Journal of Natural Gas Science and Engineering 27 (2015) 901–913

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Analysis of a fully coupled gas flow and deformation process in fractured shale gas reservoirs

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ARTICLE INFO

Article history:
Received 1 July 2015
Received in revised form
11 September 2015
Accepted 17 September 2015
Available online 25 September 2015

Keywords:
Shale gas
Coupled gas flow and solid deformation
Discrete fractures
Finite element method

ABSTRACT

Coupled gas flow and solid deformation in porous media have received considerable attention because of their importance in shale gas transport. The existence of propped and un-propped fractures makes simulating the complex flow more difficult in fractured shale reservoirs. The effect of matrix deformation on production has been ignored in most previous studies. Moreover, the influence of fracture conductivity loss has not been well studied in shale reservoirs with discrete fractures. In this study, a general porosity model and a correlation of fracture permeability loss are introduced to develop a fully coupled gas flow and deformation model that contains the shale matrix and discrete fractures. The numerical hydra-mechanical model is implemented using a finite element method and it is validated using an analytical solution with the simplified condition. The coupled model with discrete fractures is verified by reducing the fracture conductivity and comparing the results with the continuous model. Then the effects of the stress-dependent permeability of the matrix and fracture on cumulative production are analyzed. The numerical results indicate that the apparent permeability of shale gas is determined by both the effects of pore-compressibility and the non-Darcy flow. The intrinsic permeability decreases as the effective stress increases, while the apparent permeability can be enhanced because of the non-Darcy flow effect as the gas pressure is depleted. The ignorance of geomechanics about the matrix will lead to an overestimated cumulative production. The loss of fracture conductivity, including both the propped and un-propped fractures, impairs the production distinctly only when the dimensionless conductivities are small. Improving the fracture conductivity can offset the negative effect of conductivity loss on the cumulative production.

1. Introduction

A thorough understanding of the gas transport mechanism in shale plays a vital role in efficiently developing shale gas reservoirs. The multi-mechanism, which includes the gas slippage, adsorption and diffusion flow in the nano-scale pore and kerogen of shale (Akkutlu and Fathi, 2011; Civan, 2010; Javadpour, 2009; Javadpour et al., 2007; Klinkenberg, 1941; Swami and Settari, 2012), has been well studied via experiments and simulation. The key parameter, the apparent permeability of the gas proposed by Klinkenberg, is closely related to production and therefore, it has been investigated by numerous authors. Civan (Civan, 2010) derived the form of the apparent permeability from a Hagen–Poiseuille-type equation and provided an effective correlation for the gas slippage factor. Swami (Swami and Settari, 2012) constructed a pore scale model to study the contribution of Knudsen diffusion and gas slippage, gas desorption and gas diffusion from kerogen to total production. However, some of the coefficients in the model are difficult to measure for the shale reservoirs. Xiong (Xiong et al., 2012) analyzed the effect of adsorbed gas on the apparent permeability and showed that desorption would lead to an increase of the apparent permeability. Recently, the pore-size dependence of the fluid phase behavior (Didar and Akkutlu, 2013; Devegowda et al., 2012; Singh et al., 2009) has been considered in shale gas production.

Modeling gas flow in the fractured shale reservoirs is another

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http://dx.doi.org/10.1016/j.jngse.2015.09.040
1875-5100/

challenge. Barenblattand Zheltov (Barenblatt and Zheltov, 1960) initially introduced the concept of the dual continuum to model the fractured porous medium. The matrix is divided by the fracture and the flow within the domain is only achieved through the fracture network. Two conservative equations are derived for matrix and fracture in the domain, and they are coupled by the mass transfer between the two continuums. Warren and Root (Warren and Root, 1963) first applied this model to petroleum engineering and it can give satisfactory results by assuming orthogonal fracture systems and steady or pseudo-steady state flow. Significant modifications and extensions have been made since to the original dual porosity model (Kazemi et al., 1976; Rossen, 1977; Saidi, 1983). The dual permeability approach is another type of dual continuum concept that assumes that the matrix is continuous and fracture network connectivity is not required (Lamb et al., 2013). The dual permeability model is closer to reality and can provide a more accurate description of the flow path in the reservoir than the dual porosity model (Huang and Ghassemi, 2012). A new approach that has rapidly developed over the last decade in the field of fractured reservoir simulation is a single continuum model with discrete fractures (Karimi-Fard et al., 2004; Kim and Deo, 2000; Lee et al., 1999). Discrete fractures are described in a spatially explicit way and are discretized along the edge of the matrix element. Although this approach conforms to the real fracture geometry and orientation, the computational efficiency is low because of the mesh refinement near the fractures; therefore, this model is applied to reservoirs with low fracture density (Lamb et al., 2013).

Even though numerous models have been built to study the complex flow in fractured shales, the geomechanical effects on shale gas production are usually neglected. Gas transportation and the coupled hydro-mechanical (HM) process have been widely used for studying coal seams (Wei and Zhang, 2010; Zhang et al., 2008; Zhu et al., 2007). The fracture conductivity vs. pore pressure table or matrix permeability vs. pore pressure table is usually used in commercial software to consider the geomechanical effects (Yu and Sepehrnoori, 2013). However, this is a one-way coupling process assuming uniaxial strain and constant overburden. Models with coupled flow and geomechanics can be divided into four types: fully coupled, iteratively coupled, explicitly coupled, and loosely coupled, in which a fully coupled model can reveal the physics of the coupled model and has the highest accuracy (Hu et al., 2013). Lewis proposed a fully coupled double porosity model for the single phase and multiphase flow in the deformable fractured porous media (Ghafouri and Lewis, 1996; Lewis and Ghafouri, 1997). Iterative coupling between the reservoir simulator and geomechanics simulator was conducted with different time steps (Longuemare et al., 2002), but the data exchange can only be performed at given time intervals. Minkoff (Minkoff et al., 2003) solved the flow equations and deformation equations independently and sequentially. This process is loosely coupled and may not guarantee mass conservation. A fully coupled dual permeability model combined with an extended finite element method has been used to solve the discontinuous field near the fracture (Lamb et al., 2010; Sheng et al., 2012). However, the fracture permeability in these models is assumed to be constant. Huang (Huang and Ghassemi, 2012) investigated the impact of fracture closure on gas flow by using a dual permeability model. The pressure-dependent fracture aperture is a function of the effective stress that acts on the fracture element.

Although all of these previous studies have helped us to comprehensively understand the nature of shale gas flow, few studies have focused on the permeability evolution of the shale matrix during the production process. The effect of matrix deformation on production is unclear. Moreover, the influence of fracture conductivity loss has not been well studied in shale reservoirs with discrete fractures. Therefore, further efforts should be made to analyze the effects of geomechanics on shale gas production.

In this study, a fully coupled gas flow and deformation model considering the flow in discrete fractures is proposed to discuss the complex mechanism of gas flow in fractured shale gas reservoirs. Governing equations, including the mechanical equilibrium equation, conservative equation and cross coupling equations, are presented first. Then, the numerical model is implemented using a multiphysics simulator based on a finite element method and it is validated against the continuous solution. Next, the effects of stress-dependent permeability of the matrix and fracture on cumulative production are analyzed. Finally, conclusions and suggestions are given.

2. Governing equations

In this section, a set of equations are defined that govern the deformation of the solid matrix and the transport of the gas flow in a shale gas reservoir based on the poroelastic theory (Detournayj and Cheng, 1993). These derivations are based on the following assumptions: (a) shale is a homogeneous, isotropic and elastic medium; (b) plain strain conditions are adopted; (c) shale is saturated only by gas with one gas component; and (d) the gravity effect on the gas flow is negligible.

2.1. Mechanical equilibrium equation

The constitutive relationship of an isotropic linear poroelastic matrix can be expressed as:

$$\sigma_{ij} = 2G\varepsilon_{ij} + \left(\frac{2G\nu}{1-2\nu}\right)\varepsilon_{kk}\delta_{ij} - \alpha_B p\delta_{ij} \tag{1}$$

where G is the shear modulus; ν is the Poisson's ratio; δ_{ij} is the Kronecker delta tensor defined as 1 when i = j and 0 when i ≠ j; and α_B is Biot's coefficient. The equation expresses the total stresses σ_{ij} with respect to the solid strain ε_{ij} and pore pressure p (tension is considered to be positive).

For a homogeneous, isotropic and elastic medium, the strain-displacement relation is expressed as:

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \tag{2}$$

where u_i is the component of the displacement in the *i*-direction.

With the body force, the momentum balance equation is expressed as:

$$\sigma_{ij,j} + f_i = 0 \tag{3}$$

where f_i is the component of the body force in the *i*-direction.

Substituting Eqs. (1) and (3) into Eq. (2), a modified Navier equation in terms of displacement and pore pressure can be derived as:

$$Gu_{i,jj} + \left(\frac{G}{1-2\nu}\right)u_{j,ji} - \alpha_B p_{,i} + f_i = 0 \tag{4}$$

2.2. Gas flow equation

The equation for mass balance of the gas is defined as: