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Horizontal well transient rate decline analysis in low permeability gas reservoirs employing an orthogonal transformation method

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A B S T R A C T

Transient rate decline analysis (TRDA) is an important analysis in modern reservoir engineering and applications. Most studies have focused on the threshold pressure gradient (TPG) of low permeability reservoirs and have placed an emphasis on the transient pressure response or steady productivity, whereas transient production decline has not been a focus. This paper presents a transient production decline analysis model of a horizontal well in low permeability gas reservoirs considering the threshold pressure gradient. An accurate solution is determined by employing the Laplace transformation, Sturm-Liouville eigenvalue method, and orthogonal transformation. The bi-logarithmic type curves of dimensionless production and the derivative are plotted by the Stehfest numerical inversion method. Five different flow regimes were recognized, and the effects of the influencing factors, such as the threshold pressure gradient, wellbore storage coefficient, skin factor, horizontal section length, and formation thickness, are discussed. This research contributes to the understanding of transient flow behavior and provides the theoretical basis for efficiently exploiting low permeability reservoirs.

1. Introduction

As a hot research topic in modern reservoir engineering and applications, transient rate decline analysis (TRDA) has become the focus of study in recent years. TRDA can quantitatively calculate the physical parameters of gas wells and reservoirs and can also be used to monitor reservoir dynamics (Aminian and Ameri, 1989). Horizontal wells are suitable for the development of low permeability reservoirs. TRDA of horizontal wells in low permeability gas reservoirs has both theoretical and practical significance to understand fluid transport behavior characteristics and correctly guide reservoir production.

Numerous studies on the production rate transient analysis of horizontal wells have been performed. Ehlig-Economides and Ramey Jr. (1981) studied the transient rate response of a well that produced at a constant pressure according to three outer boundary conditions and several values of the wellbore skin factor by using the numerical Laplace transformation inversion algorithm. Fraim and Wattenbarger (1987) introduced the concept of normalized time for a gas reservoir producing against a constant wellbore pressure during (external) boundary-dominated flow. Therefore, type curve matching can be applicable to a reservoir with any shape. Aminian and Ameri (1989) discussed the application of the production type curves and issues concerning the production performance of horizontal wells in low permeability gas reservoirs. They obtained consistent results between the pre-stimulation data and type curve. Poon (1991) developed production decline curves for horizontal wells under various reservoir boundary conditions using Green's and source functions. He noted that the wellbore stimulation, well spacing, and well length are probably the most important factors determining the effectiveness of a horizontal well. Doublet et al. (1994) presented a type of method to perform a decline curve analysis for both the variable rate and variable bottom hole pressure cases, without regard to the structure of the reservoir (shape and size) or the reservoir drive mechanisms. The

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parameters determined using this method include the skin factor for near-well damage or stimulation, formation permeability, reservoir drainage area, and original oil-in-place.

Accounting for the relative permeability and capillary pressure, Kewen and Horne (2003) proposed a decline analysis model based on fluid flow mechanisms. The model reveals a linear relationship between the oil production rate and reciprocal of the oil recovery or accumulated oil production. Medeiros et al. (2007) employed a semi-analytical model that incorporates the key features of reservoir heterogeneity as well as the details of hydraulic fracture and the wellbore flow to compute the production decline. They proposed a transient productivity index to represent the production decline characteristics. Ozkan et al. (2009) presented a discussion of the fractured horizontal-well performance in conventional (milli-Darcy permeability) and unconventional (micro-to nano-Darcy permeability) reservoirs and provided an interpretation of the different production performances of fracturing horizontal wells in both types of formations. Cai et al. (2010, 2012) (Cai and Yu, 2011)analyzed the capillary-driven flow in gas-saturated porous media based on fractal theory and modified the classical Lucas-Washburn equation. The factors influencing the imbibition process upon approaching the equilibrium weight were also analyzed. Later, the hydraulic conductivity and effective porosity in porous media were investigated. Nie et al. (2011) proposed the negative skin problem in a transient well test and rate decline analysis; they established a new mathematical model for a horizontal well in a multiple-zone composite reservoir. The contribution of their work was the removal of the oscillation in type curves, thus solving the negative skin problem. Based on the widely familiar Arp's equation, Bahadori (2012) proposed a simple-to-use method, which was formulated to arrive at an appropriate estimation of the nominal (initial) decline rate and Arp's decline-curve exponent. This method is quite simple to apply and accurately generates the coefficients of the equations instead of using already generated coefficients with uncertainty.

Without applying the empirical concepts from Arps decline models and the explicit calculations from pseudofunctions, Ayala and Ye (2013) suggested a new generation analytical decline equation for boundary-dominated flow in a gas well producing at constant pressure for both full and partial production potential. Tan et al. (2013) created a dual fractal reservoir transient flow model by embedding a fracture system simulated by a tree-shaped fractal network into a matrix system simulated by fractal porous media. They plotted the bilogarithmic type curves of the dual fractal reservoirs and discussed the influence of different fractal factors on the pressure transient responses. Xie et al. (2014, 2015) focused on the two-phase flow caused by flow back after hydrofracturing shale gas reservoirs and established a two-phase pressure transient analysis model of a multi-stage fractured horizontal well. They studied not only the transient pressure but also the transient production rate decline features. Li et al. (2014) established a characteristic value method of the well test analysis for horizontal gas wells. Following the characteristic lines that are manifested by the pseudo-pressure derivative curve of each flow period, they developed formulas to determine the horizontal permeability, vertical permeability, skin factor, reservoir pressure, and pore volume of the gas reservoir.

However, flow in low permeability reservoirs does not obey Darcy's law due to the threshold pressure gradient (TPG), which makes the flow mechanism of horizontal wells in low permeability reservoirs more complicated. The concept of a threshold pressure gradient was suggested by Florin in 1951 (Florin, 1965). In the middle of the 20th century, numerous scholars concluded that the non-Darcy percolation that exists in low permeability reservoirs is caused by the threshold pressure gradient (TPG), and they investigated the flow problems related with TPG (Miller and Low, 1963; Thomas et al., 1968; Das, 1997; Boukadi et al., 1998; Bennion et al., 2000; Dey, 2007). Guo et al. (2012) presented a horizontal gas well model accounting for the threshold pressure gradient in tight gas reservoirs. They note that the effect of the threshold pressure gradient on the pressure behavior for horizontal gas wells mainly occurs during the mid-late time periods. Song et al. (2014) studied the steady productivity equations of fractured wells in water-bearing tight gas reservoirs under low-velocity non-Darcy flow. The influence of the threshold pressure gradient on the volumetric flow rate of a gas well is significant and should not be ignored. Zhao et al. (2014) established a nonlinear steady flow mathematical model of a horizontal well for oil-water two-phase flow, accounting for the permeability stress sensitivity and threshold pressure gradient. Xu et al. (2015) conducted TPG and stress sensitivity experiments and investigated the existing condition of the TPG and change rule of permeability modulus. Then, they presented a transient pressure analysis mathematical model for a horizontal well in low-permeability offshore reservoirs. Liu and Yao (2015) constructed a moving boundary model of the radial flow in low-permeability reservoirs, considering the influence of the threshold pressure gradient and quadratic pressure gradient term. The model was solved using numerical methods because it is nonlinear. Cai (2014) and Tan et al. (2015) investigated the low velocity non-Darcy flow, which starts the pressure gradient based on fractal theory.

Based on the above discussion, most studies on the TPG of low permeability reservoirs were mainly focused on the transient pressure or steady productivity, and solutions of an unsteady model were determined using point source functions theory following Ozkan and Raghavan (1991) and Ozkan et al. (2010). This paper presents a transient production decline analysis model of horizontal wells in low permeability gas reservoirs accounting for the threshold pressure gradient. An accurate solution is determined by applying the Laplace transformation, Sturm-Liouville eigenvalue method, and orthogonal transformation. The bilogarithmic type curves of the dimensionless production and derivative are plotted using the Stehfest numerical inversion method. The characteristics of the transient rate decline behavior are thoroughly analyzed, and different flow regimes are observed in each type of curve. In addition, the effects of the relevant parameters are discussed, which improves the understanding of transient flow behavior and efficient exploitation of low permeability reservoirs.

2. Mathematical model

A physical model of a low permeability gas reservoir, as shown in Fig. 1, is based on fluid flow in a horizontal well. To make the mathematical model more tractable and easier to understand, the following hypothesis and descriptions are outlined:

(1) The reservoir is homogeneous with impermeable top and bottom boundaries, and the lateral boundary is infinite. The initial formation pressure is p_i and is equal everywhere;
(2) The reservoir is anisotropic, and the horizontal and vertical permeability are K_h and K_v, respectively;
(3) The horizontal section of the well is parallel to the closed top and bottom boundaries, and its location is unlimited and represented by z_w;
(4) The single-phase gas flow obeys a non-Darcy law that accounts for the threshold pressure gradient;