THE KINETICS AND THE MECHANISM OF ACOUSTIC DRYING OF CAPILLARY-POROUS MATERIALS

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We present the results of an experimental investigation into the kinetics of acoustic drying of silica gel and felt at a frequency of 500 cps; we examine the mechanism of the intensifying effect of acoustic energy on the drying process.

The drying of moist materials in an acoustic field is a comparatively little-studied process which, however, exhibits some promise for industrial application in the drying of capillary-porous products which are difficult to dry. Of particular interest is a study of the kinetics and the mechanism of drying capillary-porous materials, particularly during the second concluding stage of the process, for which information is scarce and contradictory.

The investigation of the kinetics of acoustic drying for several capillary-porous materials which we have undertaken was carried out at a frequency of 500 cps; the generation of this frequency is considerably more economical than the higher frequencies, while absorption in air is considerably reduced.

The experimental installation consisted of a pneumatic siren of the SPM-1 type, separated from the drying zone by an F-42 teflon diaphragm 60 μ in thickness, as well as of a circular box, 7.5 mm in diameter, for the specimen being dried, this box being covered on the inside with a layer of porolon 10 mm in thickness for thermal insulation, automatic high-speed scales of the VTK-500 type to ensure weighing accuracy of ± 10 mg, chromel-copel thermocouples of wire 0.2 mm in diameter, set into the center porttion of the specimen to depths of 5, 13, and 18 mm. The entire installation was housed in a soundproof chamber.

The sound level in all of the experiments was 158 dB. Silica gel and felt were used as the materials to be dried. The silica gel (KSM-6) contained particles 1–3 mm in size; its dry bulk density was 0.7 g/cm^3, and its initial moisture content was 0.39 kg/kg. The felt was made up primarily of fibers 50 μ in diameter; its dry bulk density was 0.07 g/cm^3, while its initial moisture content was 1.8 kg/kg.

The specimen together with the box was weighed periodically for 30 sec, with the siren turned off. The final moisture content of the silica-gel and felt specimens fell below the sensitivity of the scales and was assumed to be equal to zero.

The results of the acoustic drying of the silica gel and of the felt are presented in Fig. 1. As we can see, the nature of the curves for the low-frequency drying (curve 1) of the materials in an acoustic field differs little from the nature of the curves for conventional drying of porous materials. As in the case of conventional drying, the process is divided into two periods: 1) a constant drying rate and 2) a declining drying rate. In the first period we have a subperiod of heating and an increasing drying rate. The rate of the acoustic drying of the felt retaining the wetting moisture and the moisture of the macrocapillaries is greater by approximately an order than the rate of drying for the silica gel containing adsorbed moisture which is bound more strongly with the material.

The nature of the variation in temperature during acoustic drying (curves 2, 3, 4) differs substantially from that of the temperature curves for conventional forms of drying. During the period of the constant drying rate a slow increase in temperature continues, and this doubtlessly intensifies the process of dehydration as a result of an increase in the surface drying potential. On reaching the first critical moisture content (Fig. 1b, point K_1) the felt exhibits a pronounced increase in temperature in all layers of the specimen. In the case of the silica gel, as in all adsorbents, exhibiting a second critical moisture content (the point of transition for the drying rate from a uniform decline to a nonuniform decline), the acceleration in the rise in temperature begins precisely in the vicinity of this point (Fig. 1a, point K_2). In either case, the temperature reaches its maximum at the end of the drying process, and this is particularly evident in the curves showing the variation in the local temperature of the material as a function of the change in the mean moisture contents of the silica gel and the felt (Fig. 2).

The rise in temperature continues until there is dynamic equilibrium between the quantity of absorbed acoustic energy and the heat lost to the ambient medium. In our case, the rise in temperature in the silica gel amounted to 33° C and in the felt to 76° C.

Both in the first and in the second drying period there is a temperature gradient directed toward the bottom surface and this gradient increases with reduction in the moisture content, attaining a maximum at the conclusion of the drying process. Under the conditions of the experiment the moisture-content gradient in the second drying period was also directed towards the lower surface, as a result of which the diffusion and the thermal moisture conductivity were identically directed and complemented each other.

The experiments that we carried out make it possible to draw the following important conclusion as to the mechanism intensifying the effect of sound during the second stage of the drying process for the materials in question. It differs markedly from the

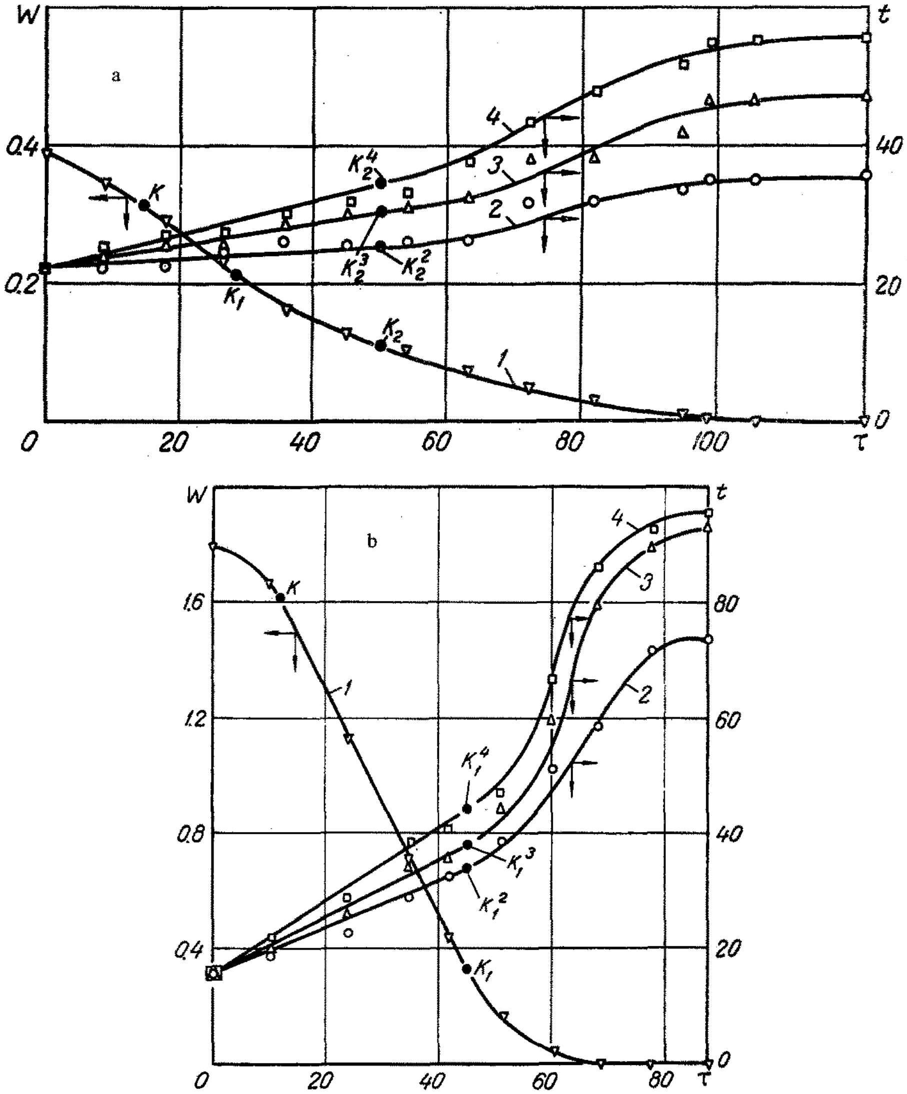

Fig. 1. Drying and local temperature curves for silica gel (a) and felt (b) (f = 500 cps and L = 158 dB): 1) drying curve 2) sample temperature at a depth of 5 mm; 3) sample temperature at a depth of 13 mm; 4) sample temperature at a depth of 18 mm.

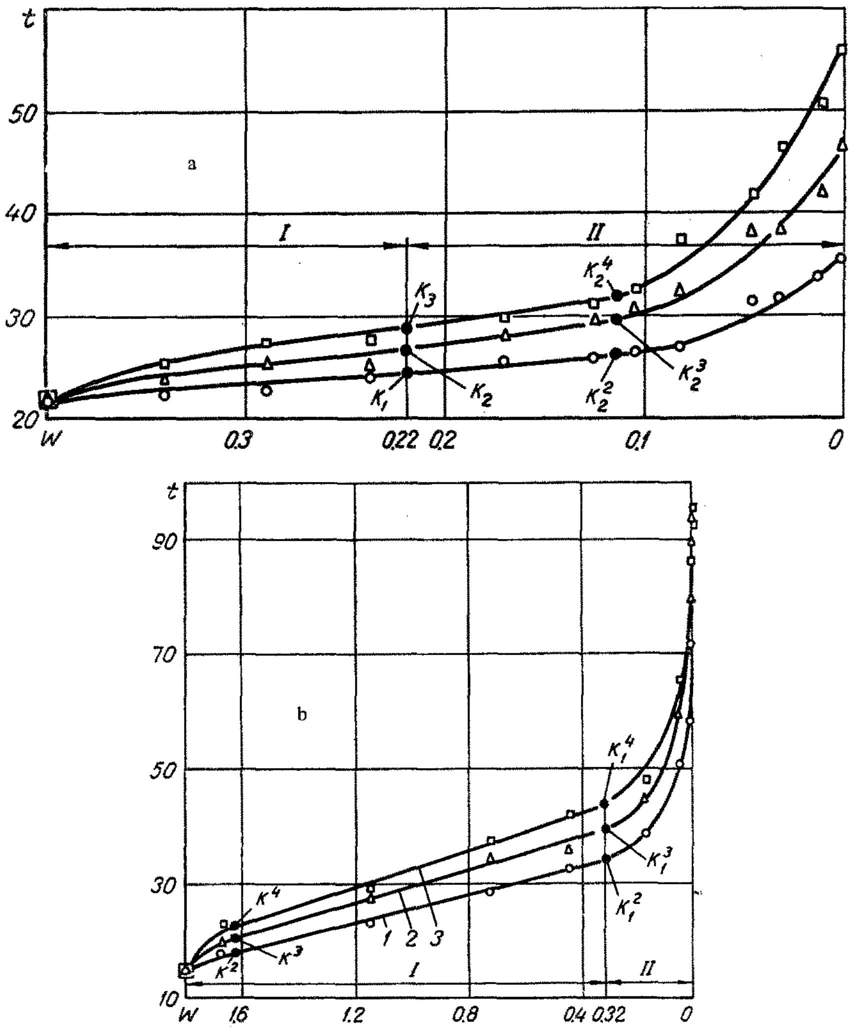

Fig. 2. Local temperature dependence on mean moisture content of silica gel (a) and felt (b) (I and II, first and second stages, respectively): 1) temperature at a depth of 5 mm; 2) temperature at a depth of 13 mm; 3) temperature at a depth of 18 mm.

mechanism of the first stage of the acoustic drying process in which, as demonstrated by the research of the Acoustics Institute [1], the oscillatory and circulatory motion of the sound-treated medium along the material surfaces open to the sound play the dominant role.

Boucher [2] and Greguss [3] assumed that the increase in the intensity of moisture diffusion in the material is enhanced in the second stage of the drying process as a result of the reduction in the viscosity of the sound-treated liquid, the pulsations in the air bubbles found in the pores and capillaries, and the radiation pressure of the sound; however, no experimental support for this hypothesis has been obtained to the present time.

It seems to us that the primary mechanism for the effect of acoustic energy on the drying process during the second period is the earlier noted local heating of the moist air in the pores and capillaries as a result of their absorption of sound, which is necessarily accompanied by a rise in the temperature of the material and an increase in the intensity of diffusion and thermal moisture conductivity. According to literature data [4], for capillary-porous materials (silica gel, quartz sand, etc.), the coefficient a_m of moisture diffusion increases with a rise in the absolute temperature of the material from 5 to 18 degrees. For gypsum at 50° C, a_m is twice its value at 20° C.

The coefficient a_m^T for thermal moisture conductivity also increases with a rise in the temperature of the material [5].

It is important to note that during the second stage of the drying process only a certain portion of the acoustic energy is useful, namely, that portion which penetrates into the pores and capillaries of the porous material being dried, and which is absorbed there as a result of friction at the walls, thus being converted into heat. The quantity of sonic energy penetrating through the porous surface into the material increases with a rise in porosity and with a reduction in the quantity of moisture filling the pores and capillaries. Thus when quartz sand is sound-treated [6] a pronounced rise in the absorption of sound was recorded on transition from a moisture content of $W = 6-7\%$ to a moisture content of $W = 2-3\%$. This fact indicates that the use of acoustic energy in the second stage of the drying process is more complete than during the first.

According to Kirchhoff [7], the coefficient of sound absorption in round tubes is defined by the formula

$$\alpha = 1.1 \sqrt{f}/c_g R.$$

It follows from this formula that in the microcapillaries the sound is absorbed more strongly than in the macrocapillaries, therefore the temperature in the microcapillaries must be higher, while the temperature gradient must be directed from the macro- to the microcapillaries. As proof we can cite reference [8] in which it was noted that when a clump of copper wire is sound-treated, the temperature in the pores between the wires increases by 150° C with a reduction in the wire diameter (and thus, with reduction in the dimensions of the pores) from 1 to 0.1 mm. This is also indicated by our curves shown in Fig. 2, from which we see that there is a pronounced rise in the local temperature of the material at the end of the second drying stage when the main mass of the microcapillaries is freed of moisture. As a result of the marked heating of the liquid in the microcapillaries there is a drop in the surface tension of the polymolecular moisture films, and at the same time the forces bonding the moisture to the walls of the microcapillaries weaken. This leads to an increase in moisture diffusion a_m and thermal moisture conductivity a_m^T. The intensity of the thermal moisture conductivity is also increased as a result of a rise in the pressure of the "trapped air" in the microcapillaries as the air is heated, thus resulting in an increase in the pressure gradient in the direction of the finer pores and toward the higher temperatures.

Contemporary temperature measurement techniques (microthermistors, microthermocouples, etc.) do not provide for the measurement of the temperature of the moisture in microcapillaries whose radii in silica gel, for example, reach magnitudes of $R \sim 10^{-6}$ cm, as a result of which it has been impossible up to the present time to trace the above fact directly.

As we pointed out earlier [2, 3], the drying in the second period is accelerated in the acoustic field primarily as a result of a reduction in the viscosity of the capillary moisture as a result of the oscillation of the air. We cannot agree with this contention for the following reason. We know [9] that the thickness of the decelerated acoustic layer of air near the walls is equal to

$$\delta_{ac} = \sqrt{2\nu/\omega} = \sqrt{\nu/\pi f}.$$

This thickness is independent of the sound intensity and at frequencies of 0.5–10 kc is equal to 100–20 μ. Thus the capillaries with radii less than 10^{-2} cm actually represent the stagnation zone; there are virtually no oscillations within these capillaries and the viscosity of the moisture cannot vary significantly as a result of oscillation.

Neither can the gradient of the sound pressure accelerate the drying in the second period, as is maintained in [10]. In view of the pronounced absorption of sound energy through the height of the material being dried, this gradient is directed toward the surface of the material layer and suppresses the diffusion of the moisture. The effect of the mechanical displacement of moisture noted in [10] in the drying of polyurethane foam through the action of sound pressure can accelerate the removal of the free wetting moisture (the first drying period) in materials with a spongy soft skeleton, but can have no effect on the drying of porous materials with a rigid skeleton during the second drying period.

This study permits us to draw certain practical conclusions.

1. In acoustic drying of thermally unstable products it is necessary to meter the acoustic energy to avoid the thermal destruction of these items.

2. In sound-treating the upper layers we find that the lower frequencies are more efficient. This follows from the theory of sound [11] which indicates that the depth H of acoustic-energy penetration with a drop to half the intensity is inversely proportional to the sound absorption coefficient α in the material

$$H = \frac{0.693}{2\alpha}.$$

The sound absorption coefficient α for finite oscillation amplitudes is proportional to the sound frequency. Here we must bear in mind the fact that the sound absorption coefficient for the majority of porous materials exhibits a clearly defined resonant nature [12], in connection with which, for more uniform drying, the height of the layer must be matched to the frequency of the sound.

3. The application of acoustic drying is feasible only for the final drying operation of materials that are difficult to dry, i.e., during the second drying stage when the quantity of acoustic energy absorbed in the layer is rather great and when the coefficient of effective acoustic-energy utilization is high.

NOTATION

a_m is the moisture diffusivity coefficient; a_m^T is the coefficient of thermomoisture conductivity; α is the sound absorption coefficient; f is the oscillation frequency; L is the level of sound intensity; c_g is the speed of sound; R is the radius of the capillary or pipe; δ_{ac} is the thickness of the acoustic boundary layer; ν is the kinematic viscosity of the medium; ω is the circular frequency; H is the depth of sound penetration when intensity is reduced by half.

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