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A Two-Phase Flow Simulation of Discrete-Fractured Media using Mimetic Finite Difference Method

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Abstract. Various conceptual models exist for numerical simulation of fluid flow in fractured porous media, such as dual-porosity model and equivalent continuum model. As a promising model, the discrete-fracture model has been received more attention in the past decade. It can be used both as a stand-alone tool as well as for the evaluation of effective parameters for the continuum models. Various numerical methods have been applied to the discrete-fracture model, including control volume finite difference, Galerkin and mixed finite element methods. All these methods have inherent limitations in accuracy and applicabilities. In this work, we developed a new numerical scheme for the discrete-fracture model by using mimetic finite difference method. The proposed numerical model is applicable in arbitrary unstructured gridcells with full-tensor permeabilities. The matrix-fracture and fracture-fracture fluxes are calculated based on powerful features of the mimetic finite difference method, while the upstream finite volume scheme is used for the approximation of the saturation equation. Several numerical tests in 2D and 3D are carried out to demonstrate the efficiency and robustness of the proposed numerical model.

AMS subject classifications: 76S05, 65N08, 65N55, 35J25

Key words: Fractured porous media, discrete-fracture model, two-phase flow, mimetic finite difference method.

1 Introduction

In response to stress, all rocks in the earth's crust are fractured to some extent. Fractures are important in many engineering and environmental practices. They can behave as either hydraulic conductors or barriers, and occur on different scales, from microscopic to continental. These cause modeling fluid flow in fractured rock to be a challenging work.

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Since 1960s, various conceptual models have been developed, which can be classified into four broad classes: dual-porosity model and its variations, equivalent continuum model, discrete-fracture model, and hybrid model [1].

The dual-porosity concept was introduced by Barenblatt et al. [2]. In this model, there are two parallel continua, i.e. the fracture and the matrix systems, which are connecting with transfer function. Because of its computational efficiency, dual-porosity model has been widely used to simulate the fluid flow in fractured hydrocarbon reservoirs [3–7]. However, how to accurately evaluate the transfer function is still an open problem, especially for multi-phase flow [8–10]. By further subdividing individual matrix blocks, the Multiple INteraction Continua (MINC) method [11–14] have better accuracy and features than the conventional dual-porosity model.

In comparison, the equivalent continuum model (ECM) represents the fractured rock as a single-porosity continuum. The heterogeneity of fractured rocks is modeled by using effective parameters, such as equivalent permeability and effective porosity. The ECM has long been used for modeling fracture-matrix flow due to its simple data requirements and computational efficiency [14, 15]. However, the calculation of the effective parameters for multi-phase flow is still a challenge, such as relative permeabilities and capillary pressure [16]. In addition, the instantaneous equilibrium assumption for fracture-matrix systems also limits the application of the ECM approach for modeling general multiphase flow.

As effective continuum models, either dual-porosity model or ECM is not well suited for the modeling of discrete-fractured media, in which a small number of large-scale fractures may dominate the flow. For this reason, the discrete-fracture model (DFM), which describes the fractures explicitly in the medium, are received a growing attention in the past decade. Most DFMs are based on meshing the fractures explicitly, either with an equi-dimensional formulation where fracture gridcells have the same dimension as the matrix [17–19] or with a hybrid formulation where the fractures are geometrically simplified by using $(d-1)$-dimensional gridcells in a d-dimensional domain [20–24]. An alternative approach is to deal with fractures as immersed interfaces in gridcells, including embedded-fracture model [25, 26] and non-matching grid method [27]. In the former, the fractures are embedded into a coarse structured grid and modelled through transport indices.

Limited to the present computational capacity, the DFM is only applicable to the situations where a small number of fractures dominate the fractured rock. One approach to overcome this deficiency is to combine the DFM with the continuum model, i.e. the hybrid model [1, 14, 28]. While large-scale fractures are represented as discrete elements explicitly, small-scale fractures are included as effective parameters in building continuum approximations [25, 29]. As the effective permeability are generally full-tensor, an efficient numerical scheme handling anisotropy in the permeability and discrete fractures is necessary. Various numerical methods based on DFM have been used to simulate fluid flow in discrete-fractured media, including the finite difference (FD) [30, 31], finite volume (FV) [32–35], Galerkin finite element (GFE) [21, 36], and mixed finite element