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NUMERICAL MODELING OF HEAT AND MASS TRANSFER DURING THE DRYING OF GRANULATED POLYMERS IN A PACKED BED

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A model is proposed for calculating heat and mass transfer in a packed bed exposed to a drying agent. Results are presented from a numerical realization of the model for the drying of granulated polyamide of type PA-6.

In connection with the continual and substantial increase in the volume of plastics that is processed in industry, the drying of these materials has become an important issue. Processing plants currently use several different drying methods — vacuum drying, drying in fluidized beds, and convective drying. Meanwhile, there are no scientifically substantiated recommendations on the most expedient drying methods for different types of materials. The goal of the present investigation is to numerically model the high dessication of a dispersed polymer in a packed bed injected with dried air.

We know of several studies which have examined similar problems [1-4]. However, either the methods used in these studies are too laborious or the formulations involve limitations that make it difficult to obtain detailed results.

For example, the authors of [1-3] examined internal mass transfer on the basis of the equations of A. V. Lykov. Such an approach complicates the problem excessively for materials such as polymides, polycarbonates, and ABS-plastics. First of all, considering the relatively small dimensions of the grains, the temperature gradients which develop inside them during normal heating regimes should not be very large. Thus, it is possible to exclude the heat-conduction equation for the grains and to ignore thermodiffusional transport of mositure. Secondly, the evaporation of moisture in such materials occurs only on the surface of the grains, since there is almost no capillary-pore structure inside them. Thus, it also makes no sense to employ a phase transformation criterion. The main advantage of the model used in [4] is the use of enthalpy instead of temperature to describe the energy state of the medium. Such an approach permits a thermodynamically more rigorous accounting of processes involving the transport of moisture between the air and the material. At the same time, this model does not contain a diffusion equation and thus may yield sizable errors for materials with a large diffusional component. It also fails to account for certain other physical factors, such as changes in injection rate in relation to an increase or decrease in the quantity of water vapor in the gas-air flow.

The model of the process which we propose here provides a better foundation for allowance for all of the main factors in the process while not being excessively difficult in a methodological sense. The following physical limitations are used in the model: the material is

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represented as consisting of monodisperse granules (grains) with the same geometric form; the sizes of the granules are considerably smaller than the geometric dimenions of the bed; heat conduction by the material and air along the x axis is negligible compared to the convective component; since the Lykov criterion for grains is small (Lu $\approx 1 \cdot 10^{-4}$), the heat-conduction equation can be excluded from the system of equations used in the model. The problem is examined in a unidimensional approximation.

The mathematical model includes the following equations:

the continuity equation for the air and the vapor

$$\frac{\partial \rho_a}{\partial t} + \frac{\partial}{\partial x}(V_g \rho_a) = 0, \tag{1}$$

$$\frac{\partial \rho_v}{\partial t} + \frac{\partial}{\partial x}(V_g \rho_v) = J; \tag{2}$$

the energy conservation equation for the gas and the moist material

$$\frac{\partial H_g}{\partial t} + \frac{\partial}{\partial x}(V_g H_g) = -E, \tag{3}$$

$$\frac{\partial H_{m.m}}{\partial t} = E; \tag{4}$$

the equation for the diffusion of moisture in the material

$$\frac{\partial \rho_{ms}}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \gamma) = 0, \quad \gamma = -D\frac{\partial \mathring{\rho}_{ms}}{\partial r}. \tag{5}$$

The pressure of the vapor—air mixture is taken to be constant

$$p = \mathrm{const}, \tag{6}$$

while p = $p_a = p_v$, where

$$p_a = \frac{\rho_a}{\varepsilon} R_v T_g; \quad p_v = \frac{\rho_v}{\varepsilon} R_v T_g. \tag{7}$$

The relationship between enthalpy and temperature is defined by the equations

$$\begin{gathered} H_g = \rho_v h_v(T_g) + \rho_v h_v(T_g), \\ H_{m.m} = \rho_m h_m(T_{m.m}) + \rho_{ms} h_{ms}(T_{m.m}), \ \rho_m = (1-\varepsilon)\mathring{\rho}_m, \\ \rho_{ms} = \frac{(1-\varepsilon)}{\frac{4}{3}\pi R^3}\int_0^R \mathring{\rho}_{ms}(r)\, 4\pi r^2 dr, \\ h_a = c_a T_g; \ h_v = c_v T_g; \ h_m = c_m T_{m.m}; \\ h_{ms} = c_{ms} T_{m.m} - \varkappa. \end{gathered} \tag{8}$$

The equation for the velocity of the gas follows from (1-8)

$$\frac{\partial V_g}{\partial x} = \frac{J R_v T_g}{P} - \frac{E + J c_v T_g}{H_g}. \tag{9}$$

To determine the rate of evaporation, we used the relations

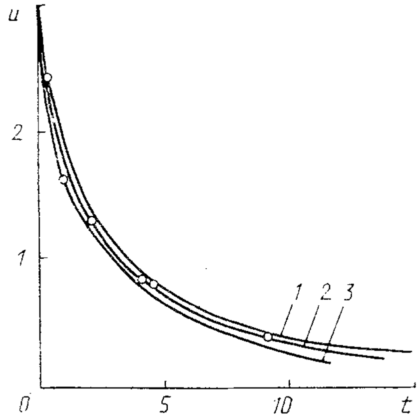

Fig. 1. Dependence on time t (h) of the bed-averaged moisture content $\bar{u}$ (%) of the material for different values of moisture content in the injected air: 1) $u_{in} = 12$ g/kg; 2) 6; 3) 1.

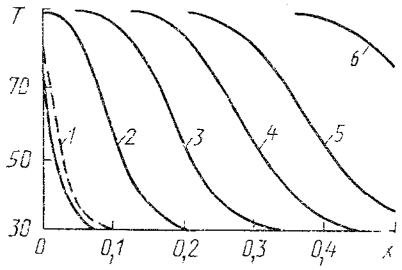

Fig. 2. Distribution of the temperature T (deg C) of the polymer (solid curves) and air (dashed curve) over the height x (m) of the bed for different moments of time: 1) t = 1 min; 2) 5; 3) 10; 4) 15; 5) 20; 6) 30 min.

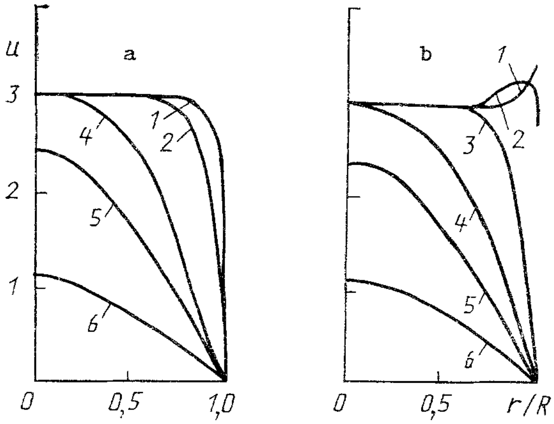

Fig. 3. Distribution of moisture content u (%) through the thickness of the grains at the beginning (a) and end (b) of the bed of polymer for different moments of time: 1) t = 5 min; 2) 20; 3) 30 min; 4) 2 h; 5) 4; 6) 8 h.

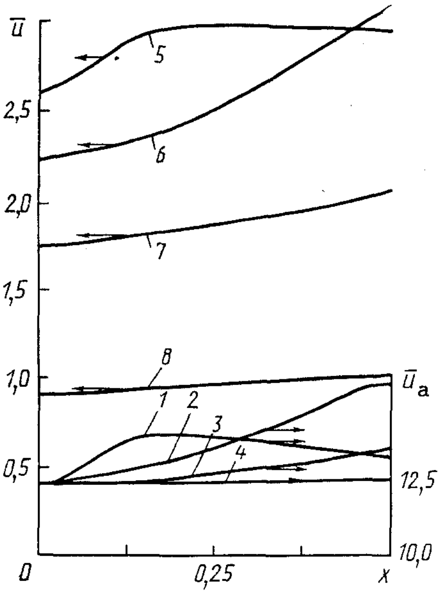

Fig. 4. Distribution of moisture content $\bar{u}$ (%) of the material and air $\bar{u}_a$ (g/kg) over the height of the bed with an injected-air moisture content u_{in} = 12 g/kg for different moments of time: 1) t = 5 min; 2) 20 min; 3) 1 h; 4) 4 h; 5) 5 min; 6) 20 min; 7) 1 h; 8) 4 h.

$$J = Fj,\quad j = \beta(p_e(u_e,\ T_{m.m}) - p_v). \tag{10}$$

The mass-transfer coefficient β was found from the criterional equation [5]: $Nu_m = 1.3 \cdot Re^{0.5} Pr^{0.33} Gu^{0.135}$; Re = 100 ÷ 810. The determining dimension here is the diameter of the grains. The velocity of the air is referred to the cross section of the channels in the bed, while the values of the physical parameters are taken for the average temperature of the boundary layer.

The rate of energy transfer includes the heat flux transmitted from the gas to the moist material and the energy flux removed from the material by the evaporating moisture:

$$E = Fq - Jh_v(T_{m.m}). \tag{11}$$

The heat flux is equal to

$$q = \alpha(T_g - T_{m.m}),$$

where α is determined from the criterional equation [5]: $Nu = 1.43\ Re^{0.5} \times Pr^{0.33} Gu^{0.175}$.

The boundary condtions for system (1-11):

$$x = 0:\ (\rho_a + \rho_v)V_g = G_{in},\ \rho_v/\rho_a = u_{in},\ T_g = T_{in};\ r = R:\ \gamma = j.$$

The initial conditions:

$$t = 0:\ T_{m.m} = T_g = T_0,\ u_{m.m} = u_0.$$

System (1-11) was numerically integrated by an explicit difference scheme that was oriented counter to the flow. In the calculations, we used the following values for the thermophysical coefficients and ratios entering into system (1-11) (the material was polyamide PA-6): $u_e = 0.06\ (p/p_s)$, $\lg P_s = 10.9778 - 2224.4/T_{m.m}$, $D = 10^{-11}$ m²/sec [5], $V_g = 0.5$ m/sec. The characteristics of the bed for which the calculations were performed: R = 1.3 mm; ε = 0.41; F = 1093 m^{-1}; L = 0.5 m; T_0 = 20°C; T_{in} = 90°C.

The results of the calculations are shown in Figs. 1-4. Figure 1 compares the numerical calculations with experimental data obtained for the same conditions (curve 2). Here, the layerwise moisture content of the polymer was determined by the gravimetric method. It can be seen from the figure that the difference between these sets of data is no greater than 7%, which is evidence of the acceptable level of reliability of the numerical results.

Analysis of Fig. 1 permits us to make two important conclusions. First, the degree of drying of the air has almost no effect on the kinetics of drying of the given material up to moisture contents of 1-1.5%. Here, in the calculations we varied the moisture content u_{in} of the air; it differed by more than an order of magnitude, ranging from the dew point −15°C (the parameters of the air after its high dessication for the given process) to the dew point +6°C (the normal parameters of air for most shops). At the same time, during the final stage of drying the use of dried air shortens the process by 2-3 h. Second, no significant difference was found in drying kinetics for the lower differential layer, under ideal conditions, and the mean-integral values for the entire bed. This was true for all air moisture contents. The two sets of results differ only during the initial stage of the process and only by an amount on the order of 2-5%.

There was also no significant difference between the temperatures of the gas and solid phases (Fig. 2). The largest temperature difference was roughly 3°C and arose only during the initial period in the first layers. The velocity of the thermal wave in the bed for the given conditions was about 2 cm/min.

The distribution of moisture content through the thickness of the grains (Fig. 3) shows that moisture begins to be removed from the center of the grains only after 2 h of drying. If the drying conditions (the initial moisture content of the air and the thickness and moisture content of the bed) are improperly chosen, the surface layers may even gain moisture. This is illustrated by curves 1 and 2 in Fig. 3b.

Curves 1, 5, and 6 in Fig. 4 illustrate the same phenomenon in integral form. It can be seen from the figure that during the initial period the moisture content of the air may have a maximum inside the bed (curve 1). Some of the drying of the air which occurs with its subsequent filtration through the bed is evidence that the polymer is being moistened. It followed from a comparison of curves 5 and 6 that the moistening wave passes through the bed in 20 min. The slope of lines 5-8 determines the rate of evaporation at the given point of the bed.

Thus, the model of heat and mass transfer proposed here makes it possible to obtain the basic results needed for practical applications.

NOTATION

c, heat capacity; D, coefficient of diffusion of mositure in the material; E, rate of energy transfer between the gas and the material; F, surface area of the material per unit volume of the bed; G, mass rate of flow of the injected air per unit cross-sectional area of the bed; h, specific enthalpy; H, enthalpy density; j, rate of evaporation of moisture from a unit surface of the material; J, rate of evaporation of moisture in a unit volume of the bed; L, height of bed; P, pressure; q, heat flux from the gas to the material; r, distance from the center of grain; R, radius of the grain; R_a, R_v, individual gas constants of the air and vapor; t, time, T, temperature; $u_e = u|_{r=R}$, value of the mosisture content of the material at the surface of the grain; V, velocity; u, moisture content; x, distance along the long axis of the bed; α, heat-transfer coefficient; β, mass-transfer coefficient; γ, diffusion flux of moisture in the material; ε, porosity; κ, heat of vaporization; ρ, mass density (per unit volume of the bed); ρ, true mass density. Indices: a, air; ms, moisture; m.m, moist material; g, gas (vapor-gas mixture); m, material; v, vapor; e, equilibrium; s, saturated; in, injected air; 0, initial.

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INFLUENCE OF THE MARANGONI EFFECT ON THE STABILITY OF FLOWS OF STRATIFIED LIQUIDS

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A study is made of the effect of a change in interfacial tension on the stability of shear flows of two-component systems. A linear analysis of the stability of motion is performed using the concept of waves of negative energy.

INTRODUCTION

Shear flows of stratified media take place in the pipeline transport of multicomponent systems. Instability of these flows causes internal waves to be generated in the fluid. Capillary waves at the interfaces play an important role in the generation and propagation of such waves [1, 2].

In the present study, we examine the problem of the generation of capillary waves in an incompressible two-layer liquid with a tangential velocity discontinuity accompanying manifestation of the Marangoni effect — a change in interfacial tension which leads to the motion of adjacent volumes of fluid.

The change in interfacial tension may be due to the presence of surfactants or (in the case of charged systems) the interaction of charges and dipoles in electric double layers, since surface-active ions have a substantial effect on the electrical component of interfacial tension [3]. Since the tension of the "film" of surfactant under the influence of perturbations of the surface is described in a manner wholly analogous to the tension of a "film" of ions, we will limit ourselves to consideration of the effect of surfactants.

As is known, Kelvin—Helmholtz instability occurs during the motion of a two-layer liquid in the region of fairly large wave numbers. Waves with negative energy are present in the region of lower wave numbers, these waves becoming unstable when allowance is made for the factors which deplete them of their energy [4, 5]. Such waves are of particular interest to us, since it is they that promote long-wave instability. The latter phenomenon, in turn, has a serious adverse effect on the efficiency with which stratified liquids can be transported. In physical terms, waves with negative energy are waves for which an increase in amplitude is accompanied by a decrease in the total energy of the system. The concept of negative energy waves was first proposed in studies dealing with electronics and plasma physics [6, 7]. It was later shown that such waves can also be generated in the presence of shear flows in hydrodynamics [4, 5].

In the present investigation, we examine the influence of the Marangoni effect on negative energy waves in a two-layer liquid. It is shown that when such waves are present, the use of surfactants may intensify small disturbances of the interface.

We will examine the motion of two layers of liquid with a sharp interface. The two-dimensional motion of the liquid in a linear approximation is described by the equations

$$\frac{\partial u_j}{\partial t} + u_{0j}\frac{\partial u_j}{\partial x} + \frac{1}{\rho_j}\frac{\partial p_j}{\partial x} = \nu_j \Delta u_j - v_j \frac{\partial u_{0j}}{\partial z}; \tag{1}$$

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