Solute transport in a horizontal porous layer at a high solute concentration

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Abstract. Solute transport in a porous media has not been studied systematically up to present, and there is an uncertainty about the proper governing law for describing the transport process in such media. In this study, we analyze the data of solute transport experiments in a horizontal sand column packed with uniform glass beads. Sodium chloride (NaCl) is chosen to be the tracer. A number of tracer tests are conducted to examine the transport process under different NaCl concentrations. The obtained velocity-time profiles and BTCs indicate different stages of filtering. Based on the results a possible scenario of solute transport under fixed flow rate is proposed.

1. Introduction

Solute transport through porous media is a topic of interest in many branches of science and engineering, including chemistry, soil science, groundwater hydrology, chemical engineering, sanitary engineering and petroleum engineering [1, 2, 3]. Presently, contaminant movements are described by the standard advection-dispersion model (ADE) assuming that dispersion behaves as a diffusion-like (Fickian) process. However an increasing number of examples display a strongly Non-Fickian or anomalous transport for dissolved contaminants [4, 5, 6, 7]. Non-Fickian diffusion has long been believed to relate to interaction (adsorption/desorption) between an impurity and the solid matrix of the medium. The most popular approach to describing such transport is the concept of MIM (mobile / immobile media) [8]. Further, several more complex concepts are proposed: the model which assumes that pore-scale dispersion is negligible relative to the spreading (stochastic-convective model), visualizing solute transport as a series of particle jumps (continuous time random walk model), description of mass transfer between a mobile domain and any number of immobile domains with varying properties (Multi-Rate Mass Transfer Model) etc. A brief description of these models may be found in [9, 10]. Different transport models have a potential benefits as well as a number of limitations. Thus, fundamental challenges remain in applications regarding model selection and parameter definition. It leads to great importance of laboratory experiments producing an accurate database for models validation.

In turn, there is a great diversity of laboratory experiments which can be classified in quite different way: by the type of contaminants – various colorants [9, 11, 12, 13], salinity water [12, 13], non-aqueous phase liquids [14] and even bacteria [15]; by the method of observation – injecting a tracer pulse [11, 9, 12, 13, 14] and leaching experiments [16, 17]; by direction of transport – vertical [17, 12, 14, 9] and horizontal [16, 18, 5]; and by the inflow conditions: using of hydrostatic pressure [16, 17, 12] or using a pump [19, 13]. Unfortunately, here are no consistent studies that allow covering the main features of
the transport of pollutants in porous media. In addition, we have not found works related to high concentration of pollutants.

Here we present results of column experiments to study a scenario of pulse contamination of porous media under hydrostatic pressure drop and various solute concentrations as a first step in creating comprehensive database.

2. Experiment

The experiments were conducted using cylindrical column with length $L = 392\text{mm}$, and internal diameter $D = 15.6\text{mm}$. The column was packed as uniformly as possible with glass beads of a size $0.8–1.2\text{mm}$ (mean porosity $\phi = 0.365$). The column was closed at both ends using a perforated brass cap to prevent the loss of fines. The horizontally-placed columns were slowly saturated from the bottom up using distilled water. A steady saturated flow field was established in the column by maintaining the constant flow rate using a Mariotte bottle. Single-limb liquid-column manometers were located at the inlet and outlet of the porous medium to measure the actual pressure drop between the ends of such column. The liquid flow rate was measured using an electronic balance, the resolution of the balance is $0.01\text{g}$. Schematically the experimental setup is presented in Fig. 1.

![Figure 1. The experimental setup: 1 – Mariotte bottle; 2 – single-limb liquid-column manometers; 3 – column with porous media; 4 – sample bottle](image)

Permeability $\kappa$ was measured with the pumping test before the tracing experiments using the dependence of flow rate on applied pressure differences. The obtained permeability value was $\kappa = 3.6\times10^{-10}\text{m}^2$.

Experiments were conducted under the initial value of mass flow rate $0.05\text{g/s}$ to observe the transport characteristics of NaCl solution due to the change of its concentration. We considered the following concentrations of NaCl ($C_0$): 50 g/L, 100 g/L and 200 g/L. The solution of NaCl with a volume of 27 mL was embedded at inflow way without any additional pressure. The volume of NaCl solution corresponded to one pore volume of the column. Samples were collected at the outlet of the column, representing a transporting distance of 392 mm. The samples were analyzed by refractometry method with an accuracy of 5 g/L. To evaluate the reliability of solubility measurements all experiments were repeated two times. Agreement between repetitions was good and, therefore, the results are presented only for one of them.
3. Results and Discussion

The seepage (Darcian) velocity is an essential element in solute transport and is calculated as follows:

\[ q = \frac{Q}{S}, \]  

where \( q \) is the Darcian velocity (m/s), \( Q \) is the total discharge (m\(^3\)/s) which was measured during the experiments, and \( S = 191.1 \text{ mm}^2 \) is the inner cross-sectional area of the column.

![Darcian velocity versus time (a) and breakthrough curve (b) for C\(_0\) = 200 g/L.](image)

Fig. 2 shows the measured flow rate and breakthrough curve for \( C_0 = 200 \text{ g/L} \). There are three distinctive stages in a velocity-time profile. The first stage (A) is a tracer introducing period. In this period of time minimum of Darcian velocity is observed. We believe that it may be linked with counterflow formation due to the horizontal gradient of salt concentration. Following the theory of stability of vertical flow in porous media we can evaluate velocity of the counterflow as:

\[ \Delta q = \frac{g \beta_c \Delta C k h}{\nu D}, \]  

where \( \Delta q \) is the drop of seepage velocity, \( g \) is the gravity acceleration, \( \beta_c \) is the coefficient of concentration expansion [20], \( \Delta C \) is the concentration difference, \( \nu \) is the kinematic viscosity and \( h \) is the depth occupied by the counterflow. Following this ratio, \( h \) is about 3 mm, which should be taken into account in the modeling of transport processes. It is interesting that the depth of flow blocking weakly depends on concentration difference for fixed flow rate. Variation in solute concentration leads mostly to changes in counterflow intensity. When tracer introduction is finished, the blocking flow gradually vanishes leading to the growth of Darcian velocity. The seepage velocity at stage (A) decreases by almost 50 percent for \( C_0 = 200 \text{ g/L} \) and by 16 and 9 percent for \( C_0 = 100 \text{ g/L} \) and \( C_0 = 50 \text{ g/L} \), respectively.

The second stage (B) is a flushing period, which also shows a sharp decline in Darcian velocity, suggesting the decline of media permeability due to adsorption process. The third stage (C) is a stabilized Darcian velocity after quite a long time of flushing, indicating that the permeability of the media has reached an initial value again. The long BTC tail measured for stage (C) (Fig. 2) is quite non-Fickian and generally attributed to sorption process.
The dependences of seepage velocities on time for different concentration are shown in Fig. 3 (a). The velocity-time profiles for diluted solutions exhibits another interesting phenomenon. For $C_0 = 100$ g/L and $C_0 = 50$ g/L the processes of adsorption/desorption occur two times. According to the Langmuir adsorption model, adsorption and desorption are reversible processes, since the adsorbed molecules are retained only for a certain period of time, after which these molecules are desorbed and the same number of new molecules are adsorbed.

Breakthrough curves (BTCs) are presented in Fig. 3 (b). Removal of $C_0 = 200$ g/L occurs significantly later than for other $C_0$ values due to the presence of blocking flow. More intense mixing provides a lower pick amplitude compared with $C_0 = 100$ g/L. With a decrease in concentration, the difference in the peak speed declines, while the pattern remains unchanged.

![Figure 3](image.png)

**Figure 3.** Darcian velocity versus time (a) and BTCs (b) for different NaCl concentration.

**Conclusions**
A series of experiments with NaCl transport through horizontal column packed with uniform glass beads have been conducted. The dependence of transport dynamics on NaCl concentration for fixed values of the flow rate has been evaluated.

The value of seepage (Darcian) velocity is shown to drop dramatically in the tracer introducing period. Assumingly, the horizontal gradient of concentration leads to formation of counterflow blocking the filtration. A decrease in NaCl concentration leads to a decline of counterflow intensity and has a weak influence on the mixing depth.

BTCs exhibit late-time tailing behavior due to the sorption process. The presence of counterflow makes the peak of a higher concentration late while reducing its amplitude.

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