# AN EXPERIMENTAL METHOD OF STUDYING THE KINETICS OF CONVECTION DRYING IN THE CASE OF VARIABLE PARAMETERS FOR THE DRYING AGENT

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We propose a new experimental method of studying the kinetics of convection drying in connection with solid materials in a variable temperature regime. A theoretical basis is provided for the proposed method.

Use of the widely known approximation methods involved in an analytical determination of the duration of drying [1, 2] presupposes the availability of experimental data to permit calculation of the kinetic coefficients. Such experimental coefficients for a specific material are usually obtained in laboratory installations in which a moist material is dried and the parameters of the drying agent are constant throughout the entire procedure.

However, in industrial convection dryers the process of drying a moist material proceeds primarily under variable conditions (temperature, the moisture content of the drying agents). This leads to a need to experiment on an industrial scale with experimental drying installations, or with models that are in industrial use. Consequently, the development of effective drying installations is made more complicated and more expensive.

Because of this lack of reliable kinetic data, industrial drying installations, in a number of cases, do not operate in an optimum regime, and their output is at a low level.

Progress in drying techniques depends to a considerable extent on improvements in the experimental research related to the kinetics of drying.

A laboratory procedure which would enable us to model the drying conditions in industrial drying installations would be extremely useful, particularly if it would enable us to derive more reliable results with respect to the kinetics of drying, data that are needed in the design of drying installations and in achieving optimum operating regimes for those installations that are on line.

A new method of studying the kinetics of convection drying has recently come into use; it involves a change in the drying potential that is uniform with respect to time [3, 4]. The drawback of this method is the arbitrary manner in which the rate of change in the drying potential is selected.

We have made an attempt to develop an experimental method for laboratory studies of the kinetics of convection drying in the case of variable drying-agent parameters, and this method should make it possible to simulate the temperature conditions of industrial drying installations.

The development of such a procedure required the solution of two primary problems: 1) the development of a drying chamber exhibiting very low thermal inertia for the change in the temperature of the drying agent at the required speed; 2) the development of a device to control the temperature of the drying agent and of its relative humidity, in relation to the average moisture content of the material being dried.

The first problem was solved in the following manner. Thin metallic foil is used to construct the drying chamber, and a system of screens – also made of this foil – serves as the thermal insulation of the chamber.

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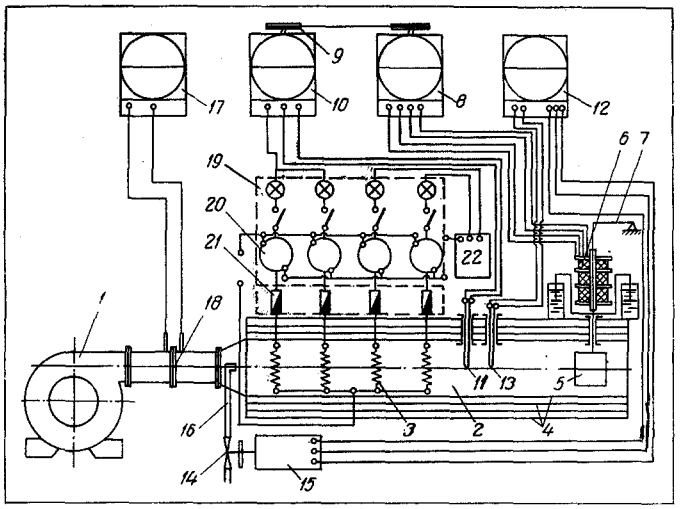


Fig. 1. Diagram of the installation for the simulation of the temperature regime in the convection drying process: 1) fan; 2) drying chamber; 3) air heater; 4) screens; 5) specimen of material being dried; 6) weight sensor; 7) elastic element; 8) potentiometer; 9) pulley; 10) potentiometer; 11) thermocouple; 12) potentiometer; 13) thermocouple; 14) regulating valve; 15) servo mechanism; 16) vapor tube; 17) flow meter; 18) diaphragm; 19) indicator light panel; 20) relay; 21) fuse block; 22) time relay with motor.

The second problem is solved by means of conventional electronic potentiometers. Two electronic potentiometers are used to control the temperature of the drying agent. The first potentiometer measures and records the loss in specimen weight, and on the basis of a specified mathematical relationship alters the position of the temperature control of the second potentiometer, which measures and regulates the temperature of the drying agent in front of the specimen being dried, in accordance with a specified mathematical relationship. The change in the relative moisture content of the drying agent is achieved by means of a follow-up system consisting of an electronic potentiometer, a wet bulb thermocouple, and a valve to regulate the flow of the water vapor to the drying chamber.

The equation for the mathematical relationship between the average temperature of the drying agent and the average moisture content of the material being dried can be derived from the familiar heat-balance equation for convection drying, i.e.,

$$J = J_1 + \frac{\Delta}{l}. \tag{1}$$

In most cases, in studying the kinetics of drying, we find that the design of some forthcoming drying installation, its dimensions, the form of the transport devices, and the optimum regime parameters for the drying agent are not known and the determination of the heat loss on the heating of the transport devices, on the heating of the material to be dried, and the heat loss to the ambient medium presents considerable difficulty. It is therefore rational to assume that the drying process takes place under conditions that are close to the adiabatic, i.e., when $\Delta = 0$.

Expanding Eq. (1) for $\Delta = 0$ and solving it for the temperature of the drying agent, we find

$$T = \frac{(c_{dg} + x_i c_v) T_i - r_0 (x - x_i)}{c_{dg} + x c_v}. \tag{2}$$

Relating (2) to the solution for the material balance of the drying chamber, we find

$$\frac{T_i - T}{T_i - T_f} = \frac{B(1 + c_v B)\Theta}{B(1 + c_v \Theta)}, \tag{3}$$

where B is a coefficient which characterizes the drying regime and is determined from the formula

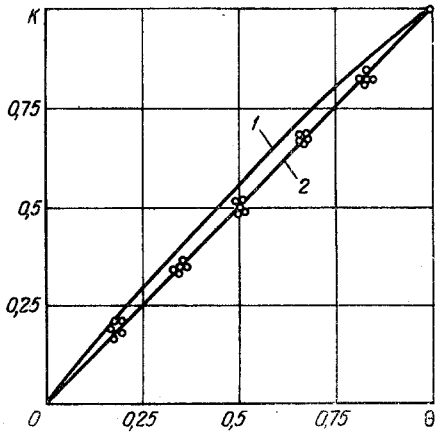

Fig. 2. Relative change K in the temperature of the drying agent as a function of the relative change Θ in the moisture content of the material: 1) according to formula (7), $x_f - x_i = 0.1$ kg/kg; 2) according to formula (8).

$$B = \frac{x_f - x_i}{c_{cr} + x_i c_n};$$

Θ is the relative loss in the moisture content of the material being dried, and this is determined from the following formulas:

for direct flow

$$\Theta = \frac{u_i - u}{u_i - u_f},$$

for counterflow

$$\Theta = \frac{u - u_f}{u_i - u_f}.$$

Formula (3) establishes the relationship between the average temperature of the drying agent and the average moisture content of the material being dried, for some arbitrary cross section of the drying unit.

Let us examine certain possible variants of the drying process.

1. B = 0, i.e., $x_f = x_i$ (according to formula (4)) the drying is performed at constant parameters for the drying agent, and the air flow rate per 1 kg of evaporated moisture is infinite. It follows from formula (3) that $T = T_i$ and it is independent of the moisture content of the material. This drying regime is found in laboratory installations at constant parameters for the drying agent.

2. $B \neq 0$. It is convenient in this case to put formula (3) into the form

$$T = \frac{(1 + c_v B)\Theta}{1 + c_v B\Theta}.$$

Calculations on the basis of (7) for various drying regimes have demonstrated that with a deviation of up to 10% the formula can be simplified:

$$\frac{T_i - T}{T_i - T_f} = K = \Theta.$$

If the increase in the moisture content of the drying agent does not exceed 0.08 kg of moisture per kg of dry gas, in the practice of drying techniques we most frequently find that the accuracy of (8) is raised.

We use formula (8) to simulate the temperature regime of the drying procedure in a laboratory installation, a diagram of which is shown in Fig. 1.

The installation consists of fan 1, drying chamber 2 with a cross section of 150 × 150 mm, made of steel foil 0.1 mm in thickness, electric air heater 3, and various metering and regulating devices. The system of screens 4, also made of steel foil 0.1 mm in thickness, and separated from each other by 15 mm, provides for a reduction in the temperature of the drying agent at a rate of 80-100°K/min. The specimen 5 of the material being dried is suspended from an electric-balance sensor which consists of an induction pickup 6, an elastic element 7, and an electronic potentiometer 8, which continuously records the loss of weight in the specimen being dried. The shaft of the potentiometer rheostat 8 is kinematically connected to the temperature regulator of the electronic potentiometer 10, designed to record and regulate the temperature of the drying agent. The kinematic coupling is achieved by means of two pulleys 9 of identical diameter and an inelastic thread which holds them together. One of the pulleys is seated on the shaft of the rheochord of the potentiometer used to record the loss of weight in the specimen being dried, while the other pulley is seated on the shaft of the device used to control the temperature of the drying agent. The pickup of potentiometer 10 is a Chromel–Copel thermocouple 11, situated within the drying chamber ahead of the specimen being dried. Potentiometers 8 and 10 form a follow-up system which reproduces the mathematical relationship between the average temperature of the medium and the average moisture content of the material in accordance with formula (8). The temperature is regulated by connecting or disconnecting the coils of the air heater. The efficiency of operation for the follow-up system is shown in Fig. 2, where the straight line plotted in accordance with (8) shows the points derived from direct and counterflow drying regimes. The deviation of the experimental data from the theoretical does not exceed ±3°K.

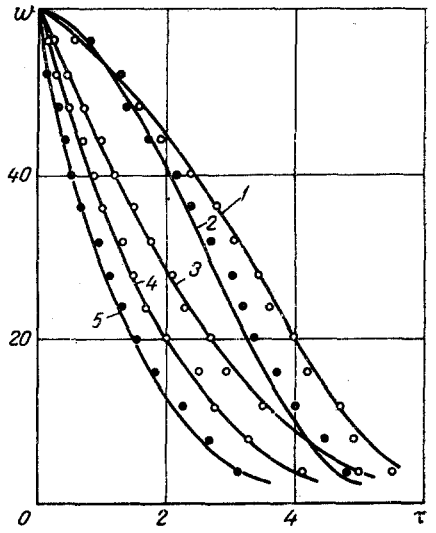


Fig. 3. Curves showing the drying of asbestos in variable regimes (the solid lines denote experiment, and the points denote theory) for the following parameters of the drying agent: 1) $T_i$ = 460°K, $T_f$ = 370°K, $T_{wb}$ = 321°K, v = 1.5 m/sec; 2) $T_i$ = 505°K, $T_f$ = 366°K, $T_{wb}$ = 325°K, v = 1.5 m/sec; 3) $T_i$ = 471°K, $T_f$ = 381°K, $T_{wb}$ = 321°K, v = 1.5 m/sec; 4) $T_i$ = 523°K, $T_f$ = 393°K, $T_{wb}$ = 325°K, v = 1.5 m/sec; 5) $T_i$ = 563°K, $T_f$ = 398°K, $T_{wb}$ = 323°K, v = 1.5 m/sec; 1 and 2) counterflow; 3, 4, and 5) direct flow.

The change in the relative moisture content of the drying agent is achieved by another follow-up system consisting of potentiometer 12, wet-bulb thermocouple 13, and regulating valve 14, with the servomechanism 15, installed in the water-vapor feed line 16. In carrying out the drying process we find that the temperature of the wet-bulb thermometer remains virtually constant along the constant heat-content line. The required change in the relative moisture content in the drying chamber therefore reduces to the maintenance of a constant value for the readings of the wet-bulb thermocouple in the chosen drying regime. The regulation system provides for the maintenance of the temperature of the wet-bulb thermocouple to an accuracy of ±1.5°K.

The weight flow rate for the dry air in the cross section of the drying chamber is measured by means of flow meter 17 and diaphragm 18, installed ahead of the air heater. Throughout the entire drying process, the weight flow rate for the air is kept constant.

The installation makes it possible to reproduce the variable regime of direct-flow and counterflow single-zone drying units. With a slight structural change in the regulator system, the installation can be used to model the variable regime of multizone drying units in which the parameters of the drying agent may vary arbitrarily in each zone. It is also possible to use such a unit for reverse drying regimes.

To verify the accuracy of this newly developed method, we studied the kinetics of the drying of asbestos sheet 1.5 mm in thickness at constant and at variable parameters for the drying agent. The choice of this material is based on the effort to eliminate the effect of shrinkage, as well as to enable us to use a given specimen over again, for drying in other regimes. Parallel tests showed that the repeated drying of a given specimen has no effect on the kinetics of the process. Moreover, in a thin material the gradient for temperature and moisture content are at a minimum through the thickness and the parameters of the drying agent will exert decisive influence on the duration of the drying procedure.

The asbestos test specimen, made up of four plates with dimensions of 50 × 75 mm, positioned parallel to each other and separated by a distance of 30 mm, were suspended from a flame connected to the balance sensing element. The plates were streamlined across the surface over a length of 50 mm. This suspension method reduced the effect of radiative heat exchange with the chamber walls. The initial moisture content of the specimens was 60-65% of the dry weight. The automatic balance permitted weighing operations correct to 0.1 g.

In the first series of experiments the specimen was dried in various constant regimes. The purpose of the tests was to determine the theoretical relationships for the drying rate in the first and second period. The air temperature in the drying chamber varied from 373 to 500°K. The linear air speed, referred to a temperature of 293°K, amounted to 1.5 m/sec.

The experimental drying rate in the first period, in the constant regimes, was compared with the theoretical drying rate, derived from the formula

$$\left(\frac{dw}{d\tau}\right)_{\text{I}} = \frac{\alpha}{r}(T - T_{wb})\frac{F}{G_d} \cdot 100. \tag{9}$$

The coefficient of convection heat transfer was determined [5] from the criterial equation

$$\text{Nu} = 0.8\,\text{Re}^{0.5}. \tag{10}$$

In calculating the Nusselt heat-transfer number and the hydrodynamic Reynolds number, we took the specimen length in the streamlining direction as the decisive dimension, and for the decisive temperature we chose the temperature of the oncoming stream of the drying agent. The drying rate in the first period, calculated from (9), differed from the experimental value by ±8%.

To determine the drying rate in the second period, we used the relationship from [4] for the reference drying rate

$$\Psi = \frac{dw}{d\tau} \Big/ \left(\frac{dw}{d\tau}\right)_{\text{I}} = \left(\frac{w}{w_{cr}}\right)^n, \tag{11}$$

where n is an experimental coefficient determined from the drying curves (for asbestos sheet n = 0.55).

We were unable to determine the effect of the drying regime on the critical moisture content for the entire series of experiments. For thin sheets of asbestos the values of the critical moisture content varied from 32 to 34% of the dry weight.

Formulas (9) and (10) permit us to calculate the drying rate for any constant parameters of the drying agent, when the asbestos sheet is 1.5 mm thick.

In the second series of experiments, the specimens were dried in various direct-flow and counterflow regimes. To determine the effect of time variations in the parameters of the drying agent on the duration of the drying process, we compared the experimental drying curves with the theoretical. The comparison was carried out in the following manner.

1. For the points on the experimental drying curve (variable regime), corresponding to a change of 4% in the moisture content of the specimen, we used formula (8) to calculate the temperature of the drying agent.

2. For the calculated temperature of the drying agent we determined the drying rate in the first period from (9) and (10).

3. The drying rate at the theoretical points was determined from the formula

$$\left(\frac{dw}{d\tau}\right)_p = \left(\frac{dw}{d\tau}\right)_{\text{I}} \Psi, \tag{12}$$

where $(dw/d\tau)_p$ is the drying rate at the theoretical point, %/h.

When the specimen moisture content $w > w_{cr}$, it was assumed that $\psi = 1$, while for $w < w_{cr}$ the drying rate was calculated from (11).

4. We plotted the theoretical curve for the drying rate.

5. The method of graphical integration was used to determine the duration of the drying process from the initial moisture content to the moisture content that was specified.

6. We compared the experimental and theoretical drying curves.

The results from the calculations of the drying curves and from the experiment are shown in Fig. 3. The maximum deviation between the theoretical quantities and the experimental does not exceed ±12%.

The identity of the results confirms the satisfactory functioning of all automatic-regulation systems and the reliability of the results obtained for drying in a variable regime in the installation described here.

The proposed method of studying the kinetics of drying enables us not only to reduce the number of tests, but given appropriate dimensions for the drying chamber, we can achieve results which can serve as the basis for the design of the drying installation.

## NOTATION

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| $J$ and $J_1$ | are the specific enthalpies of the moist gas at some arbitrary cross section of the drying installation and at the inlet, J/kg of dry gas; |
| $\Delta$ | are the specific heat losses in the drying installation, J/kg of the evaporated moisture; |
| $l$ | is the flow rate of dry gas to achieve the evaporation of 1 kg of water from the material, kg of dry gas per kg of evaporated moisture; |
| $T_i$, $T_f$, and $T$ | are, respectively, the initial, the final, and the instantaneous temperature of the drying agent, °K; |
| $c_{dg}$ and $c_v$ | are the specific heat capacities of the dry gas and the water vapor, J/(kg·deg); |
| $r_0$ | is the heat of vapor formation for water at 273°K and a pressure of 760 mm Hg, J/kg; |
| $u_i$, $u_f$, and $u$ | are, respectively, the initial, the final, and the instantaneous moisture content of the material, kg of moisture per kg of dry material; |
| $Nu = \alpha l_0/\lambda$ | is the Nusselt number; |
| $\alpha$ | is the coefficient of convection heat transfer, W/(m$^2$·deg); |
| $l_0$ | is the characteristic dimension, m; |
| $\lambda$ | is the coefficient of thermal conductivity, W/(m·deg); |
| $Re = vl_0\gamma/\mu g$ | is the Reynolds number; |
| $v$ | is the velocity of motion for the drying agent, m/sec; |
| $\gamma$ | is the specific weight of the drying agent, N/m$^3$; |
| $\mu$ | is the coefficient of dynamic viscosity for the moist gas, N·sec/m$^2$; |
| $r$ | is the heat of vapor formation for the water, J/kg; |
| $T_{wb}$ | is the temperature of the wet-bulb thermometer, °K; |
| $G_d/F$ | is the weight of the specimen, with an evaporation surface of 1 m$^2$, N/m$^2$; |
| $w_i$, $w_{cr}$, and $w$ | are, respectively, the initial, the critical, and the instantaneous moisture content of the material, % of dry weight; |
| $(dw/d\tau)_I$ and $dw/d\tau$ | are the drying rate in the first and second periods, %/min; |
| $\tau$ | is the duration of the drying process, min; |
| $\psi$ | is the reduced drying rate; |
| $\delta$ | is the thickness of the asbestos, mm; |
| $x_i$, $x_f$, and $x$ | are, respectively, the initial, the final, and the instantaneous moisture content of the drying agent, in kg of moisture per kg of dry gas. |

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