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Pressure response and production performance for multi-fractured horizontal wells with complex seepage mechanism in box-shaped shale gas reservoir

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ABSTRACT

The development of shale gas reservoir has becoming tremendously thrived around the world in recent years. The horizontal well drilling, advanced completion and massive hydraulic fracturing are the key technologies. How to accurately evaluate the production performance of the wells in these reservoirs, especially for multi-fractured horizontal wells, has always been the hot topic for the engineers and relevant researchers. In this paper, we presented a mathematical model to describe a horizontal well with multiple fractures in rectangular outer-boundary reservoir, which uses the Knudsen diffusion to describe the gas flow in nano-pores and also takes the slippage effect into account. By the method of point source function, Laplace transform and numerical discrete fracture methods, a semi-analytical solution of the model is obtained. Thereafter, the well test type curves and the production performance curves are plotted through Gauss elimination and Stehfest numerical inversion methods. Finally, the effects of related influential factors on well performance are also analyzed. It can be concluded that the Knudsen diffusion coefficient and slippage factor mainly affect the interporosity flow period when well producing with constant rate. When well producing with constant bottom hole pressure, the bigger the values of Knudsen diffusion coefficient and slippage factor are, the larger production rate will be. The research results summarized in this paper have significant theoretical meanings for the development, well test interpretations and production performance analysis of such unconventional gas reservoirs.

1. Introduction

It becomes possible for horizontal wells by widely applying massive hydraulic fracturing techniques to make the economic development of unconventional gas reservoir. Reliable evaluation of formation and fracture parameters are the key points for design and management of such wells. It's common to use transient well testing to determine these unknowns. As well recognized, the fluid flow mechanism in shale gas reservoir is much more complex and pressure response analysis of fractured horizontal well in such gas reservoir is much more difficult than that in conventional reservoirs, due to the unique storage mechanism and multi-scaled pores media.

Since the exploitation of shale gas in North American got a great success, lots of countries and people start to pay attention to the fluid flow in this unconventional reservoir. Furthermore, the transient pressure analysis of multi-fractured horizontal well in this reservoir is also conducted by many researchers, and lots of physical and mathematical models related on the shale gas reservoirs are established to obtain the corresponding semi-analytical solutions by various methods. The physical models with circle or infinite out boundaries are widely reported in the previous literature by source functions and integral transform methods (Raghavan et al., 1997; Wan and Aziz, 1999; Crosby et al., 2002; Mayerhofer et al., 2006; Wang and Liu, 2011; Zhao et al., 2013, 2015). Recently, in order to overcome the limitations of complicated solving process, the linear flow models with various configurations are established, and pressure and production performance of multi-fractured horizontal well are also analyzed (Al-Ahmadi

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et al., 2010; Freeman, 2010; Ozkan et al., 2011; Nobakht et al., 2012; Nobakht and Clarkson, 2012; Stalgorova and Mattar, 2012; Xu et al., 2013).

According to the well partner in field or isobar distribution simulated with numerical simulation software, it can be clearly observed that the rectangular outer-boundary model is much closer to the real situation. If we still apply the circle or infinite out boundaries model to simulate the pressure response of such wells, the results will cause significant deviation from the actual ones. Although, the linear models can be easily used to analyze the pressure characteristic of fractured wells in rectangular outer-boundary reservoir, these models always make the assumptions that the hydraulic fractures are two wing equal space and symmetrical distribution along the horizontal well, which are very difficult to achieve these requirements in real (Chau, 2007; Freeman, 2010; Ozkan et al., 2011; Nobakht et al., 2012; Nobakht and Clarkson, 2012; Stalgorova and Mattar, 2012; Xu et al., 2013). Another flaw of the linear models is that it cannot observe and analyze the interface between the fractures, which is important to the fracturing design. Therefore, for the shale gas reservoir, the multi-fractured horizontal well with rectangular outer-boundary is much more reliable than the conventional models, and also the specific seepage mechanism of shale gas should be taken into account (Wang et al., 2014).

In view of the deficiency in the predecessor's research, this paper presented a dual-mechanism and dual-porosity model to describe a horizontal well with multiple fractures in rectangular outer-boundary shale gas reservoir. In the model, the Langmuir's equilibrium sorption equation (Zhao et al., 2013) and the Knudsen diffusion (Javadpour, 2009) were employed to describe the gas ad-/de-sorption characteristics and flow in nanopores separately, and the slippage effect was also taken into account (Klinkenberg, 1941). This work presented the first time that Knudsen diffusion and slippage effect were both incorporated into the transient flow model of fractured horizontal well in rectangular outer-boundary shale reservoir.

2. Transport mechanism of gas in shales

Due to the reservoir physical property, pores type and accumulation mechanism have a significant difference from conventional low-permeability gas reservoir, the pores structure and gas storage mechanism in shale gas reservoir have its uniqueness. For conventional sandstone reservoirs, its pore sizes are always in the range of 1–100 μm while shale reservoirs have pore throat radial in the range of 1–200 nm. For the sandstone reservoir, the macropores are the main storage space, and the development of natural fractures is poor. Therefore, people always neglect the contribution of fractures system to the fluid flow, and just treat the model as a single porosity model (Freeman et al., 2009). For the carbonate reservoir, however, the situation is opposite, which is always rich in natural fractures, sometimes with the development of caves, thus, researchers always apply dual-porosity or tri-porosity flow models to describe it (Zhao et al., 2013, 2014). Gas flow in these reservoirs can be described by the classical Darcy's law. As it for shale gas reservoir, although the development of natural fractures is not too rich, its contribution to the fluid flow is significant. Moreover the gas flow in the nano-pores cannot be represented by Darcy equation, which must be modified based on specific flow mechanism.

Apart from the above dissimilarities, one major difference between shale gas reservoir and conventional reservoir is that most of gas does not store in the pores and fractured (as free gas) but adsorbed on the solid material surface (either organic material or minerals). According to Hill and Nelson (2000), the adsorbed gas takes up more than 85% of the total gas. So we must take into account the effect of adsorption gas and its diffusion impact on the well pressure response and production performance. Fig. 1 illustrates the sequence of gas production at different length scales.

When the gas mean free path is smaller than the pore diameter, the motion of gas molecules is determined by their collision with each other, and gas molecules collide with the wall less frequently. During this period, the gas flow under the pressure gradient can be described by the Darcy law, the massive flux (J_V) can be expressed as:

$$J_v = -\frac{pM_g}{ZRT}\frac{k}{\mu_g}\nabla p \tag{1}$$

When the diameter of the pore is small enough, the gas mean free path will be very close to it. If that happens, the gas molecular collision between each other will be dominated. Then, the gas will be flow under the concentration gradient, which can be described by the Knudsen diffusion formula. So, the mass flux can be expressed as

$$J_K = -M_g D_k \cdot \nabla C \tag{2}$$

In above equation, the definition of Knudsen diffusion coefficient D_k is reported in many papers and some empirical formulas are shown in Table 1.

According to the gas state equation, the gas mole concentration can be expressed by the following equation, which is

$$C = \frac{\rho_g}{M_g} = \frac{p}{ZRT} \tag{3}$$

Substituting Eq. (3) into Eq. (2) gives

$$J_K = -\frac{M_g D_k}{RT}\nabla\frac{p}{Z} \tag{4}$$

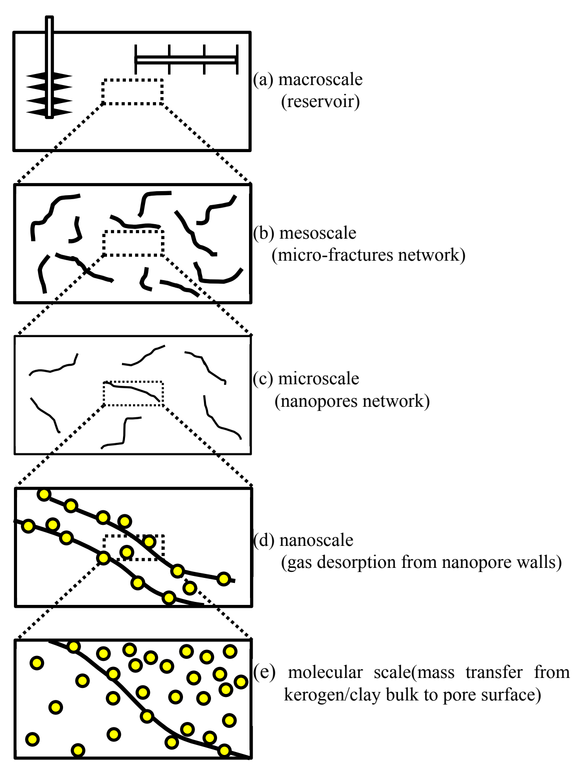

Fig. 1. Schematic of gas flow mechanisms in shale sediments at different length scales (Javadpour et al., 2007).