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# ПРИМЕНЕНИЕ МЕТОДА «МИКРОПРОЦЕССОВ» ДЛЯ МОДЕЛИРОВАНИЯ ПРОЦЕССОВ ТЕПЛОПРОВОДНОСТИ И ДИФФУЗИИ В ТЕЛАХ КАНОНИЧЕСКОЙ ФОРМЫ

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***В работе показано, что во многих технологических процессах сырьевые материалы подвергаются высокотемпеатурной термической обработке и, в большинстве своем, имеют геометрическую форму канонического вида: пластина, цилиндр и сфера. В качестве типового тепломассообменного процесса в работе рассмотрен процесс конвективной сушки. Процессы, протекающие в условиях термической обработки, приведены к задачам переноса для неограниченной пластины, цилиндра и шара с граничными условиями первого рода, когда на поверхности твердого тела задан потенциал переноса (температура, влагосодержание). Представлены выражения для расчетов в условиях произвольного распределения начальных значений потенциалов переноса, так и для равномерных распределений. Показано, что при моделировании тепловых и массообменных процессов, в которых теплофизические характеристики твердого тела существенно меняются во времени процесса термообработки, использование ранее разработанных известных решений становится проблематичным. Рассмотрены «зональный» метод и метод «микропроцессов». Показано, что для обоих методов, на основе экспериментальных данных о динамике температуры и массо - (влагосодержания) материала с течением времени процесса, определяют их зависимости от средних (по «зоне» или «микропроцессу») температур и массосодержаний. Последующим этапом для расчетов по «зональному» методу представлена формализация результатов, полученных в виде гистограмм значений коэффициентов массопроводности от средних значений массодержаний. Для метода «микропроцессов» в расчетах одновременно можно задействовать и кинетическую кривую. Адекватность расчетных экспериментальных данных тем больше, чем меньше диапазон измеряемых значений температур и массосодержаний. Отмечено, что при неравномерных начальных условиях аналитические решения задачи теплопереноса, как правило, представляются в форме бесконечных рядов Фурье. Сходимость ряда Фурье ухудшается с уменьшением временных интервалов. Большая актуальность применения рассмотренных методов прослеживается при моделировании тепломассопереноса с интенсивными процессами фазовых переходов.***

**Ключевые слова:** термическая обработка, тепломассоперенос, пластина, цилиндр, сфера, «зональный» метод, метод «микропроцессов»

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# APPLICATION OF «MICRO-PROCESSES» METHOD FOR MODELING HEAT CONDUCTION AND DIFFUSION PROCESSES IN CANONICAL BODIES

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***This paper shows that, in many technological processes, raw materials are subjected to high-temperature heat treatment and, in most cases, they have a geometric shape of the canonical form: a plate, a cylinder and a sphere. The convection drying process is considered as a typical heat and mass transfer process. The processes occurring under heat treatment conditions are reduced to transfer problems for an unbounded plate, cylinder, and ball with boundary conditions of the first kind, when the transfer potential (temperature, moisture content) is set on the surface of a solid. A number of expressions for calculations in the context of arbitrary distribution of initial values of transfer potentials as well as for uniform distributions are presented. It is shown that, when modeling heat and mass transfer processes in which the thermophysical characteristics of a solid body change significantly in the course of thermal treatment thereof, the use of already known solutions that have been previously developed becomes problematic. The «zonal» method and the «micro-processes» method are considered herein. It is shown that, for both methods, on the basis of experimental data referring to the dynamics of temperature and mass (moisture) content of the material over the course of the process, their dependences on the average (for the «zone» or «micro - process») temperatures and mass contents are determined. The next stage for calculations using the «zonal» method is formalization of the results obtained in the form of histograms of the values of mass conductivity coefficients from the average values of mass contents. For the «micro-processes» method, the kinetic curve can be used in calculations simultaneously. The smaller the range of measured values of temperatures and mass contents is the greater is the adequacy of calculated experimental data. It is emphasized that, under uneven initial conditions, analytical solutions to the heat transfer problem are usually presented in the form of infinite Fourier series. The convergence of the Fourier series deteriorates with decreasing time intervals. The great relevance of the application of the considered methods can be traced when modeling heat and mass transfer with intensive processes of phase transitions.***

**Key words:** heat treatment, heat and mass transfer, plate, cylinder, sphere, «zonal» method, «micro-processes» method

## INTRODUCTION

In many technological processes of chemical [1], construction [2, 3], food [4], textile [5] and other industries, the evolution of raw material to the final commodity product is accompanied by heat treatment of the material having a geometric shape in the so-called canonical form: a plate, a cylinder and a sphere.

Under such conditions, in bodies, regardless of the specific technology like drying plywood (boards) at woodworking enterprises or drying fabrics at textile enterprises, the material being processed can be represented from a geometric point of view by an unlimited plate. At the same time, modeling of the phenomena of heat and mass conductivity (diffusion in the solid phase) can be carried out on the basis of a unified theory of heat and mass transfer [6-9].

## METHODS OF THEORETICAL ANALYSIS

As a mathematical basis for solving boundary value problems of heat and mass transfer, the differential equation of non-stationary transfer of a substance (heat or mass of a substance) with the corresponding boundary (initial and boundary) conditions is used:

$$\frac{\partial\theta(x,\tau)}{\partial\tau} = div[\,К_{tr}(x,\tau)grad\theta(x,\tau)] \pm q_V(x,\tau) \quad (1)$$

where $\theta(x,\tau)$ – the potential of substance transfer for heat transfer; $\theta$ – temperature, *K*; $К_{tr}$ – the substance transfer coefficient depending arbitrarily on the transfer potentials ($К_t - a$ – thermal conductivity, $m^2/s$; $К_r$ – $k$ – mass conductivity (diffusion in the solid phase), $m^2/s$); $q_V(x,\tau)$ – specific volume source (flow) of heat or mass of the substance, respectively, *K/s*; $kg/(m^3 \cdot s)$, conditioned by the phase transition of the substance.

As a typical heat and mass transfer process, we will consider thermal convection drying [6, 10], which increases the temperature – *t*, and reduces the mass (moisture content – *u*. This changes the coefficients of heat and mass conductivity:

$$a = a(t,u); \qquad k = k(t,u) \quad (2)$$

The further analysis of the methodology will be performed with reference to transfer problems for an unbounded plate, cylinder, and ball with boundary conditions of the first kind, when the transfer potential (temperature, moisture content) is set on the surface of a solid body. Some examples of this type of problem for an unbounded plate are given in [7, 11].

In this case, for the sake of simplicity, we shall consider the condition which involves the absence of an internal source.

Solutions to the problems of non-interconnected internal transfer of heat and mass of a substance, provided that the transfer coefficients are constant, will be written in the form [8, 9]:

- for a plate:

$$\theta(x,\tau) = \frac{2}{R}\sum_{n,m=1}^{\infty} \sin(\mu_{n,m}\cdot\bar{x})\exp(-\mu_{n,m}{}^2 Fo_{n,m}) \times \times\int_0^R \theta_0(x')\sin(\mu_{n,m}x^{-1})dx' \quad (3)$$

- for a cylinder:

$$\theta(x,\tau) = \frac{2}{R^2}\sum_{n,m=1}^{\infty}\frac{J_0(\mu_{n,m}\cdot\bar{x})}{J_1^2(\mu_{n,m})}\exp(-\mu_{n,m}{}^2 Fo_{n,m})\times \times\int_0^R x'\theta_0(x')J_0(\mu_{n,m}x^{-1})dx' \quad (4)$$

- for a ball:

$$\theta(x,\tau) = \frac{2}{R}\sum_{n,m=1}^{\infty}\frac{1}{x}\sin(\mu_{n,m}\cdot\bar{x})\exp(-\mu_{n,m}{}^2 Fo_{n,m})\times \times\int_0^R x'\theta_0(x')\sin(\mu_{n,m}x^{-1})\,dx' \quad (5)$$

where $R$ – is half the thickness for an unlimited plate; radius, for a cylinder, or a ball; $\mu_{n,m}$ – the root of the corresponding characteristic equation; index n refers to heat transfer problems ($\mu_n, Fo_n$), and index $m$ – refers to mass transfer problems ($\mu_m, Fo_m$); $x$ – the dimensional coordinate, $x'$ – the current coordinate in the integration interval [*0-R*]; $\bar{x} = x/R$ – the dimensionless coordinate; $J_0$, $J_1$ – Bessel functions of order 0 and 1. It's worth noting that the calculations using expressions (3)-(5) allow us to obtain results for a arbitrary initial distribution of the transfer potential.

In a particular case, for uniform initial distributions of temperatures and mass contents, expressions (3)-(5) can be written in dimensionless form:

- for a plate:

$$\theta(\bar{x}, Fo_{n,m}) = \sum_{n,m=1}^{\infty} A_{n,m}^{p}(\mu_{n,m})\times \times\cos(\mu_{n,m}\bar{x})\exp(-\mu_{n,m}^2\, Fo_{n,m}) \quad (6)$$

- for a cylinder:

$$\theta(\bar{x}, Fo_{n,m}) = \sum_{n,m=1}^{\infty} A_{n,m}^{c}(\mu_{n,m})\times \times J_0(\mu_{n,m}\bar{x})\exp(-\mu_{n,m}^2 Fo_{n,m}) \quad (7)$$

- for a ball:

$$\theta(\bar{x}, Fo_{n,m}) = \sum_{n,m=1}^{\infty} A_{n,m}^{s}(\mu_{n,m})\times \times\frac{1}{x}\cdot\sin(\mu_{n,m}\bar{x})\exp(-\mu_{n,m}^2 Fo_{n,m}) \quad (8)$$

Where $A_{n,m}(\mu_{n,m})$ – coefficients of characteristic equations and, respectively, for heat and mass exchange problems will be:

$$\theta(\bar{x}, Fo_n) \rightarrow T(\bar{x}, Fo_n) = \frac{t(x,\tau)-t_c}{t_0-t_c} \quad (9)$$

$$\theta(\bar{x}, Fo_m) \rightarrow U(\bar{x}, Fo_m) = \frac{u(x,\tau)-u_0}{u_p-u_0} \quad (10)$$

Where $t(x,\tau)$ и $u(x,\tau)$ – values of physical quantities of temperature and mass (moisture) content; $t_o$, $u_o$ – the values at a certain point taken as the initial; $t_c$ – the temperature of the medium; $u_p$ – the equilibrium mass (moisture) content.

It is important to notice that the calculations using expressions (3)-(5) allow us to obtain results for an arbitrary distribution of transfer potentials, and the calculations using formulas (6)-(8) – only for uniform initial distributions of potentials.

## RESULTS AND DISCUSSION

For modeling heat and mass transfer processes in which the thermophysical characteristics of a solid body change significantly over time due to changes in *t* and *u*, the use of solutions becomes very problematic.

Fig. 1 shows typical curves of changes in temperature and humidity of the material during convection drying [6].

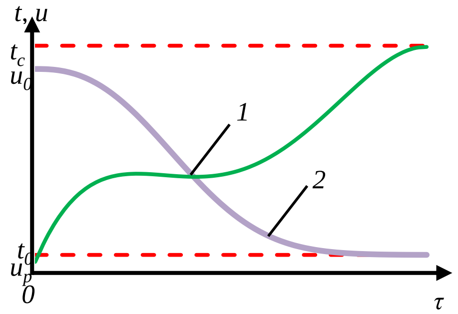


Fig. 1. Typical curves of changes in temperature (1) and humidity (2) of the material during convection drying
Рис. 1. Кривые изменения температуры (1) и влажности (2) материала при конвекционной сушке

Fig. 2 shows the data corresponding to this solution in respect of the change in the coefficient of thermal conductivity from temperature [3, 12], as well as the coefficient of mass conductivity as a function of mass content [9].

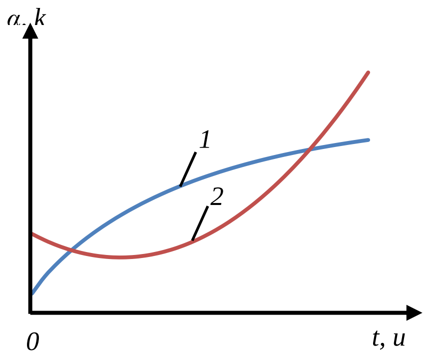


Fig. 2. Thermal curves of changes in the coefficient of thermal conductivity -1 (from temperature) and mass conductivity -2 (from mass content)
Рис. 2. Тепловые кривые изменения коэффициента температуропроводности - 1 (от температуры) и массопроводности - 2 (от массосодержания)

The difficulties in using these solutions lie in the significant dependence of the transfer coefficients on the values of local temperatures and mass contents at any given time of the process.

In this case, expressions (6)-(8), which allow calculating the dynamics of the fields of heat and mass transfer potentials based on the results of known values of the coefficients at the beginning of the process (at $\tau = 0$), will give increasing calculation error over time. Applying formulas (3)-(5) will lead to difficulties under the given initial condition.

However, the difficulties [10, 13, 14] that used to be principal before do not cause significant problems in calculations and design when using the «zonal» method [9] or the «micro-processes» method [3]. Both methods provide preliminary experimental information about changes in temperature and mass (moisture) content of the material during the process (kinetic curves during drying), and determine dependencies of the type of expressions (2) (usually in the form of power formulas).

The next stage for calculations using the «zonal» method is formalization of the results obtained in the form of histograms of the values of mass conductivity coefficients from the average values of mass contents. According to the «micro-processes» method, the kinetic curve is simultaneously used in the calculations.

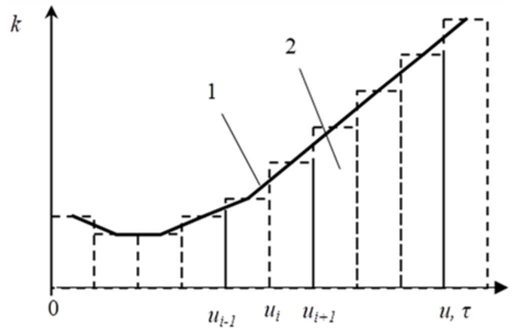


Fig. 3. Illustration for the «zonal» method and the method of «microprocesses»:1- kinetic curve of changes in average values of mass contents from time to time; 2- histograms of values of mass conductivity coefficients from average values of mass contents
Рис. 3. Иллюстрация к «зональному» методу и методу «микропроцессов»: 1- кинетическая кривая изменения средних значений массодержаний от времени; 2- гистограммы значений коэффициентов массопроводности от средних значений массодержаний

At the same time, the smaller the range of measured values of temperatures and mass contents, the greater the adequacy of the calculated and experimental data.

However, there is another practical difficulty: most analytical cases of the heat transfer problem for non-uniform initial conditions are presented in the form of infinite Fourier series. The convergence of the Fourier series deteriorates with decreasing time intervals (*Fo*). Overcoming this difficulty can be carried out either by improving solutions [8, 9], or by using an approximate method [3], the accuracy of calculations for which increases with a decrease in the time of the «micro-process».

## CONCLUSIONS

The value of the presented methods increases when modeling heat and mass transfer processes in which intensive phase transition processes occur. Examples of this are the results given in [15-23].

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