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Predicting Dead-End Pore-Volume in a Reservoir from Single Tracer Experiment

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Abstract

Tracer studies are used to characterize the porous media for pore volume occupied by different phases and flow trajectories and velocity of the phases. When a tracer is injected as a pulse into a liquid stream flowing in a porous media, the stagnant or the dead-end pore volume in the porous media interacts with the tracer leading to a tailing effect in the outlet tracer curve. The tailing-effect impacts the determination of the flow path or the phase saturations in the porous media using the outlet tracer concentration. Generally, history matching of the effluent concentration profile is used to determine and separate the effect of dead-end pore volume from other tracer behavior in the reservoir such as dispersion or convection. History matching is computationally expensive and many simulation runs are required to match the exit concentration profile. In the present work we have used the method of moments of the Residence Time Distribution (RTD) of the tracer to determine dead-end pore volume and parameters associated with it. We are able to describe from the method devised, which parameters can be determined and which cannot be determined in different flow scenarios in the porous media. We also use numerical experiments of the tracer transport in porous media and compare the results with the method of moments. In the end, we delineate general guidelines for estimation of the parameters, especially the dead-end pore volume.

Introduction

Enhanced oil recovery techniques are dependent on the understanding of the flow behavior, heterogeneity and residual oil saturation in the oil reservoirs. Tracer tests are widely used for the reservoir characterization and evaluation. For assessment of residual oil saturation, single well tracer test is generally used which uses a tracer that partially dissolves in the oil from the water phase (Cooke, 1971; Tang and Haker, 1990; Jin et al., 1995; Al-Shalabi et al., 2017). Single phase flow and no change in oil saturation are assumed in the calculation of the remaining oil volume. Dean et al. (2016) modified the Residence Time Distribution (RTD) analysis to account for the mobile oil saturation. Inter-well tracer methods are used to determine the directional flow trends, well connectivity, relative velocity of the injected fluids, dead end pore volume and sweep efficiency (Wagner, 1977; D'Hooge et al., 1981; Allison et al., 1991; Bjornstad et al. 1994; Guan et al., 2005). Inter-well tracer technique can also be used for finding the residual oil saturation in the inter-well region (Silva et al., 2017). Interpretation of these tracer tests is dependent on the advection-dispersion

model applied. For example, the remaining oil saturation is found using the difference in the mean arrival times of the tracers. The tracers "experience" different processes during their time in the reservoir, i.e. water soluble tracer convects and disperses in the pores occupied by water in the sediments, while the oil soluble tracer convects, disperses and solubilizes and desolubilizes in the pores containing the remaining oil. The mean arrival time is dependent on the processes the tracers have gone through. Fraction of the dead-end pore volume and interaction of the tracer with the dead-end pore volume is known to impact the mean arrival time differently at different fluid flow rates, leading to a distinctly visible tailing effect. For the tracer transport in a porous medium with the dead-end volume or immobile volume, Deans (1963) first described a capacitance model using three parameters, Peclet number (Pe), mobile volume fraction (f) and the ratio of the mass transfer between mobile and immobile regions and convection in the mobile region (α). Coats and Smith (1964) validated the model experimentally. Jasti et al. (1988) pointed out that at low α , the peak arrival time (dimensionless) of the tracer 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 dead-end volume so the peak will arrive early and at slow flow rate (high α) the tracer will diffuse into the dead-end pore volume slowing the peak arrival time. The theory has been extensively used for estimating dead-end pore volume (Baker, 1977; Salter and Mohanty, 1982; Wirener et al., 2014). The parameter determination from a single experiment is a difficult task using the Coats and Smith model (Coats and Smith, 1963, Jasti et al., 1988) owing to three fitting parameters. Generally mean arrival time of the tracer or history matching is used for parameter estimation. However, the mean arrival time can be misleading at intermediate value of α , when the tracer interacts with dead-end volume enough to change the tracer breakthrough curve but not enough such that advection-dispersion model can be used. History matching is computationally expensive. Therefore, a new method is needed for parameter estimation, especially dead-end volume estimation using tracer tests.

In the present work we employ the method of moments on the residence time distribution of the tracer in the reservoir to estimate the process parameters. We first investigate the first moment of the residence time distribution of the tracer in the reservoir, which is related to the convection. We then determine and investigate the higher moments and explore the effect of truncation time i.e. the time when no more samples are taken or the concentration of the tracer at the outlet cannot be measured. We use numerical experiments to see the effect of truncation time at different Pe and α . In laboratory experiments and field trials, it is difficult to get the full tracer breakthrough curve therefore, the impact of truncation time is significant while estimating the parameters by moments, especially with tailing effects of the dead-end volume. We define conditions when the dead-end volume can be determined using tracer tests and develop a general guideline for dead-end pore volume estimation.

Mathematical Model

We employ the model developed by Coats and Smith (1964) on a homogeneous porous medium having mobile volume fraction ' f ' and immobile volume fraction ' $1-f$ ' of the total pore volume as shown in Figure 1. The tracer transport of an ideal tracer in the porous medium can be described by the Coats-Smith model (1964) by equations 1 and 2.

$$f \frac{\partial \hat{C}}{\partial t_d} + (1-f) \frac{\partial \hat{C}^*}{\partial t_d} = -u \frac{\partial \hat{C}}{\partial x} + D \frac{\partial^2 \hat{C}}{\partial x^2} \quad (1)$$

$$(1-f) \frac{d\hat{C}^*}{dt_d} = K(\hat{C} - \hat{C}^*) \quad (2)$$

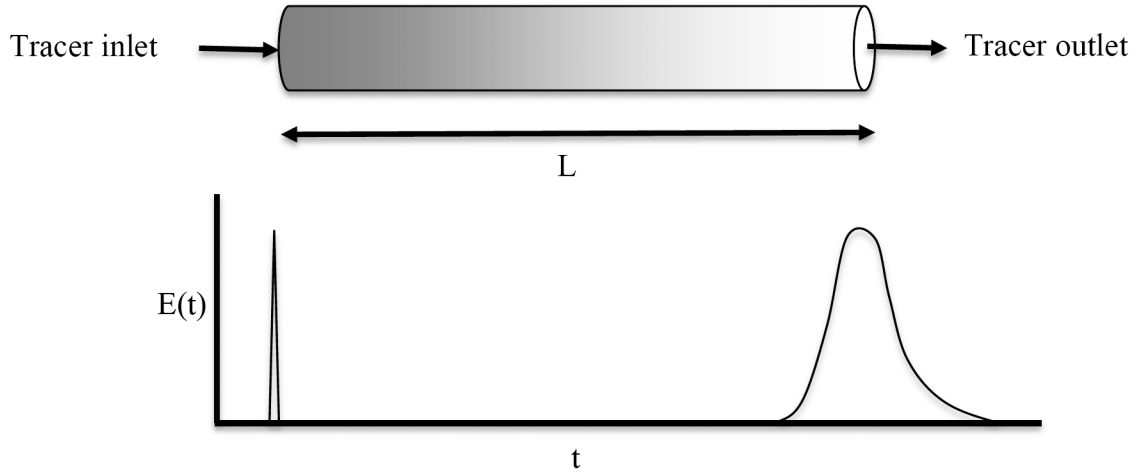


Figure 1—Schematic of tracer test in a porous medium with a mobile fraction of 'f' and immobile fraction of '1-f'. The schematic of E(t) vs t curve of the inlet pulse input and outlet concentration are shown. E(t) is the exit age distribution curve of the tracer.

Equation 1 describes the mass balance of the tracer and equation 2 is the mass transfer rate equation between the mobile and immobile zones, which is known to cause the tailing in the tracer response at the exit. Here, $\hat{C}$ is the concentration of the tracer in the mobile zone and $\hat{C}^*$ is the concentration in the immobile or dead-end zone, u is the interstitial velocity of the fluid in x direction and D is the effective axial dispersion coefficient. A linear mass transfer between the mobile and the immobile zone is assumed with a mass transfer coefficient of K . The flowing length of the fluids in the sediments is L . In the one-dimensional model, a homogeneous porous medium is assumed where the impact of tortuosity is included in the axial dispersion coefficient. The adsorption of the tracer on the sediment surface is neglected as an ideal tracer for oil or water phase is assumed. The initial condition for this system is

$$\hat{C} = \hat{C}^* = 0 \quad \text{at } t_d = 0, \forall x \quad (3)$$

The boundary conditions using Danckwerts (1953) reasoning can be written as

$$u\hat{C}_{x=0^-} = u\hat{C}_{x=0^+} - D \frac{\partial \hat{C}}{\partial x} \quad \text{at } x = 0, \forall t_d \quad (4)$$

$$\frac{\partial \hat{C}}{\partial x} = 0 \quad \text{at } x = L, \forall t_d \quad (5)$$

These equations in non-dimensional form become

$$f \frac{\partial C}{\partial t} + (1-f) \frac{\partial C^*}{\partial t} = -\frac{\partial C}{\partial \xi} + \frac{1}{Pe} \frac{\partial^2 C}{\partial \xi^2} \quad (6)$$

$$(1-f) \frac{\partial C^*}{\partial t} = \alpha(C - C^*) \quad (7)$$

$$C = C^* = 0 \quad \text{at } t = 0, \forall \xi \quad (8)$$

$$C_{\xi=0^-} = C_{\xi=0^+} - \frac{1}{Pe} \frac{\partial C}{\partial \xi} \quad \text{at } \xi = 0, \forall t \quad (9)$$

$$\frac{\partial C}{\partial \xi} = 0 \quad \text{at } \xi = 1, \forall t \quad (10)$$

where,

$$\xi = \frac{x}{L}, Pe = \frac{uL}{D}, t = \frac{t_d}{L/u} \text{ and } \alpha = \frac{KL}{u} \quad (11)$$

Pe (Peclet number) is the ratio of convective mass transport to the diffusive mass transport in the axial direction and α is ratio of the mass transfer rate between the mobile and immobile zones to the convective mass transport rate in axial direction. At higher Pe ($Pe \gg 1$), convection is more relative to the dispersion of the tracer and vice-a-versa. At lower α ($\alpha \ll 1$) the mass transfer of the tracer in the immobile zone is less as compared to convection of tracer in the axial direction. The tracer concentration $\hat{C}$ and $\hat{C}^*$ in the equations (1) – (5) can be made non-dimensional to C and C^* by total tracer mass in the pulse experiment or inlet tracer concentration for step input experiment. For pulse experiment $C_{\xi=0^-} = \delta(t)$ and for step experiment $C_{\xi=0^-} = u(t)$.

For a unit pulse input, the $C(t, \xi=1)$ curve gives the residence time density or exit age density curve, called $E(t)$ curve and cumulative exit age density curve, $F(t)$ curve, for a step input. $E(t)$ and $F(t)$ curves are related as $E(t) = \frac{dF(t)}{dt}$. The mean or the first moment of the residence time distribution, $E(t)$ curve identically equals L/u , or the mean space time (called the Central Volume Principle). In the dimensionless form of equations (6) – (10), the mean or the first moment equals unity, by definition. However, the second, third, fourth and subsequent moments of the $E(t)$ curve are related to flow patterns. We now derive these moments analytically.

To find the moments of the residence time distribution analytically, we apply Laplace transform such that $\bar{C}(s, \xi) = \int_0^\infty e^{-st} C(t, \xi) dt$. In Laplace domain, the governing equations for a pulse input become:

$$fs\bar{C} + (1-f)s\bar{C}^* = -\frac{d\bar{C}}{d\xi} + \frac{1}{Pe} \frac{d^2\bar{C}}{d\xi^2} \quad (12)$$

$$(1-f)s\bar{C}^* = \alpha(\bar{C} - \bar{C}^*) \quad (13)$$

$$1 = \bar{C}(s, 0^+) - \frac{1}{Pe} \frac{d\bar{C}}{d\xi} \Big|_{0^+} \text{ at } \xi = 0 \quad (14)$$

$$\frac{d\bar{C}}{d\xi} \Big|_{1^-} = 0 \text{ at } \xi = 1 \quad (15)$$

These equations have analytical solution for the Laplace transform of the outlet concentration at $\xi=1$ as

$$\bar{C}(s, 1) = \frac{4a e^{\left[\frac{Pe(1-\alpha)}{2}\right]}}{(1+\alpha)^2 - (1-\alpha)^2 e^{-(Pe\alpha)}} \quad (16)$$

where, $a = \sqrt{1 + \frac{4k}{Pe}}$ and $k = fs + \frac{(1-f)s\alpha}{(1-f)s + \alpha}$.

This function is called the ‘transfer function’ and can be inverted to time domain to get the outlet concentration with time curve i.e. $E(t)$ curve. Now, the moments of a probability distribution curve can in principle define the whole curve, assuming all moments exist and a well-posed moment generating function can be written (Nauman and Buffham, 1983). The moments can be determined by the ‘transfer function’. The moments of the $E(t)$ curve are related to the cumulants of the probability distribution curve which are defined in terms of the transfer function $\bar{C}(s, 1)$ as (Nauman and Buffham, 1983),

$$\kappa_n = (-1)^n \lim_{s \rightarrow 0} \frac{d^n}{ds^n} \ln \bar{C}(s, 1). \quad (17)$$

Now the cumulants are related to the moments as follows:

$$\kappa_1 = \mu_1 \quad (18)$$

$$\kappa_2 = \mu_2 = \sigma^2 \quad (19)$$

$$\kappa_3 = \mu_3 \quad (20)$$

$$\kappa_4 = \mu_4 - 3\mu_2^2 \quad (21)$$

where, μ_n are the central moments of a probability distribution curve for $n > 1$ and is mean for $n = 1$. Using equation (16) in equation (17) for moments we get that,

$$\kappa_1 = \mu_1 = 1. \quad (22)$$

As described earlier, μ_1 is related to the average time a tracer spends in the sediments which equals L/u and in dimensionless form should identically be equal to unity. Now, variance μ_2 is related to Pe if $f = 1$, i.e. the whole of the pore volume is mobile. However, if there is immobile volume fraction then using equation (16) and (17) we get

$$\kappa_2(\text{Coats} - \text{Smith}) = \mu_2 = \frac{2}{\alpha}(1-f)^2 + \frac{2}{Pe} - \frac{2}{Pe^2}(1 - e^{-Pe}). \quad (23)$$

Similarly, the skewness of the tracer residence time distribution in the coats-smith model is

$$\kappa_3(\text{Coats} - \text{Smith}) = \mu_3 = \frac{12[(1-f)^2(e^{-Pe} + Pe - 1)]}{\alpha Pe^2} + \frac{6(1-f)^3}{\alpha^2} + \frac{12[(2+Pe)e^{-Pe} + Pe - 2]}{Pe^3} \quad (24)$$

The fourth cumulant, which is related to the tailedness or kurtosis of the probability distribution curve in the coats-smith model, is given by

$$\begin{aligned} \kappa_4(\text{Coats} - \text{Smith}) &= \mu_4 - 3\sigma^2 \\ &= \frac{24(-3+f)(-1+f)^3(e^{-Pe} + (Pe-1))}{\alpha^2 Pe^2} + \frac{24(-1+f)^4}{\alpha^3} + \frac{144(-1+f)^2(e^{-Pe}(Pe+2) + (Pe-2))}{\alpha Pe^3} + \frac{12(e^{-2Pe} + (-29+10Pe) + 4e^{-Pe}(7+5Pe+Pe^2))}{Pe^4} \end{aligned} \quad (25)$$

Equations (23), (24) and (25) can be solved for Pe , f and α by equating the cumulants or moments in the parametric form to the cumulants or moments of the residence time distribution curve from the tracer experiments. However, these equations are non-linear so we analyse these equations by comparing them to numerical $E(t)$ curves we obtained by solving equation (6) – (10) for different values of Pe and α .

Comparison of theoretical and numerical moments

We solve equations (6) – (10) numerically to get the residence time distribution curve till $t = 6$, (assuming the data is collected in field trials or experiments till $t \sim 6$) i.e. the $C(t)_{\xi=1} = E(t)$ curve, and then use the exponential decay till $t = 100$ (assuming $t = 100$ approximates $t \rightarrow \infty$) to get the full response curve with the exponential decay rate at $t = 6$.

If the full response is known without truncation, then mean residence time i.e. μ_1 of the distribution should be unity according to equation (22). We investigate the $E(t)$ curves at a high Pe of 1000 and low Pe of 3. We assume that the mobile fraction is 0.7 and vary α from 0.01 to 10. At high Pe the dispersion is less in comparison to the convection of the tracer. At high α , the mass transfer in the dead end zone is high in comparison to the convection. Figure 2 shows the $E(t)$ vs t curve for $Pe = 1000$ and 3 and $\alpha = 0.01$ and 10.

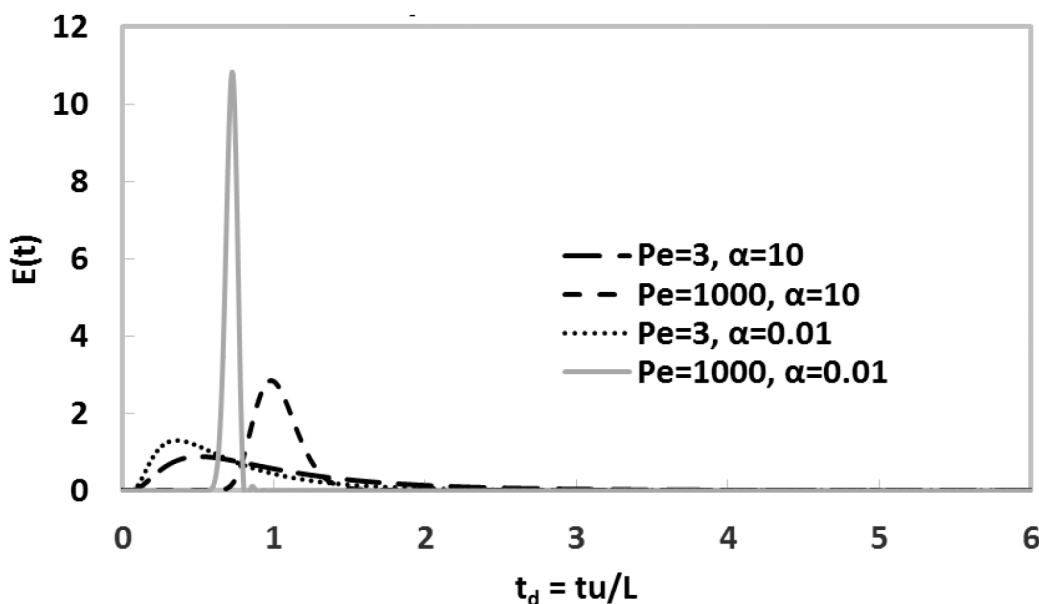


Figure 2— $E(t)$ vs t curves when mobile volume fraction $f = 0.7$.

First moment of exit age distribution curve.

The first moment of the numerical response curve is calculated as follows:

$$\mu_1(\text{truncated}) = \int_0^6 t \cdot E(t) dt \quad (26)$$

$$\mu_1(\text{exponential fit}) = \int_0^{100} t \cdot E(t) dt \quad (27)$$

Equation 22 is used for theoretical first moment. Figure 3 shows the comparison of the first moment obtained by $E(t)$ curve shown in Figure 2 with the theoretical value of 1. The open circles in Figure 3 show first moment for $Pe = 1000$ and closed circles show the first moment for $Pe = 3$. We see in Figure 3 that for $\alpha > 1$ there is no truncation error in moment calculation from $E(t)$ curve if $t > 6$. However, if $\alpha < 0.05$ then with exponential decline fit till $t = 100$ also does not give $\mu_1 = 1$. This is because of the small α , if a tracer particle enters the immobile zone, due to low mass transfer it will remain in the immobile zone for a very long time leading to a very long tail but at a very small exit concentration. However, for other values of α , the exponential fit works well to give the accurate first moment if t is extended to 100. But till $t = 6$ there is truncation error in the calculation of the first moment. It is clear from Figure 3 that the dead end pore volume estimation cannot be made from first moment only, as the first moment at intermediate value of α is dependent on the truncation time and if truncation time is extended, μ_1 should always be one. Thus, we investigate the second, third and fourth moment of the residence time distribution curves shown in Figure 2.

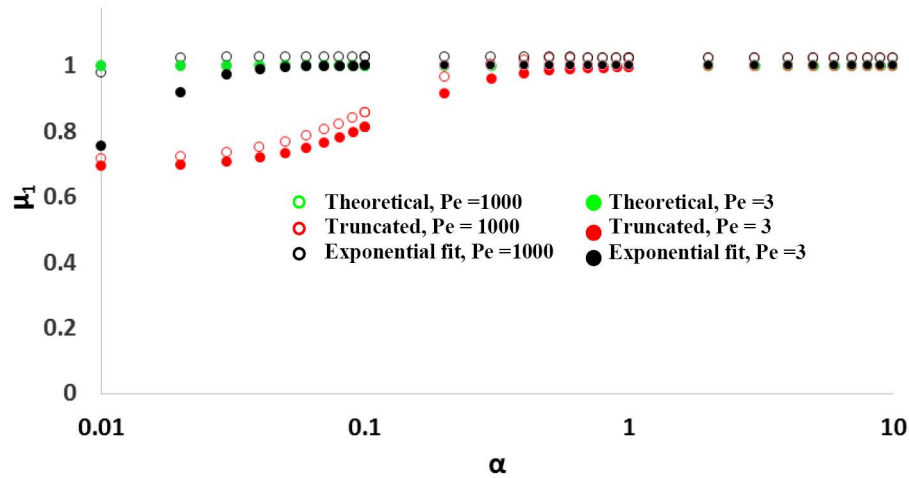


Figure 3—First moment of the residence time distribution for α varying from 0.01 to 10 and Pe 3 and 1000.

Parameter estimation using second, third and fourth moments.

The second, third and fourth moments of the $E(t)$ vs t curve from a tracer experiment or a field test are defined as:

$$\mu_2 = \int_0^{\infty} (t - \mu_1)^2 \cdot E(t) dt \quad (28)$$

$$\mu_3 = \int_0^{\infty} (t - \mu_1)^3 \cdot E(t) dt \quad (29)$$

$$\mu_4 = \int_0^{\infty} (t - \mu_1)^4 \cdot E(t) dt \quad (30)$$

Second, third and fourth moments of the $E(t)$ curves are a function of Pe , f and α according to equations (23), (24) and (25) which can be solved simultaneously by equating the equation (23), (24) and (25) with equations (28), (29) and (30), respectively. However, these equations are non-linear so finding the accurate parameter is again difficult. In Figure 4, Figure 5 and Figure 6 we show, second, third and fourth moments, respectively. We show the comparison of moments at $Pe = 3$ and $Pe = 1000$ at α varying from 0.01 to 10. We see that when α is greater than one then for high and low Peclet numbers there is no truncation error if the exit concentration profile is available till $t = 6$, similar to the first moment. If α is less than 0.05 then with exponential decline fit also the moments are not equal to the theoretical moments calculated from equations (23), (24) and (25) for the parameters used in numerical simulations, similar to first moment. Another interesting observation from the Figures 4, 5 and 6 is that if $\alpha < 0.05$ then Pe does not impact the moments calculated from equations (23), (24) and (25). This is because at low α only the term dependent on α is dominant in the equations (23), (24) and (25). $\alpha = KL/u$, and K is dependent on the diffusivity of the tracer, so if K is low and velocity is high, then we will not be able to find Pe , but $f = 1 - \frac{3\mu_2^2}{2\mu_3}$ from equation (23) and (24), neglecting terms involving Pe .

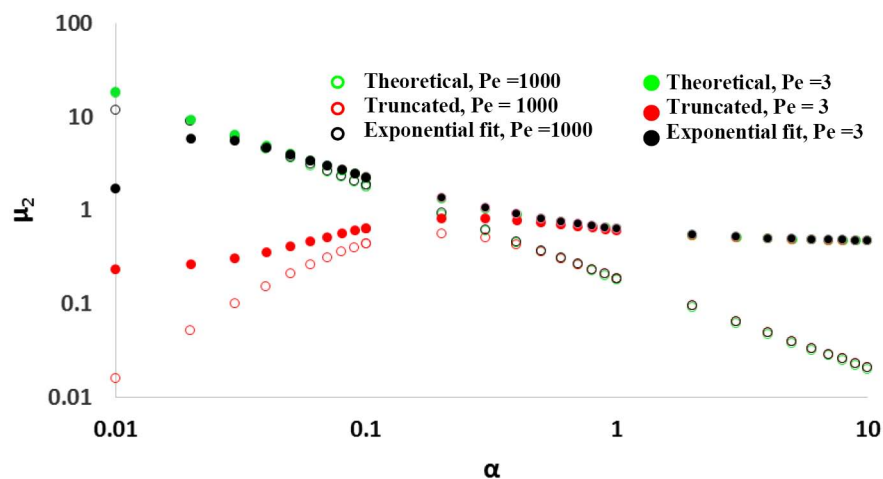


Figure 4—Second moment of the residence time distribution for α varying from 0.01 to 10 and Pe 3 and 1000.

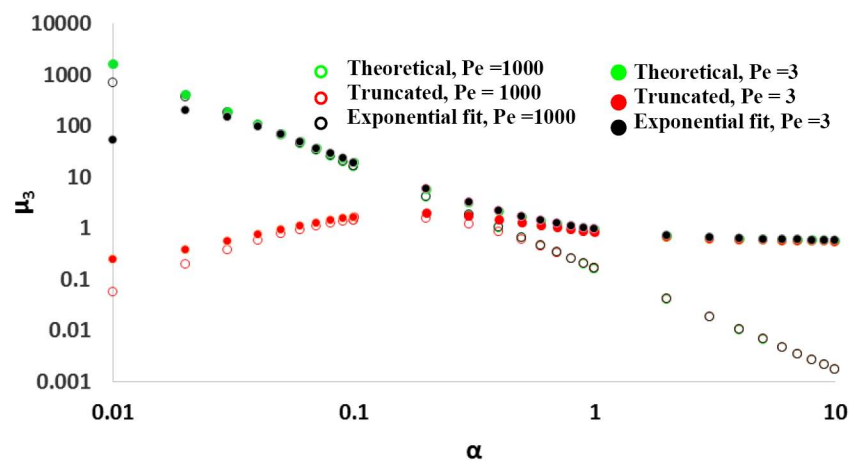


Figure 5—Third moment of the residence time distribution for α varying from 0.01 to 10 and Pe 3 and 1000.

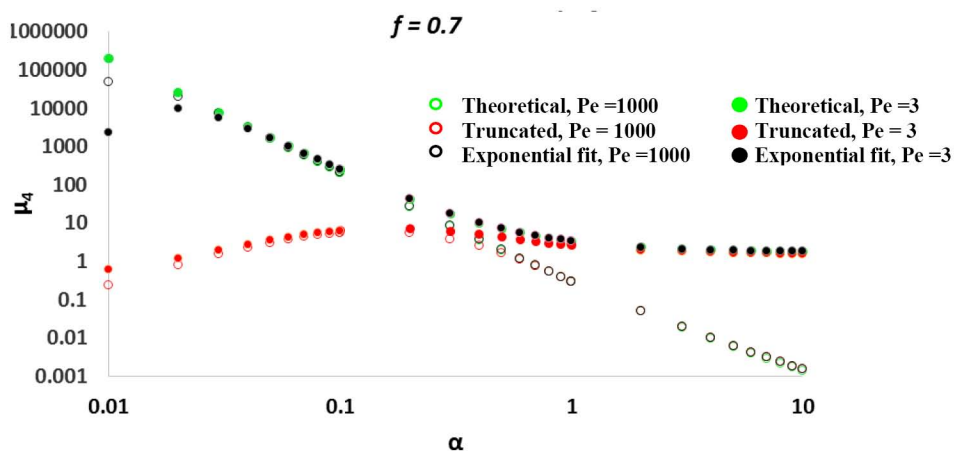


Figure 6—Fourth moment of the residence time distribution for α varying from 0.01 to 10 and Pe 3 and 1000.

At high Pe of 1000, the terms with Pe in equations (23), (24) and (25) become negligible so $f = 1 - \frac{3\mu_2^2}{2\mu_3}$ can be used to find the mobile volume fraction. This is due to Pe being in denominator and also exponential terms dependent on Pe .

For intermediate values of Pe and α , the equation (23), (24) and (25) needs to be solved simultaneously to find the mobile fluid fraction.

Guideleines for parameter estimation

To estimate the parameters corresponding to the dispersion, dead-end pore volume and mass transfer in the dead-end pore volume in a porous media, we first find the first moment. If first moment is equal to one for $t \sim 6$ (which is generally the time for which the tracers are collected) and no exponential fit is needed, we can safely assume that $\alpha > 1$. Now, based on the second moment we can infer the range of Pe . Figure 2 shows the $E(t)$ curve for $\alpha = 10$, and the first appearance time of the tracer. Now if the tracer has late breakthrough and second moment is less than one, then Pe is high in the range of 1000. Now if Pe is large then we can find $f = 1 - \frac{3\mu_2^2}{2\mu_3}$, but for small Pe we will not be able to find f from the tracer residence time distribution, as the whole volume will be traced.

Now if the first moment is less than 1 and using exponential decline also we are not able to get the first moment equal to one, then $\alpha < 0.05$. Now second, third and fourth moment do not depend on Pe , so $f = 1 - \frac{3\mu_2^2}{2\mu_3}$.

If we get first moment equal to one after using exponential decline that means $0.05 < \alpha < 1$. Also all the moments can be found correctly by adding a tail with exponential decline and extending it to $t_d = 100$. Now the equations (23), (24) and (25) can be solved simultaneously to estimate the process parameters. Further investigation is needed to simplify the procedures for parameter estimations when $0.05 < \alpha < 1$.

Summary and conclusion

In summary, we have analyzed the effect of dead-end pore volume on tracer transport in porous media. First, we find the dependence of first, second, third and fourth moment of the residence time distribution curve on the process parameters of the coats-smith model i.e. Pe , f and α . We then compare the theoretical moments and compare it with moments of the residence time distribution curves obtained from numerical experiments at various Pe and α . Using the comparison, we delineated the guidelines to determine the dead-end pore volume as follows.

1. Determine the first moment. If the first moment equals one at dimensionless time $t \sim 6$ then $\alpha > 1$. Determine the second moment, if second moment is less than one then Pe is high and $f = 1 - \frac{3\mu_2^2}{2\mu_3}$. If second moment is close to one then f cannot be determined, as tracer traces whole of dead-end volume.
2. If the first moment is less than one, even after exponential tail fit to the residence time distribution, then $\alpha < 0.05$, Pe can not be determined and $f = 1 - \frac{3\mu_2^2}{2\mu_3}$.
3. If the first moment equals one after adding an exponential tail then $0.05 < \alpha < 1$ and equations (23), (24) and (25) must be solved to find the model parameters.

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