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Multi-rate mass transfer modeling of two-phase flow in highly heterogeneous fractured and porous media

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ABSTRACT

We study modeling of two-phase flow in highly heterogeneous fractured and porous media. The flow behaviour is strongly influenced by mass transfer between a highly permeable (mobile) fracture domain and less permeable (immobile) matrix blocks. We quantify the effective two-phase flow behavior using a multirate rate mass transfer (MRMT) approach. We discuss the range of applicability of the MRMT approach in terms of the pertinent viscous and capillary diffusion time scales. We scrutinize the linearization of capillary diffusion in the immobile regions, which allows for the formulation of MRMT in the form of a non-local single equation model. The global memory function, which encodes mass transfer between the mobile and the immobile regions, is at the center of this method. We propose two methods to estimate the global memory function for a fracture network with given fracture and matrix geometry. Both employ a scaling approach based on the known local memory function for a given immobile region. With the first method, the local memory function is calculated numerically, while the second one employs a parametric memory function in form of truncated power-law. The developed concepts are applied and tested for fracture networks of different complexity. We find that both physically based parameter estimation methods for the global memory function provide predictive MRMT approaches for the description of multiphase flow in highly heterogeneous porous media.

1. Introduction

Flow and transport through highly heterogeneous porous and fractured media may be poorly predicted with equivalent homogeneous models that are characterized by effective hydraulic parameters. The impact of heterogeneity manifests in heavy tails of solute breakthrough curves or recovery curves during water flooding of an oil reservoir which is not captured well by such models. This behavior may originate from the local non-equilibrium of the flow or transport processes which are observed on a large scale.

Transport behavior caused by local non-equilibrium has been investigated for solute [1–4] and heat [5,6] transport in groundwater and for two phase flow processes like oil recovery [7] or unsaturated flow [8]. When flow and transport is considered in a medium where non-equilibrium behavior is relevant, the full porous medium structure needs in principle to be represented in a flow or transport model, in order to capture the local processes. For a fractured rock this means that fractures and rock matrix need to be resolved in a model, which is computationally very expensive. As, however, tailing often needs to be captured in a model prediction, large effort has been spent to develop simplified modeling approaches that are less expensive, but can still capture the main features. This applies also to two-phase flow problems, such as modeling of oil recovery.

The classical approaches on Darcy scale to model flow and transport in fracture networks are the equivalent porous media (EPM) approach, the discrete fracture (DF) approach and the multi-continuum approach [9,10]. For the EPM, the fractures are modeled together with the surrounding rock matrix as an equivalent porous media [11] and are thus represented by a variation of flow or transport parameters of the rock matrix locally. These approaches are often too simplified to capture tailing effects. For the DF approach, the rock matrix continuum is superimposed by lower dimensional elements, which represent the fractures. When applying a numerical scheme to solve the resulting models for the DF approach, a fine discretization is required to accurately represent the local differences in flow and transport parameters, especially at the interfaces between matrix and fractures [12].

Multi-continua approaches conceptualize the fractured medium in terms of a mobile primary continuum, the fracture network,

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and a series of less mobile secondary continua, the matrix blocks, which communicate with the primary continuum through properly posed continuity conditions at the interfaces between the continua. Mass transfer processes in the primary continuum equilibrate fast over the scale of a representative elementary volume and therefore are represented through a spatial average. Thus, the complex spatial structure of the fracture network is represented in an effective way as an equivalent porous medium, while the slower processes in the secondary continua participate in the average mass transfer in terms of non-local sink-source terms. Common multi-continua models [10,13–15] include the dual continua (DC) and triple continua (TC) [16] and the multiple interacting continua (MINC) models [17,18].

Dual porosity (DP) models or mobile-immobile models are a special case of the DC model. In fractured rock it is obvious to distinguish two zones: the fracture network and the matrix blocks. The fracture network represents the mobile zone, where “fast” flow or transport processes takes place, and the matrix blocks represent immobile zones, characterized by slow exchange processes. When the fracture network is sufficiently well connected [17], so that an REV for the fracture network can be defined [9], it is feasible to model the fracture network and the matrix blocks by applying a mass balance for each zone separately. The crucial point in this type of models is the modeling of the processes in the immobile zone respectively the exchange fluxes between mobile and immobile zone. The DP model can be solved numerically for each zone directly [19] or can be simplified using transfer functions or the multirate mass transfer (MRMT) approach.

In the transfer function approach (for example [20–22]), the exchange between mobile and immobile zone is approximated as a linear or nonlinear single rate mass transfer and the immobile zone is represented as a fully mixed system. Different types of transfer functions have been reported for diffusive solute transport, capillary counter-current flow during two-phase flow or flow driven by gravity [23–25].

A MRMT approach is obtained if the response of the immobile zone is modeled by a sink / source term that is non-local in time. The kernel of the time integration can be considered a memory function. The memory function can be expanded into a sum of exponential functions [26,27]. Exponential functions are the analytical solution for single rate transfer processes. This means that, for example, diffusion like mass transfer can be modeled by a distribution of single rate transfer processes, hence MRMT model [28,29].

The MRMT and transfer function approaches differ from each other when applied to fracture networks. For the transfer function approach there is one transfer function or one single rate transfer process for each block size [25]. The block size distribution is then modeled by a superposition of transfer functions and the resulting model is referred as multi rate double porosity (MRDP) model. MRMT models can also be represented by superpositions, however, the superposition does not necessarily represent a superposition over block sizes, but the superposition is also due to the expansion of the memory function into exponentials to capture dynamics different from single rate transfer. Naturally, a superposition over different block sizes can be carried out on top of that.

Despite the variety of different approaches to model two-phase flow in fractures in a simplified way, while capturing the effect of the heterogeneous structure, they are not much applied in practice. One reason is that more parameters are required than for a two-phase flow model in a homogeneous medium and it is not so clear how these parameters could be estimated. This is in particular true if fracture networks are considered. Also, concepts are often tested with media with one single fracture (for example [19,30]), but not often for fracture networks. Geiger et al. [31] studied a fracture network without taking heterogeneity in the capillary forces into account.

In this contribution we show the applicability of a MRMT model (presented in [30]) for immiscible two phase flow to two dimensional fracture networks, where the flow in the fracture network is simplified by a single continuum. We present timescales for characterizing flow in fracture networks to quantify conditions where the MRMT model is needed to make good predictions of recovery. We also make suggestions how parameters of the MRMT model for a fracture network can be estimated. The parameters are calculated by analyzing fracture and matrix geometry. We show two approaches to approximate the global memory functions for the MRMT model, both of them based on a superposition of functions obtained from a scaling of a reference memory function. In the one case the reference memory function is calculated numerically and in the other case it is approximated by a truncated power law function. To demonstrate the methods, we consider a forced imbibition scenario in a fracture network and spontaneous imbibition driven by capillary pressure in the matrix blocks. We compare the results of the one dimensional MRMT model with estimated parameters and the results of a full two dimensional two phase flow model applying the EPM approach, where the code Dumux [32] is used.

Although we focus on fractured media, all concepts can be easily transferred to highly heterogeneous porous media in general. The heterogeneous medium would be split into a ‘fast’ domain (equivalent to the fracture domain) and a ‘stagnant’ domain (equivalent to the matrix domain).

This paper is organized as follows. In the second section we show the equations for two phase flow in porous media and the upscaled MRMT model. In Section 3, we discuss a scaling approach to calculate the parameters for the MRMT model. In Section 4, we apply the MRMT model with estimated parameters to different fracture networks and conclude with a discussion. In the Appendix, we show how to numerically solve the MRMT as MRDP model.

2. Two-phase flow multirate mass transfer approach

In this section, we outline the two-phase flow equations that describe immiscible displacement in fractured and porous media. We then generalize the multi-rate mass transfer model derived in [30] to more realistic media, which are characterized by a distribution of immobile regions with different characteristic capillary diffusion time scales.

2.1. Two-phase flow in porous media

We model the horizontal flow of two incompressible and immiscible fluids in a rigid porous media. Based on the surface tension, one fluid is referred to as the wetting phase (index w, e.g., water) and the other one as the non-wetting phase (index nw, e.g., oil). Each phase is described by a phase pressure p_α ($ML^{-1}T^{-2}$) and normalized saturation S_α (-), with $\alpha = w, nw,$ which fulfill $S_{nw} + S_w = 1$.

Conservation of mass for each fluid is expressed as

$$n_f \frac{\partial(\rho_\alpha S_\alpha)}{\partial t} + \nabla \cdot (\rho_\alpha \mathbf{q}_\alpha) = 0, \tag{1a}$$

where n_f (-) is porosity. The specific discharge $\mathbf{q}_\alpha$ (LT^{-1}) for each phase is modeled by Darcy’s law neglecting gravity

$$\mathbf{q}_\alpha = -\frac{\mathbf{K} k_{r,\alpha}}{\mu_\alpha} \nabla p_\alpha \tag{1b}$$

where $\mathbf{K}$ (L^2) is the intrinsic permeability tensor, $k_{r,\alpha}$ (-) is the relative permeability of phase α, and μ_α its viscosity ($ML^{-1}T^{-1}$). The capillary pressure is defined as the pressure difference between non-wetting and wetting phase and is assumed to be a unique function of saturation,

$$p_c(S_w) = p_{nw} - p_w. \tag{1c}$$