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KINETICS AND APPARATUS-TECHNOLOGICAL ARRANGEMENT OF CONVECTIVE DRYING OF DISPERSE POLYMER MATERIALS

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The laws of internal mass transfer under deep drying of granular polymers depending on their state have been considered. From the point of view of the system approach, the general problem of their drying kinetics has been decomposed into two basic levels: a micro- and a macroscopic one, and, in accordance with this, the questions of mathematical modeling have been analyzed. The experimental data on the diffusion and sorption properties and longitudinal mixing of the solid phase are presented and recommendations on the apparatus arrangement of the process are given.

In many industries (chemical, food, pharmaceutical), as well as in farming production, various disperse materials — granular, grained, powdery — are dried. Their drying process entails considerable energy and material expenditures and also has an appreciable effect on the quality of the products, which places stringent requirements upon the apparatus-technological arrangement and accuracy of the kinetic calculation of the drying stage.

The majority of polymer materials require thorough removal of water from the raw material in those processes where polymer melts are used as the basis. The presence of moisture in the polymer melt even in negligible quantities leads to serious consequences: destruction and hydrolysis of the melt, a decrease in the degree of crystallinity, mass foaming, deterioration of the strength properties, lowering of the quality of the surface of products, and local change in the chromaticity and inhomogeneity of their translucence. Moreover, for products made of sheeting and fibers, the dielectric indices worsen, the degree of uniaxial and biaxial orientation decreases, and cracks are formed.

Practically all producers of polymers and polymer materials use the drying process both at the production stage and in processing into products. Polymers in various aggregate states are subjected to drying: solutions and suspensions, pasty, fine-grained, and granular polymers [1, 2]. The drying conditions strongly influence the quality of the polymeric granulate.

Depending on the drying time, all polymers can be broken down into three groups [1–5]. The first group includes polymers whose particle size ranges from dozens to hundreds of micrometers. They contain mainly surface moisture that is easy to remove. The drying time of such materials measures seconds. The second group of polymers contains, besides the surface moisture, bound moisture, whose removal takes a few minutes. The third, the widest group, is represented by granular polymer materials whose particle sizes measure a few millimeters. It is characterized by a rather long drying time (a few hours) needed for the moisture diffusion inside the particles to their surface.

In a number of features of the course of the mass-transfer process in drying, polymers differ markedly from the classical porous disperse materials. Drying at the stage of polymer production is carried out most frequently upon extraction of the low-molecular compounds in an aqueous medium or upon granulation. In so doing, mainly in a short time (a few dozens of seconds), the surface moisture in apparatuses with an active hydrodynamic regime (tube-dryer, fluidized and spouted beds, apparatuses with counter swirling flows) is removed under intensive heat and mass transfer. The internal moisture is removed only partially or stays completely. This necessitates deep drying of the granulate just before its processing by methods using melts of polymer materials as the basis. Removal of internal moisture takes several hours, and it is inexpedient to carry out this process in apparatuses with intensive regimes.

While the classical porous disperse materials are characterized by a smooth transition from the first drying period to the second one with a ratio between the durations of the periods $(\tau_1/\tau_2) = (1/(5-10))$, for the granular poly-

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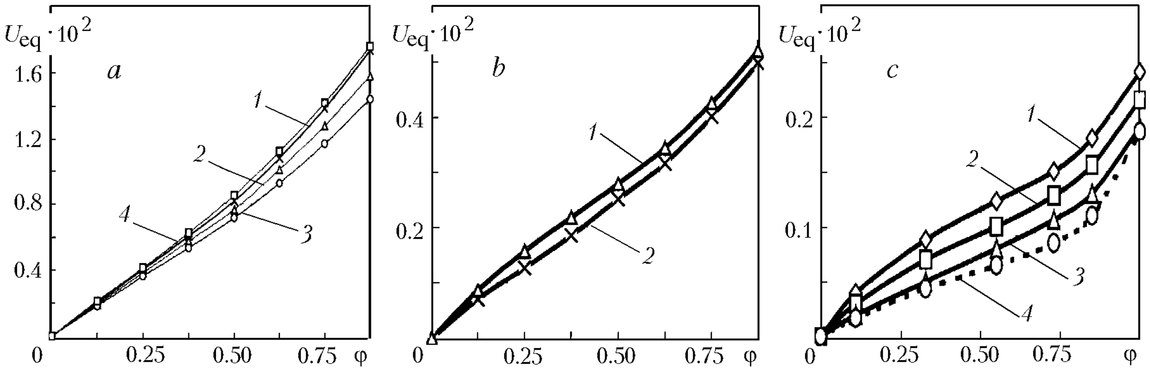


Fig. 1. Isotherms of water-vapor sorption and desorption for granular polymers: [a) P-12E polyamide [1) sorption, T = 303 K; 2) sorption, 333 K; 3) sorption, 363 K; 4) desorption, T = 303 K]; b) polycarbonate, T = 303 K [1) desorption; 2) sorption]; c) "Styron" polystyrene [1) sorption; T = 303 K; 2) desorption, 333 K; 3) desorption, 363 K; 4) sorption, T = 363 K].

mers an abrupt jump of the mass-transfer process from the region of interparticle diffusion drying (removal of external moisture) to the region of intraparticle diffusion drying (removal of internal moisture) is observed and the ratio between the drying periods is $1/(10^3–10^5)$.

The long duration of deep drying of granular polymers and its high power intensity and the insufficient study of the process stimulated the present work.

Investigations of the Hydrothermal and Diffusion Properties of Polymers. As the object of investigation, we chose granular polymers with a large value of the intraparticle diffusion drag that are of industrial importance: polyamides (P-12E, P-610L, P-610L-SV30), polystyrenes ("Styron," PSM-115, UPM-0703L), polycarbonate, polyethyleneterephthalate, polypropylene, ABC-plastic, and SFD-VM-BS. The chosen group contains the main types of polymers with respect to water (nonporous and porous ones) that are under the temperature conditions of production drying and are investigated in both the highly elastic (e.g., P-12E polyethylene, polyamides) and the glassy (e.g., polycarbonate) state.

Polymers can be considered to be inert to the substance being sorbed only in rare cases where the use of the mechanisms of adsorption and capillary condensation in solid porous bodies is justified. The interaction of water and water vapors with polymers in the general case is a combination of the processes of absorption, adsorption, capillary soaking, and chemisorption [4]. Predominance of a particular mechanism depends on the internal structure of the polymer, its compatibility with the sorbate, swelling, and many other factors. It should also be remembered that granular polymers in the absence of a special action aimed at developing a porous structure are characterized by a very small or zero porosity and a small specific surface [1, 4].

The investigation of the hydrothermal properties of the above-mentioned polymers has revealed the following facts. The sorption and desorption isotherms of the investigated nonporous polymers that are at experimental temperatures in the high-elasticity state display no capillary condensation (Fig. 1a). The practical absence of a hysteresis between the direct and inverse processes in these materials points to the absorption mechanism of moisture absorption by them and to the absence of transport-significant pores. The quantity of the absorbed low-molecular substance in them depends on the ratio between the amorphous and crystal phases of the polymer matrix [4]. It is known that a liquid is absorbed only by the amorphous part of the polymer and by the matrix defects [4]. The investigations have also shown that in nonporous polymers that are in the high-elasticity state under the experimental conditions a small temperature dependence of sorption is observed (Fig. 1a). Note that the desorption isotherms obtained at high temperatures are of great practical importance for determining the motive force of the process of deep drying of granular polymers, which is carried out until moisture-content values close to equilibrium are attained.

For nonporous polymers that are in the glassy state, a sorption–desorption hysteresis throughout the range of relative humidity of the medium is observed (Fig. 1b). In the presence of one capillary condensation a hysteresis is possible only in the region of large values of the relative humidity of air ($\varphi > 0.5–0.6$). As is seen from Fig. 1b, for the polycarbonate the hysteresis also covers the initial part of the sorption–desorption isotherms. Such a phenomenon is due to the low mobility of the glassy polymer macromolecules, which affects the rate of the relaxation processes. As the quantity of the sorbed substance increases, its plasticizing action manifests itself. The relaxation processes are promoted and the polymer structure comes closer to equilibrium. The sorption–desorption hysteresis for the glassy polymers is explained by the fact that the sorbate molecules, occupying the energetically advantageous sites in desorption, develop a pressure capable of moving individual elements of the supermolecular structure apart. In so doing, new sites accessible for the sorbate are formed to increase the sorption capacity. Thus, the form of the hysteresis loop for nonporous glassy polymers points to the absorption character of water absorption by them.

For "Styron" polystyrene that is in the glassy state under the experimental conditions, the presence of the sorption hysteresis is explained not only by such a state of this polymer but also by its microporous structure [1]. The porosity development in such materials is attributed to the appreciable local decrease in the volume of crystalline regions upon cooling of the polymer melt, which is a specific feature of the investigated polystyrene.

The hysteresis loop for the polystyrene (Fig. 1c) also covers the entire range of relative humidity of the medium but is even more pronounced than in the polycarbonate. This points to the presence of the absorption and adsorption mechanisms of sorbate absorption by this material. Thus, water absorption by "Styron" polystyrene occurs by both the absorption and adsorption mechanisms.

The major tasks of the investigations in the field of mass exchange in solid-phase systems are to obtain experimental data on the diffusion coefficients depending on the concentration of the component being distributed and to develop methods and experimental facilities for this purpose. Investigations have shown [1, 4] that at a limited solubility of low-molecular substances in polymers in most cases normal (not abnormal [1]) diffusion at which the moisture transfer obeys the Fick law is observed. The least deviations from the Fick law are noted for polymers in the high-elasticity state. The diffusion coefficient for such systems at a constant temperature depends only on the concentration. The time of the relaxation processes is insignificant; during the diffusion process the polymer-low-molecular substance system manages to acquire a structure close to equilibrium.

To determine the effective diffusion coefficient of water in the above polymers, we used the zone method [1]. It is based on integration of the diffusion differential equation provided D_{eff} is constant in a narrow range of change in the concentration of the component being distributed. The coefficient D_{eff} is found from the experimental drying curves obtained in the intraparticle diffusion kinetic regime. The thus-found dependences $D_{\text{eff}} = f(U)_t$ are given in Fig. 2. Their analysis permits the following conclusions.

The $D_{\text{eff}} = f(U)_t$ function for all investigated polymers containing no micropores increases with increasing moisture content of the material and strongly depends on the temperature (Fig. 2a–e). The low values of the diffusion coefficients (10^{-11}–10^{-9} m^2/sec) point to the moisture transfer in these polymers through molecular diffusion [1]. The increase in the effective diffusion coefficient with increasing concentration of the component being distributed at t = const can be explained by the fact that under diffusion of water molecules the number of microcavities between the polymer molecules increases. This phenomenon is connected with the plasticizing action of water and, in a number of cases, with the decrease in the degree of crystallinity of polymers. The presence of water in the polymer matrix appreciably weakens the intermolecular forces and determines the higher segment mobility. In this case, the temperature dependence of the effective diffusion coefficient is well described by the Arrhenius equation:

$$D_{\text{eff}} = D_{\infty} \exp\left(-\frac{E_D}{R_{\text{g}}T}\right). \tag{1}$$

The effective (observable) diffusion coefficient D_{eff} is a complex quantity incorporating the diffusion coefficient D_{A} of the low-molecular substance, the thermodynamic factor taking into account the imperfection of the system, the parameters giving a correction for the compensation flow caused by the polymer matrix immobility, the structural factor, and the degree of crystallinity [6].

The diffusion activation energy decreases with increasing moisture content of the material. This phenomenon is in good agreement with the hole conduction theory. The decrease in the activation energy is due to the plasticizing action of water, leading to an increase in the mobility of molecular segments of the polymer, as a result of which the potential barrier that the diffusant molecule escapes when jumping from one position of local dislocation to another is lowered. The activation energy for the investigated polymeric materials is in the 20–60 kg/mole range, which agrees with the data of other investigations (E_D = 20–50 kJ/mole [4]).

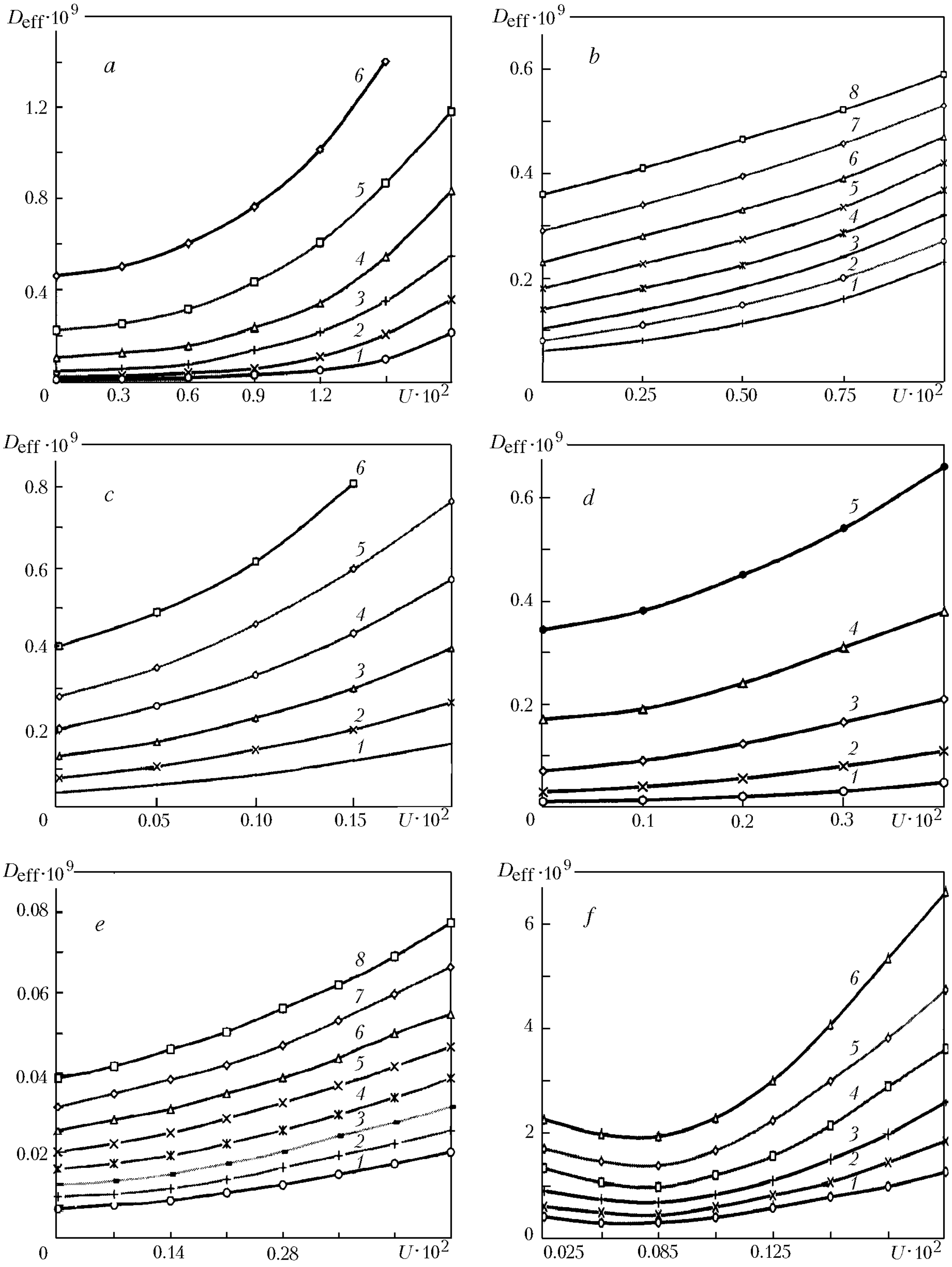


Fig. 2. Temperature–moisture dependences of the effective diffusion coefficient of moisture in granular polymers: a) P-12E polyamide [1) T = 343 K; 2) 363; 3) 383; 4) 403; 5) 423; 6) 443]; b) P610-L polyamide [1) 323 K; 2) 333; 3) 343; 4) 353; 5) 363; 6) 373; 7) 383; 8) 393]; c) polypropylene [1) 323 K; 2) 343; 3) 363; 4) 383; 5) 403; 6) 423]; d) polycarbonate [1) 343 K; 2) 363; 3) 383; 4) 403; 5) 423]; e) SFD VM-BS [1) 323 K; 2) 333; 3) 343; 4) 353; 5) 363; 6) 373; 7) 383; 8) 393]; f) "Styron" polystyrene [1) T = 303 K; 2) 313; 3) 323; 4) 333; 5) 343; 6) 353].

The $D_{\text{eff}} = f(U)_t$ dependences for the investigated nonporous materials are well approximated by a formula of the form

$$D_{\text{eff}} = D_0 \exp\left[-bU - \frac{E_{D0}(1 - dU)}{R_g T}\right], \tag{2}$$

where D_0 is the formal value of the effective diffusion coefficient at $T \to \infty$; b and d are constants; $b > 0$; $0 < dU < 1$.

From a comparison of Eqs. (1) and (2) we have $D_\infty = D_0 \exp(-bU)$, $E_D = E_{D0}(1 - dU)$. The constant b characterizes the influence of the moisture content on the diffusant molecular mobility and the constant d — that on the value of the diffusion energy barrier. With decreasing moisture content of the material the diffusant molecular mobility D_∞ decreases (due to the increase in the diffusion drag coefficient), and the diffusion energy barrier also falls. Since the second factor predominates, the coefficient D_{eff} in these polymers increases with their moisture content.

Analysis of the experimental functions $D_{\text{eff}} = f(U)_t$ for granular polymers containing micropores (Fig. 2f) shows that, unlike the analogous functions for nonporous polymers, they have a configuration somewhat concave to the abscissa axis. This points to the presence in the region of low moisture contents of the material of additional mass-transfer mechanisms characteristic of micropores (vapor diffusion, surface diffusion [1]). In general, the effective diffusion coefficients of moisture in these materials have the same order as in the nonporous materials.

Analysis of the temperature–moisture dependences of the effective diffusion coefficient of water for the investigated polymers points to a strong dependence of the coefficient D_{eff} on the transfer potential and, consequently, to the necessity of taking into account the influence of the varying temperature and moisture state of the material in the course of the process on its drying kinetics in real apparatuses.

Kinetic Calculation of the Process. The development of methods for kinetic calculation of continuous convective drying of disperse materials is characterized by a gradual departure from the various empirical methods and a wider and wider application of mathematical methods: 1) pure mathematical, analytical, and numerical methods; 2) mixed ones combining a mathematical method with the obtaining of additional experimental information on the basis of physical modeling of the process [7].

One can distinguish two radically differing approaches to the description of the drying kinetics of disperse materials in a continuously operating apparatus. The first approach consists of choosing a mobile (Lagrange) coordinate system connected to the centers of particles moving in the apparatus. The second approach is based on the use of an immobile (Euler) coordinate system fixed on the apparatus frame [8].

The process of deep drying of polymeric materials from internal moisture has the following kinetic features:

1) because of the large value of the interparticle diffusion drag, the rate of the process is totally controlled by the moisture migration inside the particles;

2) the equilibrium moisture of the material is comparable to its final moisture and has an appreciable effect on the drying kinetics;

3) in the process of drying, the material is quickly heated to the drying-agent temperature and the drying proceeds under the conditions of practical equality of the temperatures of the interacting phases (balance heat-transfer problem).

The first conclusion can be drawn by analyzing the Bi_m number [1] expressing the ratio between the external and internal diffusion drags in the process of drying polymer particles. In real processes of drying granular polymers, $\text{Bi}_\text{m} = 10^3$–$10^6$, which points to a pure internal mass-transfer problem [1].

The nonisothermality of the mass-transfer process in the course of drying polymer particles can be estimated on the basis of the following relation:

$$\text{HMC} = \frac{\tau}{\tau_\text{m}} = (\mu^2_{n=1} / \mu^2_{k=1})\,\text{Lu}\,, \tag{3}$$

where τ and τ_m are the relaxation times of the heat and mass transfer potentials to equal values of $\overline{\Theta}^*$ and $\overline{E}$, respectively.

The coefficients $\mu_{k=1}$ and $\mu_{n=1}$ are the first roots of the characteristic equations of the heat and mass conduction problems [1], which, in particular, for spherical granules are determined by the relations [1, 8]

$$\tan \mu_k = -\frac{\mu_k}{\mathrm{Bi_m} - 1}\,, \quad \tan \mu_n = -\frac{\mu_n}{\mathrm{Bi_m} - 1}\,.$$

The calculations by Eq. (3) for granular polymers under real drying conditions yield values of HMC = 10^{-2}–10^{-4}, which points to a quick heating of a moist material to the drying-agent temperature. This conclusion is corroborated by experimental measurements [1].

The form of particles of granular polymers is close to the canonical form (bounded plate or cylinder, sphere). The particle form and sizes are invariable in the course of the process and, as mentioned above, the mass-transfer kinetics is totally controlled by the intraparticle diffusion drag, and the heat-transfer problem is balanced. In this case, to describe the drying kinetics, it is expedient to use a mobile system of coordinates and calculate the microkinetics on the basis of the solution of the differential equation of moisture diffusion in the granule, and the macrokinetics — on the basis of the differential distribution functions of granules in dimensions and their residence time in the dryer. In the latter case, hydrodynamic models of the structure of the flows based on the corresponding distribution function are also applicable.

According to such an approach, we represent the mathematical model of the moisture-diffusion process at the microkinetic level for a spherical granule in the following form:

$$\frac{\partial U(r, \tau)}{\partial \tau} = \frac{1}{r^2}\frac{\partial}{\partial r}\left[rD(U, t)\,\frac{\partial U(r, \tau)}{\partial r}\right], \quad 0 < r < R\,, \quad \tau > 0\,; \tag{4}$$

$$U(r, \tau) = U_{\mathrm{in}}(r)\,, \quad 0 \le r \le R\,, \quad \tau = 0\,; \tag{5}$$

$$U(r, \tau) = U_{\mathrm{dr}}\,, \quad r = R\,, \quad \tau > 0\,; \tag{6}$$

$$\frac{\partial U(r, \tau)}{\partial r} = 0\,, \quad r = 0\,, \quad \tau > 0\,. \tag{7}$$

To describe the microkinetics of the deep drying process by Eqs. (4)–(7), one can use the experimental data on the hygrothermal $U_{\mathrm{eq}} = f_1(U, t)$ and diffusion $D_{\mathrm{eff}} = f_2(U, t)$ properties of the polymeric materials considered above.

On going, in describing the kinetic process, from the micro- to the macrolevel, of great importance is the account for the dimension nonuniformity of the granules and the difference in their residence time in the dryer. These factors are important not only for the kinetic calculation accuracy but also for the drying uniformity, i.e., for the quality of the dried product. This is particularly important for polymeric materials, since the use of a nonuniformly dried polymer granulate leads to defects when it is processed into products.

The difference in the granules' residence time in a continuously operating dryer depends on the structural arrangement of the latter and the looseness of the material. The influence of the above difference on the average moisture content of the material at the exit from dryer $\overline{\overline{U}}$ can be taken into account by the equation

$$\overline{\overline{U}} = \int\limits_{R_{\min}}^{R_{\max}} f(R) \int\limits_{0}^{\infty} f(\tau)\, \overline{U}(R, \tau)\, dR d\tau\,, \tag{8}$$

where $f(R)$ and $\overline{\overline{F}}(\tau)$ are the differential mass functions of the distribution of granules in dimensions and their residence time in the dryer; $\overline{U}(R, \tau)$ is the microkinetics dependence for isolated granules of dimension R.

We performed a numerical analysis of the influence of the considered nonuniformities on the kinetics of intraparticle diffusion drying of granular polymers. To this end, we used the solution of the differential equation of moisture diffusion in the material under the constant boundary condition [1]

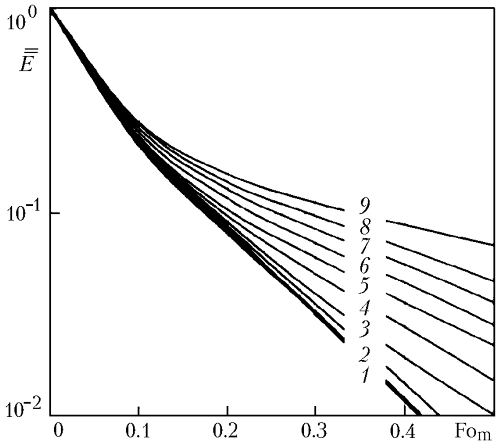


Fig. 3. Dependences $\bar{\bar{E}} = f(\mathrm{Fo_m})$ for spherical particles: 1) $\sigma_R = 0$; 2) 0.1; 3) 0.2; 4) 0.3; 5) 0.4; 6) 0.5; 7) 0.6; 8) 0.75; 9) 1.0.

$$\bar{E} = \sum_{n=1}^{\infty} B_n \exp\left(-\mu_n^2 \mathrm{Fo_m}\right) , \tag{9}$$

where B_n and μ_n are the pre-exponential factors and roots of the characteristic equation depending on the particle form.

For normal laws of size and residence-time distribution of particles

$$f(R) = \frac{1}{\sigma_R \sqrt{2\pi}} \exp\left[-\frac{(R - \bar{R})^2}{2\sigma_R^2}\right] , \tag{10}$$

$$f(\tau) = \frac{1}{\sigma_\tau \sqrt{2\pi}} \exp\left[-\frac{(\tau - \bar{\tau})^2}{2\sigma_\tau^2}\right] \tag{11}$$

a) for taking into account the polydispersity

$$\bar{\bar{E}} = \sum_{n=1}^{\infty} \frac{B_n}{\sigma_\Psi \sqrt{2\pi}} \int_{R_{\min}}^{R_{\max}} \exp\left[-\left(\mu_n^2 \frac{\mathrm{Fo_m}}{\Psi^2} + \frac{(\Psi - 1)^2}{2\sigma_\Psi^2}\right)\right] d\Psi ; \tag{12}$$

b) for taking into account the difference in the residence time

$$\bar{\bar{E}} = \sum_{n=1}^{\infty} \frac{B_n}{\sigma_\Theta \sqrt{2\pi}} \int_{0}^{\infty} \exp\left[-\left(\mu_n^2 \mathrm{Fo_m}\Theta + \frac{(\Theta - 1)^2}{2\sigma_\Theta^2}\right)\right] d\Theta , \tag{13}$$

where σ_τ^2 and σ_R^2 are the variances in the values of τ and R; $\sigma_\Psi = \sigma_R/\bar{R}$ and $\sigma_\Theta = \sigma_\tau/\bar{\tau}$ are the relative r.m.s. deviations; $\bar{R} = \int_{R_{\min}}^{R_{\max}} f(R)RdR$ and $\bar{\tau} = \int_0^\infty f(\tau)d\tau d$ are the mean values (mathematical expectations) of the quantities R and τ.

On the basis of the numerical solution of Eqs. (12) and (13), the influence of the variances in σ_Ψ and σ_Θ on the dependence of the relative moisture content $\bar{\bar{E}}$ on the number $\mathrm{Fo_m}$ for spherical particles has been analyzed. Figure

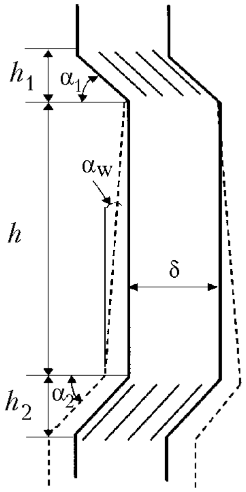


Fig. 4. Diagram of the experimental facility for investigating the structure of the solid-phase flow in the shaft dryer.

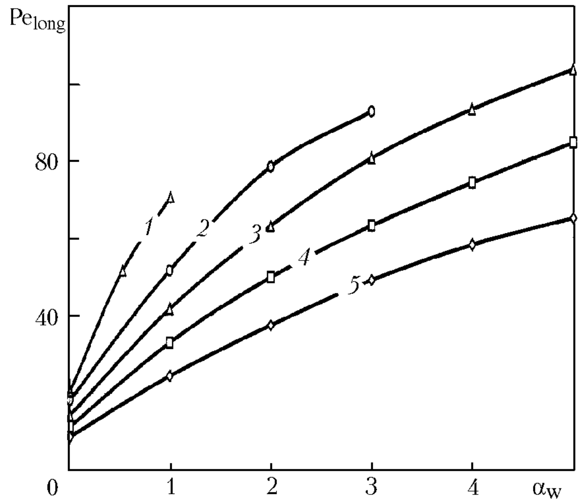
3 shows the dependences $\bar{\bar{E}} = f(\mathrm{Fo_m})_{\sigma_R}$ obtained as a result of these calculations (the functions $\bar{\bar{E}} = f(\mathrm{Fo_m})_{\sigma_\tau}$ have an analogous character [9]).

The consideration of the plots of these functions shows that in the presence of nonuniformities of the distribution of particles in their size and residence time in the dryer the calculation by only the mean values of $\bar{r}$ and $\bar{\tau}$ leads to an appreciable underestimation of the value of $\bar{\bar{E}}$; with increasing variances in σ^2_Ψ and σ^2_Θ, the error due to the neglect of these nonuniformities increases and at a value of $\bar{\bar{E}} = 2\cdot10^{-2}$ characteristic of deep drying of disperse polymers the relative error in determining the necessary dwell time of the material in the dryer at σ^2_Ψ and $\sigma^2_\Theta > 0.25$ reaches 10% or more. Analysis of the granulate polydispersity of various polymers and the structure of its flow in continuously operating shaft dryers shows that direct kinetic calculation of the macrokinetics of the process of their deep drying (to determine the necessary dwell time of the material in the dryer) should take into account the data on the material polydispersity and the intensity of its longitudinal mixing in the dryer.

Apparatus Arrangement of the Process. In accordance with the above kinetic mechanisms of deep drying of granular polymers, to carry out this process it is expedient to use apparatuses with inactive hydrodynamics — dryers of the shaft (column) type. The traditionally used apparatuses with a flat layer have the disadvantage that the height of the blown material layer in them is large. This leads to a large hydrodynamical drag of the layer, a deterioration of the hydrodynamical structure of the external phase flow, and a nonuniform drying of the material. An alternative solution to the problem of organizing the heat-and-mass exchange of a close-packed grained layer with a gas flow is the use of dryers with a ring layer pierced in the radial direction in which the blown layer thickness is independent of its height. With the use of these dryers periodic processes of heating, cooling, drying, and adsorption are carried out. In the last few years, they have also been used to carry out continuous drying processes. However, the hydrodynamics of the solid-phase flow in these apparatuses is still not clearly understood.

Below, we present the results of investigations of the hydrodynamics of the solid-phase flow performed on cold models of shaft (column) dryers with vertical and downward-expanding walls under continuous motion through the apparatus of a close-packed layer of a granular polymer.

The working chamber of the apparatus (Fig. 4) had the shape of a rectangular parallelepiped with a vertical shaft height $h = 1.5$ m. The front and rear walls of the chamber were made of glass for visual observation of the layer structure. The side walls were both smooth — from a metal sheet (steel or aluminum) and rough — from a wire netting with a wire diameter of 0.4 mm and a mesh size of 2.2 × 2.2 mm. The shaft with smooth walls modeled a dryer with axial feeding of the drying agent and that with rough (netlike) walls — a dryer with transverse motion. The possibility of setting the side walls with a departure from the vertical line by an angle α_w of up to 10^o was provided; the rate of motion of the material was given by a sector-type feeder. The layer thickness was varied over the 0.08–0.30-m range. Its minimal thickness ($\delta > 40R$) was chosen from the condition of the absence of arching and flow rate pulsations [10].



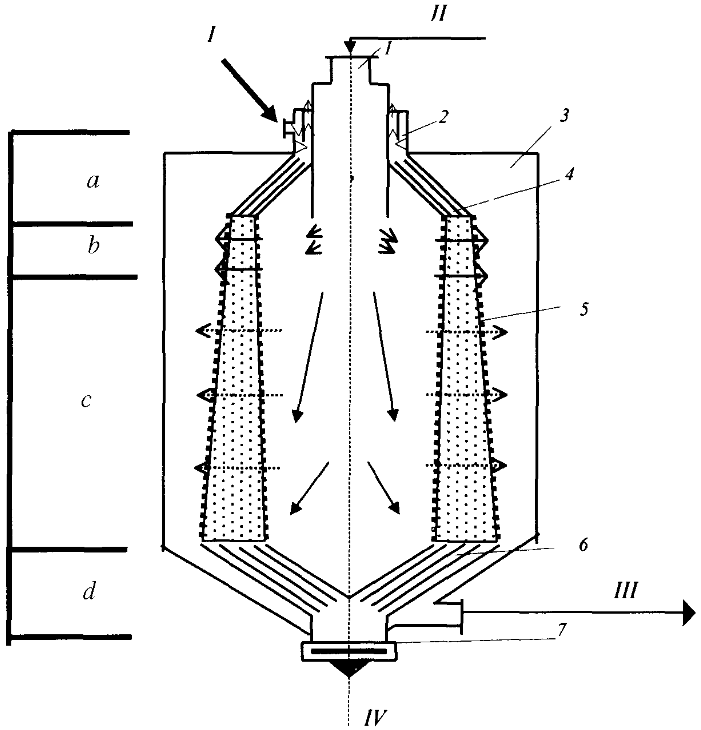


Fig. 5. Dependence $Pe_{long} = f(\alpha_w)$ for *ABC*-plastic under motion in the layer (side wall material–net) for various values of the layer thickness: 1) 0.3; 2) 0.25; 3) 0.2; 4) 0.15; 5) 0.1 m.

Fig. 6. Shaft single-zone dryer with a ring layer of disperse polymer: 1) union for supplying the heat-transfer agent; 2) moist material feed chamber; 3) used heat-transfer agent collector; 4, 6) director cones; 5) outer perforated cone; 7) union for removing dried material with a rotary table feeder; I) moist polymer (pneumatic transport); II) heat-transfer agent; III) used heat-transfer agent; IV) dried polymer; a) zone of loading and formation of a material layer; b) material heating zone; c) isothermal drying zone; d) unloading zone.

As a result of the experiments, it has been established that in the dryer with smooth walls the granules move in the regime of ideal displacement if the stagnation regions in the loading and unloading zones of the apparatus have been eliminated.

For the investigated granular polymers, the angles of their natural γ_n and dynamic γ_d slopes have been determined. It has been established that the values of γ_n are in the range of 31–36^o and the values of γ_d are in the range of 53–65^o, i.e., $\gamma_d \approx 2\gamma_n$, which is characteristic of highly free-flowing materials. To prevent the formation of a stagnation region in the lower part of the apparatus, the slope angle of the wall in its outlet part with the horizontal plane α_2 should be larger than γ_d (Fig. 4).

The high roughness of the netlike walls determines the significant nonuniformity of the distribution of the solid flow rates on the shaft cross section. For many polymers, (e.g., polyamides), a long stay in the dryer (longer than the estimated time) leads to an overdrying or a thermal destruction of the material, which has a negative effect on the quality of products in processing polymer melts.

In global practice of mathematical modeling of the hydrodynamics of the flow in continuously operating dryers, the diffusion model of longitudinal mixing, according to which, for the type of dryers under consideration ("closed" vessel according to the classification of [12]), the relationship between the parameters Pe_{long} and σ^2_Θ is defined by the relation

$$\sigma_{\Theta}^{2} = \frac{2}{\mathrm{Pe}_{\mathrm{long}}} - \frac{2}{\mathrm{Pe}_{\mathrm{long}}^{2}} + \frac{2}{\mathrm{Pe}_{\mathrm{long}}^{2}} \exp\left(-\mathrm{Pe}_{\mathrm{long}}\right) , \qquad (14)$$

has gained wide acceptance.

In the experiments performed with the use of the method of introduction of a labeled substance [11] (colored granules), the variance of granules in their residence time in the dryer was studied. The values of σ_{Θ}^{2} for various experimental conditions were calculated by the experimental data obtained and then $\mathrm{Pe}_{\mathrm{long}}$ was calculated by Eq. (14). The varied parameters in the experiments were the angle α_w and the layer thickness δ; the rate of motion of granules was constant and equaled $5 \cdot 10^{-4}$ m/sec. The material investigated in the experiments on the longitudinal mixing was *ABC*-plastic (cylindrical granules of size 3 × 3 mm).

The results of the experiments are given in Fig. 5 as the dependence $\mathrm{Pe}_{\mathrm{long}} = f(\alpha_w)$. As is seen from Fig. 5, at $\alpha_w = 0$ in the dryer with netlike walls an intensive longitudinal mixing of the solid phase takes place, and the intensity increases with decreasing thickness of the layer, which is explained by the increase in the portion of the inhibited-wall layers of the material. As α_w is increased, the effect of longitudinal mixing decreases. At $\alpha_w = 2.5^{\circ}$ the number $\mathrm{Pe}_{\mathrm{long}} \geq 40$ and, consequently, the structure of the solid-phase flow is close to the regime of ideal displacement.

Thus, the investigations performed have shown that the following constructional arrangements can be recommended for improving the structure of the solid-phase flow in shaft dryers (Fig. 6):

1. Longitudinal sectionalization of the dryer's units for feeding and withdrawing the material with a spacing between the sectionalizing guides $\delta_1 = (14\text{–}20)R$. The regime of motion of granules in such thin layers is analogous to the motion on slide boards, and the influence of the higher-lying layers of the material is leveled thereby [10].

2. Downward extension of the material layer in the vertical part of the apparatus — when the side walls of the dryer are made of a net of the investigated type — at an angle $\alpha_w \approx 2.5^{\circ}$, eliminating the negative influence of the higher roughness of the apparatus walls.

NOTATION

$A_{eq} = U_{eq}/C_{dr}$, slope of the phase-equilibrium line (kg/kg)/(kg/m^3); C, vapor concentration, kg/m^3; D, diffusion coefficient, m^2/sec; D_{long}, longitudinal diffusion coefficient, m^2/sec; D_{eff}, effective diffusion coefficient of moisture in the granule, m^2/sec; E_D, diffusion activation energy, J/mole; h, height of the working zone in the dryer, m; l_s, flow length, m/sec; r, radial coordinate, m; R, particle radius, m; R_g, universal gas constant, J/mole·K); U and $\overline{U}$, local and granule-volume average moisture content of the material, respectively, (kg of moisture)/(kg of material); v, velocity, m/sec; t and T, temperature, $^{\circ}$C and K; $\overline{t}$, volume-average temperature of the granule, $^{\circ}$C; β, mass-transfer coefficient, m/sec; ρ_0, density of absolutely dry material, kg/m^3; τ, time, sec; φ, relative air humidity, dimensionless; $\mathrm{Bi}_m = \beta R/(A_{eq}\rho_0 D_{eff})$, mass-transfer Biot number; $\overline{E} = (\overline{U} - U_{eq})/(U_{in} - U_{eq})$; $\overline{\overline{E}} = (\overline{U} - U_{eq})/(U_{in} - U_{eq})$, relative moisture contents of granules; HMC, heat and mass exchange criterion; Lu, Luikov number; $\mathrm{Pe}_{long} = v_{sol} l_{sol}/D_{long,sol}$, Peclet number for solid-phase longitudinal diffusion; Fo, mass-transfer Fourier number; $\overline{\Theta}^{*} = (t - t_{sol})/(t_{in} - t_{sol})$, relative volume-average temperature of the granule. Subscripts: g, gas; d, dynamic slope; n, natural slope; in, initial; long, longitudinal diffusion (longitudinal mixing); eq, equilibrium; dr, drying agent; w, wall; sol, solid phase; eff, effective; m, mass-exchange; max, maximum value; min, minimum value; 1, loading zone; 2, unloading zone; ∞, at $T \to \infty$; 0, at $U \to \infty$.

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