# The theory of transfer processes with short-term contact phases

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***Abstract:*** *Using the methods of systemic, mathematical and numerical analysis, as well as general physicochemical and thermodynamic laws, a complex of theoretical and experimental studies of transfer processes during short-term contact of phases has been carried out. These studies made it possible to fully reveal the regularities of external and internal heat and mass transfer, to find scientifically grounded ways to intensify the processes of vacuum, conductive and combined drying methods. Within the framework of linear nonequilibrium thermodynamics, a mathematical model of filtration-diffusion energy and mass transfer has been developed with a correct estimate of the orders of the terms in the system of differential equations of energy and mass transfer, taking into account the composition of the vapor-air mixture in the capillary-porous body. The limits of applicability of the hypothesis of short-term contact of phases according to the Fourier criterion for the transfer inside and outside the surfaces of the canonical shape (plate, cylinder, sphere) and wedge are estimated from the standpoint of the accuracy of calculating interphase flows. It is shown that in a number of cases the contact is not short-lived due to the curvature and the presence of angles on the contact surface, and not due to the finiteness of the dimensions of the contacting phases.*

***KEY WORDS:*** *DRYING, DYNAMICS, SHORT-TERM CONTACT, PHASE, SURFACE, FOURIER CRITERION, MATHEMATICAL MODELING, HEAT AND MASS TRANSFER, ANALYSIS.*

## *1. Introduction*

The properties of the product at the outlet of the apparatus and the choice of the optimal technological mode of its processing are mainly determined by interrelated processes occurring inside the contact (boundary) layer of the material being processed (heat and mass transfer) and in the boundary layer of the environment (heating wall, air, inert coolant, steam, catalyst, etc.), since changes in environmental parameters change the conditions for the transfer of matter in the whole system, and the intensification or decrease in the material of physicochemical and phase transformations affects the structure of the boundary layer. A qualitative analysis of the mechanism of transfer processes is associated with finding non-stationary fields of transfer potentials (temperature, concentration, pressure, etc.), the evolution of which makes it possible to theoretically investigate the kinetics and dynamics of the process and outline the optimal conditions for its implementation. Modern intensification of materials processing technology leads to an increase in the role of non-stationary interconnected exchange processes in comparison with stationary unrelated ones. This fact has not yet found sufficient reflection in the field of solving problems of energy and mass transfer at low Fourier numbers - with short-term contact of the phases.

## *2. Theory and results*

One of the effective means of intensifying the transfer processes, for example, with a conductive energy conduit, is mixing the product, which constantly renews the contact layer of the material and equalizes the temperature, pressure, concentration of the processed medium (possibly three-phase) in its bulk, which makes it possible to obtain large flows through the interface. Often the physical model of these processes is a series of short-term contacts product with heating surface , and the transfer rate strongly depends on the contact time τ_k For example, for drum, rake, roller, cylindrical dryers, where mixing is associated with rotation, τ_k is defined by the formula τ_k=ψ/ω where ω is the angular velocity of rotation of the mixing devices, and ψ is the characteristic angle. For shelf dryers, belt dryers, disc dryers, vibrating dryers, etc. depending on the organization of mixing τ_k determined by the period of shaking, the frequency of vibration, the residence time of the product on a given plate, conveyor belt, etc. In the packet theory of fluidized and in the simplified model of gushing beds τ_k is determined by the speed of movement of the product (package) on the heating surface [8,9].

Let us consider separately the physical and mathematical aspects of modeling transfer processes during short-term contact of phases.

Physical model of short-term contact of phases. Multiple repetition of contact interactions up to several thousand times makes it possible to describe heat transfer as stationary, using the heat transfer coefficient, the values of which are determined by unsteady heat and mass transfer during one contact.

Methods of organizing the contact of the product with the heating surface In the analysis of short-term contact, the concept of heat transfer coefficient is introduced [3].

$$\alpha(\tau) = \frac{q(\tau)}{F(T_{гп} - T)}, \#$$

and it is called instant [8], conditional [10], contact [9], given [5]. For the average value α (τ) for the time of one contact, the expression [3,7,8,10] is used

$$< \alpha^k >_{\tau_k} = \frac{1}{T_k}\int_0^{\tau_k} \alpha(\tau)d\tau = 2\frac{\sqrt{\lambda c\rho}}{\sqrt{\pi\tau_k}}, \#(2)$$

where λ is the coefficient of thermal conductivity, $\sqrt{\lambda c\rho_0}$is the coefficient of heat assimilation (thermal activity) of the product [6]. Formula (2) was obtained by O. Krisher [3] under the following assumptions due to the small thickness of the heated contact layer of the material. A flat heating surface is placed at the point x = 0, and the material occupies the entire half-space x> 0; the heat conduction problem is one-dimensional, i.e. isothermal surfaces are parallel to the heating surface. The initial temperature distribution is assumed to be uniform, due to the presence of mixing:

$$T(x, 0) = T_0. \#(3)$$

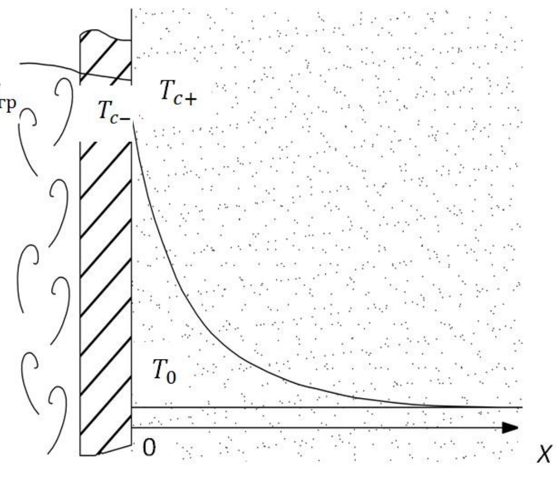


Fig. 1. On the formulation of the problem of short-term contact

Since the main thermal resistance is concentrated in the contact layer of the material, where the temperature gradients are many times higher than those in the heating agent and the shell, the temperature $T_c$. is assumed to be constant, and $T_c$ is considered in the first approximation to coincide with $T_c$ ($T_{гп}$). The condition for the applicability of (2) in [3, 7, 10) is assumed (in the dimensions of the SI system) the inequality

$$Fo_k = \frac{a\tau_k}{H^2} \leq 0,106. \#(4)$$

which is fulfilled as equality when the temperature at the outer boundary of the body changes by 0,03 |$T_{ГП}$ — To|. Here a = $\lambda/c\rho_0$

is the thermal diffusivity, H is the thickness of the material layer, which either changes in an obvious way, or requires some kind of averaging. The averaged values of H for cylindrical dryers are given in [7]. Through the criterion $Fo_k$ , expression (2) can be represented in the form

$$<\alpha^k>_{\tau_k} = \frac{2\lambda}{H\sqrt{\pi Fo_k}}.$$

In many devices, the heating surface is often curved, and the limitations of the applicability of the short-term contact model may be determined not by the thickness of the H layer, but by the curvature of the heating surface R. Estimates of type (4), taking into account the curvature of the heating surface, will be obtained below. In addition, it is known that internal evaporation, thermal diffusion, filtration of moisture contribute to heat transfer, and (2) was obtained by solving the problem of pure thermal conductivity. Finally, the coefficient $<\alpha>$ is influenced by the composition of the remote multicomponent liquid mixture [11 - 15]. Taking these effects into account is an urgent task for the development of technological calculation and analysis of local changes in temperature and composition of the liquid phase of products. The physical model of short-term contact of phases is a powerful tool for analyzing transfer processes, since in a number of cases it has properties that make it possible to obtain relatively simple solutions of the posed boundary value problems, including multi-frontal problems of the Stefan type (freezing (thawing), evaporation, drying, filtration, sorption, adsorption , crystallization, etc.)

Mathematical models, self-similarity and invariants of solutions. In the general case, any mathematical description of processes in heterogeneous media, which include wet dispersed materials (suspensions), is based on the phenomenological theory of the multi-velocity continuum and is represented as a system of balance equations for conservation of mass, momentum, and energy. Further, depending on the considered medium and process, the multi-fluid (multi-velocity) model is generalized and closed (concretized) by attracting the mechanical and thermodynamic properties of the phases.

In the framework of nonequilibrium thermodynamics [16-17], on the basis of integral conservation laws, the interrelated heat and mass transfer in stationary dispersed media and capillary-porous bodies containing multicomponent liquid mixtures can be described using the following inhomogeneous system of nonlinear parabolic equations written in the vector-matrix form and resolved with respect to time derivatives (in this form, they are usually given by the system of differential equations of the transport theory).

$$C\frac{\partial\vec{\Pi}}{\partial\tau} = \mathrm{div}(L\,\mathrm{grad}\vec{\Pi}) + \vec{I}, \#(5)$$

where $\vec{\Pi}$ is the n-dimensional vector of transfer potentials, L is the matrix of kinetic coefficients, C is the diagonal matrix of capacitance coefficients, I is the power vector of sources (or sinks). If there is an interaction of two phases, then in (5) the index i = 1,2 is added, which we omit to simplify the notation, the operators of divergence and gradient are applied in (5) separately to each component of the corresponding vectors. It should be noted that system (5) can be written with respect to each of the interacting phases with the corresponding boundary conditions of uniqueness, including at the interface, similarly multi-frontal problems of the Stefan type. If the presence of sources is caused only by liquid-vapor phase transitions, and the vector of potentials includes the vector of moisture contents of the components Ux or the total moisture content U, then the vector I can be excluded from (5). To do this, it is sufficient to use the method of introducing the criterion of internal evaporation (phase transformation) ε, which is the ratio of the change in moisture content due to evaporation to its total change $U_T$. which is widespread in the theory of drying. In the case of an multicomponent liquid mixture, the ε values for the components can be different, this criterion will be a vector. After introducing e from (5), within the framework of the model of short-term contact of phases, we obtain

$$C\vec{\Pi}_T = (L_\varepsilon, \vec{\Pi}_x)_x, \#(6)$$

where $L_\varepsilon$ is a matrix of kinetic coefficients that takes into account phase transitions. In the case when C and $L_\varepsilon$ do not explicitly depend on coordinates and time (an explicit dependence on the complex $x/\sqrt{\tau}$ is admissible), but are functions of transport potentials, the Boltzmann substitution $\xi = \frac{x}{2\sqrt{\tau}}$ reduces (6) to a nonlinear system of homogeneous second-order ordinary differential equation

$$2\xi C\vec{\Pi}' + (L\vec{\Pi})' = \vec{0}. \#(7)$$

Here and in what follows, the prime means differentiation with respect to ξ, and the subscript ε for L is dropped.

Using the assumption of the uniform distribution of $\vec{\Pi}$ at the time τ = 0, we obtain the boundedness condition as $\xi \to \infty$

$$\vec{\Pi}(\infty) = \vec{\Pi}_0. \#(8)$$

When formulating the boundary conditions in the form

$$P^{II} - \vec{\Pi}(0) = \vec{\Pi}_C \#(9)$$

(the task of linear relationships of the $\vec{\Pi}$ components on the heating surface) or

$$P^{II} \cdot L\vec{\Pi}'^{(0)} = \vec{0} \#(10)$$

(the condition of impermeability of the heating surface for certain flows) the entire problem of short-term contact of phases (7) - (10) becomes self-similar. In (9) $P^1$ and in (1.10) $P^{11}$ are orthogonal projectors, not necessarily orthogonal to each other ($P^I \cdot P^{II} \neq 0$). In the case when the fluxes of energy or matter through the HP are specified, the condition for self-similarity is their proportionality $\tau^{-0.5}$[21].

When solving problems with equations of the type (6) in the region $x > 0$, $\tau > 0$, most researchers use in addition to the initial and boundary conditions of semi-boundedness (or conditions at infinity) as $x \to \infty$ in three different forms:

$$\vec{\Pi}_x(\infty,\tau) = \vec{0}, \vec{\Pi}(\infty,\tau) = \vec{\Pi}_0, \lim_{x\to\infty} \vec{\Pi}(x,\tau) = \vec{\Pi}_0. \#(11)$$

The last two conditions in (11) for the self-similar problem coincide with condition (1.8), which reflects the initial state of the product. Therefore, additional conditions of semi-boundedness were not considered.

In the case of constants L and C, which is most studied in the theory of drying when removing individual liquids, the problem of short-term contact of phases becomes linear and greatly simplified. To solve such problems, the superposition method is often used [2, 6, 19]. Eigenfunction expansions and integral transformation methods provide systematic schemes for constructing such solutions.

If the matrix $C^{-1} \cdot L$ has real, positive and different eigenvalues $v_i^2$, $i = \overline{1,n}$, the solution (7) - (10) by the superposition method is reduced to finding the constants $A_i$ in the representation

$$\vec{\Pi}(\xi) = \vec{\Pi}_0 + \sum_{i=1}^{n} A_i f_i \,\mathrm{erfc}\left(\frac{\xi}{v_i}\right), \#(12)$$

from the conditions on the heating surface (9) and (10). In (12), the linearly independent eigenvectors $f_i$ of the matrix $C^{-1} \cdot L$ correspond to the eigenvalues $v_i^2$. Direct verification can make sure that when specifying $\vec{\Pi}(\xi)$ in the form (12), equation (7) and condition (8) are satisfied automatically.

The constancy of L and C is an idealization of real relationships, however, it provides rich material for a qualitative analysis of the influence of various parameters on the transfer process. At the same time, even without this condition, the model of short-term contact due to the self-similarity of the problem (7) - (10) has great advantages. Self-similar solutions can be used as "standards" in evaluating approximate methods for solving more complex problems; in addition, self-similarity simplifies the calculation and presentation of the characteristics of the phenomenon. In particular, assuming only the existence of a solution $\vec{\Pi}(\xi)$ one can establish the existence of a series of invariants of internal heat and mass transfer.

An integral component of $\vec{\Pi}$ in a non-isothermal process is temperature T, and its change at any point in the material can be considered monotonic: $T_\tau(x,\tau) > 0$ during heating. Therefore, from the solution T (ξ), one can obtain a unique dependence ξ (T) and write $\vec{\Pi}$ (ξ) in the form

$$\vec{\Pi}(\xi) = \vec{\Pi}(T). \#(13)$$

Thus, in the theory of short-term contact of phases, there are n - 1 invariants of internal interconnected heat and mass transfer, according to the number of acting potentials that determine this transfer. The relationships between the local values of temperature, moisture content, composition of the multicomponent liquid mixture and pressure, which are independent of time and coordinates, can serve to analyze the combined effect of heating and dehydration in various technological processes.

Such an analysis is especially relevant for biological products, since their thermal and xerolability is due precisely to the combined effect of these factors.

In connection with the large role of the model of short-term contact of phases in the study of processes with stirring, a more detailed analysis of the limits of applicability of this model is required.

The limits of applicability of the model of short-term contact of phases. The conditions under which the contact can be considered short-term depend on what characteristics of the contact are being investigated. O. Krisher's restriction (4) is associated with a change in temperature on the free surface of the body by 3% of the total temperature head, and is used as a characteristic of the applicability of formula (2) for the heat transfer coefficient. It is of interest to elucidate the influence of the finiteness of body dimensions and the shape of the heating surface directly on the heat transfer coefficient. Let us consider in the framework of pure thermal conductivity the problems for an unbounded plate (G = 0), an infinite cylinder (G = 1) and a ball (G = 2) - Fig.2.

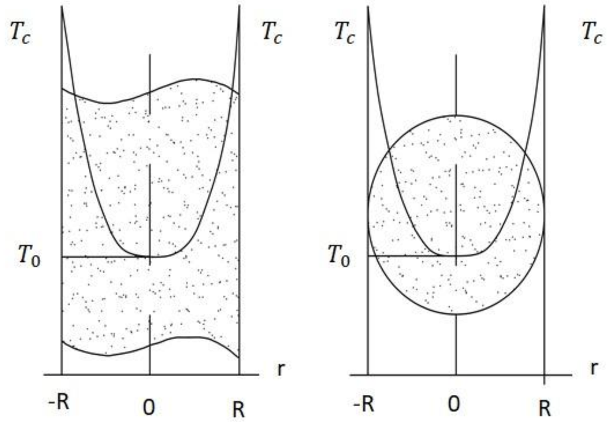


**Fig. 2** On the formulation of heat conduction problems for bodies of canonical form

All three tasks have a common formulation

$$T_\tau - a\left(T_{rr} + \frac{\Gamma}{r}T_r\right) = 0, \#(14)$$

$$T(r,0) = T_0, \qquad T(\pm R, T) = T_c$$

and the same kind of solution [6]:

$$T(Fo,\eta) = T_c + (T_0 - T_c)\sum_{i=1}^{\infty} A_i \varphi(\mu_i\eta)\exp\left(-\mu_i^2 Fj\right), \#(15)$$

Where

$$\eta = \frac{r}{R}, \qquad Fj = \frac{a\tau}{R^2}, \#(16)$$

and $\mu_i$- are the positive roots of the characteristic equation numbered in ascending order

$$\varphi(\mu) = 0.$$

The eigenfunctions of problems (14) and the coefficie - are determined by the formulas in Table. 1.

**Table 1. Parameters of solutions for heat conduction**

| G | 0 | 1 | 2 |
|---|---|---|---|
| $\varphi(\mu_i\eta)$ | $\cos(\mu_i\eta)$ | $J_0(\mu_i\eta)$ | $\frac{\sin(\mu_i\eta)}{\mu_i\eta}$ |
| $A_i$ | $(-1)^{i+1}\frac{2}{\mu_i}$ | $\frac{2}{\mu_i J_1(\mu_i)}$ | $(-1)^{i+1}\cdot 2$ |

Here $J_0$ and $J_1$ are the Bessel functions of the first kind of the zero and first orders, respectively. Taking into account the Fourier law, α (τ) is determined by the value

$$\alpha(\tau) = \frac{\lambda}{R(T_c - T_0)} T_\eta\Big|_{\eta=1}. \#(18)$$

Formal term-by-term differentiation of series (15) at different G gives a general expression

$$\alpha(\tau) = \frac{2\lambda}{R}\sum_{i=1}^{\infty}\exp\left(-\mu_i^2 F_o\right) \#(19)$$

in which the shape of the heated body is reflected only through the sets $\mu_i$ i=1,2, ... Formal term-by-term integration (19) in accordance with (2) gives

$$<\alpha>_{\tau_k} = \frac{2\lambda}{RF_{ok}}\sum_{i=1}^{\infty}\frac{1-\exp\left(-\mu_i^2 F_{ok}\right)}{\mu_i^2}. \#(20)$$

A discussion of the convergence of series (19), (20) and estimates of their remainders are given in [1]. Note that the summation of these series in the problem of short-term contact of phases must be carried out at small $F_o$, when there is no predominance of the first terms. Therefore, the numerical calculation of the sums (19), (20) was carried out on the basis of a given maximum permissible relative inaccuracies $\delta = 10^{-3}$. Separate task is the calculation of several hundred roots $J_0$ (it is precisely these quantities that are necessary for $\delta = 10^{-3}$.. This problem was solved sequentially in i, starting with the value $\mu_1 \approx 2{,}4$. The iterative rule of false position was used, and for the localization of the roots, the segments

$$\mu_{i+1} \in \left[\mu_i + \pi - \frac{0{,}1415}{i}, \mu_i + 3{,}1416\right],$$

the position of which is associated with the almost periodic nature of the growth of $\mu_i$ [19]. Due to the precise localization of the roots, their values were calculated with a relative error of no more than $10^{-6}$ for 2 - 3 iterations, with this level of error it was possible to determine 250 roots. The results coincide with the above accuracy with the data [19], where the first 60 roots of $J_0$ with 5 - 7 significant digits are given.

However, it should be noted that the classical solution in the Fourier form, consisting of the product of two functions, taking into account, respectively, the change in temperature in time and along the radius (thickness), is convenient for large Fo. For small Fo, solutions obtained by methods of operational calculus are convenient, in particular, solutions in the Laplace form (Laplace transform), which represent the well-known combination of the functions erf and erfc. In these cases, you can always limit yourself to a few first (or only the first) members of the series, discarding all the rest. In addition, operational methods make it possible to obtain a number of approximate solutions with any degree of accuracy, which are quite simple and can be used in technical calculations.

An analysis of the obtained expressions $\alpha(Fo)$ for various G shows that

$$\lim_{F_o \to 0}\left[\frac{\alpha(Fo)}{\alpha^k(Fo)}\right] = 1,$$

those. the formulas for calculating α (τ) for small Fo asymptotically coincide with the formulas used to calculate $\alpha^k(\tau)$.

By generalizing (4) to. the case of multicomponent energy and mass transfer in a plate is the same condition, in which, instead of the thermal diffusivity (or diffusion) coefficient, one should use the largest of the eigenvalues of the matrix $C^{-1}$ L [22]. Depending on the objectives of the study, the level of permissible fluctuations of various components II at the outer boundary x = II can be different, therefore, it is possible to weaken or strengthen condition (4), or a combination of this type of conditions. In a specific case, such estimates are carried out quite simply using solutions of the form (12).

The same approach is obviously extended to the case of contact between two plates of finite thickness. However, the very origin of the condition - guaranteeing the accuracy of the calculation of the potential fields in a plate of finite dimensions - has disadvantages. It is not connected with the main task of calculating energy and mass transfer with the determination of the intensity of metabolic processes and therefore does not say anything about the accuracy of calculating the fluxes of transported substances.

In addition, in real situations, a limitation associated with the curvature of the contact surface (the surface of a granule, a gas bubble, a cylindrical shell, etc.), and not with the surface of the dimensions of the contacting bodies, may be active. A significant limitation can also be the presence of two generators of length l during the contact time of the heat flux through the surface; consideration of the asymptotics as $k \to \infty$ and the subsequent approximation make it possible to determine the desired error.

When evaluating heat transfer from a cylinder of circular cross section and a sphere to the outer region, the solution was used [23]. In fig. 3 the calculated dependences of the ratio of the heat transfer coefficient to its base value calculated for the flat boundary of the half-space according to O. Krisher [3] are constructed.

As can be seen from the figure, the model of short-term contact of phases is suitable for estimating $< \alpha >_{\tau_k}$ at larger Fo than in the case of estimating $\alpha(\tau)$ - regardless of the shape of the heating surface. With an approximate coincidence of the characteristic size of the body H with the radius of curvature of the heating surface R, the applicability of the model of short-term contact of phases is limited precisely by the presence of the curvature of the heating surface. For roller dryers H << R it is necessary to analyze the influence of both factors. For dryers with flat heating surfaces - the applicability of the model of short-term contact of phases is determined by the thickness of the product layer. Fig. 3 it can also be seen that Krisher's constraint (4) is unreasonably strict for engineering estimates of heat transfer from a flat heating surface.

For example, for industrial drum and rake dryers, the $\tau_k$ value does not exceed 60 s. For a $= 10^{-7}$ м$^2/c$ and the radius of curvature of curvature of the heating surface R = 1 m, the corresponding $Fo_\kappa$ do not exceed $6 \cdot 10^{-6}$, then is the influence of the curvature of the heating surface in accordance with table. 2 can be neglected. Taking the average thickness of the product layer H = 0.2 m, we get $F_0 \leq 1{,}5 \cdot 10^{-4}$. Thus, for these dryers, the application of the short-term contact model can be considered justified.

The maximum thickness of the layer heated by 3% of the total temperature head, in accordance with (4), here is no more than 8 mm. However, for cabinet, roller, etc. devices with a small layer thickness H, the question of the applicability of the short-term contact model requires a separate analysis in each case. In the presence of a large number of mates of the heating surface with small radii of curvature, additional analysis based on table. 2 may be needed for drum and stroke.

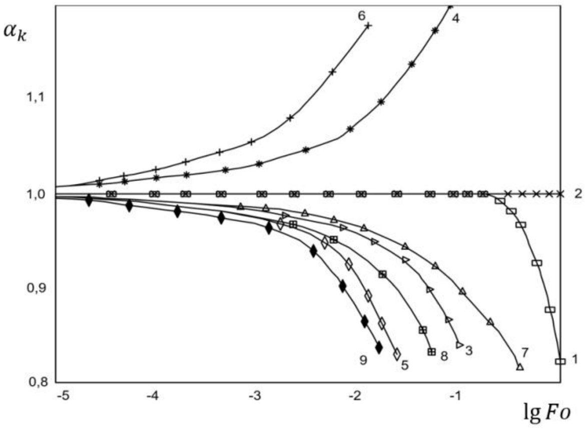


**Fig. 3**. The ratio of the calculated heat transfer coefficient to its value according to O. Krischer, depending on the Fourier number during heat transfer: 1.2 - respectively, into the interior and exterior of an infinite plate; 3.4 - into the interior and exterior of an endless cylinder; 5.6 - into the interior and exterior of the sphere; 7,8,9 - into the inside of an unlimited wedge with an opening angle of 150, 120 and 90 °, respectively.

| Coefficient heat transfer | Heating surface shape | Plane | | Cylinder | | Sphere | |
|---|---|---|---|---|---|---|---|
| | Error level, % | 3 | 5 | 3 | 5 | 3 | 5 |
| $\alpha(\tau)$ | $F_{0_{max}} \cdot 10^{-3}$ | 247 | 279 | 1,12 | 3,09 | 0,269 | 0,646 |
| $\alpha(\tau_k)$ | $F_{0k_{max}} \cdot 10^{-3}$ | 447 | 537 | 4,47 | 1,2 | 1,26 | 3,35 |

**Table 2**. The largest Fourier numbers at which the relative error in calculating $\alpha$ according to Krisher's formulas does not exceed 3% and 5%

When switching to multicomponent transfer, for a rough estimate, you can also substitute $v_{max}^2$ for a (or D). When considering the heat and mass transfer in two contacting phases, a more specific analysis is required, however, here $v_{max}^2$ plays a decisive role as well. devices.

## 3. Conclusions

The limits of applicability of the hypothesis of short-term contact of phases according to the Fourier criterion for the transfer inside and outside the surfaces of the canonical shape (plate, cylinder, sphere) and wedge are estimated from the standpoint of the accuracy of calculating interphase flows. It is shown that in a number of cases the contact is not short-lived due to the curvature and the presence of angles on the contact surface, and not due to the finiteness of the dimensions of the contacting phases.

Within the framework of linear nonequilibrium thermodynamics, a mathematical model of filtration-diffusion energy and mass transfer has been developed with a correct estimate of the orders of the terms in the system of differential equations of energy and mass transfer taking into account the composition of the vapor-air mixture in a capillary-porous body.

Depending on the value of the phase transformation criterion, the system of differential equations is simplified to three different systems of equations with the number of coupled equations in each no more than 2, describing the fields of temperature, humidity (concentration) and pressure, and the eigenvalues of the matrices of their coefficients are real, positive and different.

It has been established that during the transfer of a liquid, in the main one, in the form of vapor, the filtration-diffusion heat and mass transfer is expressed by the equations of diffusion heat and mass transfer with an increased coefficient of mass conductivity.

Boundary-value problems of diffusion and diffusion-filtration heat and mass transfer are solved under mixed boundary conditions of the first and second kind, on the basis of which integral kinetic dependences of drying processes (drying and heating rates), formulas for calculating heat and mass transfer coefficients, Rebinder numbers, temperature coefficients and subkinetic drying parameters.

Thus, a complex of theoretical and experimental studies has been carried out.

(using the methods of systemic, mathematical and numerical analysis, as well as general physicochemical and thermodynamic laws) transfer processes during short-term contact of phases (using the example of vacuum, conductive and combined drying methods), which made it possible to most fully reveal the laws of external and internal heat and mass transfer, to find scientifically grounded ways to intensify the considered processes

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