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NON-STATIONARY TEMPERATURE AND MOISTURE CONTENT FIELDS OF POROUS BODIES IN THE CONVECTION HEAT TRANSFER PROCESS

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Abstract—This paper presents the results of the experimental investigation of the moist capillary-porous bodies heating by means of convective heat supply.

It is shown that the temperature and moisture content field reflect the nature of a moisture bond character with a capillary porous structure.

The more precise definition of a mechanism of heating and removal of moisture from porous bodies is given.

Résumé—Cet article présente les résultats de recherches expérimentales sur le chauffage, par convection, des corps à porosité capillaire humides.

Il est montré que la température et le champ hygrométrique sont des caractéristiques de la nature de l'humidité dans une structure à porosité capillaire.

Une définition très précise du mécanisme de chauffage et de séchage des corps poreux est donnée.

Zusammenfassung—Die Arbeit bringt die Ergebnisse einer Untersuchung von feuchten, porösen Körpern, die konvektiv erhitzt wurden.

Aus den Feldern der Temperatur und des Feuchtigkeitsgehaltes lässt sich der Zusammenhang zwischen Feuchtigkeit und poröser Struktur des Körpers ablesen.

Die Erwärmung und die Entfernung der Feuchtigkeit aus porösen Körpern wird näher erörtert.

Аннотация—В статье приведены результаты зкспериментельных исследований по нагреванию влажных капиллярно-пористых тел при помощи конвективного подвода тепла.

Показано, что поля температуры и влагосодержания отражают специфику связи влаги с капиллярно—норпстой структурой тела.

Уточняется механизм нагревания и удаления влаги из пористых тел.

THE elucidation of the physical properties of energy and mass transfer in moist dispersed bodies at non-stationary hydrothermal processes is of great practical and scientific interest. In view of this a number of works were carried out in the course of recent years in studying the internal heat and mass transfer mechanism.

Non-stationary hydrothermal fields present the most trustworthy notion about the energy and mass transfer mechanism. In order to obtain these fields it is necessary to know local moisture contents and local temperature during the whole process of drying. The gammascopy method possesses the greatest advantages over all the available ones which serve to determine moisture content inside a body. The methods worked out for the determination of moisture content fields in dispersed bodies [1] make it possible to measure layer moisture contents in a body without breaking both the integrity of a porous structure and the régime of thermal influence on a moist body.

We have carried out an experimental investigation of non-stationary hydrothermal fields in two dispersed bodies of different structural types. Quartz sand containing 96·2 per cent of quartz and cellulose in the form of non-ash filters were chosen as objects of investigation. Quartz sand is a typical specimen of macrocapillary porous bodies (the radius of pores between sand grains is of order 10^{-5} cm). The fractional separation of sand gave the possibility to model a monodispersed body in the first approximation. The moisture is retained in quartz sand mainly by the capillary forces according to the classification of bond character and of the state of absorbed moisture as suggested by Rebinder [2]. Cellulose is a typical specimen of a broad class of polycapillary bodies. The successive moisture evaporation of different bond character and of various states of moisture is going on during the drying process of cellulose, wetted to the complete moisture content.

The known law of exponential absorption of gamma rays by a substance is a physical basis of the gammascopy method. While a pencil of gamma rays is passing through one and the same dispersed body (wet or dry) then the dependence of the pencil intensities on a moisture content of a body is determined by the expression

$$J_w = J_{dr}\, e^{-\alpha d \rho_{dr} u} \tag{1}$$

where J_w and J_{dr} are the intensities of a gamma ray pencil, passed through a wet and a dry body, respectively; α is absorption coefficient, d is a body thickness; ρ_{dr} is density of a dry body and u is moisture content of a body.

The rated formula was obtained from equation (1) to determine the moisture content of an arbitrary layer of the material at any moment of time

$$u = \frac{1}{k} \ln \frac{J_{dr}}{J_w} \tag{2}$$

where the constant value $k = \alpha \rho_{dr} d$ is determined experimentally.

When the moisture content u is much smaller than the constant value k, which is characteristic for the macrocapillary porous bodies, the linear absorption law may be adopted [1];

$$J_w = J_{dr}(1 - ku) \tag{3}$$

and the moisture content is determined according to the formula

$$u = \frac{J_{dr} - J_w}{k J_{dr}}. \tag{4}$$

The investigation of non-stationary fields of moisture contents and temperatures in dispersed

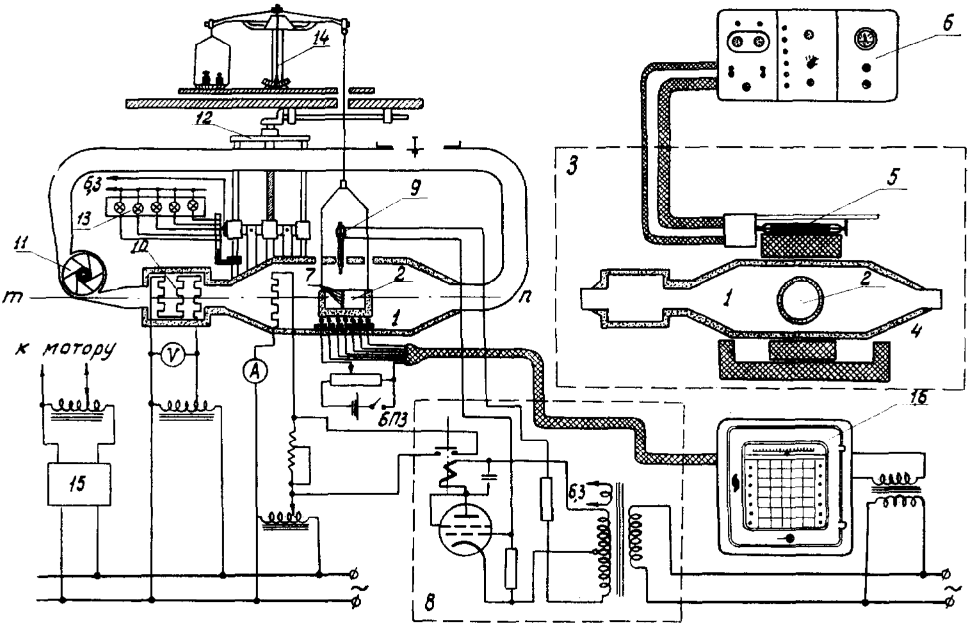

FIG. 1. A scheme of an experimental installation for the determination of moisture content and temperature fields in a body in the process of convective drying.

bodies was carried out on a laboratory installation, the scheme of which is given in Fig. 1.

Drying of a specimen of a porous body, placed in a cylindric beaker with heat and moisture insulated side walls and bottom, was carried out in a circulation drying chamber which allows the parameters of drying régime to remain constant.

The local values of temperatures inside the dried body were determined with the help of copper–constantan thermocouples, connected with a self-recording potentiometer. The curves of temperature change in five points of the body, located at distances of 5, 15, 25 and 45 mm from the open specimen surface were recorded. A temperature in the thermostat was simultaneously deciphered to keep the control. The sensitivity of record of all the temperature curves made up 0·08° per mm of the scale.

The average layer moisture contents of a specimen in each of five conditionally separated layers 10 mm thick were determined by means of counting the impulses, which correspond to the intensity of the gamma ray pencil, which had gone through the given layer.

The radioactive isotope Co^{60}, placed in a lead gun, served as a gamma ray source. The flat pencil of gamma rays passed through the given layer, was singled out with the help of a regulated slit in a lead screen.

After exposing the upper layer in the flow of gamma rays for 5 min, and after reading the intensity of the pencil passed through the layer by the micrometer, the dried specimen, together

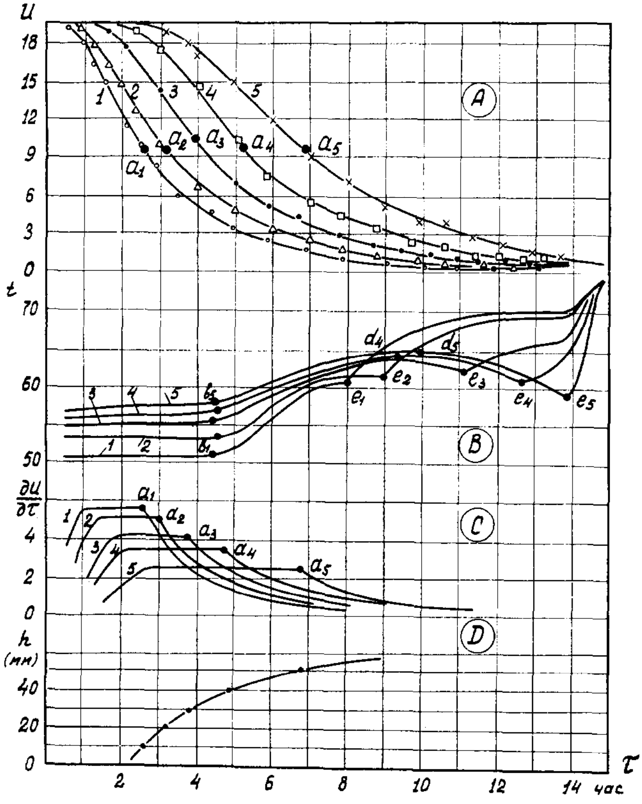

FIG. 2. Experimental curves of kinetics; A—of moisture content (in per cent relative to the weight of a dry body); B—of temperature, °C; C—of drying rate (per cent/hr); D—of deepening of evaporation zone, h is the distance in mm from the surface, τ is the time from the beginning of drying (hr) in quartz sand layers at the convective drying.

with the circulation installation, was moved upward for a distance of 10 mm, which corresponded to the disposition of the next layer in the X-rayed zone. Similar operations were carried out in succession for five layers in all. Then the following cycle of measurements of moisture contents in the same layers was begun.

The accurate fixing of a certain layer position relative to the slit at the repeated translucences of the specimen was brought about by the special signal mechanism.

The determination of the layer moisture contents was carried out to within 0·5 per cent in quartz sand and 2·5 per cent in cellulose relative to the dry weight of the substance.

The determination of the bulk loss of moisture

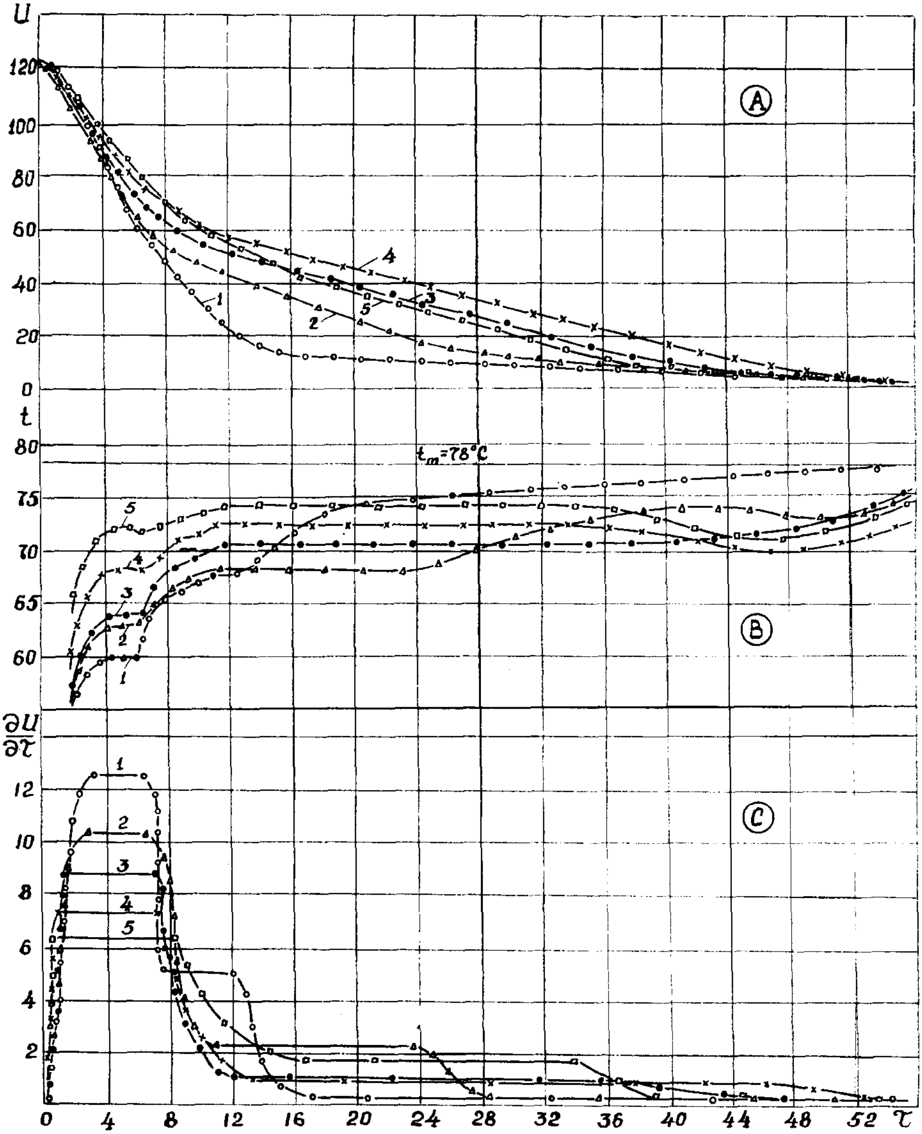

FIG. 3. Experimental curves of kinetics; A—of moisture content (in per cent relative to the weight of a dry body); B—of temperature, °C; C—of rate of drying (per cent/hr) in the cellulose layers at the convective drying.

by the material in the process of drying was carried out by means of periodical weighing of the beaker with the specimen on an arm balance.

The results of investigations are given in Figs. 2 and 3 in the form of curves of the average moisture content change of a layer (curves A), the temperatures, measured in the centre of every layer (curves B) and of the rate of layer drying (curves C). The numbers of the curves A, B and C are allotted according to the layer position relative to the open surface of the specimen.

It is seen from Fig. 2 A that on the curves of drying of each layer one may single out a linear part, limited by the position of the points *a*, which corresponds to the period of the constant drying of each layer. This is proved by the curves of the kinetic drying rate (Fig. 2 C).

Comparing the time which corresponds to the end of the period of the constant rate of drying in various layers of sand, we see that the process of drying from the very beginning is consecutively distributed from the surface into the body. In deeper layers the period of constant rate of drying begins and ends with some delay in comparison with the upper layer. The value of the constant rate of drying decreases with the increase of the layer depth.

Comparing moisture contents of various layers at the final moment of the constant rate of drying period in them, we may come to a conclusion that in all the layers this period ends at one and the same moisture content, which corresponds to the boundary of transition of capillary moisture of macropores from the capillary state into the funicular one (Table 1).

The linear parts, which end at points *b*, are singled out on the curves representing the temperature change in the layers depending on time (Fig. 2 B). From the comparison of the kinetics curves of the moisture content in every layer depending on temperature in it, it is seen that the end of periods of the constant rate of drying, in every layer, does not coincide in time with the end of periods of the linear temperature increase in the same layers.

The comparison of the moisture contents, corresponding to the critical points "*b*" on the curves of temperature kinetics for each layer (Table 1), with the moisture content of sand at

Table 1

Method of determination	The moisture content of the quartz sand		
	Funicular state	Pendular state	Maximum hygroscopy
Curves of the negative capillary pressure	8·4–10	3·4	—
Flowing down of moisture	—	3·7	—
Diffusion of the radioactive isotopes	—	—	0·3
Thermogram of drying	8·9	3·5	—

Number of a layer and its distance from the surface of a sample		Moisture content of sand layers corresponding to the points:			
		a Fig. 2 A	*b* Fig. 2 B	*d* Fig. 2 B	*e* Fig. 2 B
No. 1	10 mm	9·8	4·7	—	1·4
No. 2	20 mm	9·5	5·6	—	1·2
No. 3	30 mm	10·5	7·4	3·2	1·2
No. 4	40 mm	9·5	12·8	3·8	0·6
No. 5	50 mm	9·0	16·4	4·6	1·6

a special state of the capillary moisture shows that the end of the linear temperature increase in the layers occurs at various moisture contents, which do not coincide with the boundaries of special states of capillary moisture in the macropores of sand. Thus, the kinetics curves of the layer temperatures at the drying of thick specimens of a macroporous body do not reproduce the kinetics curves of drying according to the critical moisture contents, in contrast to the thermogram of thin specimen drying of macro- and microporous bodies [3].

Consequently, the possibility of the analysis of the kinetics of moisture contents field in a body by the kinetics of the temperature field in it has not sufficient ground for the thick specimens of macroporous bodies, thought it is proved for the case of thin ones [4].

The diagram of the kinetics of the evaporation zone deepening inside a body (Fig. 2 D) is built according to the critical points of the curves of the layer drying rates (points *a* Fig. 2 C).

Since the moisture contents at which the period of drying at the constant rate ends in every layer of sand, correspond to the boundaries of transition of the moisture contained in sand from the capillary into funicular state, then it follows from this fact, that the deepening of the evaporation zone depends on the change of special states of capillary moisture in the macropores of sand. At any moment of drying inside the sand thickness the moisture moves in the form of a vapour above the evaporation zone, and in the form of liquid and of a vapour under it.

The further heating of material occurs in all the layers of sand after the cessation of the linear temperature increase as is seen from Fig. 2 B. However at a certain stage of drying the heating of the material is followed by the marked temperature decrease in the layers, which is bound with the rise of the endothermic effect (points *e*).

The pointed effect of temperature decrease in the inner layers at the end of drying process is observed at various régimes of drying with the only difference that it is shown less strikingly at soft régimes. It was determined that the value of the endothermic effect increases with the increase of the thickness of the sand layer above the considered one.

It is possible to describe the physical nature of the above given effect on the basis of the combined analysis of the heat and mass transfer processes, going on between separate layers of wet sand, if we take into account the bond character of moisture and the solid phase of a porous body [2].

As one can see from Figs. 2 B and 4 the endothermic effect in every layer begins at 3–5 per cent of moisture content in the layers of sand after the cessation of the heating of layers (points *d*). Comparing the moisture content of various sand layers, which correspond to the beginning of the endothermic effect with the data given in Table 1, it should be noted that the beginning of the endothermic effect coincides with the moment when the moisture content reaches the phase of the removal of the sand moisture in the pendular state. The temperature drop reaches the greatest value at moisture content close to 1 per cent (points *e*).

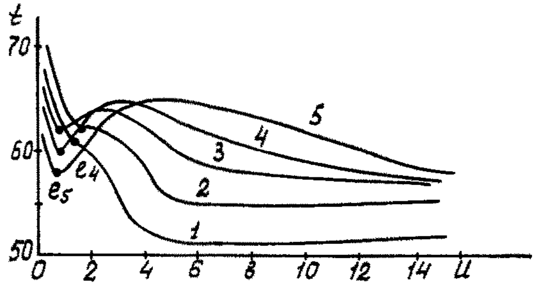

FIG. 4. The dependence of temperature, °C, in quartz sand layers and their moisture content (per cent) at the process of drying.

The removal of moisture of the pendular state is accompanied by the increase of the curvature of the concave meniscus, approaching the curvature of the microcapillaries concave meniscus (the radius of which is less than 10^{-5} cm). Some amount of heat is evolved during the period of microcapillary condensation of vapour as was shown by Isirikian [5]. Consequently, an additional amount of heat must be spent in order to remove the moisture from microcapillaries and from the surface of concave meniscuses of the equivalent curvature formed in places of contact of sand grains. If the heat losses for the evaporation of microcapillary moisture are not compensated by the heat inflow from the air, then the process of moisture removal will be going on at the expense of the heat of a body and will be accompanied by the temperature decrease in the considered layer.

Thus, one may point out from the analysis of the results of the macroporous body drying, that the removal process of moisture of the capillary state is going on in succession from one layer to another at different velocities as the moisture contents in various layers approach 4–5 per cent; and that the rates of drying in them are evened and the drying of moisture of the junction state is going on from all the layers approximately at one and the same rate.

The comparison of the kinetics layer curves of the drying of quartz sand (Fig. 2) and of cellulose (Fig. 3) is indicative of the considerable differences in the kinetics of the non-stationary hydrothermal fields in macroporous and colloidal polycapillary porous bodies.

In this connection we have carried out a differential analysis of the water-retaining properties of cellulose relative to the moisture of different bond character and of its state in pores. The analysis was fulfilled according to the method of thermograms of drying at the temperature, corresponding to the temperature of the experiments with the drying of cellulose. The result of the analysis of the water-retaining properties of cellulose is presented in Table 2. As can be seen from Fig. 3 the layer curves of drying (curves A) as well as the curves of the rate of drying (curves C) have two periods of the constant rate of drying. The moisture removes simultaneously out of all the layers in the first period of the constant rate of drying, limited by the position of the points *a*. The rates of drying of various layers end in this period at different time as the rate decreases with the increase of the layer depth.

The end of the first period of the rate of drying in all the layers occurs at 65 per cent of the average moisture content in them, which is close to the maximum moisture content of cellulose at the filling of its macropores with water, which corresponds to the removal of the osmotically connected moisture (Table 2).

The average moisture content in layers at critical points (*b*) at the beginning and (*c*) at the end of the second period of the constant rate of drying is 45 and 15 per cent, respectively, and is indicative of the fact that basically the removal of the microcapillary moisture is going on in every layer in the period of time between the critical points *b* and *c*. But beginning from the critical point *c* the removal of the adsorbed moisture is going on in the same layers.

The comparison of the curves of the temperature change with the corresponding curves of the rate of drying (Fig. 3, B and C) leads to the conclusion that the critical points on the temperature curves correspond to the end of each out of two periods of the constant rate of drying, and the drying in the periods of the constant rate is going on in each layer at the constant temperature in it. Such a conformity of the kinetics of the temperature fields and those of moisture contents inside cellulose is maintained almost towards the end of drying. As was mentioned above, the pointed conformity of fields of temperatures and moisture contents was not observed at drying of quartz sand under the same conditions.

However, the temperature decrease is observed as a result of the endothermic effect at the end of

Table 2. Moisture content of cellulose (per cent) at various forms of bound and at various states of absorbed moisture in capillaries

Results of analysis according to the drying thermograms					In critical points of curves of layer velocity kinetics (average meaning for all the layers)		
Monomolecular adsorption	Polymolecular adsorption	Moisture of micropores	Moisture of macropores	Osmotic moisture	*a*	*b*	*c*
5·9	12·3	35·0	70·0	256	65	45	15·4

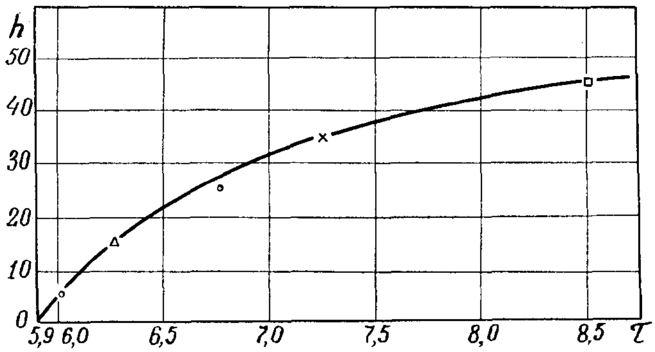

FIG. 5. The curve of the evaporation zone deepening into the cellulose, h is the distance (in mm) from surface, τ is time (hr) from the beginning of drying.

the drying of cellulose as well as at the drying of quartz sand, when their moisture contents are somewhat higher than the maximum quantity of the adsorbed moisture.

The deepening of the evaporation zone occurs at the drying of cellulose, not from the very beginning of the process, but after the removal of the osmotically bound water from a body. The kinetics curve of the evaporation zone deepening, built by critical points, corresponding to the moment of the end of the first period of the drying constant rate in every layer is given in Fig. 5. The comparison of the kinetics curves of the evaporation zone deepening in sand (Fig. 2 D) and in cellulose conforms in full with the conclusions of the drying theory [4, 6] about the parabolic low of deepening of the moisture evaporation zone.

The combined analysis of the curves of Fig. 3 with those of moisture contents and temperatures distributions inside cellulose (Fig. 6) makes it possible to picture the motion of moisture and heat in cellulose at drying.

Considerable temperature gradients arise in a body in its heating period; gradients of a temperature field ensure intensive moisture transfer in a dried body from inner layers to the body surface, from which the evaporation of the osmotic and partially of the capillary moisture of macropores is going on.

At the beginning of the first period of the constant rate of drying the removal of moisture throughout the whole thickness of a body is going on. The constant intensity of the moisture evaporation from the surface is kept towards the end of the period at the expense of dehydration, basically of the layers nearest to the upper one, which is confirmed by the minimum of

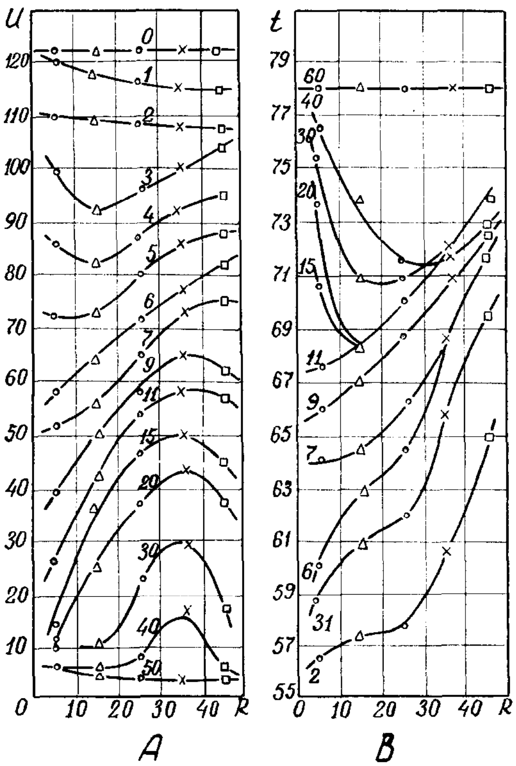

FIG. 6. The distribution of moisture content (in per cent, curve A) and temperature, °C (curve B) inside the cellulose at different time (hr) of drying.

moisture content in the second layer on curves 3–4 of Fig. 6 A. The upper layer is the most dehydrated one by the end of the first period of the constant intensity of drying, and this leads to the gradual change of distribution of moisture content in a body (the degeneration of curves 1–2 into 5–6).

The distribution of the moisture content in cellulose is close to the parabolic one (curve 6 of Fig. 6 A) at the very end of the period of constant rate of drying in the first layer. From this moment the evaporation zone deepens into the body, and the heated air penetrates into the pores of cellulose, as a result of which the rise of temperature is going on in the upper layer at first and then in the lower ones (Fig. 3 B).

As the first period of the constant rate of drying is at the end in the lowest layer, then the second period of the constant rate of drying begins in the upper layer, the moisture content of which is about 40 per cent and this corresponds approximately to the maximum quantity of moisture in microcapillaries. Thus the beginning of the removal of hygroscopic moisture from the upper layer is possible when the moisture of osmotic and macrocapillary state is removed from the whole body. This may be explained by the fact that the evaporation of the hygroscopic moisture is possible only at the relative vapour pressure in the air less than 1. As long as the evaporation of osmotic and macrocapillary moisture is going on in the material at the relative vapour pressure, which is equal to 1, the transit of vapour through the upper layer gives no possibility for the hygroscopic moisture evaporation out of it.

The second period of the constant rate of drying ends at different times but has equal moisture content of every layer, making up 15–20 per cent, and corresponds to the beginning of the adsorbed moisture removal. With the beginning of the adsorbed moisture removal the body temperature increases as a result of which the temperature gradient changes its sign and turns to be directed opposite to the gradient of moisture content field. This decreases to a greater extent the rates of adsorbed moisture removal from every layer, and the bulk rate of drying of the whole body as well.

Thus, our experimental investigations of non-stationary fields of moisture contents and temperatures indicate that the kinetics of the non-stationary hydrothermal fields is greatly determined by various forms of bounds, and of the state of the absorbed moisture in capillaries.

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