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An efficient embedded discrete fracture model based on mimetic finite difference method

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ABSTRACT

Various numerical models exist for numerical simulation of fluid flow in fractured porous media, such as dual-porosity model, discrete fracture model and equivalent continuum model. As a promising model, the embedded discrete fracture model is a powerful tool for fractured porous media with complex fracture distribution, because it incorporates the effect of each fracture explicitly without requiring the simulation mesh to conform to the fracture geometry. Moreover, it does not need mesh refinement near fractures and offers computationally-efficient simulations compared to other discrete fracture models. In this paper, the Mimetic Finite Difference method and Finite Volume Method are used to improve the numerical solution of the embedded discrete fracture model, the improved method can deal with permeability tensor and can be used to simulate fractured reservoir with complex geometrical shape, which fails to be solved by the primal method based on the finite difference method. Several numerical simulations and physical experiment demonstrate the applicability of the proposed method for studying flow processes in fractured porous media.

1. Introduction

In the past few years, numerical simulation of fractured porous media has received much attention, because of the significant contribution of fractured reservoirs to the oil and gas reserves and productions. The fractures are important for many engineering practices, such as petroleum engineering, hydrogeology, and so on. They usually behave as hydraulic conductors, and occur on various scales (from microcosmic to macroscopic). It is still a challenging to model multi-phase flow in fractured porous media. Three approaches are commonly used to model fluid flow in fractured porous media: (1) the equivalent continuum model (ECM), Huang et al. (2013), Wu et al. (1999), and Wu and Qin (2009); (2) the dual-porosity model and its variations, Barenblatt et al. (1960), Karimi-Fard et al. (2004), Kazemi et al. (1969), Lim and Aziz (1995); Pruess et al. (1985), Warren et al. (1963), and Wu et al. (1988); (3) the discrete fracture model (DFM), Geiger-Boschung et al. (2007), Hoteit and Firoozabadi (2008), Huang et al. (2014), Karimi-Fard et al. (2003), Martin et al. (2005), Noorishad and Mehran (1982), and Sun et al. (2014, 2015).

In the equivalent continuum model, fractures and matrix are represented as a single continuum based on the concept of equivalent parameters, such as equivalent permeability and porosity. The ECM has long been used for modeling flow in naturally fractured reservoirs due to its simple data requirements and computational efficiency, Wu et al. (1999) and Wu and Qin (2009). However, how to accurately and efficiently calculate the equivalent parameters for multi-phase flow is still a challenge, such as equivalent relative permeability and capillary pressure, Huang et al. (2013). In addition, the instantaneous equilibrium assumption for fracture-matrix systems also limits the application of the ECM approach for modeling general multiphase flow. The dual-porosity model is typically presented in naturally fractured reservoirs because of its simplicity and computational efficiency. In this model, there are two parallel continua, i.e. the fracture and the matrix systems, which are connecting with transfer function. However, how to accurately evaluate the transfer function is still a challenge, especially for multi-phase flow, Lim and Aziz (1995). By further subdividing individual matrix blocks, the Multiple Interaction Continua (MINC) method, Pruess et al. (1985) and Wu et al. (1988), has better accuracy and features than the conventional dual-porosity model. The discrete fracture model, which incorporates the effect of individual fractures explicitly, has received significant attention in the last few years. It provides more realistic representation of fractured reservoirs than dual-porosity model and equivalent continuum model. However, it relies on unstructured meshing, to honor the geometry and location of fractures, which is quite complicated for actual fracture distribution.

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Nomenclature

DFM	discrete fracture model
EDFM	embedded discrete fracture model
PV	pore volume
v	darcy velocity
K	permeability tensor
λ	mobility
μ	fluid viscosity
ρ	fluid density
k_r	relative permeability
p	globe pressure
V	volume of grids
q	source and exchange fluxes term
δ	dirac delta function
A	surface area or interface
d	distance
K	permeability scalar
d_f	fracture aperture
S	phase saturation
ϕ	porosity
p_c	capillary pressure
f_w	fractional flow function
$\boldsymbol{n}$	area-weighted normal vector
$\boldsymbol{x}$	coordinate vector
$\boldsymbol{T}$	transmissibility matrix
N_e	total number of matrix grids

Subscript

m	matrix
f	fracture
w	wetting phase
n	non-wetting phase
d	space dimensionality
ξ	local coordinates

superscript

in	influx
*	normalization

In the last few years, Li and Lee proposed a new discrete fracture model for simulating flow in naturally fractured reservoirs, called the embedded discrete fracture model (EDFM), Lee et al. (2001) and Li et al. (2008). In this model, the matrix is represented by the structured grid, the fractures are explicitly represented by the discrete fracture network model and embedded in the matrix grid, then matrix and fractures are connecting with the transfer function. Therefore, challenges associated with unstructured gridding are bypassed entirely, Moinfar et al. (2012) and Zhou et al. (2014). However, the numerical method applied to EDFM is based on the finite difference method, and it is difficult to simulate fluid flow in fractured reservoir with complex geometrical shape, which should be gridding with unstructured grid.

In this work, an efficient EDFM is developed for irregular fractured reservoir with anisotropic permeability based on the Mimetic Finite Difference method (MFD), Alpak (2010) and Finite Volume method (FV). The MFD method has been successfully used in Computational Fluid Dynamics (CFD) and numerical reservoir simulation, Brezzi et al. (2005) and Lipnikov et al. (2014), because of its excellent local conservation property and applicability for the complex unstructured grid. The organization of this paper is as follows: The comparison of geometrical discretization of the DFM and EDFM is described in Section 2; The equations of the EDFM are described in Section 3; Then the simulation approach is described in Section 4 and Section 5. Lastly, several numerical examples and conclusions are shown in Section 6 and Section 7.

2. Geometrical discretization

The DFM approach requires generating an unstructured grid to conform to the complexity of the fractures. Generation of such a grid for an arbitrary fracture network can be a substantial challenge, especially when the distance between fractures is very short, the gridding quality is often poor, and it will lead to miscalculation, as illustrated in Fig. 1a. However, the EDFM uses a structured grid to represent the matrix and introduces additional fracture control volumes by computing the intersection of fractures with the matrix grids, as illustrated in Fig. 1b. Therefore, challenges associated with unstructured gridding are bypassed entirely.

3. Model equations

To be convenient for writing, we consider the flow of two immiscible and incompressible phases (wetting and non-wetting) without considering the influence of gravity and assume no-flow boundary conditions in 2-D plane. The flow equations can be formulated as an elliptic equation for the globe pressure p and the total Darcy velocity $\boldsymbol{v}$ (the details can be found in Aarnes et al. (2007)), then, the pressure equations of embedded discrete fracture model are written as:

Matrix system:

$$\boldsymbol{v}_{\mathrm{m}} = -\boldsymbol{K}_{\mathrm{m}}\lambda_{\mathrm{m}}\cdot\nabla p_{\mathrm{m}} \tag{1}$$

$$\nabla\cdot\boldsymbol{v}_{\mathrm{m}} = q_{\mathrm{m}} + \frac{q_{\mathrm{mf}}}{V_{\mathrm{m}}}\delta_{\mathrm{mf}} \tag{2}$$

Fracture system:

$$\boldsymbol{v}_{\mathrm{f}} = -\boldsymbol{K}_{\mathrm{f}}\lambda_{\mathrm{f}}\cdot\nabla p_{\mathrm{f}} \tag{3}$$

$$\nabla\cdot\boldsymbol{v}_{\mathrm{f}} = q_{\mathrm{f}} - \frac{q_{\mathrm{mf}}}{V_{\mathrm{f}}} - \frac{q_{\mathrm{ff}}}{V_{\mathrm{f}}}\delta_{\mathrm{ff}} \tag{4}$$

where $\boldsymbol{v}_{i=}\boldsymbol{v}_{\mathrm{iw}}+\boldsymbol{v}_{\mathrm{in}}$, the total Darcy velocity, (i=m, f); $\boldsymbol{K}_i$ is the permeability tensor; $\lambda_i=\lambda_{\mathrm{iw}}+\lambda_{\mathrm{in}}$, denotes the total mobility, and the mobility of phase is given by $\lambda_{il}=k_{\mathrm{r}il}/\mu_l$, where μ_l is viscosity of phase l and $k_{\mathrm{r}il}$ is the relative permeability; the parameters $_{pi}$, V_i and q_i are the globe pressure, volume of grid cells and the source, and $q_i=q_{\mathrm{iw}}+q_{\mathrm{in}}$; q_{mf} is the exchange flow between fracture and matrix; q_{ff} is the exchange fluxes between two intersecting fractures; $\delta_{\mathrm{mf}}=1$, when matrix grid embedded with fractures, else $\delta_{\mathrm{mf}}=0$; $\delta_{\mathrm{ff}}=1$, when fracture grid intersects with another fracture, else $\delta_{\mathrm{ff}}=0$.

The q_{mf} can be calculated by equation below because of the assumption of pressure continuity in matrix grids

$$q_{\mathrm{mf}} = -T_{\mathrm{mf}}(p_{\mathrm{m}} - p_{\mathrm{f}}) \tag{5}$$

where $T_{\mathrm{mf}} = k_{\mathrm{mf}}\lambda_{\mathrm{mf}}A_{\mathrm{mf}}/d$; d denotes the equivalent distance between matrix grid and fracture grid; k_{mf} is harmonic average of the permeability of matrix and fracture; A_{mf} is fracture surface area in the matrix grid; λ_{mf} is the total mobility, the upstream value used