INVESTIGATION OF THE MECHANISM OF RADIATIVE-CONVECTIVE DRYING OF COLLOIDAL CAPILLARY-POROUS MATERIALS USING RADIOACTIVE TRACERS

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Radioactive tracers have been used to study the process of layerwise drying of crumbled material. The dependence of evaporation zone penetration on the maximum drying rate has been established, and the phase composition of the transferred moisture has been determined.

In spite of the intensive development of heat and mass transfer theory [1, 2], the mechanism of drying of colloidal capillary-porous materials has not yet been sufficiently studied. The basic difficulty in analysis of internal heat and mass transfer lies in determining the fraction of moisture and of thermal moisture conduction in the total moisture flux, as well as in evaluating its phase composition. Use of the method of nonabsorbing radioactive tracers allows these difficulties to be overcome; a small concentration of radioactive salt ($\sim 10^{-4}\%$) produces practically no change in the properties of the water and the colloidal capillary-porous materials. With the aid of this method a study has been made of the mechanism of thermal moisture conduction [3–5], and an investigation of the process of drying of peat has been commenced [6, 7].

However, the mechanism of radiative-convective drying of thin layers of crumbled material lying on moist ground has received little study in practice. Explanation of the mechanism of drying of disperse materials in thin layers is of great scientific and practical interest [1, 8, 9]. It should be noted that to intensify radiative-convective drying under specific values of the technical conditions and to obtain greater yield during drying, we may either reduce the specific charge in terms of the dry material per unit area, at the same time increasing the number of collection cycles of the dried material, or we may periodically collect the top dried layers, according to their degree of readiness, from thick loose beds of disperse material.

As the material to be investigated we chose top-quality milled peat with mean particle size of 4 mm. The tests were conducted in a small artificial climate chamber. Radiative heating was accomplished with a 500-W infrared lamp in the chamber, 40 cm from the material to be dried. Between the lamp and the material there was a frosted screen to obtain a uniform distribution of radiation on the drying surface. At a raditation intensity of (0.60 ± 0.028) kW/m^2 in the chamber the conditions were maintained similar to those pertaining to field drying of peat: temperature $25 \pm 1.5°$ C, relative humidity $32 \pm 3\%$, and air velocity ~ 0.5 m/sec. Under these conditions the rate of evaporation from the exposed aqueous surface was $(1.70 \pm 0.03) \cdot 10^{-7}$ m/sec, which corresponds to the rate of removal of moisture from open reservoirs for central regions of the Soviet Union in summer time during good sunny weather.

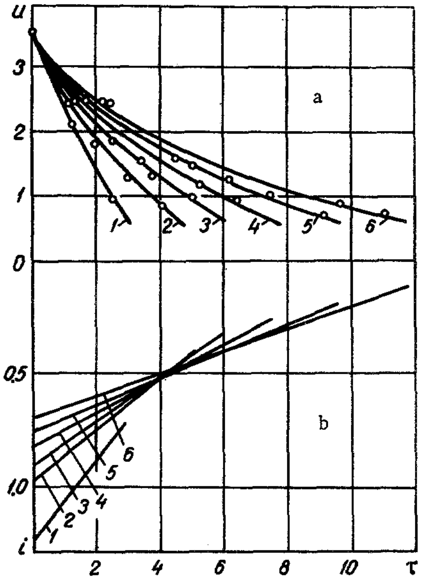

Fig. 1. Dependence of moisture content u, kg/kg (a) and drying rate i, kg/kg · hr (b) on drying time τ, hr: 1) with layer thickness of milled peat of 4 mm; 2) 6; 3) 8; 4) 10; 5) 12; 6) 14.

Before the experiments the moisture in the peat was tagged with a $Na_2S^*O_4$ tracer with the radioactive atom sulfur-35, which is not absorbed by the solid phase of peat. The peat was kept in desiccators to establish a uniform humidity and concentration of radioactive salt. Four samples for humidity and specific activity were taken by successive separation of the milled material, allowing for shrinkage of 1.6–3 mm. To separate the dried beds into layers of thickness 4, 6, 8, 10, 12, 14 and 24 mm, we used a special device, which, with the aid of a micrometer screw and guides, allowed us to divide the bed into separate layers accurately and rapidly. Samples were prepared for measurement of specific activity according to a method developed earlier [7], by drying the peat samples to absolute dryness, and subsequently pressing them into tablets of a certain size. The tablets were counted under a MST-17 counter, coupled to a B-2 radiometer, on both sides, and the values obtained were averaged. Determination of the moisture content of the specimens was conducted in a standard manner by drying at a temperature of 105° C. Drying of the material, with threefold repetition, was accomplished directly on moist soil (monolithic peat)

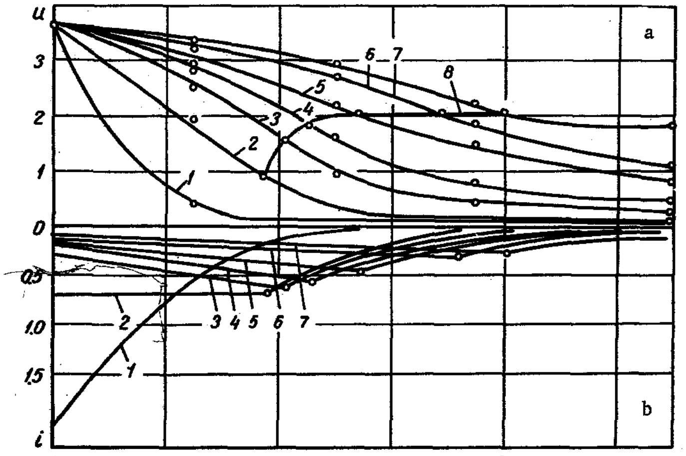

Fig. 2. Drying (a) and drying rate (b) curves for various layers of milled peat [1) at a depth of 0–2 mm from layer surface; 2) 2–4; 3) 4–6; 4) 6–8; 5) 8–10; 6) 10–12; 7) 12–14], and moisture content curve corresponding to maximum drying rate (8); u, kg/kg; i, kg/kg·hr; τ, hr.

in a thermally insulated plastic container. The surface layers of the monolithic peat had practically constant moisture content during the test, this being achieved by supplying moisture from beneath.

Analysis of the graphs of Fig. 1 shows that in drying in thin layers (4–14 mm) there is no period of constant drying rate for the layer as a whole, and the entire process proceeds in the period of falling rate. This is due to the fact that particles of material in the top of the layer are dried very rapidly to the first critical moisture content, without much removal of moisture from the bed as a whole. Because of its poor thermal conductivity, the top dry layer suppresses the supply of heat to the underlying layers of material, while the supply of moisture to the top part of the bed, due to moisture content gradients, is considerably less than the rate of evaporation from the surface of the moist crumbled material. The appreciable porosity of the material is also a great obstacle to displacement of liquid moisture to the top of the bed. The disparity between the amount of moisture evaporating from the surface and arriving from the inside layers produces drying only in the falling rate period, and causes penetration of the evaporation zone into the material.

By analogy with certain fibrous materials [8], it may be supposed that, because of the large porosity (up to 95%) of peat, deep penetration of thermal radiation occurs into the layer of material (up to 6 mm and more). This leads to deep heating of the peat bed, and therefore, to intense evaporation of moisture. Moreover, the porous bed is "ventilated" by air, which ensures the rapid removal of water vapor.

This hypothesis is confirmed by the results of tests presented in Fig. 2, which shows drying and drying rate curves for various layers of milled peat in a bed of total thickness 14 mm at the start of the test (similar graphs were obtained also for beds of 4–12 mm). Drying of the top (2 mm) layer proceeds at the greatest rate; a decrease of the rate, from an initial value of $i_i = 1.92$ kg/kg·hr occurs quite quickly, first in a linear fashion (to $u \sim 0.9$ kg/kg), and then nonlinearly until the equilibrium moisture content level is reached. For layers of material at a distance 2–4 mm from the surface of the bed, there are sections with constant intensity of evaporation, and then the rate falls off according to the curve. An increase is observed in the duration of constant drying rate in the 2–4 mm layers with increase of the initial thickness of the material. This is evidently due to more intense flow of moisture from the underlying layers with increase of bed thickness.

In the layers 4–14 mm from the surface we observe first a gradual increase in drying rate, linearly to a

Values of Maximum Drying Rate as a Function of Distance from the Surface of the Material to the Layer

Thickness of bed, mm	Maximum drying rate, kg/kg·hr, at distance from the surface of the material, mm						
	0–2	2–4	4–6	6–8	8–10	10–12	12–14
4	1.89	0.91	—	—	—	—	—
6	1.91	0.83	0.69	—	—	—	—
8	1.91	0.83	0.66	0.52	—	—	—
10	1.91	0.75	0.60	0.52	0.43	—	—
12	1.88	0.66	0.60	0.52	0.45	0.32	—
14	2.00	0.71	0.63	0.57	0.45	0.32	0.26
Mean	1.92	0.78	0.64	0.53	0.44	0.32	0.26

definite maximum value i_{max}. This is connected, apparently, with gradual radiative heating of the material, as well as with increase of the forces of capillary contraction [6]; the particles are compressed due to shrinkage, and moisture reaches the periphery of a peat particle at a brisk rate from the central regions.

Following the inclined section, a fall in drying rate is observed. It should also be noted that the lower the location of a layer, the less its initial drying rate and its maximum value (Fig. 2b). Decrease in the moisture content of the peat occurs simultaneously over the whole bed with fall-off of drying rate in proportion to increase of distance from the surface of the material.

During drying of crumbled peat in beds of from 4 to 14 mm, there is little difference (see table) in the values of maximum rates of evaporation for layers located at identical distances from the surface. The maximum drying rates of different layers are observed at different times: the deeper the layer, the longer the duration of the period of linear rate (Fig. 2), and the less the value of i_{max} (Fig. 3, curve 1). In the deeper layers the temperature is less, and this reduces the intensity of evaporation. Moreover, with increase of distance from the surface, there is a deterioration in the "ventilation" of the material by the air and in the evacuation of water vapor from the layer.

The moisture content corresponding to maximum drying rate is shown in Fig. 2 (curve 8). Decrease in the drying rate occurs for a moisture content of 1–2 kg/kg, i.e., when the weakly bound moisture has already been removed from the peat (the water of the macrocapillaries and the intracellular water), and the water of microcapillaries is being evaporated [6]. Therefore, layerwise removal of moisture absorbed by a colloidal capillary-porous material takes place in conformity with its binding energy, as noted earlier in the work of Kazanskii and Lytsik [10] and Churaev [6]. However, in our tests the final moisture content of the whole bed was higher than the amount of absorption-bound moisture in the peat, and so its influence on the course of drying was not considered.

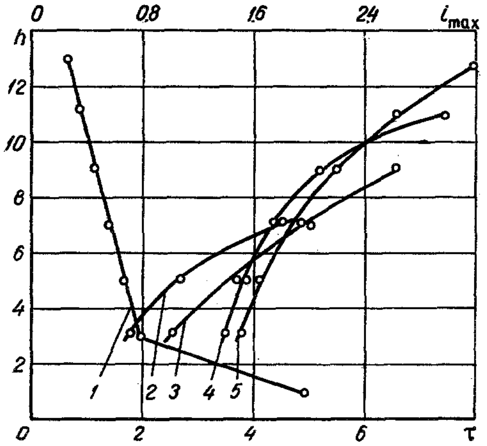

Fig. 3. Dependence of maximum drying rate, i_{max}, kg/kg·hr, on distance h, mm, from the surface (1) and dependence of depth of zone with maximum rate of evaporation on time τ, hr, in beds of thickness 8 (2), 10 (3), 12 (4) and 14 (5) mm.

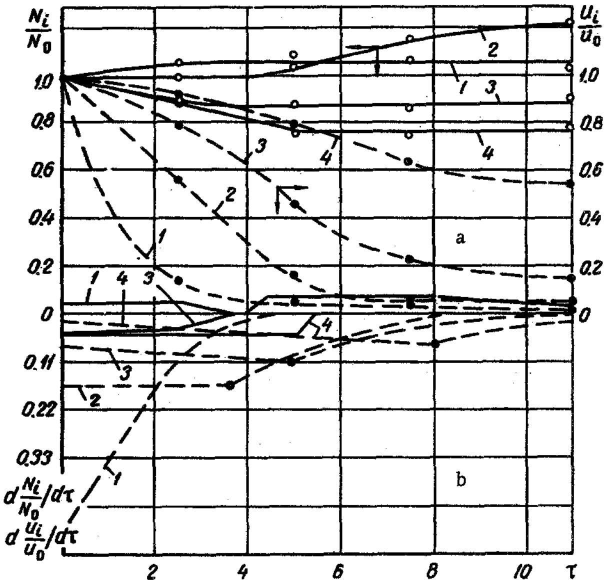

Fig. 4. Graphs of variation of (a) relative specific activity N_i/N_0 (continuous lines) and of relative moisture content u_i/u_0 (broken lines) and (b) of their rates with time τ, hr, for various layers: 1) at a distance from the surface of 0–2 mm; 2) 2–4; 3) 6–8; 4) 12–14.

From the curve of penetration of the zone with maximum drying rate with time (2–5 in Fig. 3), it can be judged that there is a parabolic law of penetration of the evaporation zone into the layer of material being dried [1, 10]. From this curve it is seen that in the thinner layers the maximum evaporation zone moves into the interior of the layer earlier. The intersection of the curves can be explained by the influence of moisture transfer between the lowest 2-mm layer and the ground. Because of moisture transfer the maximum drying rate of the layer in contact with the base is reached somewhat later than for a layer that is located at the same distance from the surface of thicker beds.

A deeper analysis of the drying mechanism is obtained by examination of the curves of distribution of relative moisture content u_i/u_0, relative specific radioactivity N_i/N_0, and their derivatives with respect to time—their rates (Fig. 4). The radioactive tag is transferred by the moisture to the liquid phase and remains at the place of evaporation. Accumulation of the radioactive tracer at some part or other of the capillary-porous material testifies to the presence of an evaporation front at that location.

From analysis of the graphs of drying and of transport of the tracer (Fig. 4) it follows that the maximum drying rate front during the first four hours was located in the 0–2 mm layer (curve 1 of the dependences of $(N_i/N_0)(\tau)$ and $(u_i/u_0)(\tau)$, and of their derivatives with respect to time also). There we observed transfer of moisture in the liquid phase from deeper layers to the top of the material (the fraction of moisture transfer in the liquid phase from more distant layers was about 10% of the total amount of moisture evaporated in this layer). After four hours of drying, when the maximum evaporation zone moves to the 2–4 mm layer, we observe a considerable removal of radioactive tracer from the lower-lying layers (curves 2 in Fig. 4). It should be noted that the tracer arrives when the moisture content of the 2–4 mm layer is about 1 kg/kg. For such a moisture content, and with a relative humidity of the air in the chamber of 32%, we might expect film transfer of moisture [11] and migration of moisture along the microcapillaries in the 2–4 mm layer at higher concentration than the initial value of the tracer. But the large porosity of the material inhibits any substantial film transfer of moisture. Transfer of radioactive tracer by films of water in the 2–4 mm layer proceeds during all subsequent drying. The moisture is evaporated completely in this layer, without reaching the surface of the material (continuous curve 2); we observed a comparatively constant intensity of migration of moisture in the liquid phase during the subsequent 3–11 hours of drying.

In the deeper layers the moisture migrated both into the maximum evaporation zone and into the ground through thermal moisture conduction, this being evidenced by the considerable variation of activity of the lower layers (Fig. 4, curve 4). The presence of thermal moisture conduction is also confirmed by the direct observations that we made of the radioactivity in the underlying ground—the monolithic peat; calculation of the transfer of radioactive tracer into the ground allows us to estimate the fraction of thermal moisture conduction during drying. The amount of moisture transferring from the material being dried to the ground as a result of thermal moisture conduction was calculated from the formula

$$q = \frac{(u_{\mathrm{i}} - u_{\mathrm{f}})\, p_{\mathrm{d}} Q}{100\tau}\ \mathrm{kg/m^2 \cdot hr}.$$

Under the condition that transfer of radioactive tracer is proportional to the amount of moisture migrating into the ground, we may determine Q (%) from the formula

$$Q = 100 \sum_{i=1}^{n} N_i^{\mathrm{g}} \Big/ \sum_{i=1}^{n} N_i^{\mathrm{c}},$$

where $\sum_{i=1}^{n} N_i^{\mathrm{g}}$ is the sum of the given values of specific activity of the samples of the underlying ground, counts/min; $\sum_{i=1}^{n} N_i^{\mathrm{c}}$ is the original calculated value of the sum of the specific activity of the layered samples of the material dried, counts /min.

The equations have been derived without allowance for diffusion of the radioactive tracer and are valid when $u_f \geq u_{\mathrm{ph.ch.}}$, where $u_{\mathrm{ph.ch.}}$ is the physically and chemically bound moisture.

It has been established by calculation that in a layer of material 4 mm thick there is transferred to the ground, as a result of thermal flux up to 30%, and in a layer of 24 mm, only 3.5% of the total amount of moisture removed in drying.

Analysis of the graphs of distribution of radioactivity and of moisture content enabled us to establish that in layers of up to 6 mm, inclusive, evaporation occurred over the entire layer; there was no migration of moisture from the lower-lying layers to the upper zone. In the layers of over-all thickness 8–14 mm evaporation was observed over the entire thickness of the layer, but up to 70–80% of the moisture was removed in the form of vapor. The remainder of the moisture reached the maximum drying rate zone in liquid form and was evaporated there, and there was also migration to the moist base.

Thus, the radioactive tracer method allows a detailed examination of the mechanism of internal heat and mass transfer, which may be used to develop high-intensity methods of radiative-convective artificial and field drying of colloidal capillary-porous materials.

NOTATION

u is the moisture content, kg/kg; τ is the drying time, hr; i is the drying rate, kg/kg · hr; $i_{\max}$ is the maximum drying rate, kg/kg · hr; h is the distance from surface of material dried, mm; N_0 is the initial specific activity of material, counts/min; N_i is the specific activity of material after passage of a certain drying time, counts/min; p_d is the specific charge of material in terms of absolutely dry substance, kg/m^2; q' is the amount of moisture transferred from material dried to ground as a result of thermal moisture conduction, kg/m^2 · hr; Q is the fraction of total amount of moisture transferred to ground in time τ, %. Subscripts i and f denote initial and final moisture content.

REFERENCES

1. A. V. Luikov, Heat and Mass Transfer in Drying Processes [in Russian], Gosenergoizdat, 1956.
2. A. V. Luikov and Yu. A. Mikhailov, Theory of Heat and Mass Transfer [in Russian], Gosenergoizdat, 1963.
3. M. P. Volarovich, N. I. Gamayunov, and N. V. Churaev, Kolloidnyi zhurn., 22, no. 5, 1960.
4. N. I. Gamayunov, IFZh, no. 4, 1960.
5. M. P. Volarovich, P. N. Davidovskii, and N. I. Gamayunov, Kolloidnyi zhurn., 27, no. 2, 1965.
6. N. V. Churaev, IFZh, 5, no. 12, 1962; **6**, no. 2, 1963.
7. M. P. Volarovich, N. I. Gamayunov, A. P. Polyanicheva, and N. V. Churaev, Kolloidnyi zhurn., 27, no. 4, 1965; Torfyanaya promyshlennost, no. 3, 1965.

8. P. D. Lebedev, Infrared Drying [in Russian], Gosenergoizdat, 1955.
9. A. S. Ginzburg, Drying of Food Products [in Russian], Pishchepromizdat, 1960.
10. M. F. Kazanskii and P. P. Lutsik, IFZh, 3, no. 11, 1960.
11. N. V. Churaev, DAN SSSR, 148, no. 6, 1961.

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