Investigation of the effect of matrix on tracer transport processes in subsurface fractured reservoirs

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ABSTRACT: Tracer testing is a commonly used method to characterize flow and transport in subsurface fractured reservoirs. The interpretation of tracer recovery data generally requires numerous forward simulations of tracer transport in the underlying fracture and matrix. Previous studies have attempted to alleviate the associated computational burden by neglecting the matrix, but the impact of such a simplification remains unclear. This study systematically investigates the effects of matrix on tracer transport processes under various fracture/matrix parameters and tracer injection conditions through an analytical solution. Based on the results, we discuss the situations in which matrix has minimal effect on tracer transport and can be ignored during inversion/data assimilation. A dimensionless number that integrates fracture/matrix parameters and injection parameters is proposed to estimate matrix effect on tracer transport. The dimensionless number offers an easy yet practical way to quantify matrix effect, providing informative guidance for model development in tracer data interpretation.

Keywords: Tracer transport, fractured reservoir, matrix effect, tracer injection condition, dimensionless number.

1 INTRODUCTION

Tracer testing is an effective technique to understand flow and transport processes in subsurface fracture-matrix systems, and has been widely used for reservoir characterization through inversion or data assimilation methods (Webster et al. 1970; Raven et al. 1988). The transport of a conservative tracer in fractured media can be described by advection-dispersion equation, and depends on both fracture/matrix properties and tracer injection conditions. As the permeability and porosity of rock formations are generally very low, fractures provide primary flow paths for tracers. To alleviate the computational burden associated with the interpretation of tracer recovery data, some previous studies ignored the impact of matrix so that the actual 3D matrix-fracture model can be simplified to a 2D fracture model (Somogyvári et al. 2017; Wu et al. 2021a, 2021b).

However, the presence of matrix affects the transport of a conservative tracer by not only advection effect but also diffusion effect. The advection effect highly depends on fluid flow in matrix and could be safely ignored due to the large permeability contrast between fracture and matrix. The diffusion effect is related to matrix diffusion coefficient, matrix porosity as well as the concentration contrast between fracture and matrix, and may exert significant impacts on tracer transport even though the matrix permeability is low. Many studies have indicated that under certain situations, matrix diffusion played important roles in tracer transport processes (Grisak & Pickens 1980; Tang et al. 1981; Małoszewski & Zuber 1985; Zhou et al. 2018).

Understanding the effects of matrix advection and diffusion on tracer transport is important for the interpretation of tracer recovery data. Peclet number is a dimensionless number that quantifies the ratio of transport rate caused by advection and diffusion (Roubinet et al. 2012). For a large Peclet number, advection dominates tracer transport, while for a small Peclet number, matrix diffusion becomes the predominant mechanism. Therefore, it is straightforward to use Peclet number as an indicator to determine whether the matrix could be ignored during the interpretation of tracer data, but the feasibility requires further investigation.

In the present study, we use an analytical solution to examine the effects of various parameters, including matrix porosity and diffusion coefficient, fracture aperture and dispersion coefficient, as well as injection time and rate, on the transport of a conservative tracer in a fracture-matrix model. The feasibility of using Peclet number to determine whether the matrix could be ignored is investigated. Based on the results, we propose a new dimensionless number to better characterize the effects of matrix on tracer transport processes.

2 METHODS

We use an analytical solution to model conservative solute transport in a fracture-matrix system represented by a smooth parallel plate fracture with a constant aperture and a semi-infinite rock matrix. Solute transport processes can be described by two coupled one-dimensional equation, one for the fracture and one for the porous matrix. It considers advection and dispersion processes in the fracture and molecular diffusion process in the matrix, and assumes a constant injection concentration into the fracture. The analytical solution was derived using Laplace transforms (Zou et al. 2016):

$$\frac{C_f(t)}{C_0} = \frac{2}{\sqrt{\pi}} e^{\frac{ux}{2D_f}} \int_{\sqrt{\frac{x^2}{4D_f t}}}^{\infty} e^{-\xi^2 - \frac{u^2x^2}{16{D_f}^2\xi^2}} \operatorname{erfc}\left(\frac{\frac{x^2\theta\sqrt{D_m}}{4D_f b\xi^2}}{2\sqrt{t-\frac{x^2}{4D_f\xi^2}}} \right) d\xi \tag{1}$$

Where $C_f(t)$ is the the solute concentration in the fracture at a distance of x from the injection point, C_0 is the solute injection concentration, u is the fluid velocity along the fracture, D_f is the fracture dispersion coefficient, t is the continuous injection time, θ is the matrix porosity, D_m is the matrix diffusion coefficient, and b is the half-aperture of the fracture.

The above analytical solution is for continuous injection scenario. However, in real-world applications, tracers are injected for a period of time (t_0), normally in several days or months. The analytical solution for such a scenario can be obtained by subtracting $C_f(t-t_0)$ from $C_f(t)$, where $C_f(t-t_0)$ is solute concentration when injection starts at t_0. The analytical solution at $D_m = 0$ m^2/s is used to represent the situation without matrix effect. The effect of matrix diffusion can be investigated by comparing the curves with and without matrix.

In this study, we consider seven parameters including matrix porosity, matrix diffusion coefficient, fracture aperture, fracture dispersion coefficient, fluid velocity in the fracture, the distance between injection point and monitoring point and injection time. For each parameter, five values are considered (see Table 1). The injection rate can be calculated as $Q = 2bu$.

The differences in peak concentration and the arrival time of the peak in tracer breakthrough curves between cases with and without matrix can be used to examine the feasibility of the Peclet number. The peak difference is defined as: Peak difference = (Peak concentration of the curve with matrix − Peak concentration of the curve without matrix) / Peak concentration of the curve with matrix. The peak arrival time difference is calculated in a similar way, and the Peclet number in the fracture-matrix system is calculated as $P_e = 2bu/D_m$, according to Wang et al. (2023).

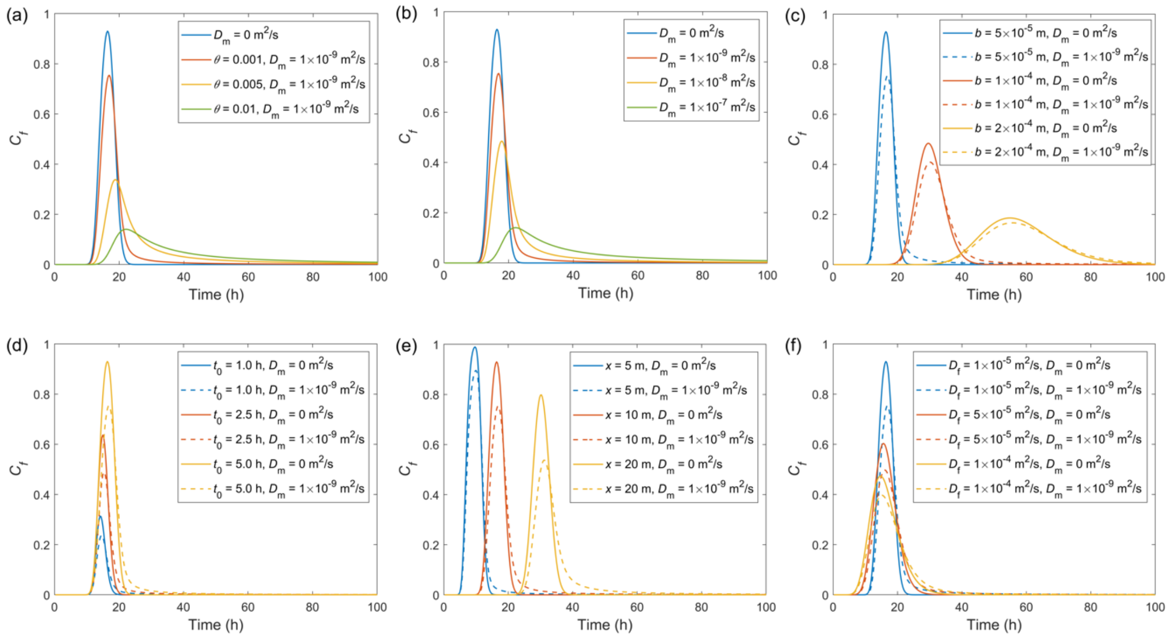
Table 1. The parameter values.

Parameters	Values
Matrix Porosity (θ)	0.1, 0.01, 0.001, 0.0005, 0.0001
Matrix diffusion coefficient (D_m, m^2/s)	1×10^{-8}, 1×10^{-9}, 1×10^{-10}, 1×10^{-11}, 1×10^{-12}
Fracture aperture ($2b$, m)	0.00002, 0.0002, 0.002, 0.02, 0.2
Fracture dispersion coefficient (D_f, m^2/s)	1×10^{-4}, 5×10^{-5}, 1×10^{-5}, 5×10^{-6}, 1×10^{-6}
Fluid velocity in fracture (u, m/s)	5×10^{-5}, 1×10^{-4}, 1.5×10^{-4}, 2×10^{-4}, 2.5×10^{-4}
Distance between injection point and monitoring point (x, m)	2, 4, 6, 8, 10
Injection time (t_0, h)	2.5, 5, 7.5, 10, 12.5

3 RESULTS

3.1 *Tracer breakthrough curves with and without matrix*

We first compare tracer breakthrough curves calculated with different parameter values to understand the impact of matrix on tracer transport processes (Fig. 1). With the increase of matrix porosity and diffusion coefficient (Fig. 1(a) and (b)), the peak concentration decreases and a long tail gradually develops. Longer injection time and larger distance between injection point and monitoring point (x) lead to more significant diffusion effect in the matrix, manifesting as the increase of the difference between tracer breakthrough curves with and without matrix (dashed and solid lines in Fig. 1(d) and (e)). The other parameters, i.e., fracture aperture, fracture diffusion coefficient and inject rate, show opposite effects on the impacts of matrix. The larger the three parameters, the smaller the difference between dashed and solid lines in Fig. 1, and the smaller the effects of the matrix. An important conclusion from Fig. 1 is that although the permeability of matrix is low, its impact on tracer transport might be significant, especially when matrix porosity and diffusion coefficient are large.



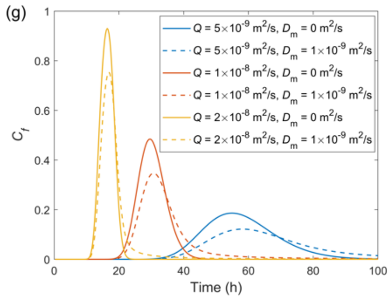


Figure 1. Comparison of tracer breakthrough curves under different parameter values. The reference values are $\theta = 0.001$, $D_m = 1\times10^{-9}$ m^2/s, $b = 5\times10^{-5}$ m, $t_0 = 5$ h, $x = 10$ m, $D_f = 1\times10^{-5}$ m^2/s, $Q = 2\times10^{-8}$ m^2/s. Note that the case ignoring the impact of matrix is represented by $D_m = 0$ m^2/s.

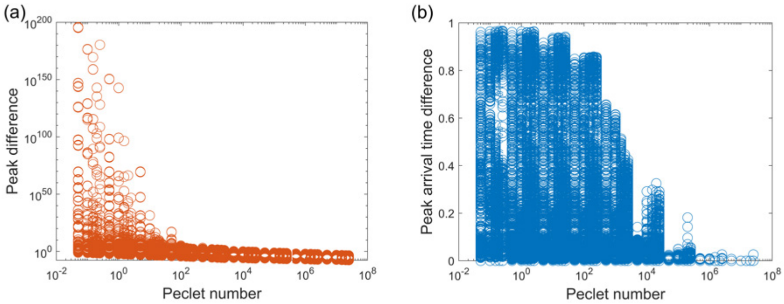


Figure 2. Relationships between the differences of peak concentration/peak arrival time and Peclet number.

3.2 Using Peclet number to characterize matrix effect

The differences in peak concentration and the arrival time of the peak in tracer breakthrough curves between cases with and without matrix (dashed and solid lines in Fig. 1) are used as quantitative measures of matrix effect. For all the combinations of values in Table 1 (78125 cases in total), we calculate the differences in peak concentration and peak arrival time, and plot them against Peclet number (Fig. 2). The Peclet number is calculated as $P_e = 2bu/D_m$, according to Wang et al. (2023). If there exists a monotonous relationship between peak concentration difference/peak arrival time difference and P_e, P_e can be used as an indicator of matrix effect. Unfortunately, although the differences are minimal under high Peclet numbers, the differences under small Peclet numbers vary significantly over wide ranges (Fig. 2). Peclet number can be used to differentiate cases that the matrix has significant effect on tracer transport, but fails to correctly characterize cases that the matrix effect is minimal. Many cases with small P_e show negligible differences in peak concentration difference and peak arrival time difference.

According to Fig. 2, using Peclet number to characterize matrix effect on tracer transport is inappropriate. A likely reason is that the Peclet number only involves three parameters, while the above analysis indicates that the other parameters also have significant effects on matrix diffusion.

3.3 A new dimensionless number to characterize matrix effect

Based on the results in Fig. 1, we propose a new dimensionless number to characterize the effect of matrix diffusion on tracer transport. The dimensionless number, as defined in equation (2), considers all the seven parameters (matrix porosity, matrix diffusion coefficient, fracture aperture, fracture diffusion coefficient, inject rate, inject time and the distance between injection and monitoring points). We follow an empirical principle to determine the power of each parameter in the dimensionless number, i.e., the parameter that shows larger impact on matrix diffusion should be assigned a larger power. We acknowledge that the equation is empirically derived in the present study, and more rigorous investigation is needed to improve its capability.

$$\text{Dimensionless number} = \frac{\theta x t_0^{\frac{1}{2}} D_m^{\frac{3}{2}}}{D_f^{\frac{1}{2}} Q^{\frac{1}{2}} b^2} \quad (2)$$

Similar to Fig. 2, we plot peak concentration difference/peak arrival time difference against the proposed dimensionless number to examine its capability in matrix effect characterization (Fig. 3). Compared with Peclet number, the newly proposed dimensionless number better characterizes matrix effect, manifesting by the relatively monotonous relationship between peak concentration difference and the dimensionless number. The relationship for peak arrival time difference shows considerable oscillations when the dimensionless number is larger than 10^{-4}, but still exhibits much smaller uncertainty compared with the result for Peclet number in Fig. 2.

When the dimensionless number is smaller than 10^{-5}, the differences in peak concentration and peak arrival time are small, indicating a minimal matrix effect so that the matrix could be safely ignored (Fig. 3). When the dimensionless number is larger than 1, the impact of matrix should be considered. To further investigate the capability of the proposed dimensionless number in the range of 10^{-5} and 1, we randomly select three cases for a dimensionless number of 10^{-4}, 10^{-2} and 10^{-1} respectively, and tracer breakthrough curves with and without matrix are compared (Fig. 4). The difference between the solid and dashed lines in Fig. 4 is negligible when the dimensionless number is small than 10^{-2}, and becomes significant when the dimensionless number increases to 10^{-1}.

According to the above results, it is feasible to use the proposed dimensionless number to characterize the significance of matrix diffusion effect on tracer transport. Specifically, we recommend a threshold of 0.01 as a criterion, i.e., when the dimensionless number is smaller than 0.01, the effect of matrix is minimal and can be ignored, otherwise the matrix should be considered in the interpretation of tracer data.

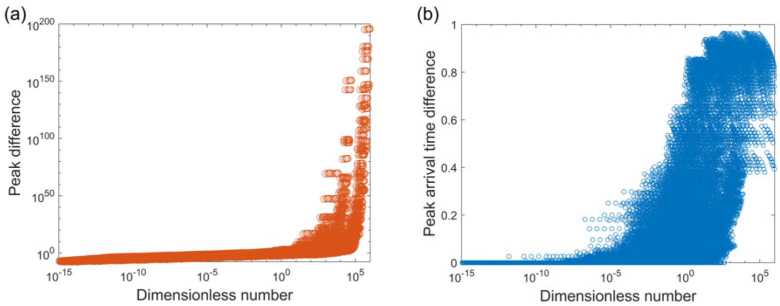


Figure 3. Relationships between the differences of peak concentration/peak arrival time and the newly proposed dimensionless number.

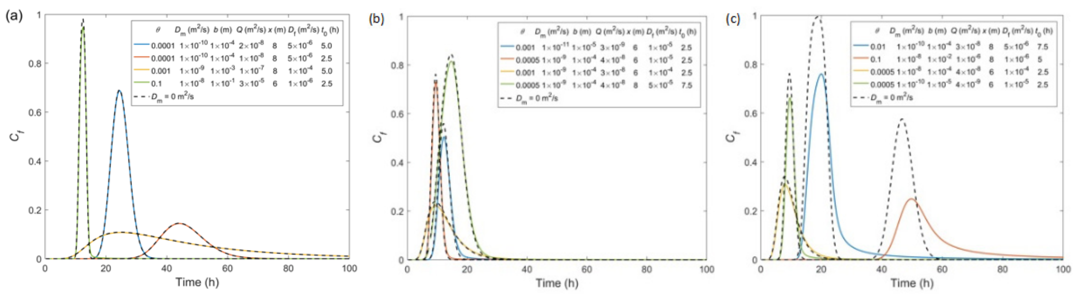


Figure 4. Comparison of tracer breakthrough curves with and without matrix. (a) Dimensionless number is 10^{-4}. (b) Dimensionless number is 10^{-2}. (c) Dimensionless number is 10^{-1}. For each dimensionless number, four cases are randomly selected. The corresponding parameter values are annotated.

4 CONCLUSIONS

In the present study, we quantitatively analyzed the effect of matrix on tracer transport processes using an analytical solution. Tracer breakthrough curves with and without matrix were compared to demonstrate the role of matrix, and a wide range of fracture/matrix parameters and injection conditions were investigated. Larger matrix porosity, matrix diffusion coefficient, inject time and distance between injection and monitoring points lead to more significant matrix effect, but larger fracture aperture, fracture diffusion coefficient and inject rate result in reduced matrix effect.

The relationship between matrix effect and the Peclet number is ambiguous, especially for relatively small Peclet numbers. Therefore, we proposed a new dimensionless number to better characterize the significance of matrix effect on tracer transport. When the dimensionless number is smaller than 0.01, the matrix effect is minimal and can be ignored in tracer data interpretation.

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