KINETIC DEPENDENCES OF THE DRYING PROCESS

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Annotation. The theory of drying developed by A.V. Lykova is based on a solid foundation of both classical equilibrium thermodynamics and the thermodynamics of irreversible processes. The central place when using thermodynamic methods for analyzing moisture transfer during drying and conditioning is the concept of potential, which is a function of the state of the system, which is equal at equilibrium at all points of the system. The potential gradient determines the direction and transfer rate of the corresponding substance. By analogy with heat transfer, in which thermodynamic methods of analysis are successfully applied, and, accordingly, the transfer potential in heat transfer is temperature, and the concept of mass content is similar to heat content.

Keywords. drying, temperature, thermodynamics, process.

Introduction. It is generally accepted to present data on the kinetics of drying in the form of dependences of the average moisture content of the dried materials on time, speed, temperature, and moisture content of the drying agent [1-3].

As a rule, at the beginning of the process there is a brief period when the moisture content of the material changes slightly. Then, in the case of removal of free moisture, a constant rate of moisture removal is established, at which time the temperature of the wet material does not change. The intensity of drying at the stage of constant speed depends on the conditions of flow around the external surface of the wet material with a drying agent, its temperature and moisture content.

The dependence of the kinetics of drying in the period of constant speed has the following form:

$$-\frac{du}{d\tau} = N,\ u = u_0 - N\,\tau \tag{1}$$

The stage of constant drying speed is followed by the stage of falling (continuously decreasing) drying speed with increasing temperature of the material. In this case, the moisture content of the material at which the transition from the first to the second stage occurs is called critical. The drying speed at this stage is mainly characterized by the value of resistance to moisture transfer in the material. The moisture transfer mechanism is diffusive, but there are several varieties of it [4-7]. The simplest form of dependence of the falling drying speed on the current moisture content of the material is linear:

$$-\frac{du}{d\tau} = K\left(u - u_p\right),\ u = u_p + \left(u_{kp} - u_p\right)\exp(-K\,\tau) \tag{2}$$

where K is the drying coefficient.

In the case of a deviation from the linearity of the velocity dependence, the following formula was proposed [8]:

$$-\frac{1}{N}\frac{du}{d\tau} = \frac{\left(u-u_p\right)^m}{A+B\left(u-u_p\right)^m} \tag{3}$$

where m, A and B are constant coefficients depending on the type of bond of moisture with the material, shape, particle size, moisture-transporting properties of the material.

For fifty years, drying models of a thin layer have been of considerable interest among researchers, in terms of using empirical or semi-empirical models to describe drying curves. Some of these models are presented in Table 1. In these models, k, A, B, k_1, k_2, n are constants depending on the drying conditions, such as ambient humidity, drying air temperature and the speed of the ventilation stream through the drying column.

Table 1
Thin-layer drying model equations

Уравнения	Источник
$E = e^{-kt}$	Allen (1960)
$E = Ae^{-k_1 t} + Be^{-k_2 t}$	Henderson (1974)
$E = Ae^{-kt^n}$	Agrawal and Singh (1977)
$E = 1 + At + Bt^2$	Wang (1978)
$E = Ae^{-kt^n} + Bt$	Midilli et al. (2002)

where, $E = \left(\frac{M - M_e}{M_0 - M_e}\right)$ is the dimensionless ratio of humidity, t is the drying period; M_0 (kg water/kg dry matter) is the initial moisture content on a dry basis; M_e is the equilibrium humidity.

To dry a thin layer of rice, twelve such models were considered in [8]. The number of parameters in these models has changed from one to four. Drying experiments were carried out on long grain of coarse rice in order to determine the parameters of these models and calculate the statistical quality of these models against experimental drying data. In all models except one, the correlation coefficients were higher than 0.98, which means that all these models can describe the drying of a thin layer of coarse rice satisfactorily. As expected, the model developed [9], which has four parameters, gave a better description of the experimental results.

The advantages of the thin layer drying model are their simplicity. However, the parameters in these models depend on certain drying conditions and therefore should be experimentally determined for each drying condition.

Deep-layer drying models take into account changes in the drying conditions of drying air and grain at various depths, which prevent the use of the only constant drying and moisture content of the equilibrium required in the drying equations in a thin layer. Two approaches have been applied to model such deep-layer drying systems. In the first case, it was necessary to determine the average temperature of the layer, then the equations of drying a thin layer with constant drying at the corresponding average temperature were used. In the second approach, deep-layer drying was considered as a series of thin layers, each of which has a different temperature and therefore different drying constants.

Results and discussion research. To study the drying of the deep layer of corn and rice in [10], the principle of dimensional analysis was used to determine the average temperature of the layer, which can be expressed as:

$$f(T_i, T_a - T_i, T - T_i, M_i - M_e, M - M_e, h, W, w) = 0 \quad (4)$$

or

$$f^1\left(\frac{T - T_i}{T_a - T_i}, \frac{T_a - T_i}{T_i}, \frac{M - M_e}{M_i - M_e}, \frac{hw}{(M - M_e)w}\right) = 0 \quad (5)$$

or $$f^1(\pi_1, \pi_2, \pi_3, \pi_4) = 0 \quad (6)$$

where T_i - is the initial temperature of the grains; T_a - is the temperature of the drying air; T - is the average temperature of the grain layer; M_i - is the initial moisture content of grains for dry weight; M_e - equilibrium moisture content of grains on dry weight; M - is the final moisture content of the grains on a dry weight basis; W - is the mass of air supplied to the bed during the drying period; w is the mass of water to be removed; h - is the humidification potential, that is, the difference in the absolute humidity of the drying air when it is saturated in constant heat content in the layer and at the entrance to the layer.

Based on the results of experiments on drying a deep layer using dimensionless parameters, diagrams were constructed that could be used to calculate the average temperature of the layer and the mass of drying air. Continuous drying could then be determined and subsequently used to predict the drying time. The predicted drying time in the case of drying of rice and corn was very close to the actual value, the difference is less than 10% of the total drying period. Once obtained diagrams for certain grains [11] were simple and used for calculation.

Compared with the empirical approach [12], the preferred approach is [13], which is based on the preparation of heat balances for drying thin layers of grain in order to determine the temperature of grains at various depths in the deep layer. In [14], a one-dimensional drying model was developed that takes into account the moisture and temperature balances in grains and drying air. This model is solved using the finite element method.

Single grain drying models based on the laws of Fick's diffusion over the past three decades have been widely used to describe the movement of moisture within the rice core in various forms: white rice, brown rice and coarse rice. In addition to the average moisture content of the kernels, such models also describe the distribution of moisture within the rice kernels and can be used to estimate the moisture gradients in rice during both drying and curing. Some studies [15–16] also took into account heat transport within the core in these models.

There are many empirical dependencies [17–20] for describing the kinetics of drying, but the problem of choosing a good empirical equation is futile because it does not make it possible to estimate the moisture distribution over the volume of the material.

To describe the kinetics of the drying process of capillary-porous bodies, the system of joint differential heat-mass transfer equations proposed by A. Lykov must be considered in the form of three connected partial differential equations for three variables - temperature, moisture content and pressure [21]. If the pressure gradient is neglected, it is possible to use [22-24] a system of two partial differential equations:

$$\left\{\begin{array}{c} \frac{\partial t}{\partial \tau} = a\nabla^2 t + \frac{\varepsilon\, r}{c\, \gamma}\frac{\partial u}{\partial \tau} \\ \frac{\partial u}{\partial \tau} = a_m \nabla^2 u + a_m \delta \nabla^2 t \end{array}\right\} \quad (7)$$

where a_m - is the mass conductivity coefficient; a - is the coefficient of thermal diffusivity; Δ is the Laplace operator; ε - is the phase transition coefficient; δ - thermogradient coefficient; r - is the specific heat of vaporization; γ - is the density; c - is the specific heat.

The general solution of this system of partial differential equations to consider the related processes of heat and mass transfer inside a wet body is associated with great difficulties [25-26]. As follows from the example given in the monograph [25], for the relatively simple case of drying an isotropic particle of a simple geometric shape in the region of constant parameters, the solution turns out to be rather cumbersome, which is often the reason for rejecting this direction.

Considering that the main thing in drying processes is moisture transfer, and the temperature quickly reaches its limit value and remains practically unchanged, often they use only one differential equation of moisture transfer of the diffusion type [27-30]:

$$\left(\frac{1}{y^m}\right)\left(\frac{\partial}{\partial y}\right)\left[y^m\left(\frac{\partial \phi}{\partial t}\right)\right] = \left(\frac{1}{D}\right)\left(\frac{\partial \phi}{\partial t}\right) \quad (8)$$

where y is the coordinate (y=z for the plate and y=r for the sphere and cylinder); m - 0, 1 and 2 for particles with the shape of a plate, cylinder and sphere, respectively; $\phi = M - M_e$.

A review of methods for identifying moisture diffusion coefficients is presented in [30].

A solution for the regular stage of the mass transfer process during drying for particles of various classical forms for different intensities of external moisture transfer is presented in [31].

Kinetics equations in the form of an exponential dependence:

$$\frac{(M-M_e)}{(M_i-M_e)} = G\ exp(-S\ t) \quad (9)$$

where S - is the drying coefficient, c^{-1}, G - is the delay factor.

The drying coefficient determines the drying rate of the body per unit time, and the delay factor determines the sign of the body's internal resistance to moisture transfer during drying.

For three regular body shapes (endless cylinder, endless plate and sphere), the moisture diffusion coefficient can be determined by the following equation:

$$D = S\,Y^2/\mu_1^2 \quad (10)$$

where μ_1 and Y are the root of the characteristic equation and the characteristic size of the body, respectively.

If G and D are known, then it is possible to determine the mass transfer coefficient during the drying process, as presented in [32].

In many cases, a constant coefficient D is adopted and the shape of the drying objects is regular (plate, cylinder, ball).

The constancy of the coefficient D, however, is not always confirmed. As shown in [33], the coefficient D is characterized by a time dependence for some objects, for example, wheat grains.

To analyze the kinetics of drying the beans in a thin layer, a diffusion model was adopted in [34], assuming that the shape of the beans is close to a cylindrical infinite length. When comparing with the results of numerical and analytical solutions of the three classical forms, it turned out that the shape of the endless plate is best suited, which, of course, does not correspond to the actual geometry of the beans.

The drying process is greatly influenced by the form of the dried materials. The study [35] proposed form factor equations for drying multidimensional bodies, presented similarly to heat transfer during cooling [36]. Using the analytical method of separation of variables, the solution of the moisture conduction equation for hemispherical particles is presented [37].

Data were obtained on the shape and size of grains of various wheat varieties [38]. If it is necessary to take into account the features of the drying process as accurately as possible, it is necessary to apply numerical methods for solving the equations of mass conductivity [39]. The finite volume and finite element method has been used in research [40]. The finite difference method has found application in research [41].

In [42], the dependence of the diffusion coefficient was proved not only on the material properties, but also on the body geometry based on a comparison of experimental data with individual cereal particles and a layer composed of these particles.

The diffusion coefficient depends, as was shown [42], on the particle geometry when comparing experiments with individual cereal particles and a layer of these particles.

In practice, the processing of grain in various mass and heat exchangers takes place in a fixed layer of particles or in a moving layer crosswise with the flow of a drying agent [43]. The study [44] considered pure heat transfer processes in layered devices.

The study [45] presented a macrokinetic method based on the use of approximate kinetic dependences for various stages of drying. The method was confirmed by experimental results [46].

Conclusions. For continuous dryers with a transverse direction, which operate in a diffusion-controlled mode, a mathematical model was proposed [47]. In this model, the transverse dryer is presented as a series of successive stages of gas contact with a solid. In this case, each stage is penetrated by the flow of a drying agent, and solid wet particles pass through these stages in series. Based on the analysis of the interaction of solid particles and gas at each stage, as well as the boundary conditions for diffusion inside the particles, model dependences were established and obtained. The model establishes the relationship between the amount of moisture removed and many technological parameters, such as the partial coefficient, diffusion coefficient, particle size,

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total number of steps, residence time, loading of solid particles, transport speed and humidity of the drying agent, which makes it possible to evaluate the effect of these parameters on the drying process.

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