KINETICS OF THE PROCESS OF ELECTROCONTACT DRYING OF MOIST MATERIALS

A. S. Zelepuga, G. L. Sirotkin,
and V. S. Karpenko

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The method and results are presented for an experimental and analytical study of the kinetics of the process of drying of moist materials impregnated with an electrolyte by the passage through them of an electric current of commercial frequency.

The relatively new and promising means of thermal treatment of various products and materials containing electrolyte by passing through them currents of commercial frequency (electrocontact treatment) [1-7] has lately been undergoing intensive development.

The attempts of several authors to generalize the results of research on electrocontact thermal treatment are known from the literature. For example, the authors of [1, 2] on the basis of thermal balance obtained a dependence for the determination of the duration of the electrocontact treatment. In our view it is not fully legitimate since the heat losses to vaporization and exchange with the external medium are not allowed for in it.

The process of electrocontact thermal treatment of the above materials proceeds in time in the following way. Upon the supply of an alternating current of 50 Hz frequency to the electrodes in contact with the material it is first heated with an intensity which increases with increasing temperature up to 85°C at atmospheric pressure. Then the evaporation of moisture from the material begins with a simultaneous smooth increase in its temperature to ~105-115°C and the subsequent drying takes place at a constant temperature. Here the layers of material near the electrodes dry more intensely than the central layers and the moisture gradient directed from the center to the periphery increases. However, for sheet materials in a number of cases the moisture gradient over the cross section of the material is slight and can be neglected.

As seen from the above, mathematical relationships for the description of the process of electrocontact thermal treatment are absent at present.

We have attempted to fill in this gap somewhat on the basis of a solution of the thermal balance equation in differential form.

The fundamental balance equation [8] in application to electrocontact drying is written in the form

$$\frac{V^2}{R}\,d\tau = G_0\,(c_0 + c_{\text{liq}}\bar{u})\,d\theta - G_0 r\,d\bar{u}. \tag{1}$$

Along with the well-known assumptions of [8, 9], here it is assumed that the material has a purely active resistance R, i.e., $\cos\varphi \cong 1$, which actually occurs in practice and is confirmed in [1, 2].

Then the total resistance of the material can be determined from the equation

$$R = \frac{1}{\varkappa_0}\,\frac{l}{S}. \tag{2}$$

By substituting (2) into (1) and performing the appropriate transformations we obtain

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$$\frac{V^2 \varkappa S}{rl}\, d\tau = G_0 (\mathrm{Rb} + 1)\, d\bar{u}. \tag{3}$$

We define

$$A = \frac{V^2 S}{rlG_0} \tag{4}$$

and obtain (3) in the form

$$\frac{d\bar{u}}{d\tau} = A \frac{\varkappa}{\mathrm{Rb} + 1}\,. \tag{5}$$

The dependence between the Rebinder number Rb and the moisture content of the material during electrocontact drying in the initial period can be described in the following way [8]:

$$\mathrm{Rb} = B(\exp n\bar{u}), \tag{6}$$

where $n > 0$; B is an empirical coefficient which depends on the operating parameters of the process.

During the period of decreasing drying rate the Rebinder number, as was established on the basis of preliminary experiments, does not change and has a constant value.

The specific electrical conductivity of the material in the process of electrocontact drying first increases with an increase in temperature from 85°C up to ~102°C, reaching a maximum, and then decreases.

On the basis of an analysis of curves of the time variation in current during the heating and drying of fibrolite plates by currents of commercial frequency and different voltages [2] and of preliminary experiments which we conducted it was established that the specific electrical conductivity of a material varies with a change in its moisture content in accordance with the equation

$$\varkappa = \frac{10^{-1}}{a\bar{u}^2 - b\bar{u} + c}\,. \tag{7}$$

The substitution of Eq. (7) into (5) leads to the equation

$$\frac{d\bar{u}}{d\tau} = \frac{A \cdot 10^{-1}}{(a\bar{u}^2 - b\bar{u} + c)\{[\exp n\bar{u}] + 1\}}\,. \tag{8}$$

Let us integrate Eq. (8) with the initial conditions $\bar{u}|_{\tau=\tau_0} = \bar{u}_i$:

$$\begin{aligned}\tau = \frac{10}{A}\Big\{Ba\Big[\exp(n\bar{u})\Big(\frac{\bar{u}^2}{n} - \frac{2\bar{u}}{n^2} + \frac{2}{n^3}\Big) - \exp(n\bar{u}_i)\Big(\frac{\bar{u}_i^2}{n} - \frac{2\bar{u}_i}{n^2} + \\ + \frac{2}{n^3}\Big)\Big] - Bb\Big[\frac{\exp(n\bar{u})}{n^2}(n\bar{u} - 1) - \frac{\exp(n\bar{u}_i)}{n^2}(n\bar{u}_i - 1)\Big] + \\ + c\frac{B}{n}[\exp(n\bar{u}) - \exp(n\bar{u}_i)] + a \cdot \frac{1}{3}(\bar{u}^3 - \bar{u}_i^3) - b \cdot \frac{1}{2}(\bar{u}^2 - \bar{u}_i^2) + c(\bar{u} - \bar{u}_i)\Big\},\end{aligned} \tag{9}$$

In a number of cases the temperature variation of the material during the drying process is slight and the fraction of heat going into the heating of the material is small in the total thermal balance of the process. In this case Rb = 0 and with allowance for (7) Eq. (5) takes the form

$$\frac{d\bar{u}}{d\tau} = A \frac{10^{-1}}{a\bar{u}^2 - b\bar{u} + c}\,. \tag{10}$$

The solution of this equation with the previous initial conditions is written in the following way:

$$A \cdot 10^{-1}\tau = a \int_{\bar{u}_i}^{\bar{u}} \bar{u}^2 d\bar{u} - b \int_{\bar{u}_i}^{\bar{u}} \bar{u}\, d\bar{u} + c \int_{\bar{u}_i}^{\bar{u}} d\bar{u}$$

and after several transformations

$$\tau = \frac{10}{A}\Big[\frac{a}{3}(\bar{u}^3 - \bar{u}_i^3) - \frac{b}{2}(\bar{u}^2 - \bar{u}_i^2) + c(\bar{u} - \bar{u}_i)\Big]\,. \tag{11}$$

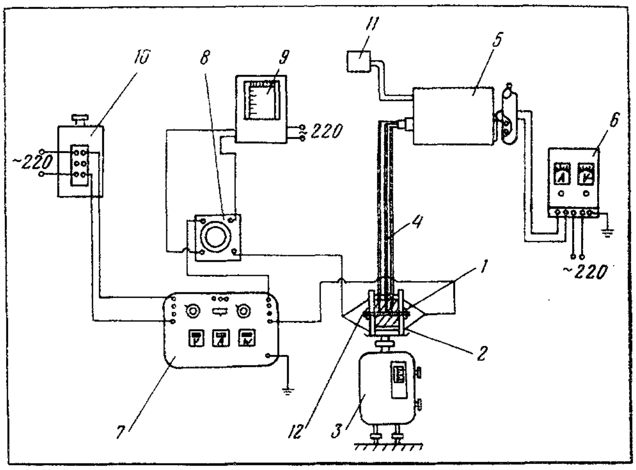

Fig. 1. Schematic diagram of experimental apparatus for the study of the process of electrocontact drying.

The experimental study of the kinetics of drying and the establishment of the form of the mathematical dependence of the specific electrical conductivity of a moist material were carried out on the laboratory apparatus shown in Fig. 1.

The apparatus consists of two lattice electrodes 2 between which is placed the specimen of test material 1, a clamping device 12 for the regulation of the tightness of fit of the electrodes to the material, an analytical balance 3 of the VTK-500 type to monitor the decrease in specimen weight during the drying process, Chromel – Copel thermocouples 4 operating in an assembly with a recording oscillograph 5 of type N-700, an oscillograph power supply 6 (VSA-6a rectifier), a recording assembly 7 of type K-50 for visual monitoring of the electrical parameters of the process through the current, voltage, and power, an N-390 recording ammeter 9 in an assembly with a current transformer 8 of brand UTT-5, an autotransformer 10 for the regulation of the applied voltage, and a nonstandard time marker 11.

Felt with a thickness of 0.018 m, which is a capillary-porous material with relatively uniform porosity, was chosen as the subject of the study. The specimen was moistened with an aqueous solution of calcium nitrate of different concentrations.

The specimen was placed between two lattice electrodes and the degree of pressing of the electrodes against the material was judged from the distance between the electrodes and it was regulated by the clamping device. The degree of tightening was determined from the equation

$$\sigma = \frac{d_0 - d}{d} \cdot 100\,(\%),$$

where d_0 is the thickness of the material in mm before compression by the electrodes; d is the thickness of the material in the compressed state in mm. In the tests presented σ was taken as equal to 17 and 20%.

Then the voltage of an alternating current of commercial frequency was supplied to the electrodes and the required parameters of the process were recorded.

Drying curves and graphs of the variation in current and in the mean integral temperature of the specimen are presented in Fig. 2 as an example.

As seen from the graphs presented, the heating of the material takes place for 10 sec and then the temperature of the material increases monotonically during its drying and is 115°C at the end of 180 sec.

An analysis of the nature of the curve of time variation with the current shows that as the material dries the strength of the current passing through it grows with the increase in the concentration of the electrolyte and with the temperature of the specimen up to a maximum value. The further drying promotes, on the one hand, an increase in the electrolyte concentration and consequently a growth in the current, but on the other hand, a decrease in the amount of moisture in the material which decreases the number of current-carrying "bridges," i.e., decreases the current strength.

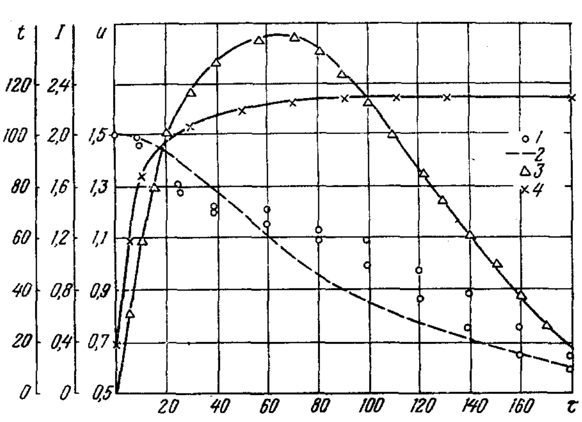

Fig. 2

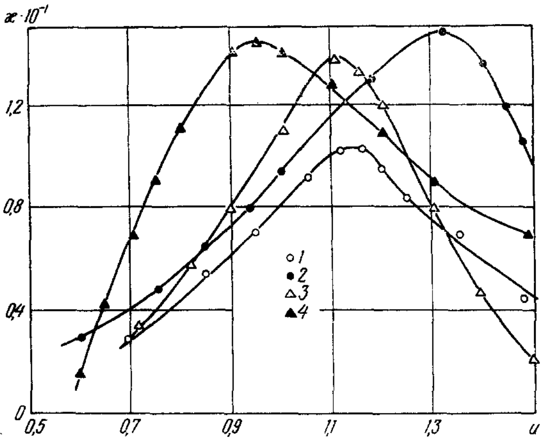

Fig. 3

Fig. 2. Curves of variation in moisture content (1, 2) [1) experimental data; 2) calculated values], current (3), and mean integral temperature of specimen (4) with time during process of electrocontact drying of felt with C = 1%, σ = 17%, and V = 130 V. τ in sec; t in °C; I in A; and u in kg/kg.

Fig. 3. Dependence of electrical conductivity of felt on moisture content, different initial weight concentrations of the chemical reagent, and voltages at σ = 20%: 1) C = 1%, V = 130 V; 2) 1% and 180 V, respectively; 3) 2% and 130 V; 4) 3% and 130 V.

The effect of these opposing factors results in a decrease in the size of the current.

Curves of the variation in current I and moisture content of the material $\bar{u}$ with time τ for different voltages V were analyzed to obtain the dependence $\varkappa = f(\bar{u})$. For this the value of R was calculated for different times and then, knowing the area S of the electrodes and the distance l between them, $\varkappa$ was determined from Eq. (2). The results of these calculations are presented in Fig. 3. It is seen from the graphs that the dependence $\varkappa = f(\bar{u})$ has an extremal nature with the maxima being shifted toward smaller $\bar{u}$ with an increase in the initial electrolyte concentration at the same applied voltage of the alternating current. At equal initial concentrations and different voltages the maximum is shifted toward higher moisture contents $\bar{u}$ and a higher voltage V corresponds to a greater maximum in the specific electrical conductivity $\varkappa$.

The use of the electrocontact method of heating for the dehydration of fibrolite at V = 220 V and t_{max} = 100°C permitted a reduction in its moisture content from 100% to 40-37% [2]. It was noted that 5-10% of the total amount of moisture was removed in the liquid phase and the rest in the form of vapor in this case while the rate of temperature rise reached 1.18 deg/sec.

The removal of part (2%) of the moisture in the liquid phase also occurred in our studies while the average rate of rise in the mean integral temperature of the material was somewhat different, being 8 deg/sec at first and 0.18 deg/sec during the drying. This difference is due mainly to the difference in the concentrations of the metal salts in the fibrolite and the felt.

The authors of [3] experimentally studied the kinetics of sausage meat during electrocontact thermal treatment in the temperature range of from 20 to 70°C. In particular, an analysis was made of the time variation in the temperature of the material at different degrees of pressing P of the electrodes against the material. For example, the duration of treatment of the sausage meat at V = 127 V was τ_{tre} = 40 sec at $P = 8.7 \cdot 10^4$ N/m², τ_{tre} = 38 sec at $P = 11.8 \cdot 10^4$ N/m², and τ_{tre} = 33 sec at $P = 41.2 \cdot 10^4$ N/m², i.e., with an increase in the degree of pressing P the intensity of heating of the material increases and the duration of the treatment naturally decreases. Our experiments also showed an analogous effect of the degree of pressing of the electrodes against the material on the intensity of its drying and heating.

An analysis of the temperature distribution in the volume of the material during the electrocontact baking of bread showed that the greatest increase in the rate of heating of the material occurs in the layer near the electrode, whose temperature reaches 99°C in 80-90 sec, at the same time that the temperature at the center of the material reaches only 63-65°C [4]. Such a temperature distribution through the volume of the material is also observed during the radiative and convective heating of materials.

TABLE 1. Values of Empirical Coefficients *a*, b, and c in Determination of Specific Electrical Conductivity of Felt

Weight concentration of $Ca(NO_3)_2$, %	Voltage, V/m	Coefficients, Ω/m			Initial moisture content, %
		a	*b*	*c*	
1	$12\cdot10^3$	5,1	13,2	9,3	150
2	$8,7\cdot10^3$	18	39,6	21,9	150
3	The same	8	16	8,7	150
1	"	12,8	30	18,4	150

TABLE 2. Experimental and Calculated Data on Drying of Felt by the Electrocontact Method

Moisture content, kg/kg	τ_{exp}, sec	τ_{calc}, sec	Δ, sec	ε, %
1,46	10	10	0	0
1,42	13	14,9	1,9	14,6
1,32	20	16,35	—3,35	16,7
1,26	25	22,4	—2,6	10,4
1,19	30	25,8	—4,2	14,0
1,13	35	29,1	—5,9	16,8
1,08	40	31,8	—8,2	20,5
0,97	50	38,5	—11,5	23
0,78	70	63,5	—6,5	12,3
0,69	80	80	0	0
0,63	90	87	—3,0	3,3
0,59	100	94,5	—5,5	5,5
0,55	115	100	—15	13

An analogous temperature distribution over the cross section of the drying felt was observed in our case, despite its relatively small thickness of 0.018 m. The difference in temperatures of the center and the electrode layer was greatly reduced, however, and was 2-5°C during the course of the drying process.

An analysis of the experimental results on the measurement of the specific electrical conductivity of specimens of felt impregnated with electrolyte showed that the dependence (7) is valid for different voltages of the power supply and different electrolyte concentrations in the material. The empirical coefficients found for this dependence are presented in Table 1.

An analysis of the results of experiments on the kinetics of the drying and heating of the material at an electric field strength of $8.7\cdot10^3$ V/m and an initial weight concentration of the salt of C = 1% made it possible to obtain the dependence of the Rebinder number Rb = (c/r)(du/dt) on the moisture content of the material for the period of constant drying rate:

where B = 0.18 and n = 1.75 at V = 130 V in the range of variation in the moisture content of 1.38-1.48 kg/kg and of 85-115°C in the temperature of the material.

In the second period the Rebinder number is constant and is determined by the conditions of the process.

Calculations were carried out to test the correctness of the analytical dependences obtained and some of their results are presented in Fig. 2 and in Table 2.

Calculated and experimental data obtained with an alternating current voltage of 180 V, specimen thickness of 0.018 m, salt concentration of 1%, initial moisture content of the material of 146%, dry mass of specimen of 0.016 kg, and a specimen area of $26.5\cdot10^{-4}$ m^2 in contact with the electrode are presented in Table 2.

The data of Fig. 2 and Table 2 show that throughout the drying process the disagreement between the calculated and experimental data on the duration of drying averages 10-15%.

This disagreement in our opinion is caused by the experimental error, by not allowing for the heat loss to the surrounding medium and for a certain fraction of the moisture removed in the liquid drop phase, and by the heat expended on heating the clamping device in contact with the material. At the same time this disagreement is quite acceptable for technical calculations.

Consequently, in the present work a sufficiently reliable equation is obtained for the drying curve during electrocontact dehydration of materials containing electrolyte by currents of commercial frequency which can be used to calculate the kinetics of the drying with an error of 10-15%.

LITERATURE CITED

1. I. A. Rogov and A. V. Gorbatov, New Physical Methods of Processing Meat Products [in Russian], Pishchevaya Promyshlennost', Moscow (1966).

2. N. N. Dolgopolov, Electrophysical Methods in the Technology of Building Materials [in Russian], Izd. Literatury po Stroitel'stvu, Moscow (1971).
3. N. V. Tkach, Author's Abstract of Candidate's Dissertation [in Russian], Kiev (1970).
4. Ya. G. Ostrovskii et al., Transactions of MTIPP. Technology and Technochemical Control of Bakery Production [in Russian], No. 4, MTIPP (1956).
5. V. V. Ivchenko and G. V. Nalivko, "Use of electrocontact heating in tobacco drying processes," Sbornik NIR VNII Tabaka, No. 155 (1971).
6. G. S. Kucherenko, "On the question of electrocontact treatment of food products," in: Research on Mechanization in the National Economy [in Russian], Urozhai, Kiev (1968).
7. V. P. Studennikov and S. S. Éppel', Avt. Svid. No. 251523, Byul. Izobr., No. 28 (1969).
8. A. V. Lykov, Theory of Drying [in Russian], Énergiya, Moscow (1968).
9. V. A. Sheiman and A. S. Zelepuga, Inzh.-Fiz. Zh., No. 4 (1969).