Journal of Engineering Physics and Thermophysics, Vol. 76, No. 1, 2003

EXTRACTION OF WATER FROM A CAPILLARY SAMPLE IN AN ACOUSTIC FIELD

Yu. G. Korobeinikov and A. V. Fedorov

UDC 532.72;669.015.23

Results of a theoretical analysis of experimental data on the acoustic drying of a model capillary sample are presented. It is shown that most of the water is extracted from the sample in the form of microdroplets. The droplet size is evaluated.

Mass exchange in an acoustic field has been investigated already for several decades [1]. The fact of a significant intensification of this process as compared to the convective mode has been reliably established and a number of hypotheses for the mechanism of the phenomenon have been put forward. Furthermore, in [1], the kinetic act of spraying of a single droplet of water in a standing sound wave with a frequency of 1.4 kHz was investigated to elucidate the mechanism of the process of drying of materials with a high initial moisture content (up to 900%).

The complexity of the internal structure of actual capillary-porous colloidal materials (grains, wood, etc.) makes it difficult to theoretically analyze the process of acoustic drying; therefore, investigations in model samples with a known quite simple structure are of interest. Lead glass of a cylindrical shape with 2790 independent cylindrical longitudinal capillary channels 70 μm in diameter has been taken as such a sample in [2]. The diameter and length of the sample are respectively equal to 5.2 and 24 mm. The results of experiments on the drying of such a sample in an unheated-air flow in the presence of an acoustic field with a frequency of 400 Hz and an intensity of 176 dB have been presented in [2]. It has been established that the acoustic action leads to a significant intensification of the process of drying. The influence of the position of the sample relative to the sound-wave front and the flow velocity has been investigated.

The investigations seek to analyze possible mechanisms of extraction of water from a capillary sample and their contributions to the process of drying. Analysis is made of three possible mechanisms: evaporation, molar motion of the liquid as a whole, and disintegration of water in the capillaries of the sample.

The experiments in [2] were conducted in the channel of a model dryer. The Hartmann generator has been used as the sound source in the regime of acoustic drying. The average over the channel cross-section velocity of the spent air and rate of blowing of the sample is $v = 26$ m/sec in acoustic and convective drying, while the temperature is $T = 20^{\text{o}}$C.

We evaluate the contribution of the mechanism of extraction caused by the evaporation of water. The initial amount of water in the sample is ≈180 mg. As follows from the kinetic curves of the process of drying, half of this mass of water (≈90 mg) is extracted from the specimen in 10 min. In accordance with the mechanism of evaporation, one must expend an energy of ≈200 J to remove this amount of water for a specific heat of vaporization of 2.26 J/mg. According to the formula for the heat-flux density [3] $q = \alpha(T - T_{\text{surf}})$, $\alpha = (5.6 + 4v)$ W/(m^2·K), we can evaluate the quantity of energy supplied to the sample over a period of drying of 10 min. Since the surface temperature of the sample is not measured in the process of drying in [2], for evaluation we can take it to be equal to the initial sample temperature $T = 19^{\text{o}}$C. Then for $\Delta T = T - T_{\text{surf}} = 1^{\text{o}}$C and $\alpha = 110$ W/(m^2·K) we obtain a quantity of supplied energy equal to 20 J. This estimate shows that no more than 10% of the energy required for evaporation can be supplied to the sample due to the mechanism of heat transfer. Thus, ≈10% of moisture can be extracted from the sample due to the evaporation mechanism. It is clear that this is the upper bound, since no possible heating of the sample by the gas flow is allowed for in the temperature difference $\Delta T = 1^{\text{o}}$C.

Another possible mechanism of extraction is capillary motion of moisture as a whole under the action of a pressure gradient. The capillary pressure of water is $p_{\text{c}} = 2\sigma/r_{\text{c}} = 4 \cdot 10^3$ Pa. We evaluate the pressure difference acting

---

Institute of Theoretical and Applied Mechanics, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, Russia; email: fedorov@itam.nsci.ru. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 76, No. 1, pp. 7–10, January–February, 2003. Original article submitted October 20, 2001; revision submitted March 15, 2002.

1062-0125/03/7601-0006$25.00 ©2003 Plenum Publishing Corporation

on a horizontal sample. When the flow velocity is $v = 26$ m/sec, we obtain a stagnation pressure of $p_0 = 4\cdot10^2$ Pa on the windward end of the sample. The same value of the pressure difference can be obtained from the tabulated data on the coefficient of resistance of a cylinder. We have $\Delta p = F/S = C\rho v^2/2$. From [4] we obtain $C = 0.91$ for the cylinder when the ratio of the length of the sample to its radius is ≈10. Hence the pressure difference on the ends of the sample is $\Delta p = 3.7\cdot10^2$ Pa. It is obvious that the aerodynamic pressure difference is inadequate to overcome the capillary pressure, i.e., motion of water as a whole is not realized under these experimental conditions.

Thus, the most probable is the "intermediate" mechanism of extraction of moisture, i.e., by disintegration into droplets. This conclusion holds true for both the convective regime of drying and the acoustic regime for the given parameters of the flow. We assume that this mechanism of disintegration is analogous to the mechanism (described in [1]) of crushing of droplets by a gas flow: under the action of the air flow, the near-surface water layers come into a motion sufficient to overcome the forces of surface tension of the liquid in the capillaries. We evaluate the rate of extraction of water according to this mechanism.

Convective Drying. Let us carry out an estimative calculation of the rate of drying in the convective regime. The energy related to the formation of a droplet of radius r is equal to $\omega = \sigma A$. It is known that the quantity of energy flowing per unit time through a unit surface without taking into account the internal energy is given by the expression [5] $E = \rho v\left(\frac{v^2}{2} + \frac{p}{\rho}\right)$. Multiplying it by the total cross-sectional area of all the capillaries, we obtain a quantity of energy approaching the total cross section of all the capillaries per unit time. If we assume that the entire energy of the flow goes into the formation of droplets (which is, certainly, approximate), the maximum number of droplets which can be formed by this energy flux is equal to

$$n = \rho v\left(\frac{v^2}{2} + \frac{p}{\rho}\right)\frac{Nd^2}{16\sigma r^2}\,.$$

Multiplying this expression by the mass of the droplet with an average size r, we obtain the estimate for the rate of extraction of water, i.e., formation of the water mass in the form of droplets per unit time:

$$\frac{\Delta m}{\Delta t} = \pi N\rho\rho_w\, v\left(\frac{v^2}{2} + \frac{p}{\rho}\right)\frac{rd^2}{12\sigma}\,. \tag{1}$$

We make the assumption that all the droplets are carried away by the flow. The average size of the extracted droplets is unknown. When $r = 2$ μm, the calculations from formula (1) and the experimental values of the drying rate in the convective regime coincide well on the initial portion of the kinetic curve with a constant rate of drying as long as the capillary zone "freed" of the liquid is rather small. The relative difference in the calculated and experimental data amounts to ≈14%. We note that the effective radius of the droplets $r \approx 2$ μm is similar to the radius of water droplets whose presence was assumed by A. V. Luikov in investigating the convective drying of capillary-porous bodies [6, 7].

Evaluations according to formula (1) for a flow velocity of $v = 26$ m/sec can hold only for a comparatively small water-free zone of capillaries. As the characteristic velocity v in (1) we take the velocity of an undisturbed incident flow and assume that all the droplets produced are carried away with the air flow.

Then the entire kinetic curve of drying of the sample can be obtained in the following manner. We believe that the extraction of moisture from the capillary sample obeys the linear relaxation equation

$$\frac{\partial W}{\partial t} = -\frac{(W - W_{eq})}{\tau}\,. \tag{2}$$

The moisture content is $W = (m/m_{dr})\cdot100\%$. Evaluation of the relaxation time according to formulas (1) and (2) for $r = 2$ μm (W_{eq} is taken from the experiment) yields $\tau = 9$ min. This enables us to obtain the entire kinetic curve of drying of the sample. A comparison of the calculated data for the convective regime and the horizontal position of the sample (see Fig. 1a) has shown their satisfactory agreement.

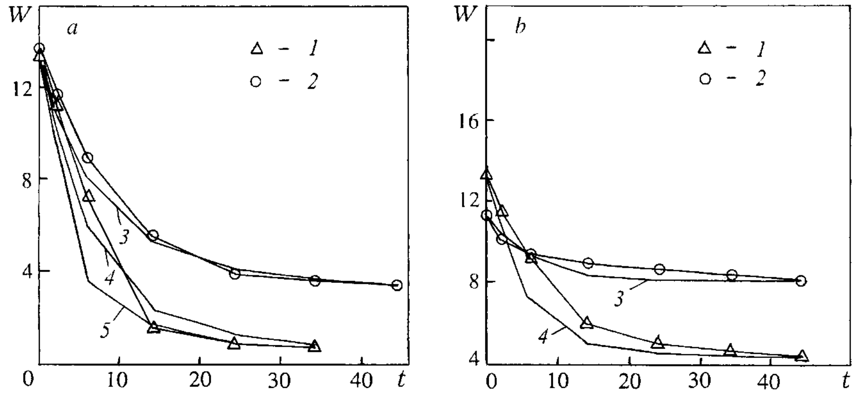

Fig. 1. Kinetics of drying of the sample in the case of longitudinal (a) and perpendicular (b) position of its axis relative to the velocity of the air flow: 1) in the acoustic field; 2) by convection; 3) r = 2 μm; 4) r = 0.2 μm; 5) r = 0.25 μm, calculations. W, %; t, min.

We do not know the value of the characteristic velocity of flow on the initial portion of the capillaries for the vertical position of the sample. The value of the velocity can be determined from the initial rate of drying obtained experimentally by assuming that the characteristic dimension of the droplets r = 2 μm for the vertical position of the sample will remain the same as for the horizontal position. It follows from (1) that v = 12 m/sec. Describing further the kinetics of drying by Eq. (2) and determining the relaxation time τ from the initial rate of drying, we can obtain the entire kinetic curve. A comparison with experiment is given in Fig. 1b (τ = 6 min). Here it is also seen that the results of the calculation according to this method yield quite a satisfactory agreement with experimental data.

Acoustic Drying. The presence of a sound field leads to the reconstruction of the pattern of flow past the sample. We note that the sample length is much shorter than the sound wavelength at a frequency of 400 Hz. The intensity of sound, i.e., the sound-energy flux through a unit area per unit time, is equal to [3] $I = \rho V_m^2 c/2$. Then, multiplying this expression by the total cross-sectional area of the capillaries, we obtain the quantity of the sound energy supplied to the cross section of all the capillaries per unit time. Having divided it thereafter by the energy of formation of a droplet and having multiplied by the mass of the droplet having a radius r, we can obtain the formula for the rate of extraction of water from the sample under sound action:

$$\frac{\Delta m}{\Delta t} = \frac{\pi N \rho \rho_w c V_m r d^2}{24\sigma}. \tag{3}$$

Here we also make the following assumptions: the entire energy goes into the formation of droplets; all the droplets are carried away by the air flow.

For an intensity of sound of 176 dB the amplitude of the vibrational speed is V_m = 44 m/sec. In the first half-period, the velocity of the flow and the speed of sound vibrations on the windward side of the horizontal sample coincide, while in the second half-period they are opposing and the leeward side of the sample becomes windward, where the velocity of flow is $V_m - v$ = 18 m/sec.

Evaluation of the extraction rate of water yields that it is necessary to take the average size of the droplets in exposure to sound $r \approx 0.2$ μm for agreement with the experimental data. The decrease in the size of extracted droplets under the action of the sound field is related, apparently, to the effect of vibration of the sample. The vibration leads to an additional (as compared to the acoustic-flow) action on the liquid in the sample capillaries. However the details of this action are not understood at present.

Just as for the convective regime, evaluation according to formula (3) can hold only for the initial period of drying when a small capillary zone is free of water. We can construct the entire kinetic curve of drying by determining the relaxation time τ in Eq. (2) from the estimates of the initial rate of drying under sound action (3). The results of the comparison with experiment are shown in Fig. 1 for the horizontal position of the sample. Theoretical curves are obtained for r = 0.2 μm (τ = 6.9 min) and r = 0.25 μm (τ = 5.2 min). Quite a satisfactory agreement between the calculated and experimental data is seen for $r = 0.2$ μm. A pronounced sensitivity of the calculated results to the quantity r is noteworthy.

We do not know the values of the velocities of flow on the initial portions of the capillaries for the vertical position of the sample. Therefore, we assume that the characteristic radius of the extracted droplets remains constant and equal to 0.2 μm. Then, on the basis of the experimental data, it seems possible to evaluate the velocity of flow over two half-periods of vibrations by the initial rate of drying in the acoustic field for the vibrational speed and the flow velocity coincident and opposite in direction. Thus, we have $r = 47$ and 12 m/sec respectively.

We obtain the calculated kinetic curve by solution of Eq. (2). The result of the comparison with experimental data is given in Fig. 1 ($\tau = 5.2$ min). The agreement between the calculated curve 4 and the experiment for the vertical position of the sample is somewhat poorer than for the horizontal position for the same $r = 0.2$ μm, which is attributable to the higher uncertainty in the value of the velocity of the flow in the capillaries.

CONCLUSIONS

1. From our viewpoint, the most probable mechanism of extraction of water from the model sample for the given parameters of the flow is the spraying mechanism. This holds true for both the convective regime of drying and the acoustic regime.

2. Irradiation with sound leads to a decrease in the average radius of water droplets.

3. It is shown that the experimental data on the time dependence of the moisture content in the processes of convective and acoustic drying are satisfactorily described by the linear kinetic equation.

This work was carried out with financial support from the Presidium of the Siberian Branch of the Russian Academy of Sciences (grant of the competition of integration programs for basic research of the Siberian Branch of the Russian Academy of Sciences).

NOTATION

v, flow velocity, m/sec; T and T_{surf}, temperatures of the flow and the sample surface, K; q, heat-flux density, J/(m^2·sec); α, heat-transfer coefficient, W/(m^2·K); p_{c}, p_0, and p, capillary pressure, stagnation pressure, and pressure in the flow respectively, Pa; d and r_{c}, diameter and radius of a capillary, m; N, number of capillaries in the sample; σ, surface tension coefficient of water, N/m; r and A, radius and surface area of a droplet, m and m^2; E, energy-flux density per unit time, J/(m^2·sec); w, energy of formation of a droplet, J; n, number of liquid droplets formed per unit time, 1/sec; ρ and ρ_{w}, density of the gas and the water, kg/m^3; F, drag force, N; C, drag coefficient; S, area of the sample end, m^2; Δp, pressure difference on the sample, Pa; m and m_{dr}, mass of the water in the sample and of the dry sample, kg; W, moisture content of the sample, kg/kg; W_{eq}, final equilibrium moisture content, kg/kg; τ, relaxation time of the moisture content of the sample, sec; c, velocity of sound, m/sec; I, intensity of sound, J/(m^2·sec); V_{m}, amplitude of the vibrational speed, m/sec; t, drying time, sec. Subscripts: c, capillary; 0, parameters of stagnation in pressure; surf, surface; w, water; eq, equilibrium; m, maximum; dr, dry.

REFERENCES

1. Yu. Ya. Borisov and N. M. Gynkina, in: L. D. Rozenberg (ed.), *Physical Principles of Ultrasound Technology* [in Russian], Moscow (1970), pp. 580–640.
2. V. N. Glaznev, Yu. G. Korobeinikov, and N. V. Terpugov, *Inzh.-Fiz. Zh.*, **73**, No. 4, 686–687 (2000).
3. H. Kuchling, *Physik* [Russian translation], Moscow (1982).
4. H. Ebert, *Physikalisches Taschenbuch* [Russian translation], Moscow (1963).
5. L. D. Landau and E. M. Lifshits, *Hydrodynamics* [in Russian], Moscow (1986).
6. A. V. Luikov, *The Theory of Drying* [in Russian], Moscow (1968).
7. G. S. Shubin, in: *Drying and Heat Treatment of Wood* [in Russian], Moscow (1990), pp. 130–132.