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THERMAL EFFECTS IN MODEL SPECIMENS UNDER ACOUSTIC AND CONVECTIVE ACTIONS

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The temperatures of three model specimens placed in a nonheated air flow under convective and acoustic drying have been measured. It has been shown that in the dry specimens containing no water there occurs an appreciable heating of the internal region of the specimens by the acoustic field. The values of the moisture-exchange coefficients of the specimens averaged over the drying period have been found.

In [1], we visualized the process of draining a field in a model specimen consisting of two glass plates with a fine-cell mesh woven from brass wire of diameter 0.1 mm with "window" sizes of 0.2 × 0.2 mm clamped between them. The mesh thickness was 0.250 mm, and its length and width were 51 and 18 mm, respectively. It was also shown that the process of moisture extraction from the specimens under the acoustic action proceeded faster than under the convective action. Experiments on the influence of the material from which the plates were made on the drying rate were begun. We used plates from three materials: steel, glass, and acrylic plastic. Under the conditions where the temperature of the air stream in the channel of the facility was higher than the initial temperature of the three specimens, a higher rate of drying was observed in the specimens with a higher heat conductivity coefficient of the material. This relation took place for both the acoustic and convective actions.

The present paper is a sequel to [1]. Figure 1 schematically represents the experimental facility in which three model specimens were placed. Each specimen consisted of two plates 1 made of steel, glass, or acrylic plastic with a fine-cell mesh 2 clamped between them by means of a plastic strip 3. The space between the plates was filled with distilled water through a medical needle 5 inserted into the internal cavity. The temperature inside the specimens was measured by thermocouples 4. We also measured the temperature of the air stream near the specimens. Chromel-alumel and chromel-copel thermocouples were used. The prepared specimen was placed in the dryer channel of rectangular section 6 so that the open edge of the mesh was on the lee of the stream. As a sound source, a Hartmann oscillator 8 was used. The operational conditions of the facility were determined by the working gas pressure at the stagnation point in the setting chamber of the nozzle p_0 and the positions of pistons 9 and 10. The acoustic-field intensity was measured by a pressure transducer 7, the signal from which was received by the spectrum analyzer and the oscilloscope.

Experiments were carried out in different regimes: with dry specimens; under acoustic and convective actions; with samples filled with water; under acoustic drying. The acoustic-field intensity was 170 dB at a frequency of 400 Hz. The stagnation pressure in the setting chamber of the nozzle was approximately the same in all these regimes, and, therefore, the air-flow velocity was also the same.

The junction of each thermocouple intended for temperature measurements inside the specimens was caulked in a small copper plate which was inserted into the specimen (see Fig. 1). The junction of the thermocouple for measuring the flow temperature was left open. To test indications, the flow temperature was measured by all thermocouples in the regime without the acoustic field. The readings of the thermocouples differed insignificantly (Fig. 2).

The measurement data for the temperature inside the dry specimens and the flow temperature in the convective regime and in the acoustic field are presented in Fig. 3. It is seen that under the convective action (Fig. 3a) the temperature inside all three samples coincides with the flow temperature. In the regime with the acoustic field (Fig.

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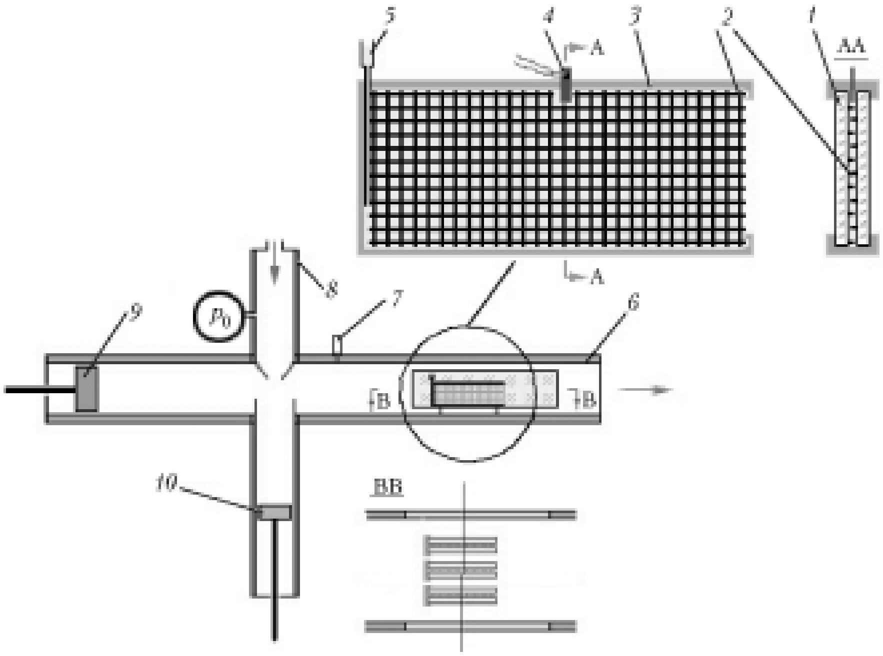


Fig. 1. Schematic representation of the facility.

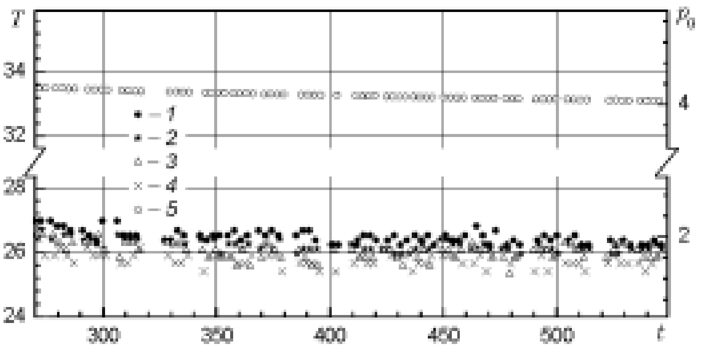


Fig. 2. Results of the gas-flow temperature measurements by four thermocouples (1–4) in the absence of acoustic action and pressure in the dryer setting chamber (5). T, $^{\mathrm{o}}$C; p_0, 10^5 Pa; t, sec.

3b), a heating of the dry specimens compared to the flow temperature is observed. In so doing, the specimen with acrylic plastic windows is heated maximally and that with steel windows — minimally. The observed phenomenon of heating can be explained, on the one hand, by the acoustic-field energy dissipation inside the specimens and the cooling effect of the flow on the other, as well as by the value of the heat capacity of the material of the mesh and walls. Apparently, a specimen with walls from a material with a high heat-conductivity coefficient (steel, glass) will cool faster.

Estimation of the Heating of Specimens by the Acoustic Field. It is known that specimens are heated because of the dissipation of the acoustic-field energy. For theoretical analysis, let us represent the mesh in the specimens as an aggregate of longitudinal capillaries, whose open cross section is on the open end of the specimens. Then we can make use of the formula for the sound energy absorbed in the capillaries [2]:

$$Q = \frac{E\sqrt{\omega}}{\sqrt{2}\, rc}\left[\sqrt{\nu} + \left(\frac{c_p}{c_V} - 1\right)\sqrt{\chi}\right]. \tag{1}$$

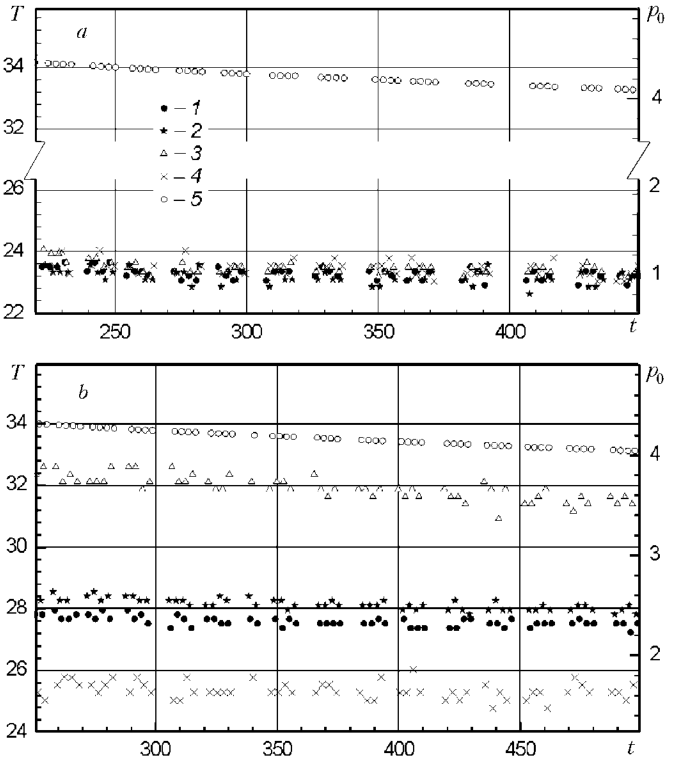


Fig. 3. Readings of the thermocouples positioned in the steel (1), glass (2), and acrylic plastic (3) specimens and in the gas flow (4) in the absence (a) and in the presence (b) of an acoustic field, pressure in the dryer setting chamber (5). T, ^{o}C; p_0, 10^5 Pa; t, sec.

For porous bodies, the portion of the intensity of acoustic vibrations that have entered the capillaries is determined by the formula

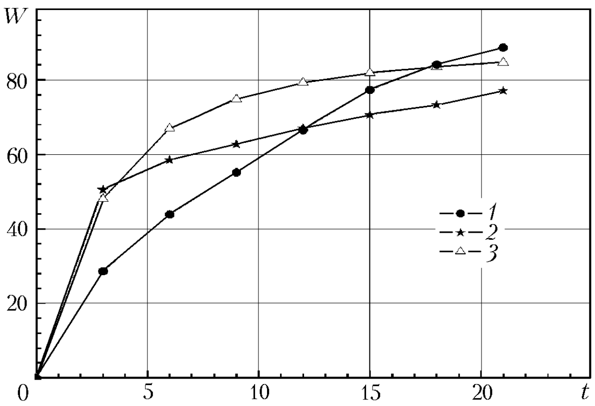
$$\gamma = \frac{4M}{2M^2 + 2M + 1}, \tag{2}$$

where

$$M = \frac{2\,(1+g)}{r} \sqrt{\frac{\nu c_p}{\omega c_V}} .$$

Assuming for the estimation that $r \approx 62.5$ μm (a quarter of the mesh thickness) and $g \approx 1$, we obtain from formula (2) that in capillaries without water the acoustic-field intensity at a frequency of 400 Hz will amount to about 30% of the field intensity in the facility channel. Multiplying this quantity by the cross-section area of the capillary, we obtain the energy E.

If we take into account that in (1) the quantity Q is the energy dissipating per unit time on the surface of the walls of a unit-length capillary [2], we can obtain the estimate for the rate of temperature growth due to the acoustic-energy dissipation in the "capillaries" of the dry specimen $\Delta T/\Delta t \approx 13 \frac{^{o}\mathrm{C}}{\mathrm{sec}}$. In the experiment, the maximum heating of the specimen with acrylic plastic walls, which is 7–8^{o}C higher than the flow temperature, is observed. Taking into account that part of the heat is removed from the specimen as a result of the heat exchange with the gas flow, and also is absorbed by the mesh and the walls, the agreement between the experimental and calculated data can be thought to



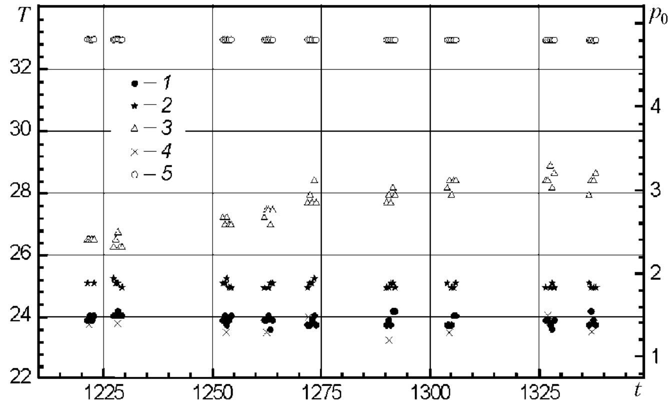


Fig. 4. Drying kinetics of three specimens [1) steel 2) glass; 3) acrylic plastic)] in the acoustic field. W, %; t, min.

Fig. 5. Results of the temperature measurements inside the specimens in the process of their drying under the acoustic action. Designations of 1–5 are as in Fig. 3. T, ^{o}C; p_0, 10^5 Pa; t, sec.

be satisfactory. The same estimations by (1), (2) for the specimens filled with water have shown that in this case the value of heating is much lower than the measured temperature of the specimens and it can be neglected.

Determination of the Moisture-Transfer Coefficients. The results of the experiments on the drying of specimens presented in Fig. 4 make it possible to determine the moisture-transfer coefficient α from the formula for the moisture-transfer intensity [4]:

$$q = \alpha \left(p_m - p_\infty\right) . \tag{3}$$

This coefficient is more convenient to use if it is referred to the partial pressure difference. In Fig. 4, W shows the quantity of water extracted from the specimens referred to the initial weight of water. In the drying process, the temperatures inside the three specimens and in the air flow were measured. The results of these measurements are presented in Fig. 5. It is seen that the flow temperature under these experimental conditions is lower than the temperature inside the specimens.

As a working gas for the Hartmann oscillator, dried air was used. Therefore, it may be assumed that in (3) $p_\infty \approx 0$. Expressing in (3) the moisture-transfer intensity q in terms of the rate of decrease in the water mass in the specimen, we obtain the formula for the moisture-transfer coefficients:

$$\alpha = -\frac{1}{S p_{\mathrm{s}}\left(T_m\right)} \frac{d m_{\mathrm{w}}(t)}{dt} . \tag{4}$$

Here it was also taken into account that the partial pressure of water vapors on the extraction surface can be considered to be equal to the saturation pressure p_{s} at the temperature inside the specimens T_m.

In [1], it was shown that the experimental time dependences of the quantity of water in the specimens can be very well described by the solution of the relaxation-type linear kinetic equation:

$$\frac{d m_{\mathrm{w}}(t)}{dt} = -\frac{m_{\mathrm{w}}(t) - m_{\mathrm{e}}}{\tau} . \tag{5}$$

Here m_{e} is the equilibrium value of the water mass; τ is the relaxation time found from the experiment.

Substituting solution (5) into (4), we obtain for the moisture-transfer coefficient the representation

$$\alpha(t) = \frac{m_{\mathrm{w}}(0)\left(1 - \frac{m_{\mathrm{e}}}{m_{\mathrm{w}}(0)}\right)\exp\left(-\frac{t}{\tau}\right)}{\tau S p_{\mathrm{s}}(T_m)}, \tag{6}$$

and the value of the moisture-transfer coefficient average in the drying time t_{d} is

$$\bar{\alpha} = \frac{1}{t_{\mathrm{d}}}\int_0^{t_{\mathrm{d}}} \alpha(t)\,dt\,. \tag{7}$$

Substituting into (7) formula (6), we find

$$\bar{\alpha} = \frac{m_{\mathrm{w}}(0) - m_{\mathrm{w}}(t_{\mathrm{d}})}{t_{\mathrm{d}} S p_{\mathrm{s}}(T_m)}\,. \tag{8}$$

Equation (8) can also be given in the dimensionless form (analog of the moisture-transfer Nusselt number):

$$\mathrm{Nu}' = \bar{\alpha}\frac{D}{l}\,. \tag{9}$$

Using the experimental results on the drying kinetics of specimens in the acoustic field and the literature data for the saturation pressure and the diffusion coefficient [5], from (8), (9) we obtain the values of the dimensionless Nusselt number Nu′. For the steel, glass, and acrylic plastic specimens this number multiplied by 10^8 is equal to 2.37, 1.75, and 1.56, respectively. The dependence of the Nu′ number on the Biot number equal to $\mathrm{Bi} = \alpha' R/\lambda$ is of the form $10^8\mathrm{Nu}' = 1.46\ \mathrm{Bi}^{-0.079}$.

If we assume that water extraction from the specimens occurs by the evaporation mechanism and evaluate the heat power needed for this, proceeding from the experimental drying rate in the first three minutes, then we obtain a value in the 1.5–2 W range. As the results of the temperature measurements show, the gas flow produces only a cooling effect on the specimens. Estimations by (1), (2) of the acoustic-field energy absorbed per unit time yield values of the order of $2 \cdot 10^{-3}$ W. Thus, it is seen that initial extraction of water from the specimens cannot occur by the evaporation mechanism. In general, the process of drying the specimens in the acoustic field proceeds, obviously, as follows: the initial portions of water from the open end of the specimens are extracted mainly by dispersion into microdroplets [6]; as, between the walls, a space free of water appears, the quantity of dissipating acoustic energy increases. In the specimens with walls from a material with a higher heat-conductivity coefficient, the dissipating acoustic energy is better transferred into the gas flow. In the acrylic plastic specimen, because of the smaller heat removal, the temperature inside the specimen increases, which leads to an increase in the fraction of the evaporation mechanism and the drying rate.

CONCLUSIONS

1. The temperature measurements inside the three model specimens placed in a stream of unheated air under the acoustic action have shown that in the dry specimen containing no water there occurs a marked heating of the internal region of the specimens. The estimation of the value of heating as a result of the acoustic-energy dissipation agrees well with the experimental value.

2. In drying in the acoustic field, as moisture is removed, in the specimen with a low value of the heat conductivity of the walls (acrylic plastic walls) there is an increase in the temperature inside the specimen caused by the growth of absorbed acoustic energy. The specimens are dried in two stages: in the first stage water dispersion occurs from the open end, and in the second stage the acoustic energy dissipation becomes enhanced in the space freed from water and the role of the moisture-evaporation mechanism increases.

3. The values of the moisture-transfer coefficients of the specimens under the acoustic action averaged over the drying period have been obtained.

NOTATION

Bi, Biot number; c, velocity of sound in the medium, m/sec; c_p and c_V, specific heat capacities of the medium, J/(kg·K); D, diffusion coefficient of water vapors in the air surrounding the specimens being dried, m^2/sec; E, sonic wave energy in capillaries, W; g, ratio of the pore-free area to the total area of pores; l, characteristic size of specimens, m; $m_w(t)$ and $m_w(0)$, current and initial wight of water in specimens, kg; Nu′, dimensionless moisture-transfer coefficient averaged over the drying period; p_0, pressure in the setting chamber of the dryer, Pa; p_m and p_∞, partial pressure of water vapors on the surface of the open end of specimens and in the surrounding gas flow, Pa; $p_s(T_m)$, saturation pressure at the temperature inside specimens T_m, Pa; Q, sound energy absorbed per unit time in unit-length capillaries, W/m; q, moisture-transfer intensity, kg/(m^2·sec); R, half-thickness of plates, m; r, capillary radius, m; S, surface area through which extraction of water from specimens occurs, m^2; T, temperature, ^{o}C; t, time, sec; W, quantity of extracted water referred to the initial weight of water in specimens, %; α, moisture-transfer coefficient, c/m; $\overline{\alpha}$, value of the moisture-transfer coefficient averaged over the drying period, c/m; α', heat-transfer coefficient, W/(m^2·K); λ, heat-conductivity coefficient of the wall material, W/(m·K); ν, kinematic viscosity of the medium filling capillaries, m^2/sec; τ, relaxation time, sec; χ, thermal diffusivity of the medium, m^2/sec; ω, angular frequency of acoustic vibrations, 1/sec. Subscripts: 0, gas parameters in the setting chamber of the dryer; ∞, parameters of the gas flow in the dryer channel; e, equilibrium; w, water; m, specimens; s, saturation; d, drying.

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