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Solute transport with adsorption in cylindrical heterogeneous media

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ABSTRACT: Solute transport in porous media with zones of high and low permeability can have anomalous character due to solute transfer between two zones. In the paper solute transport with adsorption phenomena in a heterogeneous cylindrical two-zone medium is considered. The medium consists of central cylindrical zone with high permeability surrounded by another cylindrical zone with relatively low permeability. The second cylindrical zone with very low permeability can be treated as impermeable zone where liquid is immobile (immobile domain or zone) while in the central cylindrical zone liquid is mobile (mobile domain or zone). In both zones adsorption of solute occurs. Solute mass transport in mobile zone governed by advection, diffusion and adsorption phenomena, while in immobile zone by diffusion and adsorption phenomena only. Between zones solute exchange occurs that is modelled by two approaches, diffusion and kinetic. Results obtained by two approaches are compared. A problem to fit results by two approaches is posed. Such a value of the mass transfer rate coefficient in the kinetic equation is determined for which two approaches give close results. Different kinds of adsorption, such as linear, non-linear, equilibrium, non-equilibrium are analyzed. Solute transport characteristics in both zones are determined for different analyzed cases.

KEYWORDS: adsorption, diffusion, dispersion, mass transfer, numerical solution, solute transport.

I.INTRODUCTION

Solute transport studies have become important tools in soil physics, particularly for predicting the movement of pesticides, nitrates, heavy metals and other substances through porous media, environmental protection, oil and gas recovery and other branches of techniques. These studies can provide valuable information about both the behavior of chemical in the porous medium (diffusion, dispersion, anion exclusion, adsorption, or exchange processes) and about the medium itself (pore size distribution, aggregation etc.) [1]. Attempts to study solute transport processes qualitatively have been based generally on the classical convective-dispersive equation (CDE), all solutions of which predict nearly symmetrical concentration distribution [2,3]. However, many experimental studies have shown strongly nonsigmoid and asymmetrical distribution. In particular, the appearance of highly asymmetric or nonsigmoid concentration profiles can be observed in the "tailing" of them. Many investigators have studied this phenomenon and now we can identify several conditions where the tailing has been observed. Some of them are: 1) unsaturated flow, 2) aggregated media, 3) the decreasing of pore-water velocity, 4) the presence of mobile and immobile liquid zones. It is evident that solution of CDE may not always give an accurate description of the physical processes that occur in aggregated (or unsaturated) porous media. One of the attempts to account mobile and immobile liquid zones (MLZ and IMLZ) in porous media was proposed by in [4] that is known as two-region nonequilibrium model (TRNM). In [1] an analytical solution is presented for the movement of chemicals through a sorbing porous medium with lateral or intra-aggregate diffusion. The liquid phase in the porous medium is divided into mobile and immobile regions. Diffusion transfer between the two liquid regions is assumed to be proportional to the concentration difference between the mobile and immobile liquids. Sorption processes in both dynamic and stagnant regions of the medium are assumed to be instantaneous and the adsorption isotherm is assumed to be linear. The analytical model derived describes the extensive tailing observed during flow through an unsaturated, aggregated sorbing medium and explains the often observed early breakthrough of chemical in the effluent.

The TRNM model was analyzed by many researchers. In [5,6] presented an analytical solution for the movement of solute through the porous medium, which is leached at a constant rate. The solution takes into account transfer into an immobile water fraction. In [7] authors presented analytical solutions for two convection-dispersion type transport models useful for studying simultaneous pesticide sorption and degradation. One solution is for the familiar two-site sorption model in which adsorption-desorption proceeds kinetically on one fraction of the sorption sites, and at equilibrium on the remaining sites. Another solution holds for two-region (or mobile-immobile liquid phase) transport appropriate for aggregated or fractured media. The transport models account for degradation in both the solution and sorbed phases. One of the two independent degradation coefficients may be eliminated when the solution and sorbed phase degradation rate coefficients are assumed to be identical, as for instance, for radioactive solute. Experimental verifications of the TRNM model were carried out in [8,9,10,11]. Some problems of mass transport in two zones media are solved in [12, 13].

A modified two-region approach that accounts for chemical and physical nonequilibrium of solute behavior in soils was developed in [14].

Approaches to the modelling of solute transport in aggregated porous media may be divided into three types [15]:

1) Bicontinuum approach with interchange between mobile and immobile liquid zones of specified geometry governed by Fick's diffusion law (PDMs, for spherical aggregates - SD models);

2) Bicontinuum approach with interchange described by an first-order kinetic expression (FOMs);

3) Equivalent monocontinuum approach or local equilibrium approach (LE models).

First two types are most widely used to analyze solute transport problems in non-homogeneous media. In the first type models the interfacial exchange rate is assumed to be high, and the overall rate of exchange is assumed to be governed by diffusion at the periphery of the immobile domain, as controlled by the time history of concentration gradients and fluxes within the immobile region. In the second type models, advective transport of solute is confined to the mobile region, and solute exchange between the two regions is considered to be driven by a first-order process that is based on the difference in average concentration in each region. The ability to predict the long-term contaminant behavior in aggregated media depends on the accuracy of the representation of solute transport and the exchange between the two domains [16]. As it mentioned above to model solute transport in such aggregated media TRNM are used. In [16] the validity of such models was explored by experimentally observing the influence of pore water velocity on the apparent rates of transfer within a geometrically well defined, two-region system. Tritiated water tracer (3H_2O) experiments were conducted in a 7-cm soil column with a central cylindrical zone of highly permeable material surrounded by an annulus of relatively impermeable finer-grained sediment. In general, TRNM are now commonly used to simulate three-dimensional laboratory and field-scale transport regimes that cannot be described adequately with a single domain model.

In [16,17,18,19,20] laboratory and field experiments where mass transfer rates were modeled with either FOMs or PDMs where analyzed. The authors established the effect of experimental conditions on the interpreted FOM constants and also revealed some dependence of fitted PDM rate coefficients on system conditions. The dependence of PDM parameters was less statistically significant than that of the FOM parameters. It was indicated that one of reasons of that may be the presence of alternative mass transfer mechanisms (i.e., advection-based processes rather than diffusion alone).

In this paper we consider a solute transport problem in a semi-infinite non-homogeneous two zone medium consisting of two co-axial cylinders, one in the center with high permeability (macropore) and another one with low permeability (micropore). In macropore liquid is mobile and in micropore – immobile. Solute transfer between two zones is modeled with using two approaches – diffusion (PDM) and kinetic (FOM). To converge results of two approaches appropriate value of the mass transfer rate coefficient is determined. Different kinds of adsorption in both zones are considered. For analyzed cases solute transport characteristics are determined.

II. GOVERNING EQUATIONS

Consider an area that consists of two parts: 1) macroporous cylindrical area (macropore), which has a radius a (ie area $\Omega_1\{0 \leq x < \infty, 0 \leq r \leq a\}$), with large pores, characterized by relatively high porosity and the average velocity of the fluid in it, 2) the surrounding cylindrical microporous area (micropore), which occupies region $\Omega_2\{0 \leq x < \infty, a \leq r \leq b\}$ and has a low or zero porosity, accordingly, the low flow rate (Figure 1) [18].

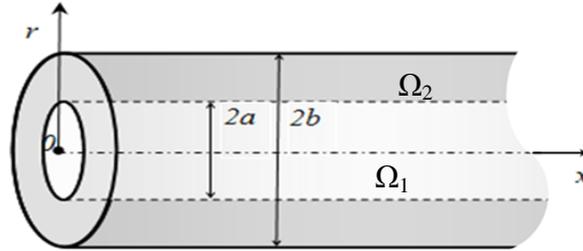


Fig.1 Cylindrical medium with a cylindrical macropore.

The following relations are used [19]

$$V_f = \frac{a^2}{b^2}, \quad V_a = 1 - V_f, \quad \theta_m = V_f \theta_f, \quad \theta_{im} = V_a \theta_a, \quad \rho_m = V_f \rho_f, \quad \rho_{im} = V_a \rho_a, \quad \rho = \rho_m + \rho_{im}, \quad f_m = \rho_m / \rho, \quad \theta = \theta_m + \theta_{im},$$

where V_f, V_a - volume fractions of macropores and micropores per unit volume of the medium $\Omega_1 \cup \Omega_2$, θ_f, θ_a - local porosity coefficients of macroporous and microporous media, θ_m, θ_{im} - relative porosity coefficients of macroporous and microporous media, ρ_f, ρ_a - local densities of macroporous and microporous media, ρ_m, ρ_{im} - relative bulk densities of two media.

In one-dimensional form the mass transfer in Ω_1 is described by the equation

$$\theta_m \frac{\partial c_m}{\partial t} + \rho_m \frac{\partial s_m}{\partial t} + \theta_{im} \frac{\partial c_{im}}{\partial t} + \rho_{im} \frac{\partial s_{im}}{\partial t} = \theta_m D_m \frac{\partial^2 c_m}{\partial x^2} - \theta_m v_m \frac{\partial c_m}{\partial x}, \tag{1}$$

where c_m - the average concentration in Ω_1 , s_m - the concentration of the adsorbed mass in the macropores, D_m - the diffusion coefficient in the macropores, v_m - the average fluid velocity in Ω_1 , c_{im}, s_{im} - the average solute concentration and the concentration of the adsorbed mass in Ω_2 , which are determined from the following relations

$$c_{im} = \frac{2}{b^2 - a^2} \int_a^b r c_a(t, x, r) dr, \tag{2}$$

$$s_{im} = \frac{2}{b^2 - a^2} \int_a^b r s_a(t, x, r) dr, \tag{3}$$

c_a - local solute concentration in Ω_2 , s_a - local concentration of the adsorbed mass in Ω_2 , t - time, x - distance.

The distribution of solute in the region Ω_2 is described by the diffusion equation taking into account the adsorption of mass

$$\theta_a \frac{\partial c_a}{\partial t} + \rho_a \frac{\partial s_a}{\partial t} = \theta_a D_a \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial c_a}{\partial r} \right), \quad a < r < b, \tag{4}$$

where D_a is the effective diffusion coefficient in Ω_2 .

Equations (1), (4) correspond to the PDM approach. In the FOM approach instead of (4) the following first-order kinetic equation is considered together with (1)

$$\theta_{im} \frac{\partial c_{im}}{\partial t} + \rho_{im} \frac{\partial s_{im}}{\partial t} = \alpha (c_m - c_{im}), \tag{5}$$

where α is mass transfer rate coefficient.

Consider the following problem. Let through inlet surface of Ω_1 , i.e. $x=0, 0 \leq r \leq a$ since $t > 0$ a non-homogeneous liquid with concentration of solute c_0 inflows with average pore velocity v_m . To solve equations (1) and (4) we are to give several initial and boundary conditions.

Transport equations (1) and (4) will be solved for initial conditions of zero

$$c_m(0, x) = 0, \tag{6}$$

$$c_{im}(0, x) = 0. \tag{7}$$

In the inlet surface of Ω_1 i.e. $x=0$, boundary conditions can be given either a first-type of the form

$$c_m(t, x) = c_0, \quad c_0 = \text{const}, \quad (8)$$

or a third-type (flux type) of the form

$$\left(c_m - D_m \frac{\partial c}{\partial x} \right) \Big|_{x=0} = c_0. \quad (9)$$

On the other boundary of Ω_1 we give a second-type condition of the form

$$\frac{c_m(t, \infty)}{\partial x} = 0. \quad (10)$$

On the common boundary of micro and macroporous media we require a concentrations continuity condition, i.e.

$$c_a(t, x, a) = c_m(t, x). \quad (11)$$

In Ω_2 , the longitudinal distribution of solute is not taken into account and the outer boundary ($r = b$) is impermeable for solute, i.e.

$$\frac{\partial c_a(t, x, b)}{\partial r} = 0. \quad (12)$$

Several cases depending on the type of adsorption are considered.

III. NUMERICAL SOLUTIONS AND RESULTS

Here we analyze several cases corresponding to different kinds of adsorption.

A.. Linear equilibrium adsorption

In this case, we consider linear and reversible equilibrium adsorption in both regions Ω_1 and Ω_2 with the following isotherms:

$$s_m = k_m c_m, \quad s_a = k_a c_a, \quad s_{im} = k_{im} c_{im}, \quad (13)$$

where, k_m, k_{im} are the adsorption coefficients in macro and microporous media Ω_1 and Ω_2 , respectively. It can be shown that $k_a = k_{im}$ [19].

Substituting (13) into (1) and (4) gives

$$\theta_m R_m \frac{\partial c_m}{\partial t} + \theta_{im} R_{im} \frac{\partial c_{im}}{\partial t} = \theta_m D_m \frac{\partial^2 c_m}{\partial x^2} - \theta_m v_m \frac{\partial c_m}{\partial x}, \quad (14)$$

$$R_{im} \frac{\partial c_a}{\partial t} = D_a \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial c_a}{\partial r} \right) \quad (15)$$

where, R_m, R_{im} - retardation coefficients:

$$R_m = 1 + \frac{f_m \rho k}{\theta_m}, \quad k = k_m + k_{im}, \quad \rho k = \rho_m k_m + \rho_{im} k_{im}, \quad R_{im} = 1 + (1 - f_m) \frac{\rho k}{\theta_{im}},$$

$$R_a = 1 + \frac{\rho_a k_a}{\theta_a}, \quad R = 1 + \frac{\rho k}{\theta}, \quad \theta_m R_m + \theta_{im} R_{im} = \theta R, \quad R_{im} = R_a,$$

and $f_m = \rho_m k_m / (\rho k)$ is the mass fraction of the adsorbed mass .

To solve (14), (15) the initial and boundary conditions (6) - (8), (10) - (12) are used.

Equations (14) and (15) are numerically solved by the finite difference method [22].

The following values of the initial parameters are used in the calculations:

$D_a = 2,5 \cdot 10^{-7} \text{ m}^2/\text{s}$, $D_m = 10^{-5} \text{ m}^2/\text{s}$, $v_m = 10^{-4} \text{ m/s}$, $c_0 = 0,001$, $\theta_f = 1,0$, $\theta_a = 0,6$, $\rho_f = 2000 \text{ kg/m}^3$, $\rho_a = 2500 \text{ kg/m}^3$, $a = 0,05 \text{ m}$, $b = 0,25 \text{ m}$.

Results of some numerical calculations, the field of local solute concentration c_a , profiles of solute concentrations changes c_m and c_{im} are shown in Fig.2,3.

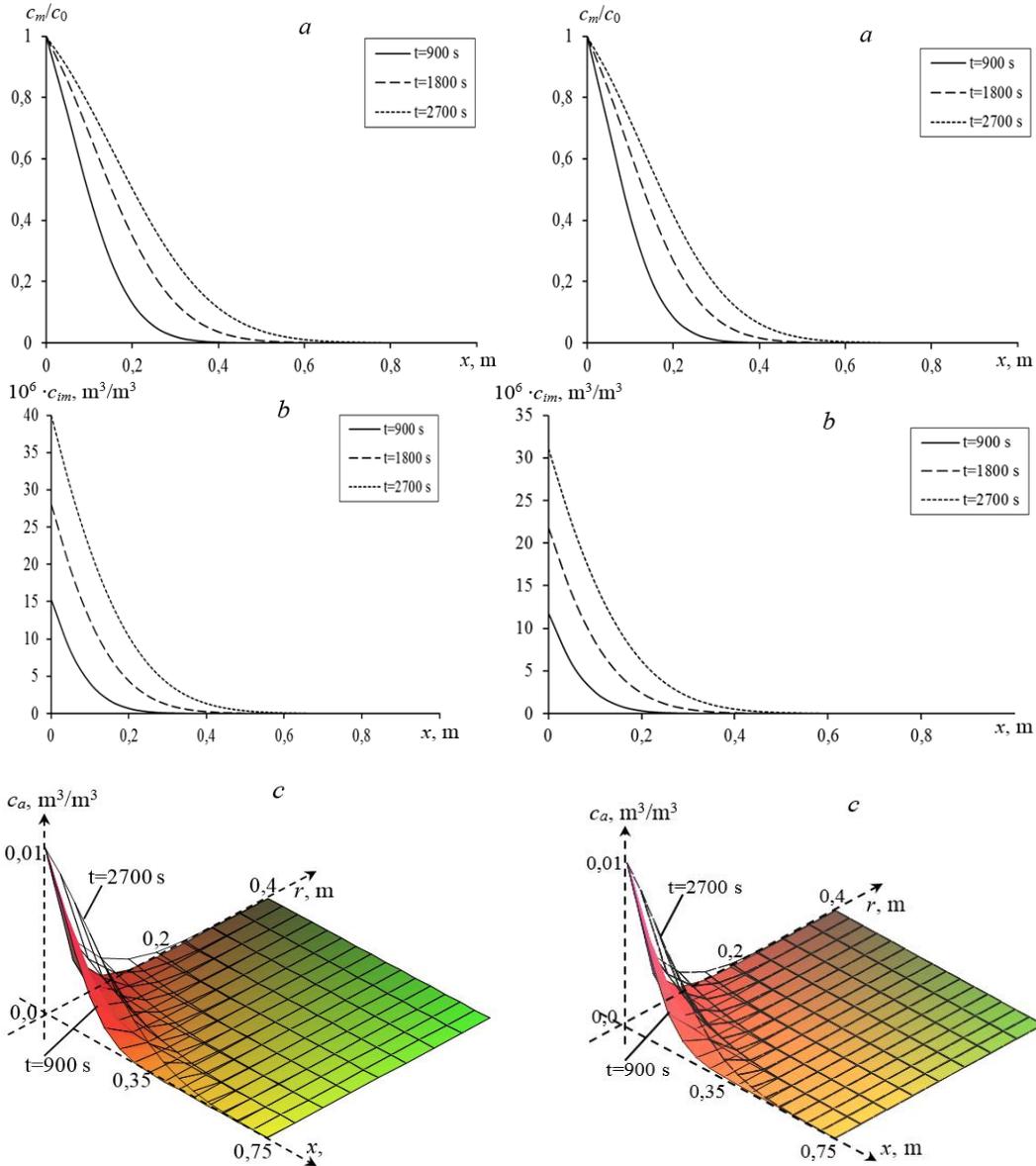


Fig. 2. Profiles of concentrations c_m (a), c_{im} (b) and surface c_a (c) at different times and $v_m = 10^{-4}$ m/s, $D_a = 2,5 \cdot 10^{-7}$ m²/s, $D_m = 10^{-5}$ m²/s, $k = 5 \cdot 10^{-4}$ m³/kg.

Fig. 3. The concentration profiles c_m (a), c_{im} (b) and the surface c_a (c) at different times and $v_m = 10^{-4}$ m/s, $D_a = 2,5 \cdot 10^{-7}$ m²/s, $D_m = 10^{-5}$ m²/s, $k = 7,5 \cdot 10^{-4}$ m³/kg.

In Fig.3 the value of k is large than in Fig.2. Comparing Fig. 2a with Fig. 3a, it can be observed that the propagation of c_m in Fig.3 is slow than in Fig.2 in x direction. Increasing of the adsorption coefficient k leads to a slow dynamics of c_{im} (Fig. 3b).

Now consider the FOM (1), (5). In the case of the linear isotherm (13), from (5) the following equation is obtained

$$\theta_{im} R_{im} \frac{\partial c_{im}}{\partial t} = \alpha (c_m - c_{im}). \tag{16}$$

Note, in the FOM approach (1), (5) (or (16)) boundary conditions (11), (12) are unnecessary.

Equations (14), (16) are solved with initial and boundary conditions (6), (7), (8), (10). Comparison of results on the basis of two approaches, PDM and FOM, is shown in Fig.4.

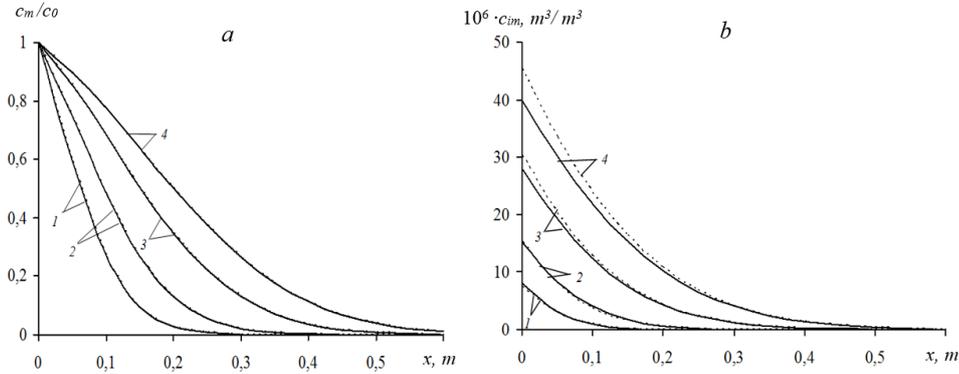


Fig. 4. The profiles of relative concentration c_m / c_0 (a) and c_{im} (b) at different times and $v_m = 10^{-4}$ m/s, $\alpha = 3 \cdot 10^{-6} s^{-1}$, $D_m = 10^{-5} m^2/s$, $k = 5 \cdot 10^{-4}$, from PDM (solid lines) and FOM (dashed lines), $t = 450$ (1), 900 (2), 1800 (3), 2700 (4) s.

It can be seen from Fig. 4 that both approaches give close results at $\alpha = 3 \cdot 10^{-6} s^{-1}$. This result shows us principal possibilities to obtain close results on the basis of two approaches by appropriate choosing the value of α .

B. Linear non-equilibrium adsorption

In this case, the kinetic equations of adsorption have the form

$$\beta \frac{\partial s_m}{\partial t} = k_m c_m - s_m, \tag{17}$$

$$\beta \frac{\partial s_{im}}{\partial t} = k_{im} c_{im} - s_{im}, \tag{18}$$

$$\beta \frac{\partial s_a}{\partial t} = k_a c_a - s_a, \tag{19}$$

where β is the characteristic transition time from non-equilibrium to equilibrium adsorption.

Initial conditions for the concentrations of adsorbed solute are taken in the form

$$S_m(0, x) = 0, \tag{20}$$

$$S_{im}(0, x) = 0, \tag{21}$$

$$S_a(0, x, r) = 0. \tag{22}$$

In diffusion approach equations (1), (4) with (20) - (22), (6) - (8), (10) - (12) are numerically solved. The calculation scheme is as following. First, the values $(S_m)_i^{k+1}$, $(S_{im})_i^{k+1}$, $(S_a)_{i,j}^{k+1}$ are determined. Then, $(c_a)_{i,j}^{k+1}$ is determined from the discretized equation (4). Finally, c_m is determined from the discretized equation (1). In FOM equation (1), (5), (17), (18) are solved with corresponding initial and boundary conditions.

Figure 5 shows the results of both approaches. In this case we obtain also good agreement of two approaches. Non-equilibrium adsorption (17) - (19) leads to the delaying of total adsorption rate in comparison with equilibrium adsorption. As a result, we can observe some advanced distribution of c/c_0 for non-equilibrium adsorption at same other parameters (Compare Fig.4a and 5a). In contrary, in the distribution of c_{im} some lagging can be observed for non-equilibrium adsorption (Compare Fig.4b and 5b). In this case also a good agreement of two approaches were obtained.

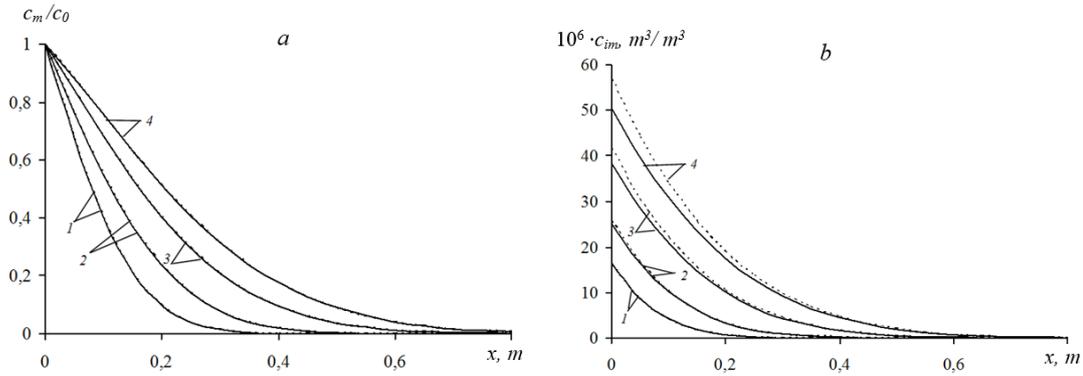


Fig. 5. The profiles of relative concentration c/c_0 (a) and c_{im} (b) and different times and $v_m = 10^{-4}$ m/s, $D_a = 2.5 \cdot 10^{-7}$ m²/s, $D_m = 10^{-5}$ m²/s, $k = 5 \cdot 10^{-4}$, $\beta = 1000$ s. for PDM (solid lines) and FOM (dashed lines), $t = 450$ (1), 900 (2), 1800 (3), 2700 (4) s.

C. Nonlinear equilibrium adsorption

Now the problem is solved for the equilibrium non-linear adsorption

$$s_m = k_m c_m^n, \quad s_{im} = k_{im} c_{im}^n, \quad s_a = k_a c_a^n, \quad 0 < n < 1. \tag{23}$$

In this case, only the retardation coefficients are changed

$$R_m = 1 + \frac{f_m \rho k_m n c_m^{n-1}}{\theta_m}, \tag{24}$$

$$R_{im} = 1 + \frac{(1 - f_m) \rho k_{im} n c_{im}^{n-1}}{\theta_{im}}, \tag{25}$$

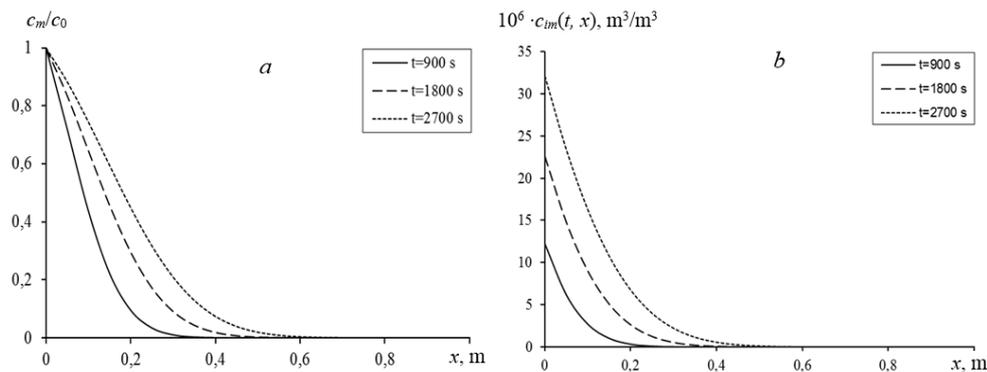
$$R_a = 1 + \frac{f_a \rho k_a n c_a^{n-1}}{\theta_a}. \tag{26}$$

The problem is also analyzed on the basis of the kinetic equation (16), in which the retardation coefficient R_{im} is determined from the relation (25).

The main goal for us now is to study the influence of n at the same values of all other parameters.

Some representative results are shown in Fig.6. We can observe some intensification of adsorption rate for $n < 1$ (Compare Fig.2a and Fig.6a). We are to remember that all results are obtained for identical model parameters, other than n . It is evident that for different parameters we are to expect different results.

Comparison of results on the basis of two approaches are shown in Fig.7. As in previous cases we have good agreement of results. Some discrepancies we observe in c_{im} distribution (Fig.7b).



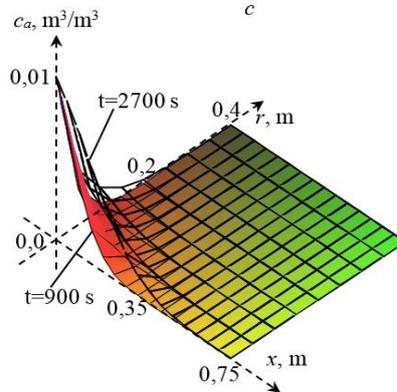


Fig. 6. Concentration profiles c_m / c_0 (a), c_{im} (b) and surface c_a (c) at different times and $v_a = 10^{-4}$ m/s, $D_a = 2.5 \cdot 10^{-7}$ m²/s, $D_m = 10^{-5}$ m²/s, $k = 5 \cdot 10^{-4}$ m³/kg, $n = 0.95$.

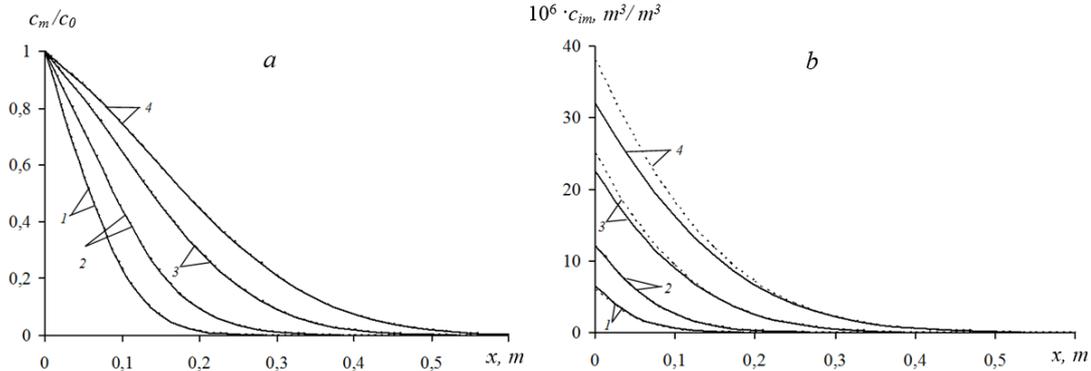


Fig. 7. The profiles of relative concentrations c_m / c_0 (a) and c_{im} (b) at different times and $v_a = 10^{-4}$ m/s, $D_a = 2.5 \cdot 10^{-7}$ m²/s, $D_m = 10^{-5}$ m²/s, $k = 5 \cdot 10^{-4}$ m³/kg, $n = 0.95$ for PDM (solid lines) and FOM (dashed lines), $t = 450$ (1), 900 (2), 1800 (3), 2700 (4) s.

D. Nonlinear non-equilibrium adsorption

Here the following nonlinear kinetic equations of adsorption are used

$$\beta \frac{\partial s_m}{\partial t} = k_m c_m^n - s_m, \tag{27}$$

$$\beta \frac{\partial s_{im}}{\partial t} = k_{im} c_{im}^n - s_{im}, \tag{28}$$

$$\beta \frac{\partial s_a}{\partial t} = k_a c_a^n - s_a. \tag{29}$$

The calculation scheme is similar to the second case, only for determining the value $(s_m)_i^{k+1}$, $(s_{im})_i^{k+1}$, $(s_a)_i^{k+1}$ following relations are used

$$(s_m)_i^{k+1} = \frac{\beta}{\beta + \tau} (s_m)_i^k + \frac{\tau}{\beta + \tau} k_m (c_m)_i^k, \tag{30}$$

$$(s_{im})_i^{k+1} = \frac{\beta}{\beta + \tau} (s_{im})_i^k + \frac{\tau}{\beta + \tau} k_{im} (c_{im})_i^k, \tag{31}$$

$$(s_a)_{i,j}^{k+1} = \frac{\beta}{\beta + \tau} (s_a)_{i,j}^k + \frac{\tau}{\beta + \tau} k_a (c_a)_{i,j}^k. \tag{32}$$

Some results are shown in Fig.8. In this case, when a nonlinear non-equilibrium kinetic equation is used, in the dynamics of adsorption in non-steady stage of the process some delays occur. It leads to the progressive distribution of concentrations c_m and c_{im} (Compare Fig.6 a,b and Fig.8 a,b).

Fig.9 shows a comparison of the results of two approaches. For the mass transfer coefficient $\alpha = 3.335 \cdot 10^{-6} \text{ s}^{-1}$, both approaches give close results.

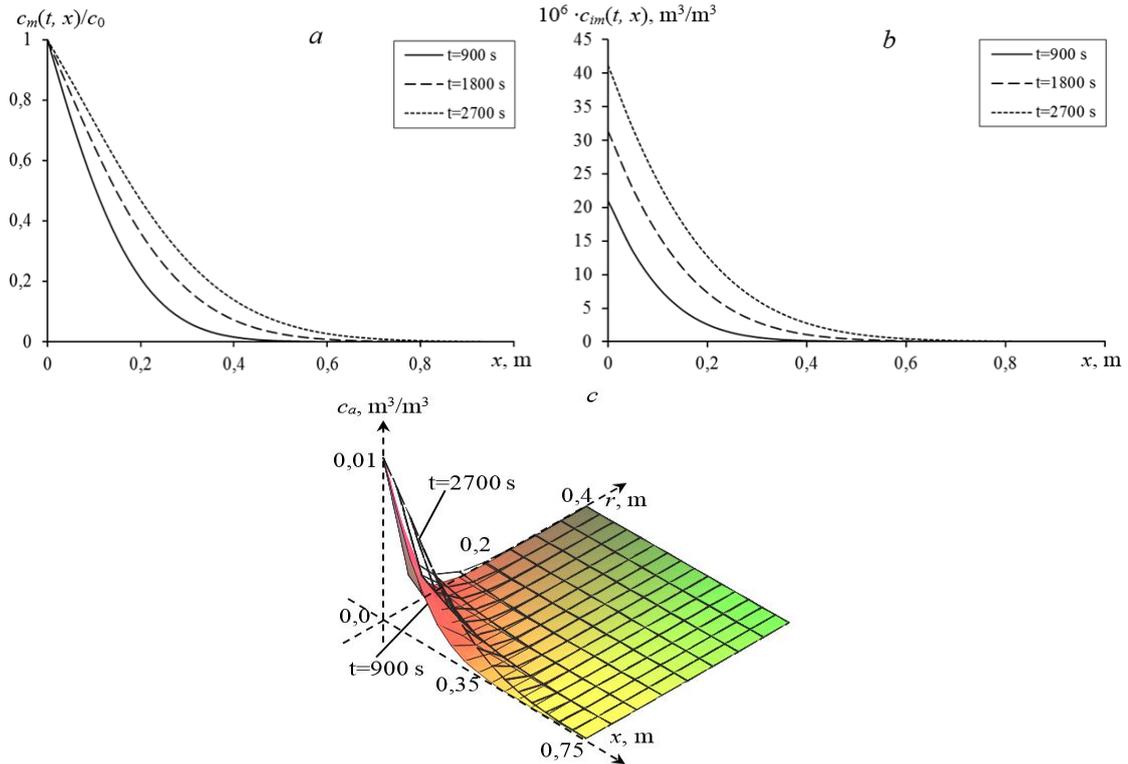


Fig. 8. Concentration profiles C_m (a), C_{im} (b) and surface C_a (c) and different times at $v_a = 10^{-4} \text{ m/s}$,

$$D_a = 2.5 \cdot 10^{-7} \text{ m}^2/\text{s}, D_m = 10^{-5} \text{ m}^2/\text{s}, k = 5 \cdot 10^{-4} \text{ m}^3/\text{kg}, \beta = 1000\text{s}, n = 0.95.$$

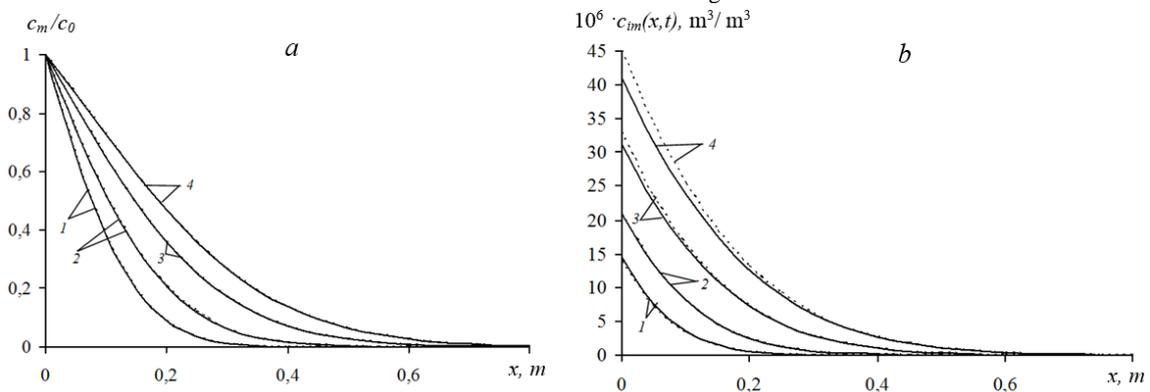


Fig. 9. The profiles of relative concentrations c_m / c_0 (a) and C_{im} (b) at different times and $v_m = 10^{-4} \text{ m/s}$, $D_a = 2.5 \cdot 10^{-7} \text{ m}^2/\text{s}$, $D_m = 10^{-5} \text{ m}^2/\text{s}$, $k = 5 \cdot 10^{-4} \text{ m}^3/\text{kg}$, $n = 0.95$, $\beta = 1000\text{s}$ for PDM (solid lines) and FOM (dashed lines), $t = 450$ (1), 900 (2), 1800 (3), 2700 (4) s.

**IV. CONCLUSIONS**

In this paper we analyzed a solute transport problem in a cylindrical non-homogeneous medium. The medium consists of two co-axial cylinders, the intrinsic one has comparatively high permeability and another one – surrounding cylinder comparatively low permeability. So, intrinsic cylindrical zone referred as micropore, while surrounding cylindrical zone – as macropore. In the macropore solute transport we model by convective – dispersion equation, where in micropore – by diffusion equation. To model the solute transport process we use also an alternative way - first order kinetic approach. Different kinds of solute adsorption (linear equilibrium, linear non-equilibrium, non-linear equilibrium, non-linear non-equilibrium) are taken into account in both zones. A solute transport problem is posed and numerically solved for both approaches – PDM and FOM. Results on the basis of two approaches are comparatively analyzed. It was shown that by appropriate choosing of the mass transfer rate coefficient α in the first order mass transfer kinetic equation results of two approaches can be converged. We note that in more strong analyses parameter α must be choosed by solving corresponding inverse problems. Results show that at all other same conditions non-equilibrium adsorption leads to the delay of solute adsorption rate. In addition, at the same all other model parameters non-linear adsorption with $n < 1$ intensifies adsorption rate. Decreasing of adsorption rate leads to the more intensive solute transport distribution in both zones. In contrary, increasing of adsorption rate leads to the more slow solute distribution in both zones - micropore and macropore. It can be concluded that in non-homogeneous media due to solute transfer from one zone to the another one common solute transport can be considerably changed. So, intrinsic solute transfer in non-homogeneous media can have principal role in solute transport.

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