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Sensitivity analysis of geometry for multi-stage fractured horizontal wells with consideration of finite-conductivity fractures in shale gas reservoirs

Mingjin Liu [b], Cong Xiao [a, *], Yancheng Wang [b], Zhun Li [c], Yayun Zhang [a], Sheng Chen [a], Guangdong Wang [d]

[a] College of Petroleum Engineering, China University of Petroleum, Beijing 102249, China
[b] Southwest Petroleum University, Chengdu 610500, China
[c] School of Petroleum Engineering, China University of Petroleum, Beijing 102249, China
[d] School of Petroleum Engineering, Northeast Petroleum University, Heilongjiang 163318, China

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ABSTRACT

A new analytical solution of pressure and rate transient analysis is proposed for MFHW with finite-conductivity transverse hydraulic fractures in shale gas reservoirs. Meanwhile, desorption, adsorption, viscous flow, stress sensitivity of natural fractures, skin damage and wellbore storage are simultaneously considered as well in this paper. Laplace transformation, line source function, perturbation method, and superposition principle are employed to solve this new model. The pressure and rate transient responses are inverted into real time space with stehfest numerical inversion algorithm. Based on this new solution, the transient pressure distribution of MFHW with multiple finite-conductivity transverse hydraulic fractures was obtained, type curves are plotted, and different flow regimes in shale gas reservoirs are identified, the effects of relevant parameters are analyzed as well. The innovation and essence of this paper is combining transient gas flow in finite-conductivity hydraulic fractures, the geometry of hydraulic fractures and dual-porosity character of shale gas reservoirs. Compared with some existing models for shale gas reservoirs, this new model is more comprehensive and can provide a relative practical analysis of the relevant parameters. Besides, the conclusions involving in the geometry of hydraulic fractures can greatly match with the previous conclusions from numerical simulation and are more persuasive than that. To sum up, this new model provides some relative real evaluation results for multi-stage fracturing horizontal well technology in shale gas reservoirs.

1. Introduction

Compared with conventional reservoirs, shale gas reservoir has its unique features, such as ultra-low permeability, ultra-low porosity, multi-scale pores, and these characters induce special flow regimes in shale gas reservoirs. According to some scholars (Xiao and Wei, 1990; Javadpour et al., 2007, 2009), flow in matrix pores which generally reaches to nona-scale for shale gas does meet diffusion principle instead of Darcy's law. At present, some scholars have conducted large amount of researches about transient pressure and rate analysis for shale gas, some analytical and semi-analytical solutions are developed as well. Shale gas reservoir is the classical naturally fractured reservoir which contains complex natural fractures and ultra-low permeability. In terms of those kinds of reservoirs, Barenblatt et al. (1960) and Warren and Root (1963) originally proposed the dual-porosity model, and then Kazemi (1969), De Swaan (1976) and Ozkan et al. (2011) developed some other dual-porosity models for shale gas reservoirs to enrich the former productivity models. However, all of these dual-porosity models did not consider the phenomenon of desorption and adsorption in shale gas reservoirs.

Multi-fractured horizontal well (MFHW) currently has been proved to be the most effective way to produce shale gas, and this method can not only create several high-conductivity hydraulic

* Corresponding author.
E-mail address: 987558984@qq.com (C. Xiao).

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fractures, but also activate and connect existing natural fractures so as to form large spacious network system (Warpinski et al., 2009). Similarly, some analytical and semi-analytical models were proposed successively with the consideration the impacts of multiple high conductivity hydraulic fractures. These models can be divided into two categories according to the conductivity of hydraulic fractures: (1) Infinite-conductivity hydraulic fractures. These models assume that there is no pressure drop along the hydraulic fractures and the pressure is equal to bottomhole pressure. In another words, the hydraulic fractures can be regarded as the parts of the wellbore. Zhao et al. (2012, 2013), Wang (2013) and so on have derived its semi-analytical solution in Laplace domain using Laplace transformation, and desorption are also considered in these models. The point source function or line source function, coupled with superposition principle, is applied to solve the governing equations so that the interference among hydraulic fractures can be analyzed. (2) Finite-conductivity hydraulic fractures. Similarly, these models assume that there is continuous pressure drop along the hydraulic fractures from the tip of hydraulic fractures to the wellbore, and the pressure distribution is distinct throughout the whole hydraulic fracture. El-Banbi (1998), Al-Ahmadi and Wattenbarger (2011), Xu Bingxiang et al. (2013), Yu et al. (2014) and Stalgorova and Mattar (2012) simplified the shale gas reservoirs as linear fractured reservoirs, they assumed that the reservoir fluid continually depletes from one media to another (from matrix to natural fractures, and then from natural fractures to hydraulic fractures). Therefore, the governing equations of every media can be derived, however, the interference among hydraulic fractures is ignored. And then, although some scholars, including Larsen and Hegre (1994), Guo and Evans (1993), Horne and Temeng (1995) and Chen and Raghavan (1996), presented some transient numerical solutions in Laplace domain for the fractured horizontal well with multiple finite-conductivity by using sink-source integral, besides, some other scholars, including Al-Kobaisi and Ozkan (2004) and Valkó and Amini (2007), coped with this issue using numerical difference method. However, the process of solution is extremely complex and is short of possibility of practical application. Riley et al. (1991) and Xiaodong et al. (2014) considered the influence of conductivity with introduction of conductivity influence function, this kind of method simultaneously can extremely reduce the complexity of calculation and obtain accurate results. However, this model is suitable for conventional homogeneous reservoirs, desorption and adsorption are not considered as well. As we all known, the conductivity of hydraulic fractures indicates the effects of stimulated treatment, therefore, it is urgent to establish a relative simple solution with consideration of conductivity to evaluate the stimulated treatment, an analytical solution may be the best choice, which is also an essence of this paper and will be solved accordingly.

As is known to all, the geometry of hydraulic fractures can be variable due to the distinctive formation situation and operation condition (Kalantari-Dahaghi, 2011). The optimization of hydraulic fracture parameters, such as fracture spacing, fracture length, fracture angle, is important (Kaiser, 2012). It is not hard to find that the current analysis of geometry of hydraulic fractures mainly focus on numerical simulation using some commercial software (Yu et al., 2014), such as CMG (Computer Model Group), Eclipse and so on. It is the common sense that the commercial software is an unknown “black box”, which is often out of our control and is very complicated to conduct the history matching, what's worse, the results of history matching usually seriously deviate from the real situation. Therefore, it is vital to conduct some analysis of geometry of hydraulic fractures with mathematical methods, which can reveal the basic micro-mechanisms. And this is another essence of this paper.

In view of this, a relative simple analytical transient analysis model of multi-stage fracturing horizontal well for shale gas reservoirs with finite-conductivity hydraulic fractures has not existed currently. Therefore, it is necessary to establish a relevant model associated with some special properties, such as dual-porosity media, desorption, adsorption and so on. Besides, in terms of natural fractured reservoirs, the stress sensitivity of natural fractures has certain influence on well performance (Samaniego and Cinco-Leg, 1980; Pedrosa and Petrobras, 1986; Archer, 2008; Wang, 2013), especially for those kinds of ultra-low permeability, therefore, the stress sensitivity is also considered in this paper.

In short, this paper firstly establishes a new simple analytical model with comprehensive consideration of multiple mechanisms, such as adsorption, desorption, viscous flow, fracture conductivity, stress sensitivity, skin factor and wellbore storage. Laplace transformation, perturbation technology, dispersion method are employed to solve this new model. The pressure and rate transient response is inverted into real time space with stehfest numerical inversion algorithm (Stehfest, 1970). Type curves are plotted, and different flow regimes in shale gas reservoirs are identified. The effects of relevant parameters are analyzed as well, especially for the conductivity of hydraulic fractures. Finally, based on this new mathematical model, the geometry of hydraulic fractures, including fracture distribution, fracture spacing and fracture half-length, is analyzed compared with the previous conclusion form numerical simulation. These results can provide guidance for the optimization development of shale gas reservoirs.

2. Physical model for multi-fractured horizontal wells in shale gas reservoir

The schematic illustration in Fig. 1 depict a multi-fractured horizontal wells located in an infinite shale reservoir. The horizontal well is intercepted by some finite-conductivity hydraulic fractures. The number of hydraulic fractures is M, the length and width of the ith ($i = 1, 2, 3,\ldots,M$) fracture respectively is equal to L_{Fi} and w_{Fi}. The other assumptions are as follows:

- The initial pressure distributed in the reservoir is uniform which equals to P_i;
- Shale gas reservoir is dual-porosity system, containing natural fractures and matrix;
- Gas flow in natural fracture meets Darcy's law. The shape of matrix is simplified as sphere and gas flow in matrix is assumed to be viscous flow with consideration of desorption from the surface of matrix particle;
- The ith-hydraulic fracture is intersected to the horizontal well with certain angle θ_i and it is also assumed to be penetrated fully, and the permeability of natural fractures is stress-dependent.
- That only reservoir fluid flows from hydraulic fractures into horizontal wellbore is considered; the horizontal well produces at a constant rate, and the flow rate of each hydraulic fracture is different and is a function of time;
- The impacts of gravity and capillary are neglected.
- Shale gas desorption and adsorption respectively meets the Langmuir isotherm equation;
- Wellbore storage and skin factor are considered.

The pseudo-function was used to account for the pressure dependent gas properties, the formulas of pseudo-pressure and pseudo-time are as follows (Xu et al., 2013):