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MATHEMATICAL SIMULATION OF THE PROCESS OF PURIFICATION OF A GAS SUSPENSION

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The process of interaction of a filtrate used in a pipe filter and a two-phase disperse mixture found in its porous wall and outside it in an isothermal medium has been mathematically simulated. Recommendations for obtaining such a filtrate are given.

Introduction. Spiral wire filter elements (SWFE) are used to advantage for purification of gas and liquid heterogeneous systems. At present, a number of apparatus based on these elements are installed for testing at the Siberian Chemical Integrated Works (Tomsk).

Formulation of the Problem. Let there exist a volume filled with a gas suspension (dust): air + particles. In this volume, pipe SWFEs are installed, and each of these SWFEs has its own zone of action with a characteristic size L_*. For the sake of simplicity, one SWFE with its own zone of action and a characteristic transverse size L_* will be considered. We will solve the problem on the mass exchange inside a typical cell, representing a cylinder of radius L_* with an impenetrable wall and coordinates $x = L_*$ and $y = 0$, where the axial coordinate y is directed from the impenetrable substrate upward along the pipe (Fig. 1).

It is assumed that the upper impenetrable face of the pipe filter has a hole for removal of the gas mixture. In this case, the flow inside the filter (zone I) is mainly determined by the forced convection arising when the initial pressure in it is decreased to $P_{\text{in}}^{\text{I}} = 5 \cdot 10^4$ N/m^2. The disperse medium inside the pipe moves transversely relative to the penetrable wall (zone II) because of the difference between the pressures in zones I and III, where $P_{\text{in}}^{\text{III}} = 1.013 \cdot 10^5$ N/m^2, and the disperse medium outside the pipe (zone III) moves due to the forced flow.

A mathematical model proposed for solving the problem being considered is based on the physical laws of mass and momentum conservation, which are formulated separately for each phase with the use of the hypothesis on mutually penetrating continuums [2, 3]. The mathematical model of a porous medium proposed in [4] is additionally used for the condensed phase in region II; in accordance with this model, the gas suspension in zone III can be filtrated through the walls of the pipe into it due to the differential pressure in the pores of the filter.

The following assumptions are made for a laminar flow of the above-described isothermic medium in the SWFE being considered: a) the particles represent spheres of equal radii; they do not interact with the walls of the filter pores in region II but can coagulate with each other, with the result that the pores are clogged, the penetrability of the filter walls decreases, the gas-suspension flow decelerates, and the purified filtrate enters the pipe; b) the volume fraction of the particles is negligibly small and phase transitions are absent; c) the viscosity is taken into account only in the process of interaction of particles with the gas; d) the porous wall is a medium in which $v_1^{\text{II}} = v_2^{\text{II}}$ (the inertia of the relative motion of the phases is insignificant); e) in the SWFE volume, one homogeneous reaction, similar to the process of filling of the intrapore space with disperse particles, proceeds with effective kinetic constants; f) the porous wall of the SWFE consists of three components: an inert skeleton, particles, and liquid; g) the penetrable wall of the filter is an ideal porous medium, in which all the pores represent cylinders with axes parallel to each other and to the x axis; h) the porosity of the filter wall is active, i.e., all the pores can interact with each other and the phase boundary; i) the actual densities of the condensed components are constant (the particles are incompressible); j) in the SWFE, the mass flow propagating transversely relative to the surface of the wall is much larger than the mass flow propagating along it; k) the body is not destroyed in the process of interaction with the gas suspension and heterogeneous chemical reactions and phase transitions are absent on its surface; l) the gas-flow rate is determined from

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the solution of the continuity equation with the use of the linear Darcy law [4, 5]; m) the width of the zone of action $L_* \sim 0.055$ m is much smaller than the longitudinal size of the filter $L = 0.5$ m.

The last-mentioned assumption makes it possible to use equations similar to the boundary-layer equation proposed in [4] for the gas phase inside the pipe and in the zone of action. The equations of disperse-phase conservation were obtained on the basis of the data presented in [6].

The viscosity and diffusion coefficients of the disperse particles were determined from the relations [6]

$$D_2 = \frac{3}{16}\frac{1}{n\pi r^2}\sqrt{\frac{2\pi kT}{m}}\frac{1}{\Omega_{ij}^{(1.1)*}(T^*\sigma_{ij}/r)}\,, \quad \mu_2 = \frac{5}{3}\frac{nm}{A_{12}^*}D_2\,, \tag{1}$$

where $T^* = kT/\varepsilon_{ij}$, $m = m_1m_2/(m_1 + m_2)$, and $n = P/kT$; in this case, A_{12}^* depends weakly on the temperature and its value is close to unity, i.e., it is suitable for approximate calculations.

It was established in [6] that, at $r > 0.05$ μm, the Ω-integrals remain practically unchanged when the radius of the particles increases and their value is close to unity. In this case, at $\Omega_{ij} = 1$, $R = 8.314$ J/(mole·K), $M = mN_A = 0.0184$ kg/mole, $P = 1$ atm, $r = 5\cdot10^{-7}$ m, $M_2 = 0.046$ kg/mole, $M_1 = 0.029$ kg/mole, $N_A = 6.022\cdot10^{23}$ mole^{-1}, and $\varphi_2^j \sim 10^{-7}$, where φ_2^j is the volume fraction of the particles (j = I, III), the estimations of D_2 and μ_2 in (1) give

$$\rho_2 D_2 \varphi_2^j \sim 5\cdot10^{-10}\ \text{kg/(m·sec)},\ \mu_2\varphi_2^j \sim 10^{-19}\ \text{kg/(m·sec)}\,.$$

As a result of the above estimations, we obtained a series expansion parameter of the higher (second) space derivative in the linear-momentum conservation equation and in the equation of carried-phase diffusion. In this case, the conservation equations for the particles can be represented in the form of the Euler equations [2, 7] with account for the force interaction between the carrying (air) and carried (particles) media. With the above-indicated assumptions, the following conservation equations for the gas suspension in regions I and III are true:

$$\frac{1}{x}\frac{\partial}{\partial x}(x\rho_1\varphi_1 v_1)^j + \frac{\partial}{\partial y}(\rho_1\varphi_1 w_1)^j = 0\,, \quad j = \text{I, III}\,, \tag{2}$$

$$\frac{1}{x}\frac{\partial}{\partial x}(x\varphi_2 v_2)^j + \frac{\partial}{\partial y}(\varphi_2 w_2)^j = 0\,, \quad j = \text{I, III}\,, \tag{3}$$

$$(\rho_1\varphi_1)^j\left(\frac{\partial w_1}{\partial t} + v_1\frac{\partial w_1}{\partial x} + w_1\frac{\partial w_1}{\partial y}\right)^j = \frac{1}{x}\frac{\partial}{\partial x}\left(\varphi_1\mu_1 x\frac{\partial w_1}{\partial x}\right)^j$$

$$-\left(\varphi_1\frac{\partial P}{\partial y}\right)^j - A_{w_1}(w_1 - w_2)^j - (\rho_1\varphi_1)^j g\,, \quad j = \text{I, III}\,, \tag{4}$$

$$\left(\frac{\partial P}{\partial x}\right)^j = 0\,, \quad j = \text{I, III}\,,$$

$$(\rho_2\varphi_2)^j\left(\frac{\partial w_2}{\partial t} + v_2\frac{\partial w_2}{\partial x} + w_2\frac{\partial w_2}{\partial y}\right)^j = A_{w_1}(w_1 - w_2)^j - (\rho_2\varphi_2)^j g\,, \quad j = \text{I, III}\,, \tag{5}$$

$$(\rho_1\varphi_1)^j\left(\frac{\partial c_1}{\partial t} + v_1\frac{\partial c_1}{\partial x} + w_1\frac{\partial c_1}{\partial y}\right)^j = \frac{1}{x}\frac{\partial}{\partial x}\left(x\rho_1\varphi_1 D_1\frac{\partial c_1}{\partial x}\right)^j\,, \quad c_2^j = 1 - c_1^j\,, \quad j = \text{I, III}\,. \tag{6}$$

To determine the transverse velocity of the disperse-medium flows v_1^j and v_2^j, j = I, III, inside and outside the filter, we integrated the continuity equations (2) and (3):

$$\int_{L_{j-1}}^{L_j} \frac{\partial}{\partial y} (x\rho_1\varphi_1 w_1)^j \, dx + (x\rho_1\varphi_1 v_1)_{K_j}^j = 0 \,, \quad \int_{L_{j-1}}^{L_j} \frac{\partial}{\partial y} (x\varphi_2 w_2)^j \, dx + (x\varphi_2 v_2)_{K_j}^j = 0 \,, \tag{7}$$

$$j = 1 \quad (K_1 = L_1) \,, \quad j = 3 \quad (K_3 = L_2) \,, \quad L_0 = 0 \,, \quad L_3 = L_* \,;$$

and obtained

$$P^j = R \left(\frac{\rho_1 T_{\text{in}}}{M_1} \right)^j , \quad \varphi_k^j = \frac{c_k^j}{\left(\rho_k \sum_{m=1}^{2} c_m / \rho_m \right)^j} \,, \quad j = \text{I, III} \,, \quad k = 1, 2 \,. \tag{8}$$

The conservation equations for the penetrable wall of the filter [4] have the form

$$\frac{\partial \, (\rho_1\varphi_1)^{\text{II}}}{\partial t} + \frac{1}{x} \frac{\partial}{\partial x} (x\rho_1\varphi_1 v_1)^{\text{II}} = - \, U_1 \,, \tag{9}$$

$$\left(\rho_1 \frac{\partial \varphi_1}{\partial t} \right)^{\text{II}} = - \, U_1 \,, \quad U_1 = \begin{cases} \left[\alpha\varphi_1\rho_1 \exp \left(- \, \beta \dfrac{c_2}{c_{2\text{in}}} \right) \right]^{\text{II}} \,, & \varphi_1 > \varphi_{1*} \,, \\ 0 \,, & \varphi_1 \le \varphi_{1*} \,, \end{cases} \tag{10}$$

$$(\rho_1\varphi_1)^{\text{II}} \left(\frac{\partial c_1}{\partial t} + v_1 \frac{\partial c_1}{\partial x} \right)^{\text{II}} = \frac{1}{x} \frac{\partial}{\partial x} \left(x\rho_1\varphi_1 D_1 \frac{\partial c_1}{\partial x} \right)^{\text{II}} - c_1^{\text{II}} U_1 \,, \quad c_2^{\text{II}} = 1 - c_1^{\text{II}} \,. \tag{11}$$

The system of equations (9)–(11) is closed by the equation of linear-momentum conservation (Darcy law), the equation of state of the gaseous products of filtration, the Kozeni formula [4, 5], and the algebraic integral determining the volume fractions of the components [4]:

$$v_1^{\text{II}} = - \left(\frac{z}{\mu_1} \frac{\partial P}{\partial x} \right)^{\text{II}} , \quad P^{\text{II}} = R \left(\frac{\rho_1 T_{\text{in}}}{M_1} \right)^{\text{II}} , \quad z^{\text{II}} = \left[\frac{\varphi_1^3}{(1 - \varphi_1)^2} \right]^{\text{II}} \frac{d_{\text{p}}^2}{120} \,, \quad \varphi_2^{\text{II}} = (1 - \varphi_1 - \varphi_{3\text{in}})^{\text{II}} \,, \tag{12}$$

where $\varphi_{3\text{in}}$ is the volume fraction of the skeleton of the SWFE wall, the value of which is given below in the representation of the initial data.

It has been experimentally established [5] that the fractions of the dead-end and closed pores comprise 2–5% at $\varphi_1 \ge 0.18$. They are somewhat larger at $\varphi_1 < 0.18$; at $\varphi_1 \sim$ 0.07–0.08, the opened porosity disappears and the flow decelerates (U_1 = 0). Hereinafter, it was assumed that $\varphi_{1*} \approx 0.07$.

Kinetic and Interphase-Exchange Coefficients. In the case where the diffusion coefficient decreases or increases with concentration, it is approximated more adequately not by the fractional-linear [8] or power [9] functions but by the exponential function [8]. Therefore, because of the absence of a unique correlation, which could be satisfactorily used for estimation of the influence of the particle concentration on the diffusion coefficients of the disperse-medium components (gas, matter, etc.), we will use the exponential approximation [8]

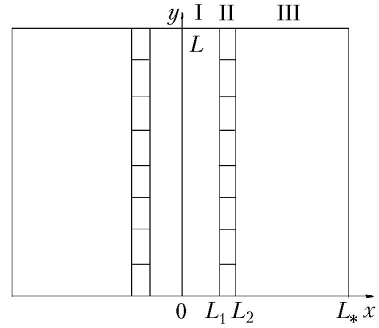


Fig. 1. Diagram of a typical cell.

$$D_1^j = D_{1\text{in}}^j \exp\left[-\gamma_m \left(\frac{c_2}{c_{2\text{in}}}\right)^j\right], \quad j = \text{I, III}, \quad D_1^{\text{II}} = \frac{D_{1\text{in}}\varphi_1^{\text{II}}}{[1 + 0.274\,(1 - \varphi_1^{\text{II}})]^2}, \tag{13}$$

where $0 < \gamma_m < 1$, γ_m (m = 1, 3) is a constant dependent on the temperature and the structure of the medium [8].

The equation of motion includes a term defining the force interaction of the phases. When a particle moves in the gas, it is subjected to the action of the friction force and the average static differential pressure (including, in part, the static lift) [2, 7]. It is assumed that the particles move with a slippage relative to the carrying medium and the force of their interaction with the medium is determined by the Stokes law [2, 7]: $f = \frac{3}{2}\frac{c_*}{l}\frac{\rho_1}{\rho_2}(\mathbf{v}_1 - \mathbf{v}_2)^2$, $c_* = 24/\text{Re}$. If $\text{Re} = \rho_1 |v_1 - v_2| l/\mu$, the Stokes law for a laminar flow around a sphere is obtained [2]; in this case, $f = \frac{18\varphi_2\mu_1}{\rho_2 l^2}(v_1 - v_2)$.

The system of equations (2)–(6), (9)–(11) is solved:
at t = 0 with the initial conditions

$$\rho_1^{\text{II}} = \rho_{1\text{in}}, \quad w_k^j = 0, \quad k = 1, 2, \quad j = \text{I, III}; \quad c_1^j = c_{1\text{in}}^j, \quad j = \text{I, II, III}, \quad \varphi_1^{\text{II}} = \varphi_{1\text{in}}^{\text{II}} \tag{14}$$

and at x = 0 with the boundary (symmetry) conditions

$$\frac{\partial w_1}{\partial x} = 0, \quad \frac{\partial c_1}{\partial x} = 0, \quad v_j = 0, \quad j = 1, 2. \tag{15}$$

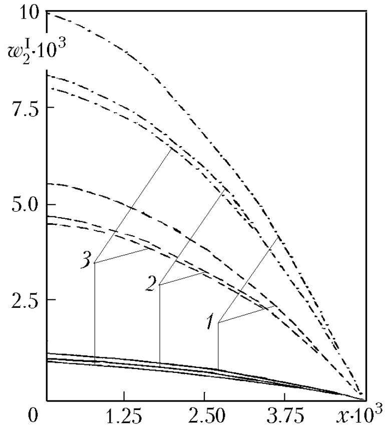
The conditions of equality of the diffusion and mass flows and the adhesion conditions for ω_j, j = 1, 2, were set along the 0y axis (Fig. 1) to the left and right of the filtration partition: $x = L_i$, i = 1, 2:

$$w_m|_{L_j} = 0, \quad m = 1, 2, \quad (\rho_1\varphi_1 v_1)|_{L_j-0} = (\rho_1\varphi_1 v_1)|_{L_j+0}, \quad j = 1, 2,$$
$$\left(\varphi_1\rho_1 D_1 \frac{\partial c_1}{\partial x}\right)_{L_j-0} = \left(\varphi_1\rho_1 D_1 \frac{\partial c_1}{\partial x}\right)_{L_j+0}, \quad c_1|_{L_j-0} = c_1|_{L_j+0}, \quad j = 1, 2. \tag{16}$$

At the closed bottom of the pipe, where y = 0,

$$0 \le x \le L_*, \quad w_m = v_m = 0, \quad m = 1, 2. \tag{17}$$

In the case where the zone of action of the pipe filter L_* is in an impenetrable cylindrical shell with a symmetry axis coincident with the symmetry axis of the pipe, the adhesion conditions for v_i^{III}, w_i^{III}, i = 1, 2, and the conditions of air-gradient (penetration) absence are realized in zone III at $x = L_*$:



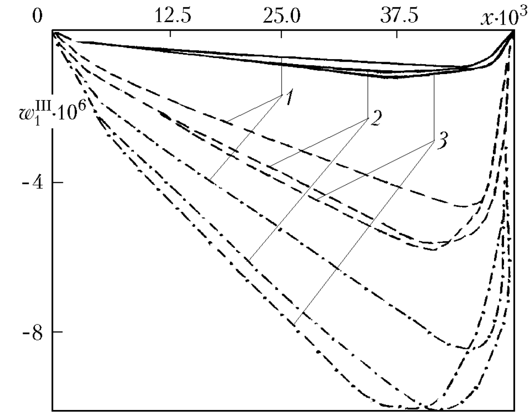


Fig. 2. Distribution of the longitudinal velocity w_2^{I} of the filtrate at three cross sections along the axial coordinate y inside the pipe (zone I) along the transverse coordinate x at different instants of time: solid curves) $y_1 = 0.05$ m, dashed curves) $y_2 = 0.25$ m, dash-dot curves) $y_3 = 0.45$ m; $t = 0.5$ (1), 1 (2), and 2 sec (3). w_2^{I}, m/sec; x, m.

Fig. 3. Distribution of the longitudinal velocity of the carrying medium w_1^{III} (air) at three cross sections along the axial coordinate y in the action zone (zone III) along the x coordinate at different instants of time. The designations are identical to the designations used in Fig. 2. w_1^{III}, m/sec; x, m.

$$v_i = w_i = 0\,, \quad \frac{\partial c_1}{\partial x} = 0\,, \quad i = 1, 2\,. \tag{18}$$

Calculation Method and Initial Data. The boundary problems (2)–(6), (9)–(11), and (14)–(18) were solved numerically with the use of the Simuni method [10] and formulas (7) and (8) in the boundary layer as well as the iteration-interpolation method [11] and the local one-dimensional scheme of splitting [12] in zones I and III. In the condensed phase, the rate of filtration of the carrying medium and the volume fraction of particles in the porous wall were determined from expressions (12). The viscosity and diffusion coefficients for air at $T_{\mathrm{in}} = 293$ K are presented in [13].

We used a quartz sand SiO_2 as the dust particles and a stainless steel with known thermophysical parameters [14, 15] as the skeleton of the porous wall. The main results were obtained for $\rho_{1\mathrm{in}} = 1.3$ kg/m^3, $D_{1\mathrm{in}} = 1.5 \cdot 10^{-5}$ m^2/sec, $\mu = \mu_{1\mathrm{in}} = 1.81 \cdot 10^{-5}$ kg/(m·sec), $\rho_2 = 2.610$ kg/m^3, $r = 5 \cdot 10^{-7}$ m, $\varphi_{1\mathrm{in}}^{\mathrm{II}} = 0.1$, $\varphi_{3\mathrm{in}}^{\mathrm{II}} = 0.899$, $L = 0.5$ m, $L_1 = 5 \cdot 10^{-3}$ m, $L_2 = 5.5 \cdot 10^{-4}$ m, $L_* = 5.5 \cdot 10^{-2}$ m, $T_{\mathrm{in}} = 293$ K, $d_{\mathrm{p}} = 2 \cdot 10^{-6}$ m, $c_{2\mathrm{in}}^{j} = 10^{-5}$, $j =$ I, II, $c_{2\mathrm{in}}^{\mathrm{III}} = 10^{-3}$, $P_{\mathrm{in}}^{\mathrm{III}} = 1.013 \cdot 10^5$ N/m^2, $P_{\mathrm{in}}^{\mathrm{I}} = 5 \cdot 10^4$ N/m^2, $\gamma_1 = 0.08$, $\gamma_3 = 0.4$, $\alpha = 0.1$ sec^{-1}, and $\beta = 0.5$.

The computational program was tested for a laminar flow inside a plane slot with an impenetrable side wall, in which free convection was absent; the longitudinal velocity of this flow at the input of the slot was $w_* = 10^{-3}$ m. The rate of motion along the slot, determined as a result of numerical solution of the nonstationary boundary problem at the instant of time $t = 10^3$ sec, was equal to the analogous stationary solution with an accuracy of up to 0.1%. Moreover, the program of numerical calculation was verified by an exact analytical solution [11]. For different space steps, the deviation of the numerical solution from the exact value, determined for a definite period of time, did not exceed 1%.

Analysis of the Results of the Numerical Solution. Figure 2 presents the distribution of the longitudinal velocity of the particles inside the pipe filter, and Fig. 3 presents the distribution of the longitudinal velocity of the carrying phase (air) outside the pipe along the transverse coordinate x in three cross sections along the axial coordinate y, determined at different instants of time.

It follows from Fig. 2 that the flow in zone I of the disperse medium ($w_1^{\mathrm{I}} \approx w_2^{\mathrm{I}}$) propagates under the action of the forced convection (the pressure inside the pipe filter at the initial instant of time is two times lower than the

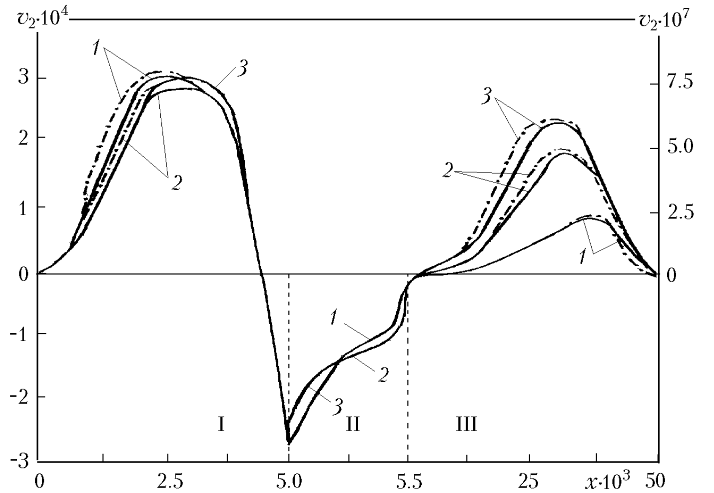


Fig. 4. Distribution of the transverse velocity of the filtrate v_2 in three cross sections along the axial coordinate y in zones I–III along the radial coordinate x at different instants of time. The designations are identical to the designations used in Fig. 2. v, m/sec; x, m.

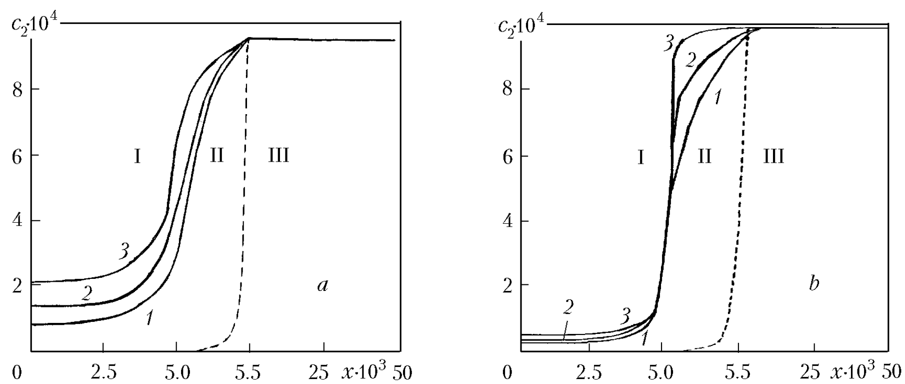


Fig. 5. Distribution of the particle concentration in zones I–III on the transverse coordinate x at y_1 = 0.05 m at different instants of time for γ_1 = 0.08 (a) and γ_1 = 0.4 (b). x, m.

pressure outside the pipe) to the closed upper face of the filter with a hole for removal of the filtrate. At the same time, in zone III, the carrying phase ($w_1^{\text{III}} \approx w_2^{\text{III}}$) moves to the closed lower substrate in the direction of its filtration in zone II.

Figure 4 shows the distribution of the transverse velocity of the particles v_2 in zones I–III along the radial coordinate x. Analysis of Fig. 4 shows that, away from the porous wall, in zone I, the filtrate moves to the penetrable wall of the pipe, and the particles in zone III move to the impenetrable wall $x = L_*$, which is apparently due to the forced-convection action. In the neighborhood of the pipe-filter walls, the behavior of the velocity v_2 in zones I and III is mainly determined by the direction of filtration of the carrying medium in zone II.

Since the pressure in the pipe is decreased, the rate of filtration of the gas suspension in the porous wall of the filtrate is negative and its flow is directed to zone I (this result is qualitatively coincident with the data of [16]). The latter is, in addition to the diffusion, a reason for the transfer of the gas suspension from zone III into the filter.

Of interest is the distribution of the filtrate concentration c_2 in zone I. Figure 5a shows this distribution along the x coordinates in designations of Fig. 2; the dashed curve in zone II corresponds to $t = 10^{-4}$ sec. In the cross sections y_2 = 0.25 m and y_3 = 0.45 m, the distribution of the particle concentration c_2 in zones I and II is practically identical to that at y_1 = 0.05 m at later instants of time because of the isothermal flow of the gas suspension. The calculation results point to the fact that c_2 increases with time (Fig. 5a, curves 1–3) due to the diffusion and convection processes. Then, as the pores in zone II are clogged by particles, the rate of filtration of the carrying phase (Fig. 4, curve 2 in zone II) at $t \geq 1$ changes insignificantly in absolute value and the concentration of the filtrate in zone I increases.

The change in the initial pressure from $P_{\text{in}}^{\text{I}} = 7.5 \cdot 10^4$ N/m^2 to $P_{\text{in}}^{\text{I}} = 2.5 \cdot 10^4$ N/m^2 practically causes no change in c_2. The kinetic coefficients α, β, and γ_1 in expressions (10) and (13) have a much larger influence on the value of c_2 in zone I. The change in the coefficient γ_3 from 0.4 to 1, all other input data being equal, practically has no influence on the results of calculation of c_2. However, an increase in the parameter γ_1 to 0.4 leads to a decrease in the filtrate concentration c_2 in zone I (see Fig. 5b) by more than 2.5 times in the neighborhood of $x = L_{1-0}$ at $t = 2$ sec.

Conclusions. By decreasing the pressure inside a pipe filter of the design being considered (the mathematical model of a porous medium [4] in the condensed phase), one can obtain a filtrate providing a definite degree of purification of a gas suspension. To obtain a fine purification of a gas suspension [1], it necessary to develop a more exact mathematical model of heat and mass transfer in the filter in the condensed phase with kinetic constants and transport coefficients (in particular, α and β in (10) and γ_1 in (13)) determined experimentally.

NOTATION

A_{w_1}, interphase-exchange coefficient, kg/(m^3·sec); A_{12}^*, reduced Ω-integral; c, mass concentration of a component; D, diffusion coefficient, m^2/sec; d_p, diameter of the pores in zone II, m; g, free fall acceleration, m/sec^2; k, Boltzmann constant, J/K; l, diameter of particles, m; L_*, width of the action zone, m; L, longitudinal size of a pipe filter, m; L_1 and L_2, inner and outer radii of the filter, m; m_1, molecular mass of the carrying medium, kg; m_2, mass of a disperse particle, kg; M, molecular weight, kg/mole; n, particle number density of the mixture, m^{-3}; N_A, Avogadro number, mole^{-1}; P, pressure of the carrying phase in (1), atm; r, characteristic radius of a Brownian particle, m; R, universal gas constant, J/(mole·K); Re, Reynolds number; t, time, sec; T, temperature, K; $\mathbf{v}$, velocity vector in the transverse direction, m/sec; w and v, longitudinal and transverse velocity components, m/sec; x and y, transverse and longitudinal coordinates of the cylindrical coordinate system, m; z, penetrability coefficient in zone II, m^2; α, β, kinetic constants; ε_{ij}, potential energy of interaction of molecules, J; μ, coefficient of viscosity, kg/(m·sec); ρ, density, kg/m^3; σ_{ij}, interaction cross sections, Å; φ, volume fraction; $\Omega_{ij}^{(1,1)}$, collision integrals. Subscripts: 1, 2, and 3, carrying phase (air), particles of the disperse medium and the condensed phase in zone II of the filtrate; I, II, and III, internal parameters of the filter (zone I), characteristics of the condensed phase of the filter wall (zone II), and quantities in the zone of action of the SWFE (zone III); *, characteristic quantities; in, initial values; p, pore; K_j, $j = 1$ and 3; b, boundary between zones I–III.

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