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MODEL OF SUSPENSION FILTRATION WITH ACCOUNT OF COLMATATION AND SUFFOSION

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A model of suspension filtration is suggested, which takes into account the effects of colmatation and suffosion in a porous medium.

Filtration of suspensions in a porous medium forms the basis for many technical, industrial, and other processes. Among them special attention is given to hydrological (filtration of waters through dams, grounds, etc.) [1], chemical and food [2, 3] processes, as well as to processes of extraction of petroleum and gas [4].

The construction of rather general mathematical models, describing important features typical of the suspension filtration process is the field of investigation, which has been studied until now with insufficient completeness. The results of the separate theoretical and experimental researches are presented in [5-7]. In work [5] a system of equations is derived for determination of the concentration of solid suspensions in liquid n and the saturation density of the porous medium by deposit ρ. The processes of colmatation and suffosion and also the result of their simultaneous action are considered separately in [6]. Together with a balance equation use is made of the equation characterizing the intensity of a change in the deposited mass volume ζ, which is analogous to the equation of the gas adsorption kinetics [8, 9] in the case of a linear dependence of the equilibrium concentration on the concentration of a substance under sorption. Consequently, the equilibrium concentration, at which the process intensity will be equal to zero, depends only on the deposited mass volume. However, as is shown in [10], the intensity of the change of characteristics (in the work we consider the current value of the active porosity but not the volume of the deposited mass) depends not only on the values of n and ε, but on grad p; this fact is confirmed by experimental investigations. In [10] we considered a new model of the filtration, where colmatation and suffosion were taken into account in terms of certain probability coefficients, characterizing the intensity of the blockage and freeing process of pores by fluid particles. However, in [10] we studied the model with concentrated parameters, and the particle distribution in longitudinal and lateral flow directions was disregarded. In this work the model [10] is generalized to the model with distributed parameters.

Suppose that a suspension with the initial volume concentration of solid particles n_0 enters the porous medium filled with a liquid without particles. Because of deposition of the suspension particles, the pores of the medium are blocked, the liquid flow in them is stopped up, i.e. they are disconnected from the filtration process. This fact, naturally, leads to the change in the active porosity. Later the colmated pores may become free of particles under the action of the pressure drop. As in [10], we assume that each deposited particle blocks up one isolated pore and, consequently, changes the active porosity. Then we may write the substance balance equation in the volume unit of the porous medium without reference to convective dispersion in a one-dimensional case as follows

$$\frac{\partial n}{\partial t}+\frac{v(t)}{\varepsilon}\frac{\partial n}{\partial x}=\frac{1}{\varepsilon_0}\frac{\partial \varepsilon}{\partial t}. \qquad (1)$$

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The change in the porosity with time, similarly to [10], takes on the form

$$\frac{\partial \varepsilon}{\partial t} = (\varepsilon_0 - \varepsilon)\,\omega_1 P - \omega_2 \varepsilon n, \quad P = \left|\frac{\partial p}{\partial x}\right|, \tag{2}$$

where ω_1, ω_2 are the phenomenologically introduced probability coefficients, which define the intensity of suffosion and colmatation.

Equations (1) and (2) should be added by Darcy's law

$$v(t) = K(\varepsilon)\,P. \tag{3}$$

On the assumption of incompressibility of the suspension and the porous medium we obtain $\partial v/\partial x = 0$ from the continuity equation.

The form of $K(\varepsilon)$ in (3) is evaluated in different ways. In the simplest case we may take that $K(\varepsilon) = k_0\varepsilon$, $k_0 = \text{const}$, as it was considered in [10]. In the general case, we should make use of other dependences of the filtration coefficient on the porosity, as it was made in [11].

At small values of n, when the change in the porosity is noticeable, in the second term in (1), and in the last term in (2), one may assume that $\varepsilon \approx \varepsilon_0$. Therefore, instead of (1)-(3) we have

$$\begin{gathered}\frac{\partial n}{\partial t} + \frac{K(\varepsilon_0)\,P}{\varepsilon_0}\frac{\partial n}{\partial x} = \frac{1}{\varepsilon_0}\frac{\partial \varepsilon}{\partial t}, \\ \frac{\partial \varepsilon}{\partial t} = (\varepsilon_0 - \varepsilon)\,\omega_1 P - \omega_2 \varepsilon_0 n, \quad v(t) = K(\varepsilon)\,P.\end{gathered} \tag{4}$$

System (4) is much simpler in the solution than the initial one (1)-(3).

Let the suspension with the volume concentration of solid particles n_0 begin to enter into the porous medium, filled by liquid without particles, with the initial porosity ε_0 of the moment $t = 0$. Then

$$n(0, x) = 0, \quad n(t, 0) = n_0, \quad \varepsilon(0, x) = \varepsilon_0. \tag{5}$$

In the given problem at $x = 0$ we may assign the mode of the change in the filtration rate. Suppose, that the mode with $v = v_0 = \text{const}$ is developed. Then it is possible to write system (1)-(3) for $K(\varepsilon) = k_0\varepsilon$ as

$$\begin{gathered}\frac{\partial n}{\partial t} + \frac{v_0}{\varepsilon}\frac{\partial n}{\partial x} = \frac{1}{\varepsilon_0}\frac{\partial \varepsilon}{\partial t}, \\ \frac{\partial \varepsilon}{\partial t} = (\varepsilon_0 - \varepsilon)\,\omega_1 \frac{v_0}{k_0\varepsilon} - \omega_2 \varepsilon n, \\ v_0 = k_0 \varepsilon P.\end{gathered} \tag{6}$$

At large t the steady-state fronts of the concentration and porosity are formed, which propagate with the certain constant velocity. At this asymptotic stage for determination of the functions $\varepsilon(t, x)$ and $n(t, x)$ we may use the method of propagating waves and consider the steady-state fronts of the concentration and porosity as certain waves. Introducing a new variable $z = x - ut$, where u is the front propagation velocity of the change in the porosity and concentration, which will be evaluated further, we arrive at the system with respect to $n(z)$ and $\varepsilon(z)$ from (6):

$$\begin{gathered}\left(-u + \frac{v_0}{\varepsilon}\right)\frac{dn}{dz} = -\frac{u}{\varepsilon_0}\frac{d\varepsilon}{dz}, \\ -u\frac{d\varepsilon}{dz} = (\varepsilon_0 - \varepsilon)\,\omega_1 \frac{v_0}{k_0\varepsilon} - \omega_2 \varepsilon n, \\ v_0 = k_0 \varepsilon P.\end{gathered} \tag{7}$$

Since we consider the asymptotic stage of the colmatation and suffosion dynamics, then the determination of the initial conditions in (5) no longer arises. For new variable z the boundary conditions take the form

$$\begin{gathered}n(-\infty) = n_0, \quad n(\infty) = 0, \\ \varepsilon(-\infty) = \varepsilon_{\text{st}}, \quad \varepsilon(\infty) = \varepsilon_0,\end{gathered} \tag{8}$$

where ε_{st} is the steady-stable value of the porosity, which is evaluated as the solution to the second Eq. (7) at $d\varepsilon/dz = 0$, $n = n_0$:

$$(\varepsilon_0 - \varepsilon)\,\omega_1 \frac{v_0}{k_0\varepsilon} - \omega_2\varepsilon n_0 = 0. \tag{9}$$

From (9) we solve easily

$$\varepsilon_{\text{ст}} = \frac{1}{2}\left(-\theta + \sqrt{\theta(\theta + 4\varepsilon_0)}\right), \tag{10}$$

where $\theta = (\omega_1 v_0)/k_0\omega_2 n_0$.

By integrating the first Eq. (7) with account of the conditions $\varepsilon(\infty) = \varepsilon_0$, $n(\infty) = 0$, we obtain

$$n = -\frac{1}{\varepsilon_0}(\varepsilon_0 - \varepsilon) + \frac{v_0}{u\varepsilon_0}\ln\left|\frac{v_0 - u\varepsilon}{v_0 - u\varepsilon_0}\right|. \tag{11}$$

Under the conditions that $n(-\infty) = n_0$ and $\varepsilon(-\infty) = \varepsilon_{st}$, from (11) we derive an equation, from which we define the front motion velocity u:

$$(n_0\varepsilon_0 + \varepsilon_0 - \varepsilon_{st})\frac{u}{v_0} - \ln\left|\frac{v_0 - u\varepsilon_{\text{cT}}}{v_0 - u\varepsilon_0}\right| = 0. \tag{12}$$

By integrating the second equation of (7) with account of (11), we have $z = c + z_0(\varepsilon)$ or

$$x = ut + c + z_0(\varepsilon), \tag{13}$$

where c is the integration constant, and

$$z_0(\varepsilon) = -u\int\left[(\varepsilon_0 - \varepsilon)\frac{\omega_1 v_0}{k_0\varepsilon} + \frac{\omega_2\varepsilon}{\varepsilon_0}\left(\varepsilon_0 - \varepsilon - \frac{v_0}{u}\ln\left|\frac{v_0 - u\varepsilon}{v_0 - u\varepsilon_0}\right|\right)\right]^{-1} d\varepsilon. \tag{14}$$

In much the same manner we may obtain a self-similar solution for n: $z = c + z_0(n)$ or

$$x = ut + c + z_0(n), \tag{15}$$

where $z_0(n)$ is expressed in terms of an indefinite integral analogous to (14).

For determination of the integration constant c, we use the substance conservation law in the same way as it was made in [8]:

$$\int_0^{n_0} x\,dn + \int_{\varepsilon_{st}}^{\varepsilon_0} x\,d\varepsilon = (n_0 + \varepsilon_0 - \varepsilon_{\text{ст}})\,ut.$$

With account of (13), (15) from the latter we derive

$$c = -\frac{1}{n_0 + \varepsilon_0 - \varepsilon_{st}}\left(\int_0^{n_0} z_0(n)\,dn + \int_{\varepsilon_{st}}^{\varepsilon_0} z_0(\varepsilon)\,d\varepsilon\right).$$

It is possible also to evaluate this constant from the balance equation (the first equation of (6)) by integrating it over x and t within the limits of $[0, x_0]$, $[0, t_0]$, respectively, and passing into the limit at $x_0 \to \infty$, $t_0 \to \infty$.

At small n, when the colmatation effects are insignificant, the porosity differs slightly from ε_0. Therefore, in the left-hand side of the first equation of (6) one may take that $\varepsilon \approx \varepsilon_0$, as it was made when deriving Eq. (4). In this case instead of (13), (15) we obtain

$$\frac{x - ut}{r} = \frac{1}{2}\left(\frac{1}{\varepsilon_0 + \varepsilon_{st}}\ln\frac{2\varepsilon_{st}}{\varepsilon_0 - \varepsilon_{st}} + \frac{1}{\varepsilon_0 - \varepsilon_{st}}\ln\frac{\varepsilon_0 + \varepsilon_{st}}{2\varepsilon_{st}}\right) + \\ + \ln\frac{(\varepsilon - \varepsilon_{st})^{\alpha}(\varepsilon_{st} + \varepsilon)^{\nu}}{(\varepsilon_0 - \varepsilon)^{\beta}}, \tag{16}$$

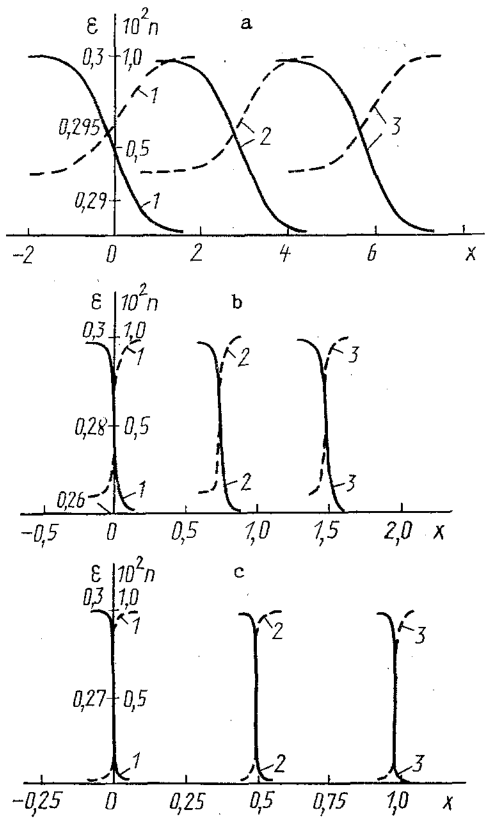

Fig. 1. Asymptotic profiles n (solid lines), ε (dashed lines) at $\omega_1 = 0.1$ m/(MPa·sec) and $\omega_2 = 0.1$ (a); 0.5 (b); 1.0 sec^{-1} (c), t = 0 (1); $4 \cdot 10^3$ (2); $8 \cdot 10^3$ sec (3) for $K(\varepsilon) = k_0\varepsilon$. x, m.

$$\frac{x - ut}{r} = \frac{1}{2}\left(\frac{1}{\varepsilon_0 + \varepsilon_{\text{st}}}\ln\frac{2\varepsilon_{\text{st}}}{\varepsilon_0 - \varepsilon_{\text{st}}} + \frac{1}{\varepsilon_0 - \varepsilon_{\text{st}}}\ln\frac{\varepsilon_0 + \varepsilon_{\text{st}}}{2\varepsilon_{\text{st}}}\right) + \ln\frac{(n_0 - n)^{\alpha}\left(\frac{\varepsilon_0 + \varepsilon_{\text{st}}}{\varepsilon_0 - \varepsilon_{\text{st}}}n_0 - n\right)^{\gamma}}{n^{\beta}}, \tag{17}$$

where

$$\alpha = \frac{1}{2(\varepsilon_0 - \varepsilon_{\text{st}})}, \quad \beta = \frac{\varepsilon_0}{\varepsilon_0^2 - \varepsilon_{\text{st}}^2}, \quad \gamma = \frac{1}{2(\varepsilon_0 + \varepsilon_{\text{st}})}, \quad r = \frac{\varepsilon_0 u(\varepsilon_0 - \varepsilon_{\text{st}})}{\omega_2 n_0}.$$

Here the front propagation rate is determined by the formula

$$u = v_0 n_0 / (\varepsilon_0 n_0 + \varepsilon_0 - \varepsilon_{\text{ст}}). \tag{18}$$

In the given mode the relationship between n and ε, unlike (11), is written in the simple form

$$\frac{n}{n_0} = \frac{\varepsilon_0 - \varepsilon}{\varepsilon_0(\varepsilon_0 - \varepsilon_{\text{st}})}. \tag{19}$$

The pressure gradient is defined from Darcy's law at the known ε:$P = v_0(k_0\varepsilon)$.

Consider the more realistic case, when the filtration coefficient is taken in the Carman–Kozeny form [10]: $K(\varepsilon) = k_0\varepsilon^3/(1 - \varepsilon)^2$. In the mode $v = v_0 = \text{const}$, then system (1)-(3) becomes

$$\begin{gathered} \frac{\partial n}{\partial t} + \frac{v_0}{\varepsilon}\frac{\partial n}{\partial x} = \frac{1}{\varepsilon_0}\frac{\partial \varepsilon}{\partial t}, \\ \frac{\partial \varepsilon}{\partial t} = (\varepsilon_0 - \varepsilon)\frac{\omega_1 v_0 (1 - \varepsilon)^2}{k_0 \varepsilon^3} - \omega_2 \varepsilon n, \\ v_0 = k_0 \varepsilon^3 P / (1 - \varepsilon)^2. \end{gathered} \tag{20}$$

TABLE 1. Filtration Parameters at $\omega_1 = 0.1$ m/(MPa ·sec)

ω_2, sec^{-1}	0,1	0,5	1,0
$\varepsilon_{\text{ст}}$	0,2915	0,2649	0,2416
α	58,8406	14,2495	8,5645
β	59,6859	15,1346	9,4877
γ	0,8453	0,8851	0,9232

Passing to the variable z = x − ut, from (20) we obtain the system with respect to the functions $\varepsilon(z)$ and n(z),

$$\begin{gathered}\left(-u+\frac{v_0}{\varepsilon}\right)\frac{dn}{dz}=-\frac{u}{\varepsilon_0}\frac{d\varepsilon}{dz},\\ -u\frac{d\varepsilon}{dz}=(\varepsilon_0-\varepsilon)\frac{\omega_1 v_0(1-\varepsilon)^2}{k_0\varepsilon^3}-\omega_2\varepsilon n,\end{gathered}\tag{21}$$

which is solved on conditions of (8).

The steady-state value of the porosity is determined from the equation, derived from the second equation of system (21) under the conditions that $d\varepsilon/dz = 0$, $n = n_0$:

$$\varepsilon^4-\theta(\varepsilon_0-\varepsilon)(1-\varepsilon)^2=0.\tag{22}$$

In order to calculate the wave front motion velocity, we obtain an equation, identical to (12), and determine the relationship between ε and n from Eq. (11).

Integration of the second equation in system (21) with account of (11) leads to

$$z=c+z_0(\varepsilon),\tag{23}$$

where

$$z_0(\varepsilon)=-u\int\varepsilon^3\left[\frac{v_0\omega_1}{k_0}(\varepsilon_0-\varepsilon)(1-\varepsilon)^2+\frac{\omega_2}{\varepsilon_0}(\varepsilon_0-\varepsilon)\varepsilon^4-\frac{\omega_2 v_0\varepsilon^4}{u\varepsilon_0}\ln\left|\frac{v_0-u\varepsilon}{v_0-u\varepsilon_0}\right|\right]^{-1}d\varepsilon.$$

As above, the integration constant in (23) is solved from the balance equation. Using the relationship between ε and n, we derive the analogous equation with respect to n: $z = c + z_0(n)$, where $z_0(n)$ is given by the indefinite integral, similar to (23).

Using formulae (16) and (17), we carried out calculations at the following values of the initial data: $v_0 = 10^{-3}$ m/sec, $k_0 = 10^{-2}$ m^2/(MPa ·sec), $n_0 = 0.01$, $\varepsilon_0 = 0.3$. Values of ω_1(m/MPa ·sec) and ω_2 (sec^{-1}) were taken to be different. The results are presented in Fig. 1. As can be seen from this figure, when ω_1 does not vary, at small ω_2 the wave front both for ε and for n is extremely "blurred," and with increasing ω_2, it becomes sharp. The change in the value of ω_2 exerts an effect on the wave propagation velocity character. With the increase in ω_2 the wave velocity diminishes. From the physical viewpoint this phenomenon is understandable, because with increasing colmatation, the perturbed zone moves at the lower velocity and the steady-state porosity value decreases. The values, characterizing this dynamics, are given in Table 1.

Profiles of ε and n with change in t are not distorted similarly to the case that occurs during adsorption of the substance in the porous medium at the linear steady-state sorption isotherm [8]. However, in the general case, when simplifying assumptions (used in deriving (16) and (17)) are taken off, the conservative character of the wave front may not be observed. The analysis in this phenomenon can be carried out through numerical calculations by the corresponding equations.

It should be noted that the profiles of concentrations n are defined simultaneously and by (19) at the known ε. The obtained results coincide well.

Although the above-mentioned solutions represent the general pattern of the process, but due to their asymptotic character, they do not describe the evolution of the leading wave front into the initial stages of the process. Such description may be obtained with the help of the numerical analysis of systems (6) or (20). These systems are solved by a method of finite differences under conditions of (5) and $\varepsilon(t, 0) = \varepsilon_{st}$, where ε_{st} is determined by (10) (when $K(\varepsilon) = k_0\varepsilon$) or by solution (22) (when $K(\varepsilon) = k_0\varepsilon^3/(1-\varepsilon)^2$). The second-order difference approximation with respect to grid pitches h, τ along x and t is of the nonregular nature, respectively [12]. Regularization of the difference scheme is usually realized by methods of smoothing, "artifi-

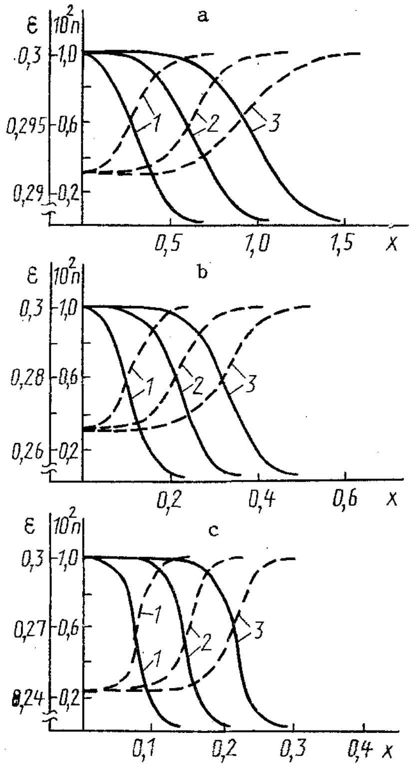

Fig. 2

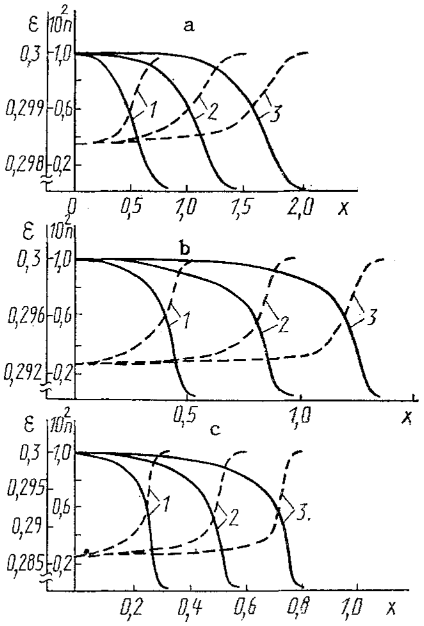

Fig. 3

Fig. 2. Profiles n (solid lines), ε (dashed lines) at $\omega_1 = 0.1$ m/(MPa·sec) and $\omega_2 = 0.1$ (a); 0.5 (b); 1.0 $\sec^{-1}$ (c), t = 180 (1); 360 (2); 540 sec (3) for $K(\varepsilon) = k_0\varepsilon$.

Fig. 3. Profiles n (solid lines), ε (dashed lines) at $\omega_1 = 0.1$ m/(MPa·sec) and $\omega_2 = 0.1$ (a); 0.5 (b); 1.0 $\sec^{-1}$ (c), t = 180 (1); 360 (2); 540 (3) for $K(\varepsilon) = k_0{}^3/(1 - \varepsilon)^2$.

cial viscosity," "temporal viscosity," and by other techniques. In order to avoid these procedures, we composed an implicit scheme of the first order of accuracy with approximation of derivatives at points (i, j), (i − 1, j + 1), (i, j + 1). Here, the calculated formulae for system (20) on determining grid functions $\varepsilon_i^{j+1} = \varepsilon(t^{j+1}, x_i)$, $n_i^{j+1} = n(t^{j+1}, x_i)$ take the form

$$\varepsilon_i^{j+1} = \varepsilon_i^j + (\varepsilon_0 - \tilde{\varepsilon}_{ij}) \frac{3600\tau\omega_1 v_0}{k_0} \frac{(1 - \tilde{\varepsilon}_{ij})^2}{\tilde{\varepsilon}_{ij}^3} - 3600\tau\omega_2\tilde{\varepsilon}_{ij}\tilde{n}_{ij},$$
$$n_i^{j+1} = \left[n_i^j + a n_{i-1}^{j+1} + \frac{1}{\varepsilon_0}(\varepsilon_i^{j+1} - \varepsilon_i^j) \right] / (1 + a), \qquad (24)$$

where

$$a = \frac{3600\tau v_0}{h\tilde{\varepsilon}_{ij}}, \quad \tilde{\varepsilon}_{ij} = (\varepsilon_i^j + \varepsilon_{i-1}^{j+1})/2,$$
$$\tilde{n}_{ij} = (n_i^j + n_{i-1}^{j+1})/2, \quad i = 1,\ 2,\ \ldots,\ j = 0,\ 1,\ \ldots,$$
$$n_0^j = n_0,\ \varepsilon_0^j = \varepsilon_{st},\ n_i^0 = 0,\ \varepsilon_i^0 = \varepsilon_0,\ i,\ j = 0,\ 1,\ \ldots$$

The difference scheme for system (6) has the analogous form. In (24) conversion coefficients are employed so as time t is measured in hours.

The calculation results with the above used values of v_0, k_0, n_0, ε_0 are presented in Figs. 2 and 3. Development of profiles of n and ε in time, as can be seen from figures, depends on values of ω_1 and ω_2, as well as on the form of the filtration coefficient $K(\varepsilon)$. With the increase in the value of ω_2 at constant ω_1, one observes the decrease in the propagation velocity of fronts n and ε. Here the width of the fronts also diminishes, i.e. the profiles become steeper. When the filtration coefficient is taken in the form $K(\varepsilon) = k_0\varepsilon^3/(1 - \varepsilon)^2$, as compared to $K(\varepsilon) = k_0\varepsilon$, then the propagation velocities of the fronts grow (Fig. 3). Besides, the wave front is more "smeared" and ε_{st} is not much less than ε_0. This fact may be regarded in such a way: in the case $K(\varepsilon) = k_0\varepsilon$ at $v = v_0 = \text{const}$ the colmatation process occurs more actively in comparison with $K(\varepsilon) = k_0\varepsilon^3/(1 - \varepsilon)^2$. However, for the generalized relationship of $K(\varepsilon)$ the leading wave front with increasing ω_2 at constant ω_1 becomes steeper, and the wave propagation velocity diminishes.

The calculations, carried out on the basis of a discrete system, corresponding to (6) (when the coefficient v_0/ε is substituted by v_0/ε_0), have shown that the results differ slightly from those presented in Fig. 2. But this difference becomes essential with the growth of ω_2. Therefore, generally speaking, there is no sense in comparing the results at $\omega_2 = 1.0$ sec^{-1}, when $\varepsilon_{st} = 0.2416$. Correspondingly, the asymptotic solution, shown in Fig. 1c cannot be compared with the solution given in Fig. 2c, although the configurations of the profiles are similar. As is seen from Fig. 2a and b at t = 540 sec the profiles are almost the same as in Fig. 1a and b. Besides, at the front of the concentration and porosity waves, especially in its leading part, (where approximately $n < n_0/2$ and $\varepsilon > (\varepsilon_0 + \varepsilon_{st})/2)$, the steady-state mode is almost established. The front points in the indicated region propagate practically at the constant velocity u; therefore, we may consider this time range as the formation stage of the asymptotic solution. Duration of the formation stage of the steady-state front in the general case depends on values of ω_1 and ω_2 and on the form $K(\varepsilon)$.

An estimate of the values of P is made on the basis of Darcy's law at the known ε. It is evident, that at $K(\varepsilon) = k_0\varepsilon$ the decrease from $v_0/(k_0\varepsilon_{st})$ up to $v_0/(k_0\varepsilon_0)$ is a characteristic feature for dynamics of P; the first value is established behind the front, and the second one ahead of the front, i.e., in the filtration region of liquid without particles. The front region is transitional for P. In the case $K(\varepsilon) = k_0\varepsilon^3/(1 - \varepsilon)^2$ we observe the decrease of P from $v_0(1 - \varepsilon_{st})^2/(k_0\varepsilon_{st}^3)$ up to $v_0(1 - \varepsilon_0)^2/(k_0\varepsilon_0^3)$, respectively.

For the further development of the work it seems to be very interesting to consider a problem, when pores are not completely blocked by the deposition of suspension particles, i.e. the localization of particles in any volume is not always accompanied by the colmatation effect. Within the scope of the presented model it is possible also to investigate the multicomponent suspension filtration, where the colmatation and suffosion effects for each component are analyzed in the interconnection with the concentration of other components.

NOTATION

h, grid pitch of the difference scheme along the coordinate; $K(\varepsilon)$, filtration coefficient; k_0, coefficient in $K(\varepsilon)$; n, n_0, current and initial concentrations of particles in a suspension; p, pressure; P, pressure drop module; t, time; u, front propagation velocity of variation in porosity and concentration; v(t), v_0, variable and constant of the filtration velocity; x, coordinate; $z = x - ut$, variable; α, β, γ, exponent constants in (16) and (17); ε, ε_0, ε_{st}, current, initial, and steady-state porosity of the medium; τ, grid pitch of the difference scheme in time.

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