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Efficient evaluation of gas recovery enhancement by hydraulic fracturing in unconventional reservoirs

Junchao Li [a], Zhengdong Lei [a,*], Huiying Tang [b], Changbing Tian [a], Bin Gong [b]

[a] *Research Institute of Petroleum Exploration and Development, PetroChina, Beijing 100083, China*
[b] *Department of Energy & Resources Engineering, College of Engineering, Peking University, Beijing 100871, China*

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A B S T R A C T

Hydraulic fracturing is an important approach to improve production rate in unconventional gas reservoirs. A proper evaluation of the effectiveness of fracturing process is essential for designing and optimizing future stimulation operations. The recent advances in diagnostic techniques and mineback observations provide evidences of the existence of complex fracture networks. Decline curve analysis also highlights the impact of pre-existing fractures on production. In this paper, we propose a hybrid model which is capable of simulating the multi-scale complex fracture network in a very efficient way.

A uniformly global upscaling technique is used to get reliable calculation of transmissibilities between sim-grids of different media without introducing artificial parameters such as shape factors. In the upscaling framework, a high-resolution discrete fracture model of the complex fracture network is firstly built as the reference model. Then a coarse unstructured grid conforming to primary fractures is generated based on this fine scale model and serves as the simulation grid. In the coarse model, large scale fractures are treated explicit like conventional discrete fracture models, while relatively small-scale fractures are upscaled into dual porosity grids by global upscaling procedures.

A synthetic case and a field scale problem are designed and implemented to validate and illustrate the capability of the proposed method. The results show that our model can save considerable computation time while preserve the accuracy of simulation. This model can serve as a reliable tool to fast evaluate different plans for enhanced gas recovery, especially in the case when multiple realizations are required for uncertainty analysis.

1. Introduction

Unconventional gas reservoir recovery often meets the challenge of low production rate and unsatisfactory ultimate recovery. Gas is trapped in the ultra-tight formation and the conventional exploitation methods usually fail in such reservoirs. Hydraulic fracturing is the most effective approach to obtain economic gas production rate and has been widely used for decades. The application of hydraulic fracturing increases the complexity as well as brings more uncertainties to the production process. A large number of case studies may be needed to optimize the well placement, stimulation designs and production schedules. In this situation, an effective model for fast simulating the recovery process without significantly loss of accuracy becomes necessary for unconventional gas reservoir exploration and development.

The fracture network formed by hydraulic fracturing consists of two kinds of fractures which are defined as primary fractures (PFs) and secondary fractures (SFs). The primary fractures represent the large scale hydraulic fractures which are usually perpendicular to the direction of minimum principal stress. They provide high conductive channels for gas to flow from formation to wellbore. Different from the primary fractures, the secondary fractures are formed by the stimulated pre-existing natural fractures or small cracks in the rocks. They locate in the vicinity of primary fractures, connect each other and form a complex fracture network in the stimulated reservoir volume (SRV).

The traditional method for modeling the flow in the SRV region containing complex fracture network is the dual-porosity model (DP). DP model was first proposed by Barenblatt and Zheltov (1960) and later introduced to the petroleum industry by Warren and Root (1963) In DP models, reservoir is represented by matrix and fracture media. The matrix medium is the source of reserves, while the

* Corresponding author.
E-mail address: leizhengdong@petrochina.com.cn (Z. Lei).

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fracture medium acts as the channel through which main flow occurs. Fluid interaction between these two continua is represented by a transfer function called shape factor. DP model is widely applied in the past decades due to its efficiency and robustness (Kazemi et al., 1976; van Golf-Racht, 1982; Thomas et al., 1983; Wu and Pruess, 1988; Dershowitz et al., 2000; Sarda et al., 2002; Sarma, 2003; Di Donato et al., 2003). However, the idealized sugar cube representation of the fracture network can be problematic in certain circumstances. For example, DP models are not well suited to model the situation when a small number of large fractures exist and dominate the flow direction, which is common in SRV regions.

The discrete-fracture model (DFM) was hence proposed as a substitute for fracture description and modeling which has gained a lot of attention and application in recent years (Kim and Deo, 2000; Juanes et al., 2002; Karimi-Fard and Firoozabadi, 2003; Karimi-Fard et al., 2004; Matthäi et al., 2005; Hoteit and Firoozabadi, 2006; Hui et al., 2013; Gong et al., 2013). Different from DP models, DFMs precisely characterize each fracture based on its realistic geometry and treat each fracture control volume as a single block during simulation. DFMs can be regarded as a special single porosity model, which utilizes much fewer grids to explicitly characterize fractures compared to Cartesian grid with the benefit of more flexible unstructured grids. Without any equivalence or simplification, DFMs can capture the complex flow inside fracture media and between matrix and fractures. Although DFMs are generally acknowledged and have become a promising method to provide a more accurate way for modeling fractured reservoirs, it is still a challenge to apply those models to field scale problems with large number of multi-scale fractures. Since each single fracture needs to be discretized with conforming grids, the computation time can be too long to be acceptable for practical use.

Hybrid models which combine different scales of fractures and different scales of grids have received much attention. Gong et al (Gong, 2007; Gong et al., 2008) proposed a hybrid grid model to represent different sets of fractures. In their model, fractures are characterized and classified according to the inner connection relationship of fractures by analyzing the pressure field of a pseudo-steady state flow process. In their model, however, the multiple subregion grids are determined by a tessellation of coarse grid blocks, which means this method is unable to maintain some explicit fractures circumstantially. Moinfar et al. (2013) proposed an embedded discrete fracture model (EDFM) to process all different scales of fractures into dual-porosity type of fractures. The great advantage of EDFM is that it avoids unstructured mesh generation which may be a tough task before reservoir simulation. However, in EDFM the transmissibilities between matrix grid blocks and fractures are calculated analytically based on the assumption of a linear pressure distribution (Li and Lee, 2008; Hajibeygi et al., 2011). Zhang et al. (2015) provided a model with prismatic meshing for enhanced coalbed methane recovery. In their method, the large scale fractures are represented as discrete fractures and the smaller fractures (cleats) are modeled by shape factor similar with dual-porosity method. The flux between matrix grid blocks and cleats is characterized by the shape factor which only depends on the geometric distribution of the cleats. This treatment is appropriate for the regions with high density of small fractures. However, it is not suitable for handling meso to large scale hydraulic fractures. Wang (2015). proposed a hybrid dual-continuum discrete fracture model for SRV regions. This model uses DP models and DFM models for the dense micro-fractures and sparse macro-scale fractures respectively. The transmissibilities between different media are calculated based on the grid's shape. However, the shape factor obtained in this model is based on regular fracture patterns and specific flow boundary conditions which limits its applicability to arbitrary fracture systems.

The hybrid models developed by far have made great contributions to improving the efficiency of simulations. But they have certain drawbacks in determining the transmissibilities between grids in different media as discussed above. In this paper, we present a hybrid model for effectively modeling the complex fractures stimulated during hydraulic fracturing. Primary fractures and secondary fractures are modeled by discrete fractures and dual-porosity fractures respectively. A uniform upscaling framework is designed to compute the transmissibilities between matrix and fractures and between different scales of fractures. The global upscaling procedures are totally adaptive to model any specific problems regardless the changes of well locations, fracture distributions or flow patterns. That means it is no longer needed to introduce extra parameters like shape factors under some artificial assumptions, which infers its capability to provide more reliable and stable results.

This paper is organized as follows: Section 2 illustrates the theoretical basis and the workflow of the proposed approach. Section 3 is devoted to several applications demonstrations. The first example is implemented for model validation and the rest are designed to illustrate the ability of the proposed framework to fast evaluate the effect of hydraulic fracturing on EOR in unconventional gas reservoirs. Conclusions are then presented in Section 4.

2. Methodology

2.1. Governing equations

The mass conservation equation for gas-water two-phase flow in porous media is given in EQ (1) which applies Darcy's equation in velocity calculation:

$$\nabla\cdot\left(\frac{\rho_l k k_{r,l}}{\mu_l}\nabla p\right)+q=\frac{\partial(\phi\rho_l S_l)}{\partial t} \tag{1}$$

Where, l denotes the phase; ρ_l is the density of phase l; p are the pressures; μ_l is the viscosity of phase l; k is the permeability and $k_{r,l}$ is the relative permeability of phase l; S_l is the saturation of phase l; ϕ is the porosity. The full description also requires the saturation constraint $\sum S_l=1$. In this paper, we neglect the capillary pressure for simplicity.

2.2. Reference discrete fracture model

A fine-scale discrete fracture model based on unstructured grids fully conforming to both the primary and secondary fractures is first generated as the reference grid. A control volume method based on two point flux approximation (TPFA) proposed by (Karimi-Fard et al., 2004). is used to represent flux between adjacent grids as:

$$Q_{l,ij}=T_{ij}\frac{\rho_l k_{r,l}}{\mu_l}\left(P_{l,i}-P_{l,j}\right) \tag{2}$$

Here, l denotes the phase; ρ_l, $k_{r,l}$ and μ_l are the same variables as EQ (1); P is the grid center pressure, and T_{ij} is the transmissibility between grid i and j which depends on the geometry and permeability of each control volume.

This high-resolution model is not suitable to do numerical simulation directly for the efficiency reason. However, it is a good reference to provide detailed information of the flow behavior. Therefore it is recommended to generate the grids as fine as possible to improve the precision of the upscaled model. Then the solution gained with reference grids will be used to compute the upscaled simulation model, which will be discussed in the next