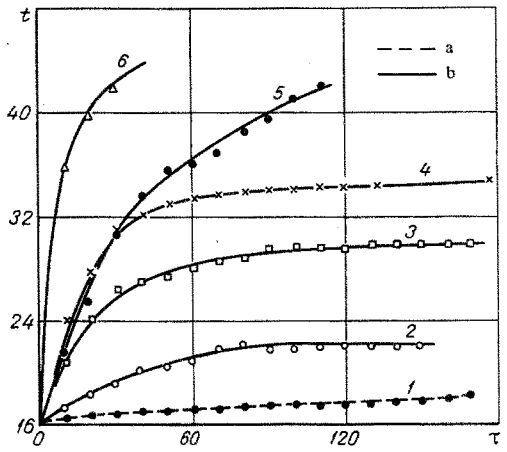

Fig. 2. Change of temperature (°C) in time (sec) in a bed of silica gel-indicator depending on sound pressure (f = 6.8 kc; a) moisture content of silica gel u = 24%; b) 3%): 1) 151 dB; 2) 157; 3) 161; 4) 163; 5) 165.5; 6) 168.

as well as of the relationship between the dimensions of the evaporation surface and the wavelength. However, if we take into consideration that under the conditions of our experiments the parameters of the sound field remained constant, the various accelerations of evaporation for the test liquids can be explained by the change in the relationship between the mass flow in natural convection and in the forced flow of the acoustic field.

The relative change in the coefficient of mass transfer, obtained in the sound field, can be written in the form

$$\frac{Nu_a - Nu_0}{Nu_0} = \frac{\alpha_{ma} - \alpha_{m0}}{\alpha_{m0}} = \frac{f_1(Re_a, Pr)}{f_2(Gr, Pr)} - 1.$$

Bearing in mind that Re_a in our experiments remains constant, we processed the results (Fig. 1) in the form of the relationship

$$\frac{Nu_a - Nu_0}{Nu_0} = f(\psi), \text{ where } \psi = \frac{Pr\,\gamma_s}{\gamma_s - \gamma_{me}}.$$

We see from the cited figure that the application of sound is most effective for liquids which evaporate poorly under ordinary conditions ($\psi > 20$). For liquids with a small parameter ψ the intensifying effect of sound is less significant, since these also evaporate well under conditions of natural convection.

Let us now turn to the problem of the effect exerted by sound on internal mass transfer. In the majority of references on acoustic drying, particular note is taken

of the fact that the given method makes it possible to intensify the processes at low material temperatures even during the second period when the moisture content is small. This statement—valid for comparatively low levels of sound pressure (and with a high moisture content in the material)—proves to be unreliable in the processing of a material exhibiting a low moisture content in sound fields of high intensity (above 163 dB). The process of removing the moisture in such fields proceeds quite intensively, but as the capillaries are freed of moisture there is a rapid rise in temperature which may reach 60–100° C. Figure 2 shows the curves for the change in temperature with time in a layer of dry (moisture content, 3%) silica gel-indicator (particle dimensions, 1–2 mm) for various levels of the sound field. The dashed line shows the temperature curve for the material at a moisture content of 24%.

As a rule, the temperature of the material drops during the first drying period. This is a result of the fact that the heat expended on the evaporation of the liquid is provided primarily by the material itself and the temperature of the material therefore begins to rise only during the second period. This is clearly seen from the curves shown in Fig. 3. The curves showing the variation in the mass content of carbon tetrachloride in a ceramic plate under conditions of natural convection (1) and in a sound field (2) are shown in this figure. Curves 3 and 4 correspond to the change in the temperature of the material for the same evaporation conditions.

It is thus obvious that one of the significant factors enhancing the intensification of the mass-transfer process during the second drying period is the elevation of the material temperature resulting from the absorption of sonic energy. To ascertain the mechanism of the effect of sonic oscillations on the diffusion of moisture in a capillary-porous material it therefore becomes necessary to investigate this process in the absence of heating.

The experimental determination of the diffusion coefficient as a rule is associated with great expenditures of time, thus making it unsuitable for the acoustic drying method. We therefore used the Ermolenko method [8] in which the diffusion coefficient is obtained from the drying curve by comparing the average moisture content of the entire specimen with its center section. The theoretical formula for the specimen in the form of a plate has the form

$$a_m = \frac{d\bar{u}}{d\tau}\left\{\frac{R^2 - R_1^2}{6\left[\bar{u}_1(\tau) - \bar{u}(\tau)\right]}\right\}.$$

The specimen was fashioned in the form of three plates of fireclay ceramic, 20 mm in diameter. The thickness of the center plate was 2.7 mm, while the thickness of the entire sandwich was 9 mm. The plates were soaked in distilled water and then pressed against each other by means of a metal mandrel which served to moistureproof the side surface of the specimen. The presence of the metal mandrel, in view of the excellent thermal conductivity of the latter, caused the heat received by the specimen as a result of the absorption of acoustic energy to be removed to the surrounding space, and thus there was virtually no heating of the specimen.

The installation on which the experiments were carried out consisted of a square horizonal tube ($50 \times 4 \times 4$ cm^3) connected by means of matched speakers to a sound source—a dynamic UZG-7G siren. A standing wave on frequencies of 2.3 and 1.4 kc was set up in the tube. The same tube was used for comparative convective-drying tests, with the velocity of the air chosen so as to achieve identical drying curves during the first period. It was assumed that if the sound exerts a specific effect and accelerates the motion of the liquid in the capillaries, this must have an effect on the various drying curves during the second period. Accordingly, the diffusion coefficients for convective and acoustic drying should be different.

The determination of the moisture content of the specimen in its center section was accomplished gravimetrically. Figure 4 shows the change in specimen moisture content with time on the action of sound (1) at a frequency of 1.4 kc and a sound pressure of 159 dB and in an air stream (2) with the latter moving at a speed of 3.7 m/sec (a relative humidity of 68% for the air and a temperature of 22° C). Here we also find the curves showing the change in the temperature of the specimen surface (3) and at the boundary between the center and external plates (4). Since the temperature inside the specimen is 0.5° C higher than at the surface during the second period, and in view of the fact that the temperature gradient is small, the displacement of the moisture occurs exclusively as a result of the existence of a moisture gradient. The process of drying by means of acoustic and convective methods under these conditions proceeds in a virtually identical manner.

After 90 min of drying, the moisture content of the middle portion of the specimen amounts to approximately 5.3%, so that the coefficients of diffusion calculated with and without the action of a sound field are virtually equal and are respectively, $a_{ma} = 1.55 \cdot 10^{-6}$ m^2/hr and $a_m = 1.45 \cdot 10^{-6}$ m^2/hr. The difference in the diffusion coefficients (6%) falls within the limits of accuracy for our measurements and in the absence of specimen heating we were therefore unable to detect any specific effect from the sound during the second drying period.

Proceeding from the derived results we assume that during the first drying period for materials whose dimensions considerably exceed the oscillation amplitude of the sound wave the acceleration of the drying process is associated with the appearance of acoustic flows at the surface of the moist material. The accelerating action of sound is a function of the sound field, the configuration of the moist material, and the relationship between the dimensions of the material and the wavelength; moreover, the accelerating action of the sound is a function of the physical nature of the liquid being evaporated and is all the more considerable the lower the vapor pressure of the liquid.

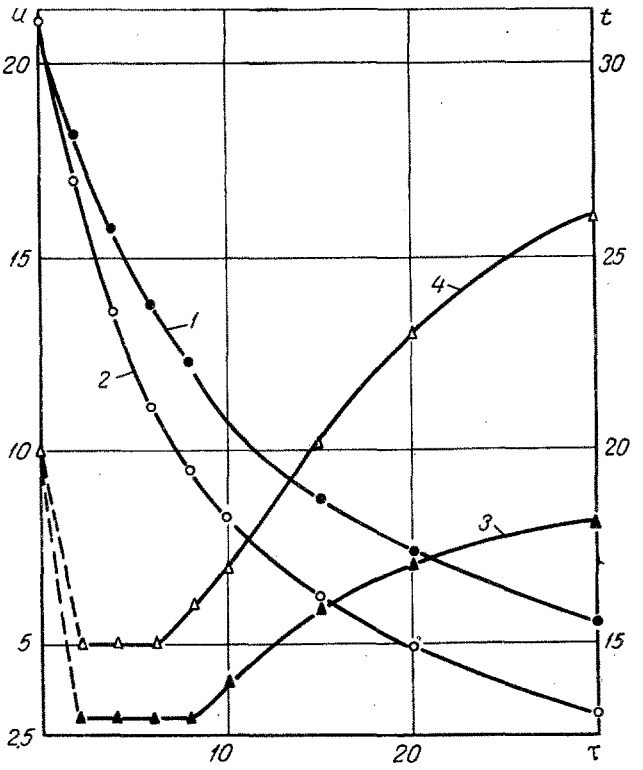

Fig. 3. Change in mass content u(τ) and in temperature t(τ) of ceramic plate with evaporation of carbon tetrachloride (u, %; t, °C; τ, min); 1) u(τ); 3) t(τ) without sound, v = 15 cm/sec; 2) u(τ); 4) t(τ) with sound, f = 6.2 kc, P = 148 dB; v = 15 cm/sec.

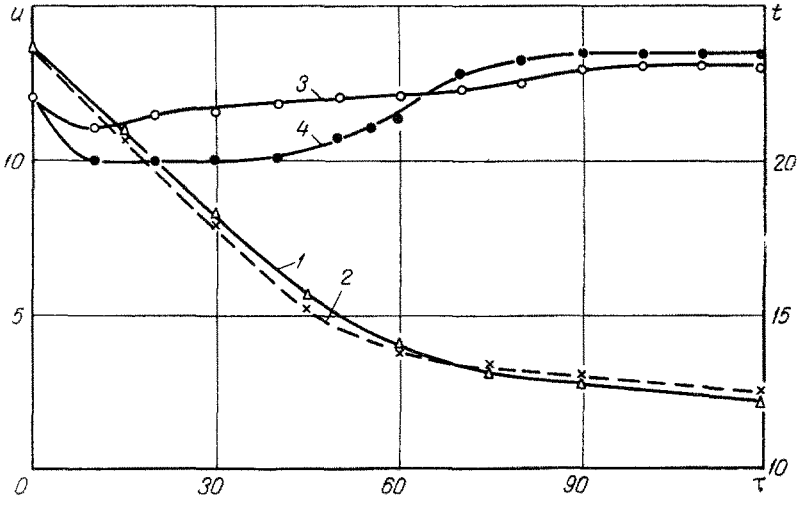

Fig. 4. Change in moisture content u(τ) and temperature t(τ) of a ceramic plate with water evaporation (u, %; t, °C; τ, min): 1) u(τ) with sound, f = 1.4 kc, P = 159 dB; 2) u(τ) without sound, v = 3.7 m/sec; 3) t(τ) and 4) t(τ) at a plate surface and inside a sound field f = 1.4 kc, P = 159 dB.

During the second drying period, given the identical relationship between the dimensions of the material and the oscillation amplitude, the acoustic field exerts no specific effect on the internal mass transfer and can accelerate the process only by elevating the temperature of the material through the absorption of acoustic energy.

NOTATION

q_{m0} and q_{ma} are the evaporation intensity with natural convection and in a sound field; t_s is the surface temperature of the body; p_s and p_{me} are the pressure of saturated vapors at the body surface and in the surrounding medium α_{m0} and α_{ma} are the mass transfer coefficients with natural convection and in a natural convection and in a sound field; Re_a is the Reynolds number for acoustic flows; Pr and Gr are the Prandtl and Grashof numbers; γ_s and γ_{me} are the specific weight of a vapor-gas mixture at the surface of the material and in the surrounding medium; a_m and a_{ma} are the diffusion coefficients with natural convection and in a sound field; $du/d\tau$ is drying rate; R and R_1 are the half thickness of the whole plate and its middle part; $\bar{u}(\tau)$ and $u(\tau)$ are the moisture contents of the whole sample and its middle part; L is the body size; λ is the sound wavelength; A is the displacement amplitude; P is the sound pressure; f is the sound frequency; v is the air flow velocity.

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