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Predicting stagnant pore volume in porous media using temporal moments of tracer breakthrough curves

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ABSTRACT

The heterogeneity in complex porous media like oil reservoirs and aquifers many times renders a fraction of fluid in the pores immobile. The tracer breakthrough curves that are used to characterize the porous media are impacted by the immobile volume fraction and show a tailing effect. It is important to first recognize the presence of the immobile volume and quantify it based on a single tracer breakthrough curve in complex geological environments. In this work, we use the method of moments on the tracer breakthrough curve to solve the inverse problem of porous media characterization with stagnant volume fractions. In particular, we use a three parameter model describing the tracer transport in a porous medium with an immobile fluid fraction and solve the forward problem analytically. We derive mean, variance, skewness, and kurtosis of the analytical solution for the exit age density of the injected tracer in the porous medium. We then describe the behavior of the moments in the parameter space of the transport model and relate it with the tracer transport behavior in the porous medium. We then develop the solution for the inverse problem of using these higher order temporal moments of the effluent tracer concentration to estimate the immobile fluid volume in the porous medium.

1. Introduction

Tracer transport in porous media is important for many applications e.g., characterization of oil reservoirs for enhanced oil recovery (Lake and Hirasaki, 1981; López et al., 2003; Dindoruk and Dindoruk, 2008; Sharma et al., 2014; Al-Shalabi et al., 2017) and contaminant transport in aquifers (Rubin et al., 1997; Berkowitz and Scher, 1998; Elenius and Gasda, 2013; Kang et al., 2015; Seetha et al., 2015). The fluid generally has to travel complex pathways in these porous media, which cannot be accessed for visual evaluation. Therefore, tracer tests are widely used for characterization and evaluation of the porous media for flow behavior (Scholz et al., 2012), which can provide useful information about the porous media, such as, heterogeneity of oil and gas reservoirs and residual oil saturation. Interpretation of the tracer test is dependent on the mass transport model applied on the tracer particles. For example, in an oil reservoir, the residual oil saturation is found using the difference in mean arrival times of the two tracers injected in the reservoir during water injection (Cooke, 1971; Silva et al., 2017). One of the tracers is soluble only in water and the other is soluble in both, oil and water. The tracers undergo different processes in the reservoir, i.e. water soluble tracer advects and disperses in the water phase in the reservoir, while the oil soluble tracer advects, disperses and solubilizes-desolubilises in the residual oil. The mean arrival time is dependent on the processes the tracers experience during their time in the reservoir, which is then used to determine the remaining oil or residual oil saturation. Tracers may encounter stagnant sections, called dead-end or immobile zones, in the porous media during the flow. The flow is extremely small or zero in these stagnant zones (Coats and Smith, 1964; Baker, 1977; Kandhai et al., 2002). Once a tracer particle or a contaminant moving with the fluid enters this stagnant region, it can escape only through diffusion. This phenomenon is known to increase the residence time of the particles visiting the dead-end or immobile sites in the porous media in comparison to rest of the tracer particles. Fraction of the immobile volume and interaction of the tracer with the immobile volume is known to impact the mean arrival time differently at different fluid flow rates, leading to a tailing effect.

For the tracer transport in a porous medium with stagnant or immobile volume, Deans (1963) first described a capacitance model using three parameters. These parameters are (i) ratio of axial convection and axial dispersion called the Bodenstein number which is a specific type of Peclet number (*Pe*) (Froment et al., 2011), (ii) mobile volume fraction of the total void volume in the porous medium (*f*), and (iii) ratio

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of the mass transfer between mobile and immobile regions and convection in the mobile region (α). Coats and Smith (1964) validated this model experimentally. Jasti et al. (1987) pointed out that at low α, the dimensionless peak arrival time of the tracer at the exit is less than unity while at high α the peak arrival time is always unity. They described that at high injection rate (low α) the tracer will not get time to interact with the stagnant volume so will arrive early and at a slow flow rate (high α) the tracer will diffuse into the stagnant volume slowing the peak arrival times. The theory has been extensively used for estimating immobile volume fraction and characterizing the oil and gas reservoirs using tracer test with long tails (Baker, 1977; Salter and Mohanty, 1982; Gist et al., 1990; Wirner et al., 2014; Sanchez-León et al., 2016).

The parameter determination using the Coats and Smith model is difficult owing to the three fitting parameters (Coats and Smith, 1964; Jasti et al., 1987). The mean arrival time and variance of the residence time density, i.e. second order temporal central moment, which are generally used for parameter estimation from experimental data give non-unique solution for Pe, f and α. Approach of matching the experimental exit concentration vs. time with a numerical model while searching the Pe, f and α is computationally expensive. The higher-order, non-Gaussian moments of the residence time distribution are rarely addressed for characterizing the flow behavior and the porous medium. Ginzburg (2017) addressed the higher order moments for the conventional advection-dispersion model.

In this work, we explore the use of non-Gaussian moments of the exit age density of the tracer i.e. skewness (Sk) and excess kurtosis (Ku), for parameter estimation of the three parameter model of tracer transport in a porous medium with stagnant volume. In the classical advection-dispersion model, the residence time density is close to the Gaussian distribution at high Peclet numbers, while it deviates to a more skewed distribution at low Peclet numbers. This is because, at high Peclet numbers, the retention times of all the tracer particles are similar and do not vary significantly from that of the tracer particles flowing with the mean flow. Thus overall dispersion of the tracer on both sides of the peak is similar. However, at low Peclet numbers, the retention time of the tracer particles behind the peak is significantly more, and many more tracer particles are retained for a much longer time of residence as compared to the mean flow. In turn, this enhances the dispersion leading to a non-Gaussian (skewed) distribution of residence time. The skewness (Sk) and excess kurtosis (Ku) indicate the quantitative deviation from the Gaussian distribution.

We use Coats and Smith model of tracer transport and using Laplace transforms, we solve for the exit concentration in the Lalplace domain. We analytically derive the mean, variance, skewness and kurtosis of the tracer residence time density as functions of Pe, f and α. Our analytical temporal moments of tracer exit age density show the behavior of the moments in the parameter space Pe, f, and α. At low α, all the moments have a negligible impact of Pe and in addition, non-Gaussian moments have a negligible impact of immobile volume fraction $(1-f)$. The second central moment is monotonic and decreases with increasing Pe, increasing α, and increasing f. However, the higher order non-Gaussian moments show non-monotonic behavior in the parameter space, unlike the classical advection-dispersion model. We use the behavior of the moments in the parametric space to device a methodology of parameter estimation, especially the immobile or mobile volume fraction of the fluid in the porous media.

2. Mathematical model

We first state the classical advection-dispersion-reaction model (ADR) for flow in a porous medium with reaction term signifying the tracer loss due to reaction or partitioning in the other phase. It may be noted that in the present study we have considered no loss of tracer due to reaction or partitioning (advection-dispersion model, ADM). Next we state the Coats-Smith model (CSM) (Coats and Smith, 1964) for a porous medium with immobile volume. These models are used for deriving the Gaussian and non-Gaussian moments analytically. The governing equation for the tracer concentration in a porous medium using advection-dispersion-reaction model is

$$\frac{\partial \widehat{C}}{\partial t} = -u\frac{\partial \widehat{C}}{\partial x} + D\frac{\partial^2 \widehat{C}}{\partial x^2} - k\widehat{C}, \tag{1}$$

where, $\widehat{C}(t,x)$ is the tracer concentration, u is the interstitial velocity of the fluid in axial direction x, D is the axial dispersion coefficient, k is first order rate of consumption of tracer (=0 in the present study) and t is time. The governing equations for tracer concentration in the porous medium with mobile volume fraction f and immobile volume fraction $1-f$, as shown in schematic of Fig. 1, given by Coats and Smith (1964) is

$$f\frac{\partial \widehat{C}}{\partial t} + (1-f)\frac{\partial \widehat{C}^*}{\partial t} = -u\frac{\partial \widehat{C}}{\partial x} + D\frac{\partial^2 \widehat{C}}{\partial x^2}, \tag{2a}$$

$$(1-f)\frac{\partial \widehat{C}^*}{\partial t} = K\left(\widehat{C} - \widehat{C}^*\right) \tag{2b}$$

where, $\widehat{C}(t,x)$ is the tracer concentration in the mobile zone, $\widehat{C}^*(t,x)$ is the tracer concentration in the immobile zone of the porous medium, and K is the mass transfer coefficient for the tracer transport between mobile and immobile zones. All other symbols are the same as used in the advection-dispersion model. Eq. (2b) is known to cause the tailing effect in the tracer response at the exit. The flowing length of the fluids in the porous medium is L. The initial condition for these systems is

$$\widehat{C}(0,x) = \widehat{C}^*(0,x) = 0 \quad 0 < x < L \tag{3}$$

The boundary conditions for eqs. (1) and (2), using Danckwerts reasoning (Danckwerts, 1953) is

$$u\widehat{C}\left(t,0^-\right) = u\widehat{C}\left(t,0^+\right) - D\left.\frac{\partial \widehat{C}}{\partial x}\right|_{x=0^+} \tag{4a}$$

$$\left.\frac{\partial \widehat{C}}{\partial x}\right|_{x=L^-} = 0 \tag{4b}$$

We now write these equations in non-dimensional form

$$\frac{\partial C}{\partial \tau} = -\frac{\partial C}{\partial \xi} + \frac{1}{Pe}\frac{\partial^2 C}{\partial \xi^2} (\text{ADM}), \tag{5}$$

$$f\frac{\partial C}{\partial \tau} + (1-f)\frac{\partial C^*}{\partial \tau} = -\frac{\partial C}{\partial \xi} + \frac{1}{Pe}\frac{\partial^2 C}{\partial \xi^2} (\text{CSM}), \tag{6a}$$

$$(1-f)\frac{\partial C^*}{\partial \tau} = \alpha(C - C^*)(\text{CSM}) \tag{6b}$$

With initial condition

$$C(0,\xi) = C^*(0,\xi) = 0 \quad 0 < \xi < 1, \tag{7}$$

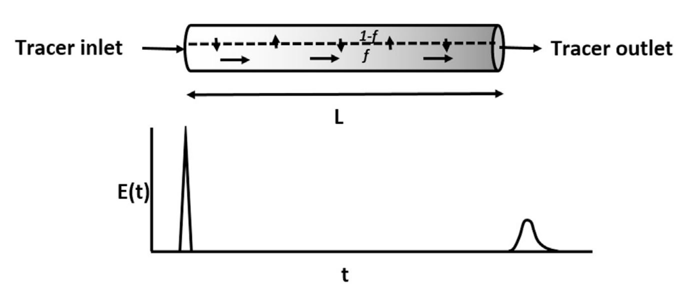

Fig. 1. Schematic of a pulse tracer test in a porous medium with a mobile fraction f and immobile fraction $1-f$.