AN EXPERIMENTAL APPARATUS FOR INVESTIGATING THE KINETICS AND DYNAMICS OF CONVECTIVE DRYING WITH VARIABLE DRYING-AGENT PARAMETERS

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This article proposes a new method for simultaneous measurement of the moisture content and temperature of a material at a given point, utilizing a pulsed heat source.

1. In contrast to the apparatus previously developed for investigating the parameters of convective drying with variable drying-agent parameters [1], our new apparatus makes it possible to investigate the drying kinetics of damp materials with a more rapid rate of parameter change (temperature and relative humidity) for the drying agent and with a broader range of Reynolds-criterion values.

Figure 1 is a diagram of the apparatus.

Air from fan 1 goes into two pipes of the same cross section: that in one pipe goes to distribution unit 4, while that in the other goes to heater 6 and then to unit 4. The hot air is mixed with cold in the distribution unit and one portion goes to the drying chamber 7, while the remainder is discharged into the atmosphere. Gate valve 2 serves to regulate the amounts of hot and cold air entering the distribution unit. The amount of air is measured with diaphragms 5 and 5a and type TNZh differential manometers 9 and 9a. Screens 8 provide a uniform air flow speed over the pipe cross section. A type EPP-09 bridge 11 with an inductive sensor measures and records the weight of the specimen being dried. A type EPP-09 potentiometer 12 with an auxiliary mechanism measures, records, and regulates the air temperature in the drying

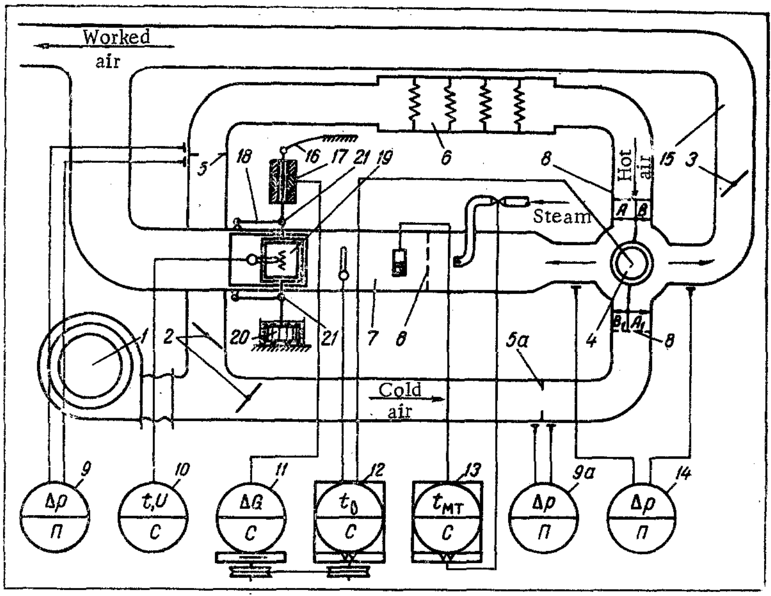

Fig. 1. Diagram of apparatus for studying dryingkinetics and dynamics.

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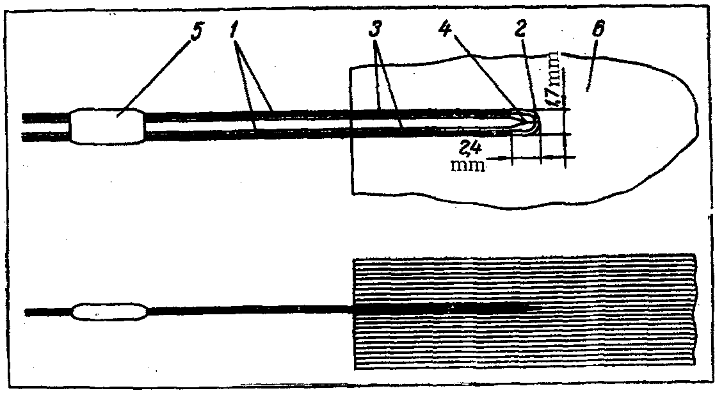

Fig. 2. Construction of temperature–moisture sensor. 1) Copper wire with diameter of 0.3 mm; 2) heater bow 0.07 mm thick; 3) thermocouple leads with diameter of 0.1 mm; 4) thermocouple junction; 5) sensor stop; 6) specimen.

chamber 7 by changing the position of gate valve 4. A type MS-1 bridge 13 measures and records the temperature of the wet thermometer in the chamber and feeds its signal to the servomechanism that drives the steam blower, thus regulating the steam delivery. The sensor is a wet thermoresistor. A type EPP-09 MZ potentiometer 10 with special sensors measures and records the temperature and moisture content of the material at six points simultaneously.

TABLE 1. Experimental and Calculated Results for Determination of Heated-Zone Thickness

U, %	$\delta \cdot 10^3$ m, experimental	$\delta \cdot 10^3$ m calculated
160	1,7	1,5
7	1,7	1,9

A necessary condition for modeling of the drying process is a constant gravimetric flow speed during the experiment. During experiments, the hydraulic resistances of the drying chamber and pipe 15 are equilibrated by gate valve 3 and measured by a type TNZh differential manometer 14. The air flow speeds beyond the gate valves are adjusted so as to be equal. All four pipes leading from the distributor 4 have the same cross section and are arrayed symmetrically. The gravimetric air flow speed under these conditions is independent of the position of gate valve 4 and constant during the experiment.

The gravimetric air flow speed before and after the heater is constant, so that

$$\gamma_c w_c = \gamma_h w_h = \text{const.} \tag{1}$$

The air mixture enters the drying chamber and the amounts of hot and cold air are proportional to the size of apertures A and B respectively (Fig. 1).

It follows from the symmetry condition that

$$A = A_1, \quad B = B_1. \tag{2}$$

The amount of air entering the chamber is therefore

$$G_c = \gamma_c w_c B_1 + \gamma_h w_h A. \tag{3}$$

Taking into account Eqs. (1) and (2),

$$G_c = \gamma_h w_h (A + B).$$

Since the sum (A + B) is constant and independent of the position of the gate valve, the gravimetric air flow speed in the chamber is constant.

The tracker system consisting of instruments 11 and 12 and gate valve 4, with a reversible motor, adjusts the air temperature in the drying chamber in accordance with the change in the weight of the specimen being dried, following a relationship derived from the equation for the heat and material balance of of convective drying process [1].

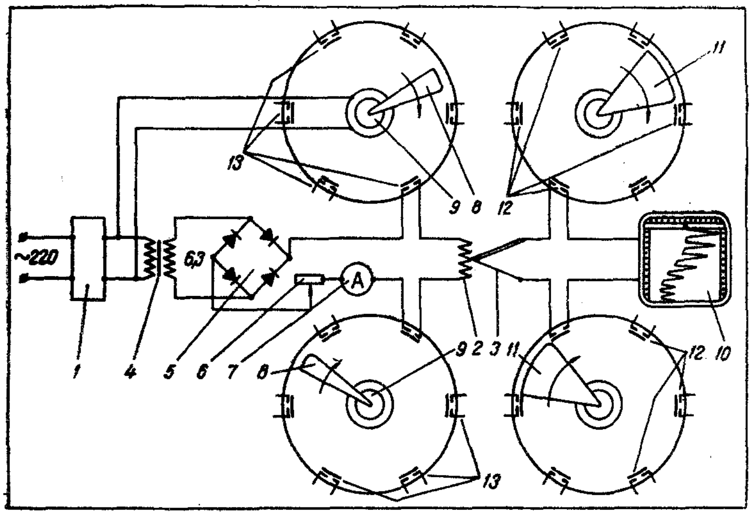

Fig. 3. Diagram of instruments and mechanisms for measuring and recording material temperature and moisture content.

The specimen is suspended from frame 19, which is connected to the core of induction coil 17 and to flat spring 16. When the specimen weight changes, the spring bends and the position of the core is altered, being determined to within 1.5% by bridge 11. The rotation of the shaft of rheochord 11 is transmitted through two identical pulleys and a steel cable to the rheochord shaft of potentiometer 12, on which is a two-position regulator. The pulses from the regulator go to the reversible motor 4, which moves the gate valve that regulates the amount of cold and hot air in the mixture entering the chamber.

Connecting rods 18, with needle bearing 21, keep the frame and specimen from rotating or moving in the horizontal direction and also prevent movement in the vertical direction. Float 20, which is completely immersed in liquid, bears part of the frame and specimen weight (a portion that remains constant during the experiment), thus relieving spring 16 and preventing large deformation and distortion of the readings.

The apparatus can be used to simulate a through-flow regime (the air temperature is reduced as the specimen weight decreases), a counterflow regime (the temperature is raised as the specimen weight decreases), and various combinations by switching the leads from coil 17 to bridge 11. The maximum deviation of the air temperature in the drying chamber from the present level was found to be 2.4%.

The heat insulation of the drying chamber, which has a cross section of 0.23 × 0.3 m, consists of five Duralumin screens, which permit a reduction in the thermal inertia of the chamber. The maximum possible rate of change in the air temperature is 330°K/min during heating and 280°K/min during cooling. Reynolds number of up to 45,000 can be obtained in the drying chamber,

2. In studying the drying of various materials, it is of great scientific and practical interest to make a joint analysis of the temperature and humidity fields, for which purpose the following conditions must be met:

1) the temperature and material moisture content must be measured almost simultaneously;

2) the sensors inserted in the specimen must not affect the course of the process;

3) the instruments and mechanisms must have the requisite rapid action;

4) the sensors must be mechanically strong, reliable, and durable;

5) the conversion of the instrument readings to temperatures and moisture contents must be a simple procedure.

Most publications dealing with problems of heat and moisture transfer in dispersed solids have been devoted to analytic descriptions of the processes that take place. Experimental investigations of hydrothermal fields have been conducted with methods that do not fully satisfy the above requirements. The

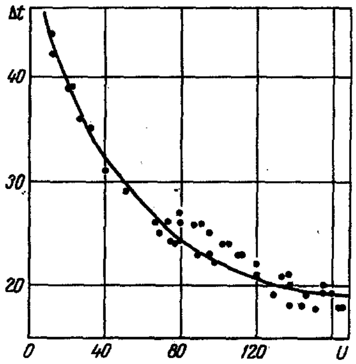

Fig. 4. Experimental (dots) and calculated (curve) functions Δt = f(U).

local moisture contents were determined by gravimetric analysis of samples taken from given points [2]. A method has been devised for determining the average layer-by-layer moisture content by gammascopy [14].

A survey of the literature on moisture measurements in dispersed solids [3-5, 10-13] led to the conclusion that the most suitable method for determining of local moisture content is that based on the dependence of the thermophysical characteristics of a material on its moisture content.

We attempted to devise a temperature–moisture sensor and a system of auxiliary instruments and mechanisms for experimental determination of the hydrothermal fields during drying of capillary-porous colloidal solids that would satisfy the above requirements.

Figure 2 shows a temperature–moisture sensor consisting of a flat Nichrome bow 2 soldered to copper leads 1 and a Nichrome–constantan thermocouple 3 coated with enamel insulation. The thermocouple junction 4 is connected to bow 2 with a piece of Nichrome wire. The entire sensor is cemented with heat and moisture resistant cement and is a flat monolithic rod. The lead exits are sheathed in Teflon film, which produces the protuberance 5; the latter serves as a stop.

The efficiency of sensor operation was checked by measuring the moisture content of filter paper. Sensors were inserted between the layers of a stack of filter paper 6, as shown in Fig. 2. In order to ensure good contact between the sensor and paper, the stack was compressed from above with a uniformly distributed weight that created a pressure of 1000 N/m^2.

Figure 3 is a diagram of the instruments and mechanisms used to measure and record temperature and moisture content at six points simultaneously (with six temperature–moisture sensors). The sensor heating element 2 is supplied with direct current from rectifier 5, which is supplied with 6 V current through stabilizer 1 and transformer 4. The current in the heating element is regulated with rheostat 6 and measured with ammeter 7. The emf from thermocouple 3 is measured and recorded by potentiometer 10, which has a scale reading from 293 to 423°K. Successive activation of the heaters 2 of the sensors is affected with six pairs of normally open contacts 13, which are closed by cam 8, which is mounted on the shaft of a DR-1 servomechanism 9 and makes one rotation every 67 sec. Cam 8 provides a pulse duration of 2-2.2 sec. Mounted on the same shaft as cam 8 is cam 11, which closes normally open contacts 12 to connect the thermocouple of the appropriate sensor to potentiometer 10. Cam 11 provides for simultaneous opening of one pair of contact and closing of another, connecting in the thermocouple of the next sensor. Cam 8 is shifted with respect to cam 11 in such fashion that the thermocouple is switched in first and a current pulse is then applied to the heating element of the corresponding sensor; the current is then discontinued while the thermocouple remains hooked into the circuit for a short time.

Potentiometer 10 (Fig. 3) records a curve whose left-hand end characterizes the material temperature before application of the current pulse, while the amplitude of the temperature peaks characterizes the moisture content in the material adjoining the heating element, a region of very small size (up to 3 mm in diameter).

Figure 4 shows the temperature-peak amplitude as a function of moisture content, as determined experimentally.

Calibration was conducted with a cylindrical specimen assembled from individual round sheets of filter paper (type F-1, GOST 7246-54). The specimen moisture content was determined to within 0.5% (with respect to dry weight) by the gravimetric method. In order to avoid changes in moisture content during measurement of the temperature peak, the specimen was placed in a special hermetically sealed beaker.

The experiments conducted to check the influence of a temperature sensor on the measurement stability during prolonged operation showed that the temperature peaks remained constant when the specimen moisture content was unchanged. The material temperature in the measurement region dropped to the initial level before the next thermal pulse was applied, which indicates complete dissipation of the heat liberated through the surrounding material during the period between pulses.

The width and length of the pulsed-heat-source region were commensurable and it approximated in shape to a round plate with a radius $\rho = 9 \cdot 10^{-4}$ m (see Fig. 2).

The temperature at the center of a pulsed source of circular shape can be calculated from the formula [6, 9]

$$\Delta t = 2q \frac{\sqrt{a\tau_p}}{\lambda} \left(\sqrt{\frac{1}{\pi}} - i \operatorname{erfc} \frac{\rho}{2\sqrt{a\tau_p}} \right). \tag{3}$$

The applicability of this formula to the sensor under investigation was determined from the graph given by Dul'nev and Semyashkin [7].

The depth of the zone in which the material was heated to 5% of the temperature at the center of the heat source at the end of a pulse was determined experimentally with a battery of thermocouples.

The measurement results were compared with those calculated from the formula [7]

$$\delta = 2{,}36 \sqrt{a\tau_p} \tag{4}$$

and are given in Table 1, from which it can be seen that the depth of the zone in which the filter paper was heated did not exceed 2 mm for moisture contents of from 7 to 160%.

The temperature-peak amplitudes were calculated from Eq. (3). The specific power of the heating element was determined experimentally from the current and voltage. The thermophysical properties of the material in the heated zone were assumed to be those for the average zone temperature [8]. The maximum deviation of the experimental temperature differences from the calculated differences was 12%.

NOTATION

γ_c, γ_h	specific gravities of cold and hot air respectively;
Δt	temperature difference;
q	heater power per unit surface area;
a	thermal diffusivity of damp material;
τ_p	pulse duration;
λ	thermal conductivity of damp material;
ρ	radius (arbitrary) of heating element;
δ	thickness of damp material;
U	moisture content of material, % of dry weight;
w_c, w_h	linear flow speeds of cold and hot air respectively.

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