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Pressure and rate transient analysis of composite shale gas reservoirs considering multiple mechanisms

Hui Zeng, Dongyan Fan*, Jun Yao, Hai Sun

School of Petroleum Engineering, China University of Petroleum, Qingdao, Shandong 266580, China

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A B S T R A C T

Based on multiple mechanisms, including adsorption/desorption, viscous flow, diffusive flow in shale matrix and stress sensitivity of natural fractures, a new semi-analytical composite model is presented for multi-stage fractured horizontal well (MFHW) in shale gas reservoirs. The simplified composite model of an actual gas reservoir is composed of an inner and an outer region. Inner region represents stimulated reservoir volume (SRV) and contains natural fractures and matrix. Matrix-natural fracture transfer flow is assumed to be pseudo-steady state (PSS) or transient state (TS) which are described by the Warren & Root and the De Swan models respectively. Outer region is un-stimulated reservoir volume (USRV), which is described by single porosity medium model. First, transient flow model for continuous line source in composite shale gas reservoir is established. Perturbation method is applied to linearize the model. Then the line source solution is solved by Laplace transformation. Pressure responses of multi-stage fractured horizontal well is obtained using principle of superposition. The model is verified with the available field data from the Barnett Shale. In addition, transient pressure and production rate of MFHW in shale gas reservoirs with consideration of multiple mechanisms and SRV are analyzed and five typical regimes are identified: radial flow in SRV, interporosity flow, region pseudo-steady flow, diffusive flow and late pseudo-radial flow. In PSS transfer model, type curve has two cavities: the early one is caused by pseudo-steady interporosity flow between natural fractures and matrix and the late one is caused by diffusive flow in the matrix. But in TS transfer model, there is no obvious cavity in interporosity flow period due to subtle pressure fluctuation. The effects of relevant parameters on transient pressure and production rate are analyzed, including SRV radius, stress sensitivity coefficient, adsorption index, storability ratio, interporosity coefficient and diffusivity coefficient. The results demonstrate that larger SRV can reduce formation energy depletion and improve production rate. Stress sensitivity causes more pressure depletion, while desorption and diffusion can compensate for the pressure loss in the formation. The production rate increases as adsorption index σ rises. Storability ratio of natural fractures ω_f and interporosity coefficient λ_1 mainly affect interporosity flow period while storability ratio of matrix ω_m and diffusivity coefficient λ_2 mainly have effects on diffusive flow period. The larger the value of these four parameters, the larger the production rate in corresponding periods.

1. Introduction

Shale gas reservoir has received increasing attentions (Wu et al., 2013) over the world in the past decades. Multi-stage fractured horizontal well (MFHW) has been proved to be an effective way to exploit shale gas. The reason is that economic production of shale gas reservoirs requires an interconnected fracture network of moderate conductivity to obtain reasonable recovery factors (Warpinski et al., 2009) and microseismic fracture mapping has shown that large fracture networks can be generated after hydraulic fracturing in many shale reservoirs (Clarkson, 2013; Mayerhofer et al., 2010). The volumetric extent of the reservoir which is interconnected by the fracture network is defined as stimulated reservoir volume (SRV). SRV is considerably beneficial to shale gas production and can improve ultimate recovery and production rate (Wang et al., 2014). However, shale gas exploitation still faces many challenges because pore structures and fluid transport mechanisms in shales are significantly different from

* Corresponding author.
E-mail addresses: zhyanyy2008@126.com (H. Zeng), fandongyan2010@126.com (D. Fan), yaojunhdpu@126.com (J. Yao), sunhaiupc@sina.com (H. Sun).

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conventional reservoirs (Civan, 2010; Freeman et al., 2011). Compared with conventional reservoirs, shale has ultra-low porosity, ultra-low permeability and multi-scale pores. The size of shale matrix pores ranges from nanometers to micrometers and transport mechanisms of shale gas in these pores are notably different. Gas flow in micro pores is regarded as viscous flow while flow in nanopores cannot be described simply by the Darcy equation. Xiao and Wei (1992a,b) investigated diffusion mechanism of hydrocarbons in molecular-zeolites. Javadpour et al. (2007) found the gas flow in nanopores of the shale can be modeled with a diffusive transport regime. In addition, a formulation for gas flow in the nanopores (Javadpour, 2009) based on diffusion and slip flow was presented and compared with Darcy's flow. The results demonstrate that diffusion's contributions to flow increase sharply as pores become smaller and the effect of diffusion must be considered. Furthermore, shale gas is not only stored in the matrix pores and natural fractures but also adsorbed on the surface of solid particles (Hill and Nelson, 2000).

The existence of multiple complex transport mechanisms and SRV characterization make it notably difficult and challenging to study the performance of shale gas reservoirs. Many researchers have investigated the performance of shale gas reservoirs with various modeling methods: Kucuk and Sawyer (1980) first studied the pressure transient behavior of shale gas reservoirs. Their model did not take into account the effects of desorption and diffusion. Guo et al. (2012) established a well testing model considering desorption and diffusive flow in the matrix for MFHW in shale gas reservoirs. Zhao et al. (2013) presented a “tri-porosity” mathematical model, which contains free gas stored in matrix micropores (the first porosity) and natural fractures (the second porosity) and adsorbed gas (the third porosity). Wang (2014) proposed a model with consideration of desorption, diffusive flow and stress-sensitivity of reservoir permeability. Liu et al. (2015) also proposed a model considering adsorption/desorption, viscous flow and stress sensitivity of natural fractures simultaneously. Most of the above mentioned models study pressure transient analysis of fractured horizontal well using dual porosity model without taking SRV into consideration. Some scholars have studied the performance of conventional or unconventional reservoirs with SRV. “Trilinear” model (Ozkan et al., 2011, 2009) was proposed to study MFHW performance. The model presented in this paper is based on the assumption of “linear flow” regime in different regions. Then, the trilinear flow model was extended to the five regions model (Stalgorova and Mattar, 2012a,b) with consideration of a stimulated region of limited width. Both the trilinear and the five regions models ignore some flow regimes like early-radial flow and pseudo-radial flow. A composite reservoir model was presented (Zhao et al., 2014) which simulates the performance of MFHW with SRV in tight gas reservoir. The composite model used a circular inner region to characterize the SRV. Similar to this model, Jiang et al. (2014) studied rate transient analysis in tight oil reservoirs considering SRV. Fan et al. (2015) also proposed a composite model of hydraulic fractured horizontal well with SRV in tight oil & gas reservoir. Xu et al. (2015) analyzed production performance for composite shale gas reservoir considering multiple transport mechanisms including desorption and diffusion. However, only adsorbed gas in matrix is considered while the free gas in the matrix pores is ignored. Most of these models didn't consider the unique flow mechanisms of shale gas reservoirs or the considerations were not comprehensive.

To the best of the authors' knowledge, an analytical model for MFHW in shale gas reservoirs considering more comprehensive transport mechanisms and SRV simultaneously has not been proposed. It is necessary to establish a relevant model considering all the properties, including adsorption/desorption, viscous flow, diffusive flow in the shale matrix as well as SRV. Because naturally fractured, ultra-low permeability reservoirs such as shale gas reservoirs, the stress sensitivity of natural fractures has a significant effect on the performance of MFHW (Archer, 2008; Pedrosa Jr, 1986; Samaniego and Cinco, 1980; Wang, 2014). Therefore, the stress sensitivity of natural fractures has also been considered.

Based on multiple mechanisms, including adsorption/desorption, viscous flow, diffusive flow in the matrix as well as stress sensitivity of natural fractures, a new semi-analytical composite model for MFHW in shale gas reservoirs is proposed. The actual gas reservoir is simplified as a composite reservoir composed of inner region representing SRV and outer region representing un-stimulated reservoir volume (USRV). To solve the model, various mathematical methods were applied: Line source function, Laplace transformation, perturbation and superposition. Flow regimes of MFHW in shale gas reservoir with SRV, and relevant parameters on pressure and production rate were analyzed.

2. Physical model for MFHW in composite shale gas reservoirs

As opposed to conventional gas which is stored as free gas, the majority of shale gas is adsorbed on the surfaces of rock grains. As reported, more than 85% of shale gas is adsorbed on the surfaces of matrix particles while the other 15% is stored as free gas in natural fractures and matrix pore spaces (Hill and Nelson, 2000) (Fig. 1). During the process of production, when the pressure in the formation drops to desorption pressure, the adsorbed gas desorbs from the surface of matrix particles and diffuses into matrix pores (Fig. 1), namely adsorption-desorption process.

To simulate the performance of stimulated reservoir volume in shale gas reservoir, the actual shale reservoir is simplified as a composite model (Fig. 1). The model has two different regions: inner and outer. Inner region represents stimulated reservoir volume (SRV) and contains natural fractures and matrix. Matrix-natural fracture transfer flow is assumed to be pseudo-steady state (PSS) or transient state (TS) which can be described by the Warren & Root and the De Swan models respectively. Outer region is not affected by hydraulic fractures, namely un-stimulated reservoir volume (USRV) and can be described by single porosity medium model.

Other assumptions are presented as follows:

(1) The reservoir is horizontal, homogeneous and isotropic with uniform thickness and impermeable upper and lower boundaries. The outer region is laterally infinite and the inner region radius is r_m. The matrix properties are the same between inner and outer regions. The permeability of natural fractures is stress-dependent. The initial pressure throughout the reservoir is uniform and equal to p_i.
(2) Free gas and adsorbed gas coexist in shale gas reservoirs. Desorption and diffusion is considered. The shape of matrix particles is simplified as spherical. The adsorption/desorption phenomenon follows the Langmuir isotherm equation. Diffusion from the surface of matrix particles to matrix pores is pseudo-steady and obeys Fick's law. Gas flow in matrix pores and fractures follows Darcy's law. The gravitational and frictional effects are neglected.
(3) Shale gas reservoir is produced through a horizontal well with multi-stage transverse hydraulic fractures. All fractures fully penetrate the formation. Horizontal well produces at a constant rate q_{sc} and it only produces from hydraulic fractures, neglecting the fluid flow from the matrix.