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## A GENERALIZED EQUATION FOR THE TEMPERATURE CURVE OF THE PROCESS OF CONVECTIVE DRYING OF MOIST MATERIALS

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We present the derivation and analysis of the generalized equation for the temperature curve describing the process of drying in continuously operating convective drying installations with a nozzle-directed stream. The results from the numerical solution are compared against experimental data.

A generalized equation has been derived in [1] which describes the kinetics of the process involved in the convective heating of moist materials and which links the kinetic characteristics of the process with the properties of the material and of the heat carrier, as well as with the geometry of the drying installation, and the temperature and hydrodynamic conditions under which the drying process occurs.

The heat-balance equation for the period of a declining rate of drying has the form

$$\bar{\alpha}(T_m - T_s)F = rm_0 \left| \frac{d\bar{u}}{d\tau} \right| + (c_0 m_0 + c_{mo} \bar{m}_{mo}) \frac{d\bar{T}}{d\tau} \quad (1)$$

or

$$\bar{St}(T_m - T_s)F = \frac{1}{c_p \rho v} \left[ rm_0 \left| \frac{d\bar{u}}{d\tau} \right| + (c_0 m_0 + c_{mo} \bar{m}_{mo}) \frac{d\bar{T}}{d\tau} \right], \quad (2)$$

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TABLE 1. Range of Variation in Dimensionless Variables of the Equation [13]

Variable quantity	Constant values
$(\text{RePr}) \cdot 10^{-4} = 2 \div 6$ $\text{Ko} = 2 \div 4$ $\text{Rb} = 0,05 \div 0,4$	$\text{Ko} = 3,0; Q^* = 2,7 \cdot 10^{-4}; \text{Rb} = 0,1$ $\text{RePr} = 2,0 \cdot 10^4; Q^* = 2,7 \cdot 10^{-4}; \text{Rb} = 0,1$ $\text{Ko} = 3,0; Q^* = 2,7 \cdot 10^{-4}; \text{RePr} = 2,0 \cdot 10^4$

TABLE 2. Comparison of Numerical Solution against Experimental Data

$\text{Fo} \cdot 10^3$	$\bar{T}^* \cdot 10^3$	
	numerical solution [13]	experiment
1,00	3,20	3,58
1,50	6,40	6,34
2,25	12,60	11,57
3,00	23,20	18,50

where  $\text{St} = \bar{\alpha}/c_p \rho v$  is the Stanton number for the period of the declining drying rate.

The basic criterion for the kinetics of the drying process is the Rebinder number

$$\text{Rb} = \frac{c}{r} \frac{d\bar{T}}{|d\bar{u}|},$$

where  $c = c_0 + c_{\text{mo}} \bar{u}$  is the heat capacity of the moist material.

From the expression for the Rebinder number it follows that

$$\left| \frac{d\bar{u}}{d\tau} \right| = \frac{c}{r} \frac{1}{\text{Rb}} \frac{d\bar{T}}{d\tau}. \quad (3)$$

When we use (3), we can write Eq. (2) in the form

$$\bar{\text{St}}(T_m - T_s)F = \frac{1}{c_p \rho v} \left[ \frac{m_0 c}{\text{Rb}} + (c_0 m_0 + c_{\text{mo}} \bar{m}_{\text{mo}}) \right] \frac{d\bar{T}}{d\tau}. \quad (4)$$

Since  $m_0 c = m_0 (c_0 + c_{\text{mo}} \bar{u}) = c_0 m_0 + c_{\text{mo}} \bar{m}_{\text{mo}}$ , Eq. (4) can be simplified. In this case

$$\bar{\text{St}}(T_m - T_s)F = \frac{m_0 c}{c_p \rho v} \left( 1 + \frac{1}{\text{Rb}} \right) \frac{d\bar{T}}{d\tau}. \quad (5)$$

In accordance with [2] we will represent the Stanton number in parametric form:

$$\bar{\text{St}} = \frac{T_1 - T_2}{T_m - T_s} \frac{f}{F}. \quad (6)$$

With consideration of (6) Eq. (5) assumes the form

$$\frac{d\bar{T}}{d\tau} = \frac{c_p \rho v (T_1 - T_2) f}{m_0 c \left( \frac{1}{\text{Rb}} + 1 \right)}. \quad (7)$$

Let us examine the product of two quantities, i.e., the Reynolds Re and Prandtl Pr numbers:

$$\text{RePr} = \frac{vb}{v} \frac{v}{a} = \frac{c_p \rho vb}{\lambda}, \quad (8)$$

where  $b$  is the decisive geometric dimension (the width of the material).

With consideration of (8) Eq. (7) can be written in the form

$$\frac{d\bar{T}}{d\tau} = \frac{(T_1 - T_2) \lambda f}{m_0 c \left( \frac{1}{\text{Rb}} + 1 \right) b} \text{RePr}. \quad (9)$$

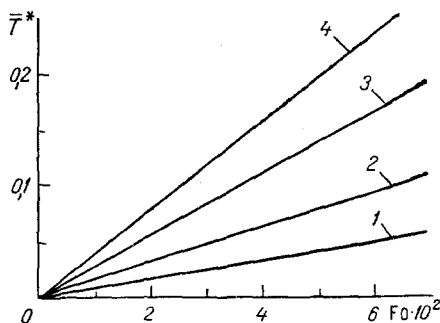


Fig. 1

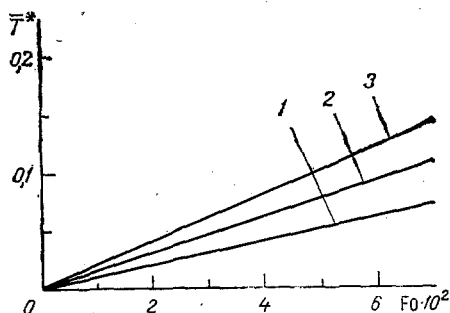


Fig. 2

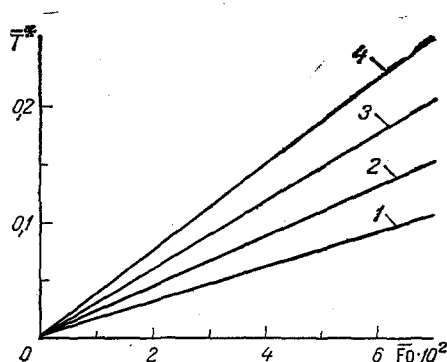


Fig. 3

Fig. 1. Dimensionless complex  $\bar{T}^*$  as a function of the Fourier  $Fo$  and Reynolds  $Re$  numbers: 1)  $RePr = 2 \cdot 10^4$ ; 2)  $3 \cdot 10^4$ ; 3)  $4 \cdot 10^4$ ; 4)  $5 \cdot 10^4$ .

Fig. 2. Dimensionless complex  $\bar{T}^*$  as a function of the Fourier  $Fo$  and Kossovich  $Ko$  numbers: 1)  $Ko = 2$ ; 2) 3; 3) 4.

Fig. 3. Dimensionless complex  $\bar{T}^*$  as a function of the Fourier  $Fo$  and Rebinder numbers: 1)  $Rb = 0.05$ ; 2) 0.1; 3) 0.2; 4) 0.4.

Let us multiply both sides of Eq. (9) by the product  $rT_{Cu_0}$ . Then

$$d\bar{T} = \frac{(T_1 - T_2) \lambda f T_m}{m_0 \left( \frac{1}{Rb} + 1 \right) bu_0 r} RePrKo d\tau, \quad (10)$$

where the Kossovich number  $Ko = ru_0 / cT_m$ .

Let us integrate (10) in the limits from the initial temperature, equal to the temperature  $T_w$  of the wet thermometer, to the instantaneous value of the temperature. In this case the time changes from 0 to the instantaneous value of  $\tau$ , corresponding to the temperature  $\bar{T}$ . As a result we have

$$\frac{\bar{T} - T_w}{T_m} = \frac{(T_1 - T_2) \lambda f}{m_0 \left( \frac{1}{Rb} + 1 \right) bu_0 r} RePrKo \bar{\tau}. \quad (11)$$

It follows from the determination of the Fourier number  $Fo$  that

$$\bar{\tau} = \frac{c_p \rho b^2}{\lambda} Fo. \quad (12)$$

Having substituted (12) into (11), we finally obtain

$$\bar{T}^* = \frac{Q^* RePrKoRb}{1 + Rb} Fo, \quad (13)$$

where  $\bar{T}^* = (\bar{T} - T_w) / T_m$  is the dimensionless temperature of the material during the period of declining drying rate;

$$Q^* = \frac{c_p \rho (T_1 - T_2) f b}{r m_0 u_0}$$

In generalized form Eq. (13) relates the temperature of the material to the basic characteristics defining the progress of the convective drying process.

We know that during the first period of drying the Rebinder number  $Rb = 0$ . Here the temperature of the material is equal to the temperature of the wet thermometer. The period of the declining drying rate is characterized by a rise in the temperature of the material, the maximum value of this temperature defined by the temperature  $T_m$  of the heat-carrying agent.

Let us examine the influence of the quantities contained in Eq. (13) on the dimensionless complex  $\bar{T}^*$ .

Table 1 shows the intervals of variation for the similarity numbers being considered here, and these have been chosen on the basis of the conditions of convective drying of fabrics with bilateral nozzle streamlining.

The results of the numerical study can be seen in Figs. 1-3. As we can see from the figures, all of the functions  $\bar{T}^* = f(Fo)$  are linear in nature, with varying degrees of effect exerted by the variables on the magnitude of the dimensionless complex  $\bar{T}^*$ .

The mechanism by which the Kossovich, Rebinder, Reynolds, and Prandtl numbers affect the quantity  $\bar{T}^*$  varies, since the  $Rb$  and  $Ko$  numbers characterize the internal processes of heat transfer and material transport, while the  $Re$  and  $Pr$  numbers characterize the external exchange of heat that occurs within the boundary layer at the surface of the material.

The greatest influence exerted on the elevation of the material's temperature is that of a rise in the Reynolds number  $Re$  (the Prandtl number  $Pr$  remains virtually constant). This is related to the intensification of the processes of heat and mass transfer in the boundary layer (when  $b = \text{const}$ ).

The rise in the Kossovich number  $Ko$ , caused by a reduction in the temperature  $T_m$  of the heat-carrying agent (we assume the initial moisture  $u_0$  to be a constant quantity), leads to an increase in the dimensionless complex  $\bar{T}^*$ . In this case, as demonstrated by calculations, there is a drop in the temperature  $\bar{T}$  of the material. And conversely, the reduction in the  $Ko$  number (as the temperature of the heat-carrying agent is elevated) leads to an increase in the absolute temperature of the material.

The magnitude of the Rebinder number has considerable influence on the kinetics of the heating of the material. The greater  $Rb$  (we assume that its mean values vary), the higher the absolute value for the temperature of the material at the given instant of time.

The results from the numerical solution of Eq. (13) were compared with the experimental data obtained in the study of the fabric drying process in a drying unit with bilateral streamlining of the material (Table 2). Here the temperature of the heating air was  $T_m = 363$  K, its velocity of motion  $v = 25$  m/sec, and the initial moisture of the material was expressed as  $u_0 = 1.2$ , the product  $fb = 2 \cdot 10^{-4}$  m<sup>3</sup>, the mass of the absolutely drying material  $m_0 = 0.00129$  kg,  $\Delta T = T_1 - T_2 = 3$  K. The Rebinder number is calculated from the formula  $Rb = 0.25[-9.5 \exp(\bar{u} - u_e)]$ .

We can see from the table that in the region  $0 \leq Fo \leq 2.5$  we can observe rather good agreement between the experimental results and the solution obtained from the proposed generalized equation. In the region  $Fo > 2.5$  we find divergence between the theoretical and experimental data (up to 15-20%). This circumstance can serve to explain the serious experimental difficulties and, as a consequence, the limited accuracy of measuring the temperature of a moving fabric under the conditions of the experiment.

#### NOTATION

$\bar{\alpha}$ , heat-transfer coefficient for the period of declining drying rate,  $W/(m^2 \cdot K)$ ;  $T_m$ ,  $T_s$ ,  $T_w$ ,  $\bar{T}$ , temperatures of the medium, material surface, wet thermometer, and the mean-volume temperature of the material, K;  $F$ , surface area of the material, m<sup>2</sup>;  $f$ , total area of the nozzle inlet section, m<sup>2</sup>;  $\tau$ , drying time, sec;  $m_0$ ,  $m_{m0}$ , mass of dry material and instantaneous value of moisture vaporized during the second drying period, kg;  $du/dt$  and  $d\bar{T}/d\tau$ , drying rate, sec<sup>-1</sup>, and rate of change for the temperature of the material, K/sec, during the second period;  $r$ , latent heat of vapor formation, kJ/kg;  $\bar{u}$ ,  $u_e$ , instantaneous and equilib-

rium moisture content of the material;  $c_0$ ,  $c$ ,  $c_{m0}$ , heat capacities of the absolutely dry, moist material, and water,  $\text{kJ}/(\text{kg}\cdot\text{K})$ ;  $c_e$ ,  $\rho$ ,  $\nu$ ,  $a$ ,  $\lambda$ , isobaric heat capacity,  $\text{kJ}/(\text{kg}\cdot\text{K})$ , density,  $\text{kg}/\text{m}^3$ , coefficient of kinematic viscosity,  $\text{m}^2/\text{sec}$ , thermal diffusivity,  $\text{m}^2/\text{sec}$ , and thermal conductivity,  $\text{W}/(\text{m}\cdot\text{K})$ , all applicable to the heat-carrying agent;  $v$ , velocity of motion for the heat-carrying agent,  $\text{m}/\text{sec}$ ;  $T_1$ ,  $T_2$ , temperature of the heat-carrying agent at the inlet to and the outlet from the drying chamber,  $\text{K}$ .

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#### THERMOPHYSICAL SPECTROSCOPY OF THE DEFECTIVE STATES IN SILICON

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UDC 536.2

Experimental research into the thermophysical properties of silicon containing defects formed under a variety of external stimuli serves to demonstrate the broad possibilities of employing thermophysical methods to study the nature of defects in silicon.

We are thoroughly familiar with the fact that the physical properties of semiconductor materials and devices are extensively determined by the presence of defect states in the crystal lattice of the semiconductor. Information on the structure of the defect state, its charge state, as well as on other properties, may be revealed by studies of the electron paramagnetic resonance (EPR) spectra, as well as by optical, acoustic, and dielectric spectroscopy, as well as by a number of electric and photoelectric methods. However, these methods are subject to well-known failings and advantages [1-3].

The utilization of "nontraditional" methods to research the physical properties of the defect states in semiconductors is of great importance, since in this case it is possible to observe earlier unknown physical phenomena whose interpretation leads to a more profound understanding of the unique features involved in the behavior of the defect states in semiconductors. In studying the nature of defects in semiconductors, as demonstrated by the research covered in [4-7], the experimental studies of the relationship between temperature and the thermophysical properties of semiconductors with defects have proved to be extremely productive, and this research can be carried out successfully over a rather broad range of temperatures, and the thermophysical methods in this case exhibit a number of positive aspects. In particular, these include the rigorous thermodynamic description of the process in which the temperature, energy, and time are measured precisely. As a result we can derive information that is both purely fundamental in nature (information regarding the properties of the phonons spectrum, unique features of the relationship between defects, the ordered or disordered location of the defects in the crystalline lattice, their interaction, as well as on the various mechanisms by means of which the defect states are restructured), as well as of a practical nature (information regarding impurities, vacancies, complexes, accumulations and associations of impurities, on the kinetics of the formation and disintegration of solid solutions of impurities, etc.), thus opening real possibilities of developing new concepts regarding the mechanisms of defect-formation in semiconductors;

In this study we examine the thermophysical properties of silicon defects in the light of the possibility of using these thermophysical methods to study the structures of deep energy centers (DEC).

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