Journal of Natural Gas Science and Engineering 21 (2014) 631–635

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

The investigation of fracture aperture effect on shale gas transport using discrete fracture model

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ARTICLE INFO

Article history:
Received 26 July 2014
Received in revised form
21 September 2014
Accepted 22 September 2014
Available online

Keyword:
Shale gas
Fracture aperture
Discrete fracture model
Numerical simulation

ABSTRACT

Discrete fracture model (DFM) numerical simulation is used to investigate the shale gas transports in fractured porous media in this paper. A new seepage flow mathematic model, in which flow in fracture meets "Cubic law" and matrix meets "non-Darcy law", is adopted and fracture aperture effect on the transport behavior is simulated by solving the nonlinear partial differential equations using finite element analysis (FEA). In this DFM, fluid flows into wellbore which is surrounded by impermeable rock matrix is merely through fractures that connect to it. The model is used to simulate a random generated fractures network to study the flow and transport characteristics in fractured porous media (FPM). Several cases with different fracture aperture in same natural fractured model are given. The preliminary simulation results show that both the natural and hydraulic fracture aperture have a significant impact on shale gas migration and production.

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The exploitation of unconventional reservoirs is increasingly a major source of long-term energy in China. Most unconventional reservoirs comprise multiple orientations natural fractures and complex hydraulic fracture patterns based on micro seismic data. Compared to the conventional porous media, FPM exhibits a higher degree of heterogeneity and complexity created by fractures. Generally, fractures play an important role in fluid flow and transport through geologic strata. Arbitrary orientations of natural fractures with variable lengths and sizes inside matrix make it computationally difficult to simulate the flow through fractured media, which cannot be well modeled by single or multi-continuum models, and thus the simulation of the fluid flow in FPM is a challenging work in engineering (Reichenberger, 2003). Since the 1960s, flow and transport behavior in FPM has been thoroughly studied, theoretically, experimentally and numerically, significant progress has been made towards the modeling of flow processes in FPM and flow models have been roughly classified into DFMs, dual continuum models (DCMs) and hybrid (Therrien, 1996; Sahimi,2012).

DFM is a kind of models for simulating fractured system distinguishes from the DCM and has received considerable attention in the last decade. Fluids Flow behavior in different DFMs has been studied by several researches (Cacas, 1990; Nordqvist, 1992; Kim, 2000; Maryška, 2005; Gong, 2008). In general, a large number of small grid blocks are required near fractures that slows the computational efficient when using DFM. So, DFM is limited to small blocks within a domain with few fractures and has not been widely used in the industry for filed-scale reservoir simulation studies, even though they can explicitly accounting for the geometry of fractures and contribution of each individual fracture to fluid flow while conventional continuous methods cannot. Furthermore, most DFMs requires generating an unstructured grid, which is a substantial challenge work for arbitrary fracture network, to conform to the complexity of discontinuous fractures assigned to the domain of the interest.

Some researchers also use finite difference, finite volume, boundary element, finite element or mixed finite methods to investigate fluid flow in FPM (Sahimi,2012; Narasimhan, 1976; Liggett and Liu, 1983). Reddy stated that the most powerful computer oriented method ever developed to solve engineering problems is the finite element methods (Reddy and Gartling, 2010) which has a major advantage in reservoir simulation in that a geometrically complex domain can be discretized with a maximum use of mesh points.

This research aimed at studying the fracture aperture's effect on gas transport in fractured shale reservoir using DFM. A mathematic model, fluid flow meets "non-Darcy law" in matrix while meets "Cubic law" in fracture, is adopted and FEA is employed to solve the nonlinear partial differential equations. We focus on the numerical evaluation of flow and transport in a synthetic FPM. Several cases

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http://dx.doi.org/10.1016/j.jngse.2014.09.029
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with different fracture aperture in same natural fractured model are given. The preliminary simulation results show that the fracture aperture has significant impact on the shale gas production.

1. DFM introduction

1.1. Model description

This paper presents an investigation of transient flow in a two-dimensional FPM, which is consisting of two rectangular plates (Fig. 1), the top gray one stands for the reservoir within 65 lines while the down red one represent horizontal well. The 58 white lines and 2 black lines (The endpoint coordinates of each line are tabulated in Table 1) represent natural fractures while the 5 blue lines stand for the hydraulic fractures. Each natural fracture has a stochastic orientation and the aperture are all same, the wellbore radius is 1.5 × 10^{-2} m. While non-Darcy's law governs time-dependent fluid flow in matrix block, cubic law accounts for a relatively small resistance to flow in fracture. This work plays an important role in the simulation of gas transport in shale formation, because shale reservoirs are natural FPM.

The DFM is an efficient and accurate method jointly model the fracture and matrix flows in FPM. Fluid moves quickly through the fractures but also migrates, albeit relatively slowly, through the tiny pores within the surrounding matrix block when it flows in FPM. Some fluid transfers are between fractures and matrix blocks, so the fluid pressure is continuous across fracture from block to block. We build fractures as the boundaries between adjacent matrix blocks (Fig. 1). Representing the fractures as an interior boundary is especially efficient.

1.2. Model definition

The geometry in Fig. 1 is a two-dimensions plate of fractured porous material that measures 1000 × 250 m^2 and also contains 65 fractures which including 60 natural fractures and 5 hydraulic fractures. The two black lines represent dead fracture that cannot connect to the outlet edge neither directly nor indirectly while all the other 63 fractures are valid fracture that can connect to the outlet edge either directly or indirectly. Production from reservoir to well is only through the fractures that connect to the well hole. Fractures are far more permeable than matrix blocks but the aperture is much smaller when comparing to blocks dimensions. The walls of the blocks are impermeable except at the fracture edges. Fluid moves from top to down through the plate entering at the top fracture edge and exiting at the down edge. The fluid initially does not move within the volume and the initial pressure is p_0. Pressure at the outlet edge is the bottom hole flowing pressure while pressure at the inlet edge remains the original pressure throughout the simulation.

1.3. DFM model assumptions

According to the properties and characteristics of shale gas reservoirs and the flow behavior, several assumptions are made during the development of the model:

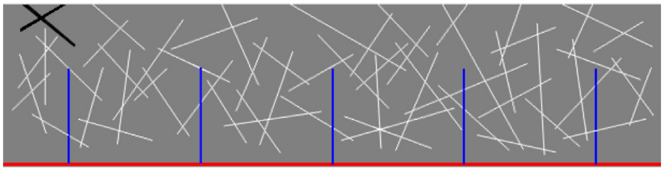

Fig. 1. Geometrical representation of a discrete fracture network.

- The fluid is methane (compressible)
- Isothermal and single-phase flow
- The flow takes place along the continuous fractures which are discrete
- Matrix blocks have a storage capacity and a low flowing capacity while the facture have a low storage capacity and a high flowing capacity
- The reservoir provides fluid for wellbore only through the fracture which connects to the well while the matrix's contribution is ignored.

2. Fluid flow model in the DFM

Modeling of shale gas flow and transport in FPM requires the solution of at least two coupled partial differential equations respectively the flow equations in the matrix blocks and the equations in the fracture depending on the problem. In this model, fluid flows in matrix rock meets the "non-Darcy law" while flow in fracture meets the fracture flow, which is also called "Cubic Law". Then the mathematic models in matrix blocks and fracture will be introduced in the following section.

2.1. Mathematic model in matrix blocks

Time-dependent fluid flow in non-FPM is described by the non-Darcy's equation. So the mass continuity equation in matrix blocks is written as (COMSOL Multiphysics Model library, Earth Science Module, 2013; Walton and Seitz, 1992):

$$\rho S\frac{\partial p}{\partial t}+\nabla\cdot(\rho u_m)=0 \tag{1}$$

The matrix storage coefficient is given by:

$$S=C_g\phi+C_m(1-\phi) \tag{2}$$

Gas isothermal compressibility is given by Yang Shenglai and Junzhi (2004):

$$C_g=-\frac{1}{V}\left(\frac{\partial V}{\partial p}\right) \tag{3}$$

In block, the Darcy velocity, u_m defined as volume flow rate per unit area of porous material is given by:

$$u_m=-\frac{k_{\text{app}}}{\mu_g}\nabla p \tag{4}$$

k_{app} is matrix block apparent permeability, which coupled the gas diffusion and gas slippage effect (Mi Lidong et al., 2014):

$$k_{\text{app}}=C_gD\mu_g+Fk_\infty \tag{5}$$

2.2. Mathematic model in fracture

Fractures in this model are a sequence of interior boundaries. Typically, at a boundary we define flow across or normal to the boundary instead of along it. In this model, however, we employ fracture flow boundary condition that allows for defining flow along the interior boundaries that are fractures.

In this boundary condition, the velocity equation in fracture follows matrix block's modification, namely Cubic law. Therefore, we modify the equation coefficients to account for a relatively small resistance to flow in fracture. Fluid flow in fractures is modeled similarly to modeling flow in porous matrix based on Eq. (1). The fracture aperture w is added to ensure dimensional consistency

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