Journal of Petroleum Science and Engineering 166 (2018) 104–120

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Performance analysis for a model of a multi-wing hydraulically fractured vertical well in a coalbed methane gas reservoir

Liehui Zhang [a], Zuhao Kou [a,*], Haitao Wang [a], Yulong Zhao [a,**], Morteza Dejam [b], Jingjing Guo [a], Jia Du [c]

[a] State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, Sichuan, 610500, China
[b] Department of Petroleum Engineering, College of Engineering and Applied Science, University of Wyoming, 1000 E. University Avenue, Laramie, WY, 82071-2000, USA
[c] Research Center of China United Coalbed Methane Corporation, Ltd., Beijing, 100011, China

ARTICLE INFO

Keywords:
Coalbed methane
Multi-wing fractured vertical well
Multiple transportation mechanisms
Production performance
Stimulated reservoir volume

ABSTRACT

This paper proposes a composite model to investigate the pressure behavior and production performance of a multi-wing hydraulically fractured multiple fractured vertical well (MFVW) in a coalbed gas reservoir with a stimulated reservoir volume (SRV). The model simultaneously considers adsorption–desorption, diffusion, and viscosity flow. The MFVW model combines line-source method with Laplace transformation and discretization method. Then, the Stehfest numerical inversion and the Gauss elimination are utilized to obtain the transient pressure responses and production dynamics.

The results show that the main flow regimes for an MFVW in a coal seam gas reservoir are linear flow between hydraulic fractures, pseudo radial flow in the SRV, transition flow from the inner to the outer region, and radial flow in the outer region. Further, a slight "hump" is observed during the linear flow period, which could not be observed in the curves of MFVWs with two-wing hydraulic fractures. The effects on MFVW performance of permeability and size of the SRV, properties of hydraulic fractures (fracture angle asymmetry, different fracture angle, and fracture number), Langmuir volume, and Knudsen diffusion coefficient are discussed. The conclusions obtained in this paper will be helpful to understand the transient performance of MFVWs in coalbed gas reservoirs.

1. Introduction

In recent years, coal seam gas has played an important role in natural gas production. Hydraulic fracturing technology has been extensively used to improve the production of unconventional low permeability gas reservoirs where the gas is widely distributed in micro- and nano-pores in the matrix.

Various models have been developed to analyze the performance of fractured wells in conventional and unconventional reservoirs (Prats et al., 1961; Gringarten et al., 1975; Tiab, 2005; Zhao et al., 2013, 2014, 2016a, 2018; Yuan et al., 2015; Moghanloo et al., 2015; Zhang et al., 2016a, 2016b; Yuan et al., 2017; Li et al., 2017; Singh and Cai, 2018). For example, Gringarten et al. (1975) analyzed the transient pressure behavior of both vertical and horizontal wells with two-wing hydraulic fractures. King et al. (1986) developed a model that used the finite difference method to simulate the flows of gas and water through micropores in coal seam gas reservoirs. Ertekin and Sung (1989) proposed a model for coal seam gas reservoirs that considered multi-mechanism flow and adsorption–desorption phenomena. Anbarci and Ertekin (1990, 1992) proposed a model for vertical wells under steady and pseudo-steady flow regimes that considered different conditions for inner and outer boundaries in coal seam gas reservoirs. Engler and Rajtar (1992) determined horizontal well bottom-hole pressure responses in a semi-infinite coal reservoir by using Laplace and Fourier transformation methods. Guo et al. (2003) considered wellbore storage and skin factor effects to study the numerical modeling of coal seam gas reservoirs. Clarkson et al. (2009) did transient pressure and production data analyses of wells with finite-conductivity hydraulic fractures in coalbed gas reservoirs. Nie et al. (2012) proposed a model to investigate the transient production performance of a horizontal well in a coalbed gas reservoir. Their model considered pseudo steady-state diffusion in the matrix and Darcy flow in the fracture networks. Zhang et al. (2015)

* Corresponding author.
** Corresponding author.
E-mail addresses: kouzuhao@hotmail.com (Z. Kou), swpuzhao@swpu.edu.cn (Y. Zhao).

https://doi.org/10.1016/j.petrol.2018.03.038
Received 29 November 2017; Received in revised form 5 March 2018; Accepted 7 March 2018
Available online 8 March 2018

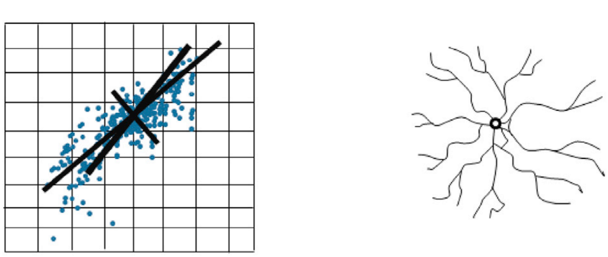
presented a semi-analytical solution to make the rate decline analyses of a multi-stage fractured horizontal well in shale gas reservoir with consideration of stimulated reservoir volume. Zhao et al. (2016b) proposed a new analytical model for coal seam gas reservoirs that uses source function method. To obtain the transient pressure responses, they categorized the complex fracture networks in the stimulated reservoir volume of gas reservoirs, which were similar to the works done by Wang et al. (2017) and Cai et al. (2017). Zhang et al. (2016b) analyzed the production performance of a multi-stage fractured horizontal well in a composite shale gas reservoir by utilizing finite element method.

Hydraulic fracturing is an effective technique for increasing the yield from unconventional reservoirs, especially coal seam gas reservoirs. Because of the different ground stresses, wells were always intersected by multiple hydraulic fractures generated along the wellbore after hydraulic fracturing (Germanovich, 1997; Sierra et al., 2008; Molenaar et al., 2012), and the fractures could be observed by microseismic imaging technology. See Fig. 1.

Different numerical and analytical models have been developed to study the performance of fractured vertical wells with multiple hydraulic fractures. First, Choo and Wu (1987) proposed time-consuming numerical models to investigate the transient pressure responses of wells with multiple hydraulic fractures. Later, Resurreicao and Fernando (1991) proposed a new semi-analytical model for asymmetrically fractured wells to study the production rate in an infinite reservoir. Berumen et al. (2000) developed a numerical model that used finite/infinite conductivity under a constant production rate to investigate the pressure responses of vertical wells with intersecting asymmetric fractures. Tiab (2005) modeled fractured wells to evaluate fracture asymmetry with finite conductivity under constant-production-rate conditions using Tiab's Direct Synthesis Technique. Craig and Blasingame (2006) and Luo and Tang (2014) proposed a model of a multiple fractured vertical well (MFVW) that considered the influence of the hydraulic fractures with finite or infinite conductivity to analyze the pressure responses in oil reservoirs. Recently, Chen et al. (2017) developed some models for hydraulically fractured wells in unconventional reservoirs with complex natural and hydraulic fractures. Tian et al. (2017) proposed a model that considered two-wing asymmetric hydraulic fractures with finite conductivity to analyze the transient pressures in conventional oil reservoirs. However, the influence of the stimulated reservoir volume (SRV), which had a positive effect on the production of coalbed methane (CBM) after hydraulic fracturing, was not considered in the above-noted models.

Because most CBM is usually absorbed on the surface of particles in coal seam matrix, most CBM is different from conventional natural gas, and CBM flow is believed to be affected by multiple flowing mechanisms, including gas desorption from particle surface, gas diffusion, Darcy's flow in matrix system, and Darcy's flow in natural fractures system. Fig. 2 shows the simplified general view of three CBM flow mechanisms.

Due to the improvement of fracturing technology and equipment, massive hydraulic fracturing (MHF), which can effectively connect original discrete micro fractures, has been widely used in the development of unconventional gas reservoirs. Depending on the rock



(a) (b)

Fig. 1. Multi-wing fractures near a vertical wellbore. (a) Craig and Blasingame (2006). (b) Germanovich (1997).

mechanical properties and the natural fracture network of the coal seams, MHF generates a unique complex fracture network around the wellbore in coalbed gas reservoirs that is called the stimulated reservoir volume (SRV). The SRV is defined as a region around the wellbore, in which both a natural fracture network and multi-wing hydraulic fractures exist. To identify the stimulated and un-stimulated sections in coalbed gas reservoirs and investigating transient pressure responses, it is useful to divide the reservoir into a dual-porosity, two-region system (inside the SRV and outside the SRV). There are more favorable properties, such as greater permeability and porosity, in the inner region than in the outer region. Moreover, due to complicated geological conditions (such as different ground in situ stresses), multiple hydraulic fractures can be generated with different lengths and angles with respect to the vertical wellbore. See Fig. 3.

The purpose of the current work is to study the characteristics of flow in multi-wing fractured vertical wells in coalbed gas reservoirs using a dual-porosity model that considers multiple transport mechanisms. Model verifications are executed by comparing our works with the models of literature, and the effects of some key parameters on transient performance are also analyzed.

2. Mathematical model for a multi-wing fractured vertical well in a coal seam gas reservoir

2.1. Model assumptions

We consider here a multi-wing fractured vertical well with an SRV in a coal seam gas reservoir, as shown in Fig. 3. After hydraulic fracturing, several fractures with different lengths and angles are formed, and an SRV is generated near the vertical well. Because of the very large differences between properties in the inner and outer regions, a coal seam gas reservoir with an SRV can be considered a bi-zonal composite gas reservoir.

For the sake of simplicity, the following assumptions are made throughout the mathematical modeling:

(1) The reservoir consists of two regions in a radial coordinate system (inside the SRV and outside the SRV), which can both be described using a dual-porosity approach. The dual-porosity system considers natural fractures and micro- or nano-pores in matrix.
(2) Gas molecules are in free and adsorptive forms within the matrix. The gas flow in the matrix can be divided into two parts: viscosity flow and diffusion. The gas flow in natural fracture networks follows Darcy's law.
(3) The total production rate of the multi-wing fractured vertical well is the constant q_{sc}. The production from each hydraulic fracture is a function of its radial coordinate and time.
(4) Due to non-uniform ground stresses, primary hydraulic fractures may not be symmetric with respect to the wellbore, meaning the hydraulic fractures could have different lengths and angles.
(5) The gas flow in the reservoir is isothermal and single-phase.
(6) The top and bottom boundaries of the reservoir are impermeable.
(7) Capillary pressure and gravity are insignificant.
(8) The outer boundary of the reservoir is infinite.

2.2. The continuous line-source function in a composite reservoir

Guo et al. (2016) proposed the governing equations describing gas flow in the matrix, which can be used to model multi-stage fractured horizontal wells in shale gas reservoirs. Based on previous works, they introduced a line-source function that considered transient and pseudo steady-state inter-porosity mass transfer for infinite and impermeable outer boundaries (Zhao et al., 2015). Because the goal of our study is to develop the model for the multi-wing hydraulically fractured vertical well in the coalbed gas reservoir with an infinite outer boundary, Eq. (1), an improved continuous line-source solution for composite reservoirs, is