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ACOUSTOCONVECTIVE DRYING OF CELLULAR GAS CONCRETE

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The present paper is devoted to the investigation of the gas dynamics of cellular gas concrete by the acoustoconvective method developed at the ITPM of the Siberian Branch of the Russian Academy of Sciences and its comparison with traditional thermoconvective and natural drying. A series of experiments have been performed on humidifying specimens and the dependence has been obtained of the rate of moisture absorption for two humidifying regimes: capillary impregnation and sorption. In the acoustoconvective drying regime, it has been shown that the frequency and intensity of the operating flow strongly influence the dynamics of moisture extraction from the specimens being dried. The obtained kinetic data for thermoconvective drying have a bilinear distribution, and their mathematical treatment permitted determining the velocities of the proceeding processes. The process of natural drying is extremely slow, and the drying velocity is strongly influenced thereby by the environment parameters. For mathematical description of the obtained experimental data, a relaxation model was used, which has made it possible to determine the relaxation time for each drying regime.

Keywords: *acoustoconvective drying, drying of cellular gas concrete, comparison of acoustoconvective and thermoconvective drying, relaxation time.*

Introduction. Drying of porous materials is widely used in making building materials in the food and chemical industries, agriculture, and many other spheres of human activity. The application of porous materials is due to the fact that most of them exhibit high heat-saving and soundproofing properties. This fact has permitted creating a variety of new building materials, one of which is cellular gas concrete. Its popularity is due to its wide use in both individual construction engineering and low-rise industrial engineering.

In making cellular concrete, one of the most important technological operations is autoclave hardening [1, 2] under the action of superheated steam at a temperature of up to 200^{o}C and pressure of about 12 atm. As a result of this operation, the obtained product is characterized by a high moisture content. To deliver manufactured materials directly to consumers, avoiding store-rooms, and use them in construction, it is desirable to considerably decrease the moisture content in cellular gas concrete blocks in a short time interval. To solve the problem of removing excess moisture from the mass of blocks removed from the autoclave, in the present work it is suggested to use the technology of acoustoconvective drying of porous materials developed at the S. A. Khristianovich Institute of Theoretical and Applied Mechanics (ITPM) of the Siberian Branch of the Russian Academy of Sciences. The given technology has demonstrated a considerable intensification of the drying process for a variety of porous materials of both technogenic (sorbents [3], granular silica gel [4, 5]) and natural (pine nuts [8], rice [7, 8], meat [9–11]) origin.

Preparation of the Investigated Material. For the investigated material, we used the porous cellular gas concrete of autoclave hardening (GOST 31360-2007). The investigated specimens were made from one partition block with characteristic sizes 650 × 250 × 100 mm. The conventional gas concrete brand is Bi-D600-B2.5, the mean density is 600 kg/m^3, and the compressive strength is B2.5. To perform a series of experiments, we prepared a number of specimens with a longitudinal cross section ($S = a \times b$) of rectangular ($a \neq b$) and square ($a = b$) form. The length l was the same for all specimens and equaled the width of the initial partition block. The geometric sizes of the prepared specimens are given in Table 1. In the experiments, to determine the mass of investigated specimens, we used an AND EK 610i laboratory balance having a maximum weight limitation of 600 g and precision of 0.01 g. The results of weighing the initial mass of the investigated specimens are given in Table 1. The specimens under consideration had been stored for a long time in a room with a temperature of 21^{o}C at an air humidity of 48.7%. The parameters of the medium surrounding the cellular concrete blocks were determined with the help of an Eksis IVTM-7MK-S humidity meter.

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TABLE 1. Dimensions and Mass of Specimens

No.	a, mm	b, mm	l, mm	m, g
0	25	40	250	159.13
1	30	30	250	148.02
2	30	30	250	152.96
3	30	30	250	147.52
4	31	31	250	158.44
5	31	31	250	154.30
6	31	32	250	154.60
7	39	31	250	175.48
8	41	29	250	184.20
9	40	31	250	165.41
10	38	28	250	148.73
11	39	30	250	176.28
12	38	31	250	176.43

Determination of the Initial Humidity of Specimens. To investigate the process of heat and mass transfer with prepared specimens, it is necessary to determine the amount of moisture in the autoclave gas concrete pores. The moisture content will correspond to the environment parameters.

For convenience of perceiving experimental data, the moisture content of gas concrete specimens was determined as both the absolute humidity by the expression

$$W = \frac{m - m_0}{m_0} \cdot 100\% ,$$

and the relative humidity by the expression

$$w = \frac{m - m_0}{m} \cdot 100\% ,$$

where m_0 is the mass of the absolutely dry material, and m is the current mass of the specimen. As follows from the above expressions, to determine the initial humidity of the investigated specimens, it is necessary to find the mass of the absolutely dry material. To this end, specimen No. 0 was subjected to microwave drying to the absolutely dry state.

Microwave drying. To find the mass of the absolutely dry block, specimen No. 0 with the initial mass of 159.13 g and volume $V = 250$ cm^3 was dried. It turned out that the density of the investigated specimen under the conditions described above was 636.52 kg/m^3, which was claimed by the manufacturer.

The specimen was dried in a Samsung M17112NR household microwave with a maximum power of 800 W. The specimen was subjected to periodic microwave action and subsequent weighing. The drying process lasted until the change in the specimen mass at 5-min intervals became less than the precision of the balance (i.e., 0.01 g). The overall duration of the experiment was 60 min. Measurements were taken thereby at varied time intervals. During the first 10 min, the specimen was weighted at 15-s intervals. In the time interval from 10 to 15 min, measurements were taken every 30 s. For the 15–30-min range, the specimen′s mass was registered at a 1 min interval. In the last time interval of up to 60 min the interval between weighings was 5 min. As a result of weight measurements, the final mass of specimen 0 equal to 145.32 g was determined. The obtained mass is assumed to be equal to the mass of the absolutely dry material (m_0). Thus, the absolute initial humidity of specimens was 9.5%, and the relative humidity was 8.68%. In subsequent investigations, the given value of the initial humidity was assumed to be the reference value for all specimens investigated in the present work.

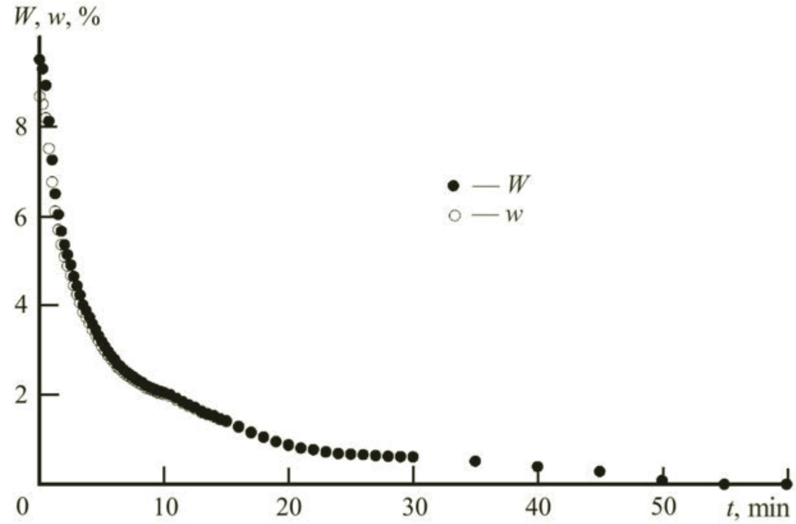

Fig. 1. Dynamics of the change in the moisture content in specimen 0 in microwave drying.

The dynamics of change in the moisture content for the investigated specimen is presented in Fig. 1. In this figure, three drying regimes for the gas concrete are clearly seen: surface, internal with free moisture evaporation and internal with bound moisture evaporation. The existence of such drying regimes was shown earlier in [4] for microwave drying of granular silica gel. A distinguishing feature of drying a specimen from cellular gas concrete is the more extended third zone of free moisture release. This can be attributed to the larger linear sizes of the specimen as compared to silica gel grains. Note that upon drying, the geometric sizes of the absolutely dry specimen remained unaltered, and the density was 581.28 kg/m^3 thereby.

Humidification of Specimens. Before the drying process, the specimens should be well humidified. In the present investigation, we used two humidification methods: capillary and sorption ones.

Capillary impregnation. To investigate the process of capillary impregnation, we prepared two groups of three specimens. The first group consisted of specimens 1, 2, and 3, and the second group included specimens 4, 5, and 6. In the investigation on the capillary impregnation dynamics, all specimens were placed for a short time in a tray with water for given time intervals. The temperature of water in the tray was equal to the air temperature and amounted to 21°C. The dynamics of the change in the absolute and the relative humidity of specimens is shown in Fig. 2.

Figure 2a shows the capillary impregnation dynamics for the first group on specimens. It is seen that in the first 15 s the absolute humidity of specimens sharply increases by about 13% (the relative humidity increases by 10%), which is due to the humidification of the surface layer. In this process, intense release of air in the form of bubbles occurs. At the subsequent instants of time the humidified surface layer begins to hinder penetration of moisture into the depth of the specimens, which leads to a deceleration of the process of capillary impregnation. By the 27th min all specimens have an approximately the same moisture content: 51.6% (34.04%) for specimen 1, 51.7% (34.49%) for specimen 2, and 54.6% (35.31%) for specimen 3. Upon averaging we have 52.95% (34.62%).

The results on capillary impregnation of the second group of specimens are presented in Fig. 2b. Here it is also seen that for all specimens there is a stepwise increase in the moisture content at the first instants of time after the specimens come in contact with the liquid surface. Then the process of moisture absorption becomes much slower, since the moisture penetrates into the deeper layers of the porous specimens. In Fig. 2b, in these regions there is a vertical-to-horizontal change of the position of the impregnation curves, the characteristic time of this period is about 15 min. Then the moisture content of the specimens increases practically by the linear law, which is clearly seen from the results of the last three measurements. The results of the last measurement have shown that the moisture content of specimens 4 was 51.71% (34.08%), that of specimen 5 was 50.69% (33.64%), and for specimen 6 it was 49.81% (33.25%). Upon averaging we have 50.73% (33.66%).

Comparison of the results of capillary impregnation in both groups has shown that the obtained results on the absolute value differ by 2.22% (0.96%), the errors is less than 4.5%. Thus, we can distinguish three stages of impregnation of the investigated specimens differing considerably in the rate of impregnation: rapid (surface), fast (capillary), and slow (diffusion) impregnation. A mathematical description of the process of capillary impregnation was proposed in [1].

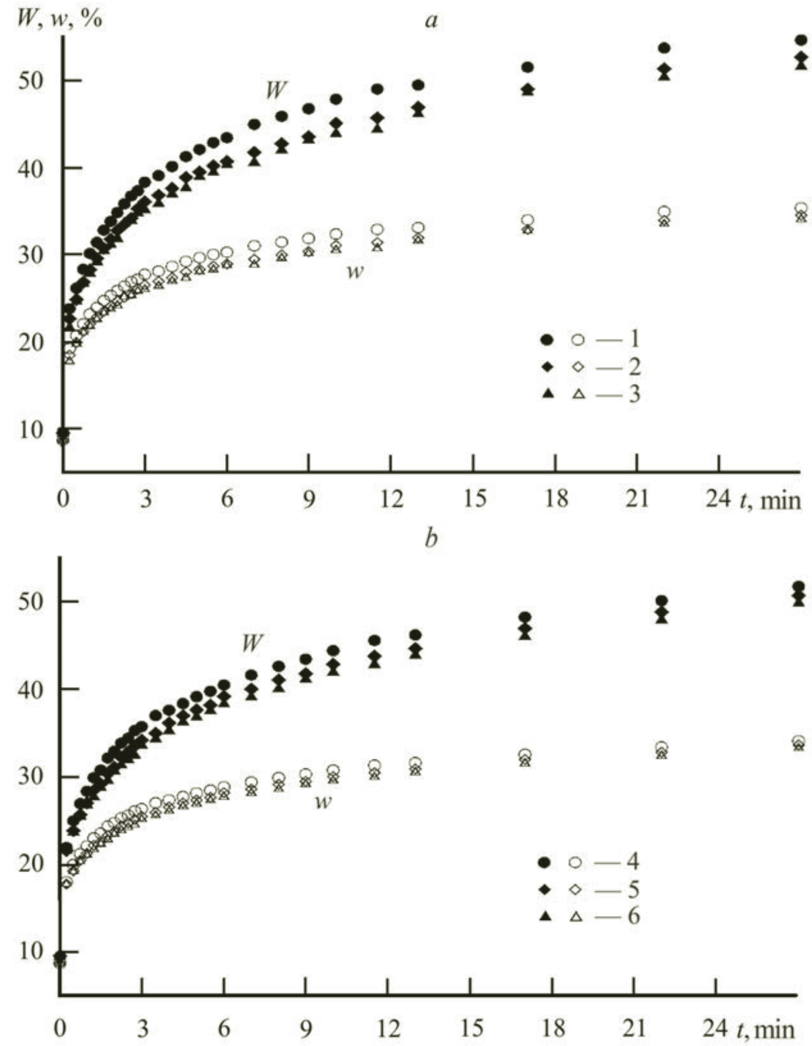

Fig. 2. Change in the absolute and the relative humidity due to capillary impregnation of the specimens of the first (specimens 1–3) (a) and the second (b) group (specimens 4–6).

Sorption humidification. To study the humidification dynamics of the cellular gas concrete by the sorption method, we prepared six specimens Nos. 7–12, their sizes and masses are presented in Table 1. To perform experiments, we made two experimental stands. They represent trays with water over which the investigated specimens were located, not touching water. To keep the parameters constant, the assembled structure was placed in a tight polyethylene bag. Due to tightness, the moisture and temperature were held constant. The thus prepared experimental stands were situated in a nonventilated closed room held at a constant temperature of 29°C, the dew point was 16.4°C. The specimens were placed in the experimental stand after the temperatures of the experimental stand and in the room were homogenized. At the moment of loading specimens and beginning the experiment on sorption humidification the experimental stands had the following conditions:

stand 1: temperature — 29°C, humidity — 88.6%, dew point — 27.0°C, density of water vapors — 25.6 g/m^3;
stand 2: temperature — 28.8°C, humidity — 87.1%, dew point — 26.4°C, density of water vapors — 24.7 g/m^3.

Specimens 7, 8, and 9 were placed in the first stand and specimens 10, 11, and 12 were placed in the second stand. During the experiment on sorption humidification all specimens were removed from the stand at given time intervals and weighed. In the weighing process, part of excess moisture left the stand, which led to a decrease in the moisture content in the investigated closed bags with the investigated specimens, and the temperature inside the stands remained constant thereby. The dynamics of sorption humidification of specimens in the experimental stands is shown in Fig. 3. It is seen that the specimens were weighed every 24 h during twelve days, and in two zones measurements were taken at three-day intervals.

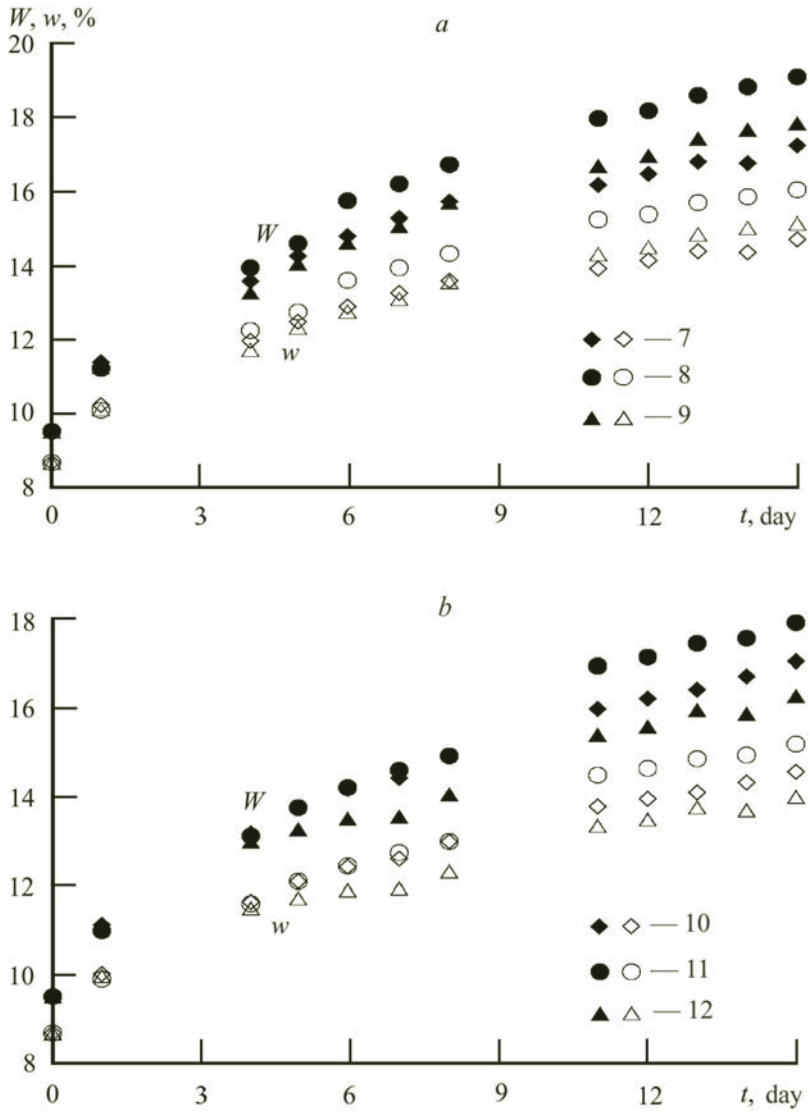

Fig. 3. Sorption humidification dynamics of the specimen: a) in the first stand for specimens 7–9; b) in the second stand for specimens 10–12.

Three-day holding of specimens in the stand permitted determination of the influence of breaking the tightness of the stand as a result of removing the specimens for weighing.

Let us consider the sorption humidification dynamics of specimens in the first stand (Fig. 3a) in more detail. After the first day of humidification, the moisture content of specimen 7 increased by 1.87% (1.54%), in specimen 8 it increased by 1.70% (1.40%), and in specimen 9 the moisture content increased by 1.74% (1.43%), i.e., by 1.77% (1.46%) on average over all specimens. In the next three days of continuous sorption humidification, the moisture content of specimens 7–9 increased by 2.21% 91.74%), 2.74% (2.16%), and 2.02% (1.60%), respectively. The average value after the three days was 2.32% (1.84%). It can be assumed theoretically that the daily average increase in the moisture content was by 0.77% (0.61%). On the fifth day of the experiment the moisture content decreased by 0.68% (0.52%), 0.65% (0.50%), and 0.79% (0.61%) for each specimen, respectively, or by 0.71% (0.54%) on average. So let us compare the results of humidifying the specimens for 24 h with their subsequent removal for a short time for weighing with the result of their 24-h humidification under continuous humidification for three days. We can see that removing the specimens and breaking the tightness of the experimental stand have no marked effect on the general humidification dynamics. The general humidification dynamics in four days (5th–8th days) with periodic removal of specimens from the stand for weighing was 2.14% (1.63%) for specimen 7, 2.78% (2.09%) for specimen 8, and 2.42% (1.85%) for specimen 9. Averaging over the specimens gives 2.45% (1.85%). The daily average increase in the moisture content is by 0.61% (0.46%). Thus, the decrease in the average value of increase in the moisture content in four days compared to the first day of the same interval is 0.10% (0.08%). Continuous humidifying during the next three days led to an increase in the moisture content of specimens by 0.45% (0.33%), 1.25% (0.91%), and 1.01% (0.74%), respectively, or the daily average value was 0.90% (0.60%), i.e., 0.30% (0.22%). Finally, the last interval for measurements during four days with daily weighing has shown that in four days the moisture content of specimen 7 increased by 1.07% (0.79%), for specimen 8 it increased by 1.13% (0.80%), and for specimen 9 the increase was by 1.15% (0.84%), the average value of increase was 1.12% (0.89%), i.e., the daily average increase was 0.28% (0.20%).

The sorption humidification dynamics of specimens 10, 11, and 12 placed in the second experimental stand is illustrated in Fig. 3b. It is seen that the humidification dynamics is analogous, but there are differences in absolute values, in particular: 1) during the first day the average moisture content of the three specimens increased by 1.56% (1.28%); 2) in the next three days the average moisture content of the three specimens increased by 2.03% (1.62%), or by 0.68% (0.54%) on daily average; 3) during fifth day the average moisture content increased by 1.56% (1.28%); 4) during the 5th–8th days the average moisture content increased by 1.54% (1.19%) or by 0.39% (0.30%) daily; 5) during the 9th–11th days the average moisture content increased by 1.47% (1.11%), i.e., by 0.49% (0.37%) on daily average; 6) during the 12th–15th days the average moisture content increased by 0.97% (0.71%), which corresponds to 0.24% (0.18%) daily. Consequently, the absolute values of moisture absorbed by specimens 10–12 are lower than for specimens 7–9.

Thus, in 15 days the total moisture content of the specimens in the first stand increased by 7.74% (6.03%) for specimen 7 and constituted 17.24% (14.07%); for specimen 8 it increased by 19.10% (16.04%), and for specimen 9 the total moisture content increased by 17.84% (15.14%). In the second stand it increased by 7.54% (5.89%) for specimen 10 and constituted 17.04% (14.56%); the total moisture content increased by 8.42% (6.52%) for specimen 11, i.e., it constituted 17.92% (15.19%), and by 6.77% (5.32%) for specimen 12, i.e., it reached 16.27% (14.00%). The average increase in the moisture content of the specimens in the first stand was 8.56% (6.62%), and in the second stand it was 7.58% (5.91%), which corresponds to humidity values of 18.06% (15.29%) and 17.08% (14.58%). The analysis performed has shown that the difference between the results for the first and the second series of experiments does not exceed 6%.

Drying of the Investigated Specimens. The prepared specimens were dried by three methods: acoustoconvective, thermoconvective, and natural drying. Let us investigate the extraction dynamics of moisture from the cellular gas concrete specimens for each drying method. Since in humidifying the specimens by capillary impregnation the finite moisture content showed a spread in absolute values, we decided to represent experimental results as a ratio between the measured and the initial moisture content weighed before the drying experiments.

Acoustoconvective drying. Experiments on acoustoconvective drying of specimens from cellular gas concrete were performed on a laboratory acoustoconvective drier (ACD) of the ITPM of the Siberian Branch of the Russian Academy of Sciences. The principle of operation of the ACD is based on a Hartmann-type jet-edge generator [13]. The ACD diagram is schematically represented in [14].

The prepared specimens were placed in a container consisting of a separable lower metal frame and an upper frame from stainless wire of thickness 3 mm limiting the displacement of the specimen in the working section of the ACD. To prevent possible spallings of specimens during drying as they come in contact with the rigid wire, strips from damping bilateral Scotch tape were attached to the wire frame elements. The total mass of the structural elements of the container was weighed both before and after each experiment, it remained unaltered and equaled 301.93 g.

The drier was started and the given mode of its operation was reached without the material to be dried. After the required parameters were set in the ACD, containers with the investigated specimens were placed for a short time in the working section and fixed. At given time intervals the container with the specimen was removed and weighed, after which it was placed and fixed again in the working section of the ACD. Measurements of the airflow parameters at the outer from the working section of the ACD have shown that the drying medium has a temperature of 12.4^{o}C, the humidity is 5.8%, the content of water vapor is 0.6 g/m^3, and the dew point is 21.3^{o}C.

The first task was to determine the influence of frequency on the drying dynamics of cellular gas concrete. To this end, investigations were conducted in two modes of operation of the ACD. The first mode was realized with the trimmer piston set at a depth of 300 mm in the resonator cup, the second mode — at a depth of 80 mm, and the third mode was realized with the piston set at the same level with the resonator throat, i.e., the depth of the resonator cup was equal to zero. The flow parameters formed at the inlet to the working section of the ACD were registered by means of an LKh-610 acoustic pressure detector. The signal obtained upon preprocessing is shown in Fig. 4. Figure 4a presents the result of signal preprocessing for the first mode. Here it is seen that the maximum intensity of the signal P' = 6.628 V is attained at a frequency of 271.5 Hz. Upon recalculation according to [15] we obtain that the flow intensity in the working section is 184.9 dB. Figure 4b demonstrates

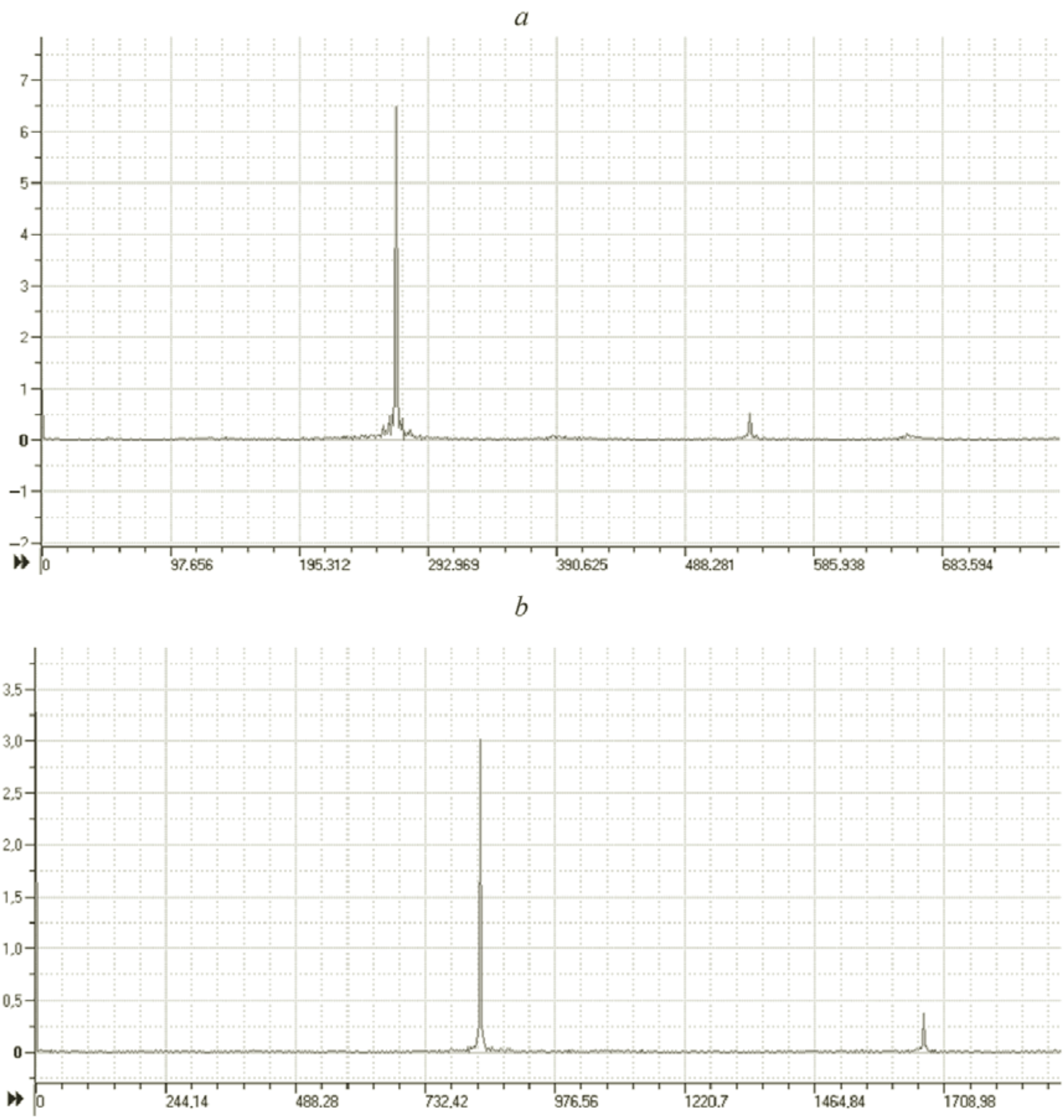

Fig. 4. Amplitude–frequency characteristic of the acoustoconvective flow measured at the inlet to the working section of the ACD without dried material with the resonator positioned at a depth of 300 mm (a) and 80 mm (b).

the operating flow parameters realized in the second mode of operation of the ACD. The maximum value of the signal amplitude P' = 3.040 V or 178.1 dB and is attained at a frequency of 835.0 Hz. In the third model of operation of the ACD, the clearly defined maximum in the signal amplitude, as was mentioned earlier in [11], is absent. Hereinafter, this mode of operation of the ACD where resonance is absent, will be referred to as the background mode.

When containers with specimens were placed in the working section of the ACD, the acoustoconvective flow parameters changed slightly, for instance, for the first mode they were as follows: the frequency was 269.5 Hz and the intensity was 188.1 dB; for the second mode the frequency was 817.9 Hz and the intensity was 178.8 dB. Thus, placing specimens leads to a decrease in the resonance frequency by 0.74% for the first mode and by 2.05% for the second mode, while the intensity increases by 0.11% and 0.39% for the first and the second mode, respectively. In the third mode of operation of the ACD, loading specimens into the working section caused no changes. The pressure in the settling chamber was held constant during all experiments and equaled 6 atm. Note that in Fig. 5 small amplitude spikes can be seen. For the first mode, from Fig. 4a it is seen that a spike is realized at a frequency of 543.0 Hz, and for the second mode Fig. 4b shows a spike at a frequency of 1670.0 Hz. These frequencies are exactly twice higher than the frequency values obtained earlier.

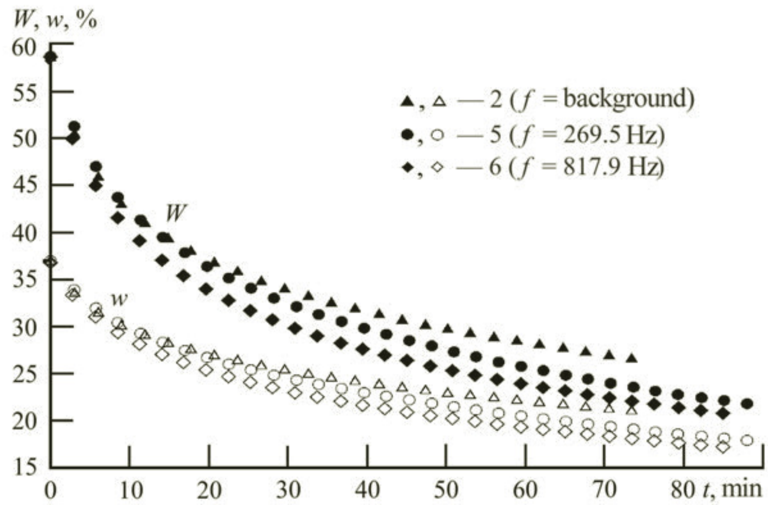

Fig. 5. Dynamics of moisture extraction from specimens 2, 5, and 6 in acoustoconvective drying.

For the acoustoconvective experiment we chose three specimens 2, 5, and 6 having practically the same moisture content 58.55% (36.93%), 58.68% (36.98%), and 58.63% (36.96%), respectively, obtained as a result of the previous experiment on capillary impregnation. The results of the experiments on the drying dynamics of specimens in three modes of operation of the ACD are presented in Fig. 5. Analyzing the data for the first and the second mode, it may be noted that insonifying specimens with a higher frequency and a lower amplitude (intensity) leads to a higher drying velocity. From Fig. 5 it is also seen that in the third mode of operation without clearly defined resonance frequency and with a low intensity the drying proceeds slower than for the two regimes considered above. An analogous phenomenon was first observed and described earlier in [4] in the process of acoustoconvective drying of samples from granular silica gel:

Comparison of the moisture extraction dynamics for two resonance frequencies at various instants of time has shown that the difference between the drying dynamics at frequencies of 817.9 Hz and 269.5 Hz is described by the drying velocity function $W = W(t)$:

1) first it increases rather fast; for instance, by the 3rd min the difference was 1.30% (0.57%), by the 5.7th min it was 2.01% (0.95%), and by the 8.5th min the difference was 2.16% (1.06%);

2) by the 15th min the difference reaches its maximum value — 2.42% (1.27%);

3) at the last stage it decreases, in particular, by the 31st min the difference was 2.30% (1.34%), and by the 45th min it was 2.13% (1.31%), by the 60th min the difference was 1.81% (1.16%), and at the end of the experiment, i.e., by the 85th min, it was already 1.32% (0.90%).

Comparing the moisture extraction dynamics from specimens 2 and 5, it may be noticed that during the first 15 min no marked difference is observed. At the following instants of time (>15 min) the difference begins to show up and increase gradually. At the end of the experiment, at the 74th min the difference in moisture content for specimens 5 and 2 reached 2.99% (1.91%). Comparison of the drying dynamics of specimens 6 and 2 shows that the difference between the moisture content values increases steadily, and by the end of the experiment it reaches 4.49% (2.9%).

Practically, the estimate of the time of reaching the required moisture content for each drying regime is the most demonstrative. To decrease the moisture content in specimens from the initial value of 58.6% to 41%, it is necessary to spend 8.5 min for the second mode of operation with a frequency of 817.9 Hz, 11.5 min for the first mode with an operating frequency of 269.5 Hz, and 12 min for the third mode — the background mode. For the moisture content in specimens to decrease from the initial value of 58.6% to 35%, it is necessary to spend 17 min for the second mode of operation of the ACD, 23 min for the first mode, and 25 min for the third mode. Decreasing the moisture content to 30% takes 31 min for the second mode, 40 min for the first mode, and 50 min for the third mode. Finally, decreasing the moisture content to 25% required 54 min and 66 min of ACD operation for the first and the second mode, respectively. Thus, the following tendency is observed: the larger the moisture content to be decreased in specimens, the more significant becomes the time interval between the modes. In particular, for the first and the second mode we have: for the moisture content to decrease by 17.6%, the time interval between the modes was 34.8%; if the moisture content decreases by 23.6%, then the difference between

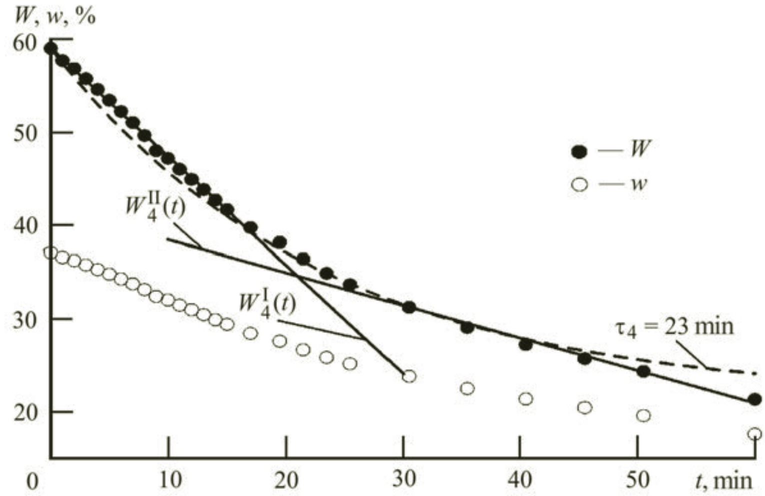

Fig. 6. Thermoconvective drying dynamics of specimen 4 (dots — experimental data, solid lines — linear approximation, dotted line — mathematical model).

the drying regimes is 34.06%; to decrease the moisture content by 28.6%, the difference in time expenditures is 28.23%; to decrease the moisture content of specimens by 33.6%, the duration of operation of the ACD in the first mode will be longer by 21.38% that in the second mode.

Thermoconvective drying. To perform a comparative analysis of drying specimens from cellular gas concrete under thermoconvective action with other drying methods, we carried out an experiment on thermoconvective drying. The thermoconvective drying regime is based on blowing heated air over the specimen. To perform a thermoconvective experiment, we constructed an experimental stand. For the heat flow source, we used an ÉTV-4.5/220 T thermal gun with a heating power of 4.5 kW and a thermoconvetive flow velocity of 7.6 m/s. The experimental stand was started and the operating conditions were attained without the material to be dried. The stand was assumed to be have reached the operating conditions if during 5 min the thermophysical parameters at the outlet from the thermal gun nozzle remained unaltered. The steady-state operating conditions had the following thermoconvective flow parameters: temperature — 109.7°C; moisture content — 4.6%; dew point — 9.3°C; content of water vapors — 8.8 g/m^3.

The humidified specimen 4 was subjected to thermoconvective drying. It was placed on a wire mount in the central part of the blowing zone on the axis of the formed heat flow. The dynamics of change in the moisture content in specimen 4 is shown in Fig. 6. It is clearly seen that the drying process has two characteristic regimes. The first regime begins at the moment the investigated specimen is placed in the thermoconvective flow and ends by the 17th min. This regime is due to the heating and evaporation of moisture from the surface of the specimen and the adjoining layers of the material being dried. The second regime is characterized by a slower outflow of moisture, since the moisture contained in the deeper layers has to pass through the pores of the near-surface layers. Moreover, the total content of moisture in the specimen′s pores becomes smaller. Both thermoconvective drying regimes can be described by the linear functions in a similar manner to [6]. For the mathematical description of the first regime a linear equation of the form

$$W_4^{\mathrm{I}}(t) = 59.055 - 1.164t, \%$$

is used.

For the second regime of thermoconvective drying its own coefficients are determined, then the linear equation has the form

$$W_4^{\mathrm{II}}(t) = 41.958 - 0.350t, \%.$$

In Fig. 6, the obtained linear expressions are plotted by solid lines. It is seen that in their time intervals the obtained expressions describe experimental data fairly well. The deviation of experimental points from the linear law is estimated with the help of the linear correlation coefficient. Calculating the linear correlation coefficient for each interval, we obtain that for the first regime it takes on a value of 0.9983, and for the second regime it is 0.9889. From the obtained equations it is seen that the rate of moisture extraction in the first regime of thermoconvective drying (1.164 %/min) is 3.33 times higher than in the second regime (0.350 %/min).

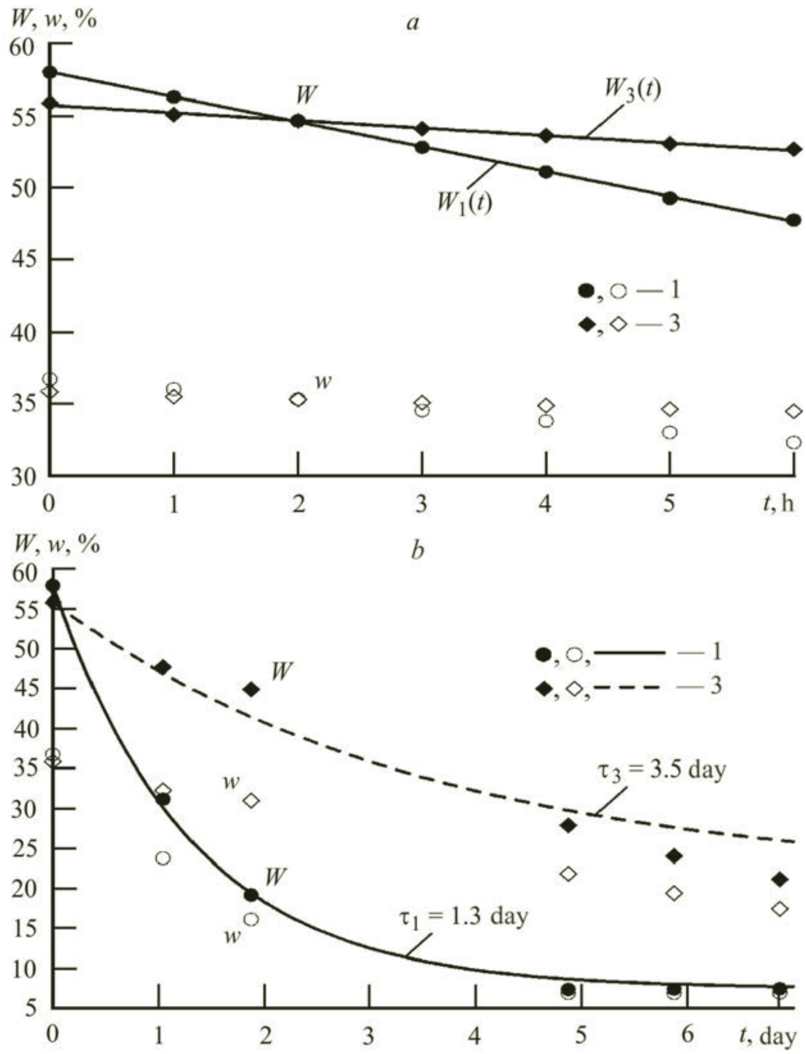

Fig. 7. Change in the moisture content in specimens 1 and 3 in natural drying: a) at the initial instants of time, b) during a week.

Natural drying. To reach the temperature at which the accoustoconvective drying regime is realized, we performed a series of experiments on natural drying. By the term natural drying is meant the process of drying specimens without energy supply. This process was carried out in closed rooms with natural ventilation. For experiments, we used two rooms-stands. The first stand represented a room with the following characteristics of the environment: temperature — 26.7°C, humidity — 60%, water vapor density — 153 g/m, dew point — 8.3°C. The environment parameters in the second stand were as follows: temperature — 18.7°C, humidity — 87%, water vapor density — 13.9 g/m^3, dew point — 16.6°C. Specimen 1 was placed in the first stand, and specimen 3 was placed in the second stand.

The results on the drying dynamics of the specimens are presented in Fig. 7. The natural drying process was considered on two time scales: one time scale during the first 6 hours (Fig. 7a) with hourly weighing, and the second scale — during a week (Fig. 7b) with weighing once a day. From Fig. 7a it is seen that the initial moisture content at the instant of time $t = 0$ h for specimen 1 — 57.98% (36.70%) — is higher than for specimen 3 — 55.88% (35.85%), but because of the different conditions in the drying stands, after two hours the humidities homogenize and become equal to 54.65% (35.34%). At the following instants of time the difference in the drying dynamics between the specimens gradually increases, and after 6 h of the experiment the moisture contents of the specimens are equal to 47.77% (32.33%) and 52.65% (34.49%) for specimen 1 and specimen 3, respectively. From Fig. 7a it can be noticed that the moisture content of the specimens changes by the linear law. To describe the experimental data for specimen 1, we obtained a linear equation in the form

$$W_1(t) = 58.005 - 1.724t, \%.$$

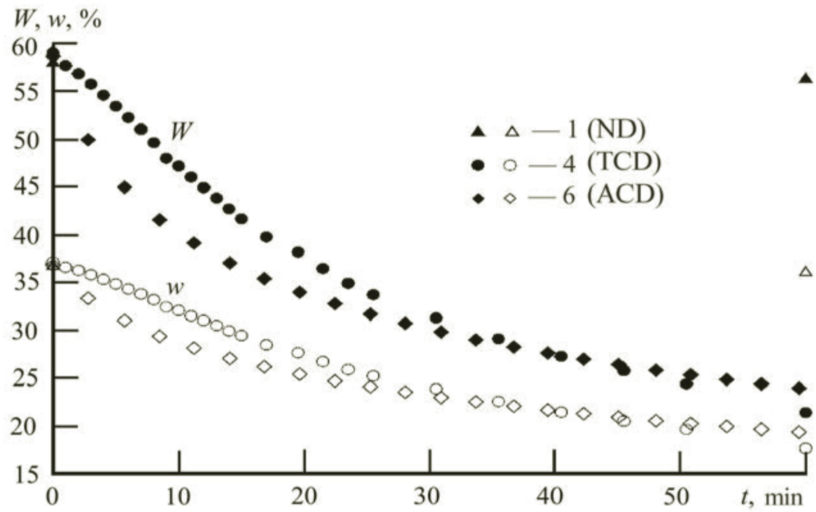

Fig. 8. Comparison of the drying dynamics of the cellular gas concrete by three methods: specimen 6 — acoustoconvective drying; specimen 4 — thermoconvective drying; specimen 1 — natural drying.

Mathematical treatment of the experimental data for specimen 3 permitted obtaining the linear law in the form of the expression

$$W_3(t) = 55.724 - 0.528t, \%.$$

These linear dependences are presented in Fig. 7a. It is seen that both lines describe well the experimental data over the entire time interval. To estimate the degree of conformation of the obtained experimental data to the linear law, let us calculate the linear correlation coefficient: for specimen 1 it is 0.9996 and for specimen its value is 0.9933. The obtained expressions permit concluding that at the initial stage the rate of moisture extraction from specimen 1 (1.724 %/h) is higher by a factor of 3.27 than from specimens 3 (0.528 %/h), which, naturally, is due to the conditions environmental in the stands.

Figure 7b presents the experimental data recorded during a week. As is seen, in the first day the moisture content of specimen 1 decreased from 57.98% to 31.16%, i.e., by 26.82%, which is approximately a half of the initial content. In the second day the moisture content decreased to 19.17%, i.e., by 11.99% or almost twice compared to the end of the first day. In the next three days of continuous drying, the moisture content of the specimen decreased to 7.34% and in the next two days remained unaltered, i.e., the moisture content of specimen 1 stroke a balance with its environment. Analysis of the drying dynamics of specimen 3 shows that it dries much slower than specimen 1. In particular, in the first day of drying the moisture content decreased from 55.88% (35.85%) to 47.68 (12.29%), i.e., by only 8.19% (3.56%), and in the second day it decreased to 44.94% (31.01%), which is 2.74% (1.28%) less than at the end of the first day. After the next three days the moisture content was 27.89% (21.81%), i.e., it decreased further by 17.05% (9.20%). In the following two days the moisture content continued to decrease and by the end of the sixth and the seventh day reached a value of 24.03% (19.38%) and 21.12% (17.43%), respectively. Thus, under the conditions realized in the first stand specimen 1 reaches the finite equilibrium moisture content in 5 days, and specimen 3 in the second stand does not manage to reach the finite equilibrium state even in seven days.

Discussion of the Experimental Results and Comparison of the Drying Methods. Figure 8 presents the results for three drying regimes: acoustoconvective drying at a frequency of 817.9 Hz and a temperature of 12.4^{o}C; thermoconvective drying at a temperature of 107.9^{o}C; and natural drying at a temperature of 26.7^{o}C. As is seen, in the 60-min interval the drying dynamics for each regime has its own peculiarities. In acoustoconvective drying, the moisture content monotonically decreases over the entire interval from 58.63% (36.96%) to 23.92% (19.30%), i.e., the loss of moisture was 34.71% (17.66%). In thermoconvective drying, the moisture loss dynamics has two stages: the first stage takes the first 17 min, and the second stage lasts for the rest of the time interval. By the end of the 60th min of drying the moisture content of the specimen decreased from its initial value of 59.01% (37.11%) to 21.36% (17.60%). Consequently, the overall loss of moisture was 37.65% (19.51%). For natural drying, in the 60-min interval there are only two points: 57.98% (36.70%) and 56.30% (36.02%). Thus, in one hour of natural drying the moisture content decreased by 1.69% (0.68%).

TABLE 2. Comparison of the Drying Time of Specimens by Different Methods

W, %	Drying time		
	acoustoconvective, min	thermoconvective, min	natural, h
50	2.8	7.5	5
45	5.7	12	9
40	11	17	15
35	17	23	21
30	31	35	27
25	52	48	35
21.36	79.5	60	41

Let us compare the moisture extraction dynamics in acoustoconvective and thermoconvective drying. From the very first instants of time the acoustoconvective drying regime has a higher efficiency than the thermoconvective regime. In particular, at the first instant of time the difference in the moisture loss dynamics for specimens having at the initial instant of time a practically equal moisture content rapidly increases and by the third minute is 5.83% (2.49%), and by the sixth minute it reaches its maximum value of 7.65% (3.46%). Then the difference between the two methods begins to decrease very slowly, so by the 9th min it is 7.27% (3.45%, and by the 11th min the difference is 6.89% (3.39%). In the following three time intervals of duration about 3 min each, the difference in the drying dynamics decreased by 1%. Then the decrease slowed down and by the 40th min the experimental data in thermoconvective and acoustoconvective drying have practically equal values of the absolute and the relative humidities of 27.58% (21.61%). Then the dynamics of moisture extraction from the specimen in thermoconvective drying begins to dominate little by little over the experimental results of specimen drying in the ACD. By the end of the experiment, i.e., by the 60th min, this difference reaches 2.56% (1.70%).

Thus, comparing the thermoconvective and the acoustoconvective drying regimes, we can distinguish three characteristic time intervals: the first interval where the acoustoconvective drying regime dominates markedly over the thermoconvective regime; the second interval where the domination of the acoustoconvective drying regime over the thermoconvective one is weak; and the third regime, where the thermoconvective drying regime dominates over the acoustoconvective one.

Table 2 presents the estimated times required to reach a given moisture content for each of the three regimes. It is seen that the loss of 10, 15, and 20% of moisture is 2.7, 2.1, and 1.5 times faster in acoustoconvective drying than in thermoconvective drying and 107, 95, and 82 times faster than in naturals drying. Thermoconvective drying is 40, 45, and 53 times faster than convective drying for the above-mentioned moisture losses. The subsequent decrease in the absolute humidity in specimens by 25, 30, and 35% requires much more time, and the ratios between acoustoconvective and thermoconvective drying become greater than unity (1.35, 1.13, and 0.92). The ratio between the drying time in the acoustoconvective regime and in natural drying decreases by a factor of 74, 52, and 40, whereas the previously increasing ratio between the thermoconvective and the acoustoconvective regimes reaches its maximum and begins to decrease by a factor of 55, 46, and 44 in accordance with the change in the moisture content. From Table 2 it is seen that even under the best conditions, but with natural convection, the specimens dry very slowly. In reality, the drying conditions can change during the day toward lower temperatures and higher humidities, which markedly increases the drying time.

Analyzing the presented data on the drying of specimens by the acoustoconvective method and comparing them with the results of thermoconvective drying, it may be concluded that the most optimum and effective method is exposing specimens to sound in the ACD for 15 min. A similar result on the optimum drying time in the ACD was presented earlier in [7] for acoustoconvective drying of husky Korean rice.

Mathematical Treatment of the Experimental Data on Acoustoconvective Drying. For mathematical description of experimental data on the acoustoconvective drying dynamics of specimens from cellular gas concrete, it is natural to use the linear relaxation equation in the form

$$\frac{dW}{dt} = \frac{W_{\mathrm{f}} - W}{\tau}, \tag{1}$$

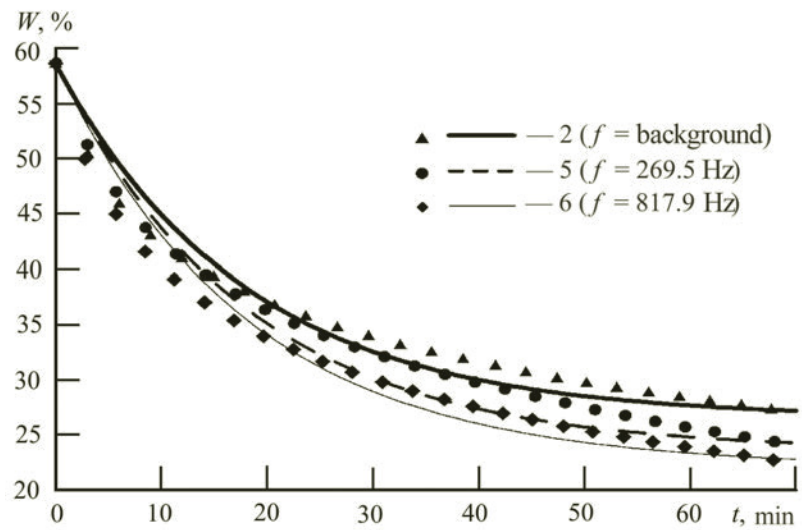

Fig. 9. Description of the experimental data by the mathematical model: dots — experimental data, lines — theory.

TABLE 3. Relaxation Time for Drying Various Materials in the ACD

No.	Material	Relaxation time, min	Reference
1	Pine nut grains	20	[6]
2	Pine nut shell	7.5	[6]
3	Pine nut core	13	[6]
4	Sorbent	18 – 50.6	[3]
5	Pipe assembly along the flow	9	[16]
6	Pipe assembly across the flow	6	[16]
7	Meat fibers	10	[11]
8	Cellular gas concrete	18	Present work

which is amplified by the corresponding initial condition

$$\text{at} \quad t = 0, \quad W = W_0 \,, \tag{2}$$

where τ is the relaxation time. Equation (1) has an analytical solution in the form

$$W = W_{\text{f}} + (W_0 - W_{\text{f}})e^{-(t/\tau)} \,. \tag{3}$$

Figure 9 presents the experimental data on the change in the absolute humidity in the three regimes of acoustoconvective drying and the results of numerical calculations by the proposed mathematical model. The series of calculations performed has shown that the most optimum value of the relaxation time for all regimes of acoustoconvective drying is 18 min. The results of numerical calculations by the relaxation model describe the obtained experimental data fairly well.

To compare the obtained relaxation time for cellular gas concrete with other materials, we compiled a table (Table 3) containing the relaxation times for other materials subjected to acoustoconvective drying. It is seen that the relaxation time determined in the present work for cellular gas concrete is comparable to the relaxation time for pine nut grains obtained in [6] and correlates with the lower value for the sorbent from [3].

The obtained mathematical expression (3) was also used to process the experimental data on thermoconvective and natural drying. In Fig. 6, the dotted line shows the results of mathematical treatment of the experimental data on natural drying. It is seen that the obtained data are well described by the relaxation equation up to 45 min, and the value of the relaxation time is 23 min thereby. In Fig. 7b, the lines show the results of calculations for natural drying of specimens 1 and 3, the relaxation time of specimen 1 was 1.3 days thereby, and for specimen 3 it was 3.5 days.

CONCLUSIONS

1. As a result of performing a series of experiments on humidifying specimens from cellular gas concrete, we have obtained the dependence of the rate of moisture absorption for two humidifying methods: capillary impregnation and sorption.

2. Experimental studies have been made of the influence of three drying regimes: acoustoconvective, thermoconvective and natural drying on the dynamics of moisture extraction from cellular concrete:

a) in acoustoconvective drying, it has been shown that the frequency and intensity of the operating flow influence the dynamics of moisture extraction from the specimens being dried;

b) the obtained experimental data on thermodynamic drying are characterized by a bilinear distribution. To describe it, we have found two linear equations of drying, which permitted us to find the characteristic rates of the processes;

c)it has been shown that the process of natural drying proceeds very slowly, and the temperature and humidity of the environment strongly influence the drying velocity.

3. Comparison of the moisture extraction dynamics from the cellular gas concrete in acoustoconvective and thermoconvective drying has shown that there exist three temporal stages: increase in the efficiency of the acoustoconvective regime as compared to the thermoconvective regime; decrease in the efficiency of acoustoconvective drying compared to the efficiency of thermoconvective drying; domination of the thermoconvective regime over the acoustoconvective one.

4. To describe the experimental data on the drying of cellular gas concrete in the three regimes, a simple relaxation model can be used, which permitted obtaining the characteristic times of the processes for each drying regime. From the point of view of the relaxation model it has been shown that for the acoustoconvective drying regime the optimum relaxation time is 18 min and it is independent of the drying flow parameters.

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