Journal of Natural Gas Science and Engineering 35 (2016) 425–443

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Transient pressure and production dynamics of multi-stage fractured horizontal wells in shale gas reservoirs with stimulated reservoir volume

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ARTICLE INFO

Article history:
Received 30 May 2016
Received in revised form
15 August 2016
Accepted 30 August 2016
Available online 31 August 2016

Keywords:
Multi-stage fracturing
Shale gas reservoir
Stimulated reservoir volume (SRV)
Primary hydraulic fracture conductivity
Non-uniform fracture length distribution
Transient pressure and production performance

ABSTRACT

Multi-stage fracturing in unconventional shale gas reservoirs always creates complex fracture network around horizontal wellbore. The existence of the stimulated reservoir volume (SRV) has significant impact on performance of fractured horizontal well, and various composite models are introduced to simulate gas flow caused by fractured horizontal wells with SRV. However, most of the existing models do not simultaneously taken into account fracture conductivity, non-uniform properties of hydraulic fractures, SRV region, multiple flowing mechanisms of shale gas.

This paper extends previous work by presenting a more comprehensive model to simulate the performance of multi-stage fractured horizontal well in shale gas reservoirs. The model takes into account not only the existence of SRV, but also the influence of fracture conductivity, multiple flowing mechanisms (desorption, transient state and pseudo-steady state viscous flow and diffusion) in shale matrix as well as the effect of non-uniform fracture distribution. By employing the source function theory, Laplace transformation and discretization method, a relatively simple semi-analytical solution is obtained. After the verification of the presented model with other published results, the transient pressure and production dynamics are compared and analyzed. The influences of relevant parameters on performance of fractured horizontal wells are also discussed. It is found that the performance of fractured horizontal wells in shale gas reservoirs is mainly affected by the parameters related to SRV (the size of SRV, the density of fractures in SRV, the configuration of primary fractures in SRV), conductivity and distribution of hydraulic fractures, and desorption and diffusion in shale matrix. The model presented in this paper can be easily simplified to simulate simpler cases, such as performance of fractured horizontal wells in tight reservoirs. The model and corresponding conclusions presented in this study will be helpful to understand transient performance of multi-stage fractured horizontal wells in shale gas reservoirs and thus to effectively develop unconventional shale gas reservoirs.

1. Introduction

Development of unconventional gas reservoirs, such as shale gas reservoirs and tight gas reservoirs, has attracted extensive attention in petroleum industry. Due to the low or ultra-low permeability of this type of gas reservoirs, the original formation needs massive hydraulic fracturing to get commercial production rate. Horizontal drilling coupled with multi-stage hydraulic fracturing has now been adopted by the industry as a common way to produce unconventional shale gas, for it can not only create primary hydraulic fractures around wellbore, but can also induce a complex fracture network (including induced micro fractures and reconnection of natural fractures) in the region around horizontal wellbore, which is the so-called stimulated reservoir volume (SRV). The existence of SRV significantly improves the permeability in the region around wellbore and thus can increase the production rate.

Various models and approaches have been proposed in literature to describe the SRV created by multi-stage fracturing and to simulate performance of fractured horizontal well with SRV in unconventional gas reservoirs. Based on linear flow and limited drainage volume assumption, Ozkan et al. (2011) introduced a trilinear-flow model to simulated the production behavior of fractured horizontal wells in shales. The trilinear-flow model couples

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http://dx.doi.org/10.1016/j.jngse.2016.08.074
1875-5100/

linear flow in hydraulic fractures, linear flow between hydraulic fractures and linear flow beyond hydraulic fracture tips. After that, many researchers have done extensive work to improve the trilinear-flow model to investigate transient pressure or production dynamics of multiple-fractured horizontal wells in unconventional gas reservoirs. The improvement of the trilinear-flow model is done either by incorporating multiple flowing mechanisms in shale matrix (Ozkan et al., 2010; Brown et al., 2011; Apaydin et al., 2012; Guo et al., 2015a) or by dividing the region around the horizontal wellbore into more linear-flow regions (Stalgorova and Mattar, 2012a, 2012b; Yuan et al., 2015; Deng et al., 2015).

The “linear-flow type models” are simple and convenient in model derivation and solution, but all hydraulic fractures in these models must have identical properties such as conductivity, width, length and spacing between adjacent fractures. In addition, one major problem of these “linear-flow type models” is that they cannot simulate the interferences between neighboring hydraulic fractures and thus the production rate of each hydraulic fracture is assumed to be identical in these models. However, in actual production of fractured horizontal wells, the rate contributions of different hydraulic fractures are different due to different locations and properties of hydraulic fractures.

To effectively simulate the interference between multiple hydraulic fractures and capture complete flowing characteristics of fractured horizontal wells in unconventional gas reservoirs, some researchers (Al-Kobaisi et al., 2006; Yao et al., 2013; Wang, 2014; Guo et al., 2015b) presented various semi-analytical models by adopting the source function approach introduced by Gringarten and Ramey (1973) and Ozkan and Raghavan (1991) into petroleum industry. In most of these semi-analytical models, dual-porosity idealization is adopted to consider the effect of natural fractures or the influence of fracture network induced by hydraulic fracturing in shale formations, but the property differences between SRV region and un-stimulated region in shale gas reservoirs are not clearly addressed.

Zhao et al. (2014) extended the above mentioned semi-analytical approach to composite reservoir systems and investigated production performance of fractured horizontal well with SRV in unconventional gas reservoirs. But only Darcy flow is considered in their model, other flow mechanisms of shale gas such as desorption and diffusion (Javadpour, 2009) are not incorporated. In addition, their model cannot simulate the effect of fracture conductivity. Zeng et al. (2015) and Zhang et al. (2015) utilized the composite model to analyze transient pressure behavior and rate decline performance of fractured horizontal wells in shale gas reservoirs, respectively. Their models incorporate gas desorption and Fick diffusion in shale matrix, but the conductivity of hydraulic fractures, viscous flow in macropores in shale matrix and non-uniform hydraulic fracture properties are not taken into consideration. Fan et al. (2015) presented a numerical composite model with finite element method to study performance of fractured horizontal wells in rectangular shaped tight reservoirs, in which only Darcy flow is considered and the un-stimulated reservoir region is represented by single-porosity model. Xu et al. (2015) proposed a dual-region dual-porosity composite model to calculate production behavior of fractured horizontal wells in shale gas reservoirs in infinitely large shale gas reservoirs. In their model, hydraulic fracture conductivity and transient diffusion and gas desorption in shale matrix are considered, but viscous flow in macropores in shale matrix and the effect of non-uniform properties of hydraulic fractures are not incorporated. In addition, their study mainly focuses on the rate decline dynamics analysis of fractured horizontal wells in infinitely large shale gas reservoir, characteristics of transient pressure behaviors of fractured horizontal wells producing at constant production rate are not addressed, and the effect of limited drainage volume is not taken into account neither.

The objective of this paper is to present a more comprehensive model to investigate and evaluate both the transient pressure and production performance of multi-stage fractured horizontal well in shale gas reservoirs. The model presented in this paper extends previous work by simultaneous consideration of the existence of SRV, primary hydraulic fracture conductivity, pressure drop in hydraulic fractures, multiple flowing mechanisms (viscous flow, diffusion and desorption) in shale matrix as well as limited drainage volume. Both transient and pseudo-steady state flow in shale matrix are considered. In addition, this paper discusses the influence of relevant parameters on the performance of fractured horizontal wells in shale gas reservoirs, including hydraulic fracture properties, hydraulic fracture distribution along the horizontal wellbore, properties of SRV, multiple flowing mechanisms of shale gas. Corresponding solutions can be useful in fracturing design in field practice.

2. Physical model of MFHWs with SRV

As sketched in Fig. 1, a multi-fractured horizontal well with stimulated reservoir volume (SRV) in an unconventional gas reservoir is considered here. During multi-stage hydraulic fracturing, not only the primary hydraulic fractures but also a stimulated reservoir volume (SRV) will be generated around the horizontal wellbore. The density of micro-fractures in the SRV is larger than that in the un-stimulated region, causing differences in permeability, porosity between different regions in the reservoir. Thus the whole shale gas reservoir with SRV can be conceptualized as a bi-zonal composite system (i.e., Region 1 and Region 2 in Fig. 1).

For the clarity of the derivation of the mathematical model for multi-fractured horizontal wells (MFHWs) with SRV, relevant assumptions are listed as follows:

1) Region 1 represents the inner SRV region close to the horizontal wellbore, while region 2 denotes the outer un-stimulated region. Considering the complex fracture network in SRV region and the existence of natural fractures in original formations, dual porosity idealization is adopted to represent both region 1 and region 2. The radius of the SRV region is represented by r_1, while the outer region can either be infinitely large or be an impermeable boundary with a radius of r_e.
2) The total number of primary hydraulic fractures generated during multi-stage fracturing treatment is represented by m. All the primary hydraulic fractures are assumed to be fully

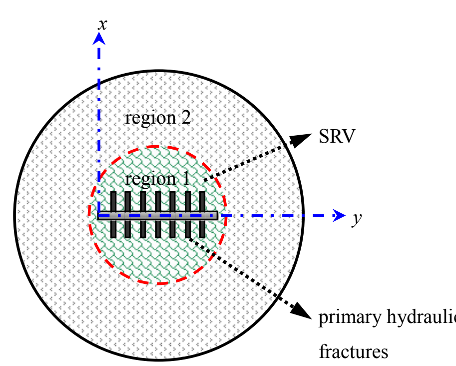

Fig. 1. Schematic of a multi-stage fractured horizontal well in an unconventional gas reservoir with SRV (Modified after Zhang et al., 2015).