International Journal of Heat and Mass Transfer 103 (2016) 627–634

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Tracer transport in naturally fractured reservoirs: Analytical solutions for a system of parallel fractures

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ARTICLE INFO

Article history:
Received 25 April 2016
Received in revised form 16 July 2016
Accepted 21 July 2016

Keywords:
Fractured reservoir
Mass transfer
Shape factor
Advection
Diffusion

ABSTRACT

In naturally fractured reservoirs, modeling of mass transfer between matrix blocks and fractures is an important subject during gas injection or contaminant transport. This study focuses on developing an exact analytical solution to transient tracer transport problem along a discrete fracture in a porous rock matrix. Using Gauss-Legendre quadrature, an expression was obtained in the form of a double integral which is considered as the general transient solution. This solution has the ability to account the following phenomena: advective transport in fractures and molecular diffusion from the fracture to the matrix block. Certain assumptions are made which allow the problem to be formulated as two coupled, one-dimensional partial differential equations: one for the fracture and one for the porous matrix in a direction perpendicular to the fracture.

Using the obtained analytical solution, tracer concentration in matrix block and fracture was calculated. The advective-diffusive equation in matrix and fracture was used for evaluation of the mass transfer shape factor. The derived analytical solution was used for analyzing early and late time periods of mass transport phenomenon in fractured porous media. Finally, validation of the analytical solution was done by comparing the obtained results with laboratory data adapted from a column tracer test conducted on a fractured till.

1. Introduction

A discontinuity that divides a rock into several blocks is called a fracture which is formed due to existence of different stresses exposed to formations [1]. Depending on rock type, rocks may be flexible enough to resist fracturing or be brittle. In brittle rocks such as carbonated sedimentary samples, fracturing is caused by stress [2]. Fractured rocks referred to as double porosity systems are composed of two different characteristic media called fracture and porous matrix systems. In a typical double porosity system, fractures are supposed to have high permeability in the range of 0.5–2 Darcy, therefore they could provide the main flow in the reservoir. Matrix blocks however, have low permeability in the range of 0.1–2 millidarcy and provide the main storativity [3]. Different techniques are available in literature in which a fracture network is numerically generated whose characteristics are as close as possible to the real situation. There exist two extreme models to simulate such systems, the first one being totally deterministic and the second one being totally random [4]. In the case of deterministic simulation, Warren and Root [5] introduced the dual porosity model for fractured reservoirs, focusing on pressure depletion of fractured system under constant production rate. In dual porosity model, porous matrix is considered to be the source, providing fluid for fracture. Several studies have been reported in the literature for fluid transport in dual porosity model [6–8,9].

In a tracer injection with no adsorption and reaction in an isothermal condition, advective, dispersive and diffusive mechanisms determine the transfer process [10]. Various experiments have been conducted to investigate parameters that affect dispersion, such as fluid velocity through porous media, solute size, porosity and permeability [11–14].

In the case of existence of regions with different concentrations such as fracture and porous media, a mass flux happens because of the diffusion mechanism [10]. Hu and Brusseau [15] reported the transport of different solutes in saturated, constructed structured media. These experiments were carried out in aggregates, stratified and macro-porous systems. Gwo et al. [16] presented the structural information in predicting solute movement within porous medium.

Tracer injection is another method that has been used to investigate diffusive mass transport. Maloszewski and Zuber [17]

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.07.078

Nomenclature

C	tracer concentration [M L^{-3}]
$\tilde{C}$	average tracer concentration over the domain [M L^{-3}]
$\overline{C}$	tracer concentration in the Laplace domain
C	tracer concentration [M L^{-3}]
D	effective matrix molecular diffusion coefficient [L^2 T^{-1}]
D_f	effective fracture molecular diffusion coefficient [L^2 T^{-1}]
h	repetitive element block height [L]
$h_{1/2}$	half-aperture of the fracture [L]
Pe	Peclet number
q_w	injection rate per repetitive element [L^{-3} T^{-1}]
r	direction of the fracture
r_w	radius from the wellbore [L]
s	Laplace variable
t	time [T]
z	direction normal to the fracture

Greek

∂	partial derivative
σ	shape factor [L^{-2}]
φ	porosity, fraction

Subscripts

D	dimensionless
f	fracture
i	initial
m	matrix

derived the governing equations of tracer movement for a model of parallel fractures with equal space and width. To develop this model, they investigated and interpreted different conditions including short term, long term and intermediate term experiments with different matrix porosities. Maloszewski and Zuber [18] used multiple tracers with different diffusion coefficients in order to quantify the effect of the matrix diffusion on the overall system dispersion. Using this method, they introduced an additional parameter to match the experimental data. Later, they used a single fracture dispersion model for several tracer tests (Maloszewski and Zuber [19]). Abelin et al. [20] reported that in the case of significant physical no equilibrium processes in subsurface media, tracers with larger molecular diffusion coefficient will be lost to the matrix porosity related to tracers with smaller molecular diffusion coefficients. Jardin et al., [21] provided an improved understanding of processes in heterogeneous matrix-fracture media to resolve inadequate knowledge about the transport processes that control contaminant migration.

Analytical and numerical modeling of diffusive mass transport in fractured media is another topic that has been investigated in literature. In order to study the fracture-matrix transport phenomenon, it is extremely simpler to consider a single fracture. This assumption has received considerable attention from researchers. Neretnieks [22] developed an analytical solution for transport in a fracture assuming negligible dispersion and diffusion along the fracture. Grisak and Pickens [23] calculated concentrations in both the fracture and the porous matrix using the finite element method. Their numerical approach could account any arbitrary boundary condition, but the effects of numerical dispersion were difficult to assess in this method. Another work was done by Tang et al. [24], who developed general analytical solutions for the problem of solute transport in fractures in the following cases: longitudinal mechanical dispersion in the fracture, molecular diffusion along the fracture axis, molecular diffusion from the fracture into the porous matrix, adsorption onto the face of the matrix and adsorption within the matrix. Sudicky and Frind [25] developed an exact analytical solution for the situation of transient contaminant transport in discrete parallel fractures. Because the solution was based on analytical inversion of the Laplace transform, numerical inversion problems have been resolved. Feenstra et al. [26] developed an analytical model for contaminant transport in a porous media with a planar horizontal fracture for a radial and semi-infinite system. The introduced model was able to evaluate the influence of matrix diffusion on the contaminant transport away from the injected well.

Lee and Teng [27] conducted a theoretical model for the radionuclide transfer phenomenon in a single fracture covering the entire range of sorption properties of rock in a linear transient case. Chen and Li [28] developed an analytical solution for radionuclide transport in a system of parallel fractures considering the constant flux as the inlet boundary condition. The assumption of negligible longitudinal dispersion along the fractures and steady-state solutions were also considered in this study.

Simulation of solute transport is difficult owing to existence of matrix diffusion, which led to some simplifications for formulations reported in literature. Carrera et al., [29] tried to resolve this problem by considering some simplified asymptotic properties for matrix diffusion. For example, matrix diffusion coefficient and block size were neglected for the late time period.

Fleming and Haggerty [30] formulated and presented a physical-based mathematical model of diffusion in sediments with variable diffusivity. They investigated the multiple matrix diffusivity along with laboratory studies and concluded that as porosity increases, diffusivity increases. Becker and Shapiro [31] investigated the effect of advective heterogeneity by analysis of the breakthrough during their forced-gradient tracer tests under various hydraulic configurations on a fractured crystalline bedrock. They proposed a theoretical model of transport that predicts tailing behavior in experiments. Liu et al. [32] reported that the effective matrix diffusion coefficient is scale dependent and increases with the test scale. They developed an introductory explanation for this scale dependent treatment. Chu et al. [33] investigated the effects of scale and reactions on lumped mass transfer coefficient. They tried to provide improved knowledge of the nature of a lumped mass transfer coefficient in the non-aqueous liquid source zone. They found out that, mass transfer coefficient stabilizes at some values after a while. Zhou et al. [34] obtained the effective matrix diffusion coefficient. They presented and interpreted the values of the effective matrix diffusion coefficient adapted from various field tests. Mathias et al. [35] used tracer in fractured rocks to investigate the effects of heterogeneity in which the importance of several parameters were presented including the input function for tracer injection, the lateral travel time, characteristic fracture, matrix diffusion times and the Peclet number. Cihan and Tyner [36] developed analytical solutions for mass transfer in macropores assuming that solute transport within the macro-pore is governed by advection while solute transport within the porous matrix is governed only by radial diffusion. They provided approximate solutions for three cases and concluded that in low permeability matrix rocks and short tracer tests, proposed approximations are helpful.

In this paper, an analytical solution for describing radial tracer transport in fractured media is presented for the first time where the injected tracer diffuses from the fracture into the adjacent