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Natural Gas Industry B 4 (2017) 120−126

www.elsevier.com/locate/ngib

Research Article

A coupling model for gas diffusion and seepage in SRV section of shale gas reservoirs☆

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Received 27 October 2016; accepted 25 January 2017
Available online 26 August 2017

Abstract

A prerequisite to effective shale gas development is a complicated fracture network generated by extensive and massive fracturing, which is called SRV (stimulated reservoir volume) section. Accurate description of gas flow behaviors in such section is fundamental for productivity evaluation and production performance prediction of shale gas wells. The SRV section is composed of bedrocks with varying sizes and fracture networks, which exhibit different flow behaviors − gas diffusion in bedrocks and gas seepage in fractures. According to the porosity and permeability and the adsorption, diffusion and seepage features of bedrocks and fractures in a shale gas reservoir, the material balance equations were built for bedrocks and fractures respectively and the continuity equations of gas diffusion and seepage in the SRV section were derived. For easy calculation, the post-frac bedrock cube was simplified to be a sphere in line with the principle of volume consistency. Under the assumption of quasi-steady flow behavior at the cross section of the sphere, the gas channeling equation was derived based on the Fick's laws of diffusion and the density function of gas in bedrocks and fractures. The continuity equation was coupled with the channeling equation to effectively characterize the complicated gas flow behavior in the SRV section. The study results show that the gas diffusivity in bedrocks and the volume of bedrocks formed by volume fracturing (or the scale of fracturing) jointly determines the productivity and stable production period of a shale gas well. As per the actual calculation for the well field A in the Changning−Weiyuan Block in the Sichuan Basin, the matrix has low gas diffusivity − about 10^{-5} cm^2/s and a large volume with an equivalent sphere radius of 6.2 m, hindering the gas channeling from bedrocks to fractures and thereby reducing the productivity of the shale gas well. It is concluded that larger scale of volume fracturing and higher fracture density in the SRV section are important guarantees for efficient development of shale gas reservoirs.

Keywords: Shale gas reservoir; SRV; Matrix; Fracture network; Continuity equation; Channeling equation; Sichuan Basin; Changning−Weiyuan Block

Effective scale-development of shale gas pool is dependent on the size of SRV area. The larger a SRV area is and the more developed a fracture network is, the higher the gas yield will be [1,2]. But how to describe complicated gas flow in a SRV section during shale gas development is a vexed question because of extremely low porosity and permeability, the higher content of clay and organic matter, and the existence of adsorbed gas (accounting for 20−80%) in shale reservoirs [3,4]. Carlson et al. [5,6] adopted a dual-porosity model in view of shale matrix with low porosity and extremely low permeability. Shale gas flow was described to have two processes: one is that with the production of free gas from fractures, the adsorbed gas after desorption from matrix surface flows through fractures to the wellbore due to the effect of the differential pressure between fractures and matrix.; the other is that the internal gas spreads to the matrix surface due to the effect of differential concentration. Gas flow inside the matrix follows the laws of molecular diffusion and the process from fractures to the wellbore is subject to the Darcy law; the

☆ Project supported by the National Science and Technology Major Project (No. 2011ZX05018) and National Basic Research Program of China (973 Program) (No. 2013CB228000).
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Peer review under responsibility of Sichuan Petroleum Administration.

http://dx.doi.org/10.1016/j.ngib.2017.07.016

process of desorption is described by the Langmuir equation. Javadpour et al. [7,8] developed an equation for nano-scale shale gas flow which involves the Knudsen number (*Kn*) based on diffusion and continuous flow. They found that the ratio of apparent permeability to Darcy permeability increases abruptly with the decreased porosity below 100 nm, implying that diffusional effect is strong at low porosity. Schepers et al. [9] presented a triple-porosity dual-permeability model, in which fluid flow in fractures and matrix follows the Darcy law. The matrix is the source of gas desorption; gas flow overwhelms diffusional effect inside the matrix. Civan et al. [10] developed the equation of gas flow in nano-scale shale pores based on the Beskok gas flow equation and adsorption effect. This equation is the function of *Kn* and applies to continuous flow, transition flow, slip flow and free molecular flow. Swami et al. [11,12] derived the equation of nano-scale shale gas flow based on a quadruple-porosity model which delineates the movement of free gas in micro-fractures and nanopores, adsorbed gas on pore walls, and intra-kerogen dissolved gas. As per the numerical solution, they suggested that *Kn* diffusion, Langmuir desorption, gas slippage and dissolved gas diffusion should be considered in the prediction and numerical simulation of shale gas production. Alharthy et al. [13] developed a dual-porosity and a triple-porosity model which includes convective, diffusive, and Knudsen flow mechanisms. In terms of numerical calculation, they thought that shale gas flow is better modeled by using the triple-porosity model because desorbed gas flow is less dependent on shale pores. Duan et al. [14] built a dual-porosity mathematical model which involves adsorbed gas, free gas and dissolved gas for macroscopic gas flow in the fractured well and estimated transient productivity of shale gas wells. Li et al. [15] considered the effect of gas desorption and diffusion in nanopores and concluded that gas permeability may be improved due to more flowing channels generated by shale matrix contraction and deformation as a result of gas desorption when reservoir pressure is lower than the critical pressure of gas desorption. They established equations for gas flow and diffusion based on the function of two parameters; one is the proportion α of molecular weight with molecular free path above pore diameter (*D*) to total molecular weight, the other is the proportion 1-α of molecular weight with molecular free path below *D* to total molecular weight. Zhao et al. [16] stated that shale gas in the nanopores moves into natural fractures and then flow into hydraulic fractures through desorption, diffusion and slip flow. Gas flow is Darcy flow in natural fractures and is non-Darcy flow in hydraulic fractures. Guo et al. [17] thought shale gas in the matrix mainly flows into the fractures across fracture planes because the influences of high reservoir pressure, small *Kn*, and weak diffusional.

The above models focus on the microscopic flow law in nanotubes or the macroscopic flow law in shale reservoirs; the effects of adsorption, desorption and diffusion on shale gas flow were also included. But an integrated study of microscopic flow and macroscopic flow and the application to productivity evaluation were seldom dealt with in published papers. This paper addresses two issues through theoretical researches and a case study. A geological–physical model was built for the SRV section and then the control equations for gas flow in the matrix and fractures were derived based on the principles of gas diffusion and flow and material balance. The equations include a parameter, interporosity flow coefficient, to mathematically integrate the matrix model and fracture model for complicated gas flow in the SRV section. Finally, a case study was made on the production performance numerically simulated based on the control equations.

1. SRV geological–physical model

Effective shale gas development is closely related to the generation of a complex fracture network by hydraulic fracturing, but it is extremely hard to delineate the fracture network in a SRV section. Conventional approaches, e.g. microseismicity, fracturing fluid volume estimation, and mechanical computation, do not capture the features of the network accurately [18,19]. Here is a model established based on geological and gas flow features in shale matrix and fractures, and it is composed of the matrix split into many small units by fractures (Fig. 1). This model can prove the same gas flow as the actual SRV area.

In such a model, gas flow from the matrix to fractures is in the form of diffusion and gas flow from fractures to the bottom hole is in the form of seepage. Assume matrix porosity is φ_{m}, diffusion coefficient is D, fracture porosity is φ_{f}, and the permeability is K_{f}; matrix porosity and diffusion coefficient can be obtained through lab tests.

The geologic reserves in the matrix and fractures may be estimated by using the above model. For the fracture system, only free gas is involved.

$$G_{\mathrm{f}} = \frac{V\varphi_{\mathrm{f}}}{B_{\mathrm{gi}}} \tag{1}$$

where G_{f} is the gas reserves in fractures, m^3; V is the apparent volume of the SRV section, m^3; B_{gi} is the dimensionless volume factor of in-situ gas.

The matrix system involves free gas and adsorbed gas; the volume of adsorbed gas is calculated with the Langmuir equation.

$$G_{\mathrm{m1}} = \frac{V\varphi_{\mathrm{m}}}{B_{\mathrm{gi}}} \tag{2}$$

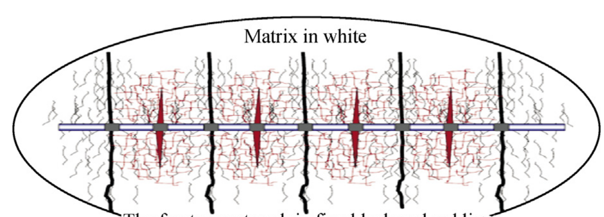

Fig. 1. A SRV model showing fracture distribution after massive hydraulic fracturing.