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Pressure transient analysis of low permeability reservoir with pseudo threshold pressure gradient

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ABSTRACT

Threshold pressure gradient (TPG) is an important mechanism for fluid flow through low-permeability reservoirs, which would explain the phenomena that pressure derivative curves exhibit a straight line of slope that is larger than zero after radial flow regime. A mathematical single-phase flow model incorporating pseudo TPG is proposed to describe the flow behavior in low permeability reservoirs. Fully implicit numerical simulation based on PEBI grid is developed to study the transient pressure response. Two field data are used to calibrate and validate the proposed model and the code. Based on one of field data, parametric studies are conducted to investigate the effect of minimum TPG, pseudo TPG and nonlinear exponent on the pressure transient response for a vertical well. We find that pseudo TPG can explain the unique and consistent characteristic of the pressure transient response in low permeability reservoirs. The finding is useful for petroleum engineers to interpret the field data to obtain some basic parameters for low permeability reservoirs.

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1. Introduction

The increasing energy demand, rising energy prices and declining conventional oil/gas reserves lead to many increasing development of oil and gas in low permeability reservoirs. In China, the implementation of a welltesting program of buildup tests conducted on wells in low permeability reservoirs has revealed a unique and consistent characteristic of the pressure transient response. The characteristic is that pressure change and pressure derivative curves exhibit a straight line of slope larger than zero after radial flow regime. The test pressure responses seem to describe a composite reservoir behavior with high mobility of inner zone and small mobility of outer zone. However, the test pressure responses cannot be interpreted by a composite reservoir model because a composite reservoir model should not exist for every well in a reservoir with very small water cut that is less than 1%. Therefore, the welltesting program may shed light on the drive mechanism of low permeability reservoirs. Research shows that Darcy's law should be corrected by the threshold pressure gradient (TPG) in low permeability reservoirs.

Many researchers have studied TPG in low permeability reservoirs. Miller and Low (1963) reported the existence of TPG in the water flow through soils with high clay content. Pascal (1981) studied the effect of TPG on the fluid flow through a porous media. Prada et al. (1999) pointed out that Darcy's law should be corrected for the effect of the threshold pressure gradient. Wang et al. (2006) studied TPG of heavy oil through the dynamic viscoelastic experiments. In nanopermeability shale-gas reservoirs, threshold pressure gradient also would exist for gas flow due to the extremely low permeability (Civan, 2013).

TPG is defined as the level of pressure gradient below which fluid cannot flow. When pressure gradient is larger than TPG and overcomes the viscous forces, fluid starts to flow, which is always called as low velocity and non-Darcy flow. When TGP exists, the fluid flow boundaries are controlled by TPG and extend outward continuously, while the fluid beyond this boundary cannot flow.

In China, some low permeability reservoirs are under development and the pressure data measured during well shut-in are urgent to be interpreted to evaluate the reservoirs. The study of mechanism of TPG and its application have aroused wide attention (Hao et al., 2008; Cai et al., 2008; Wang et al., 2006, 2011; Guo et al., 2012; Luo and Wang, 2012). During the derivation of the analytical solution (Luo and Wang, 2012; Wang et al., 2011), the governing equations were transformed into homogeneity

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equations through the definition of dimensionless pressure. Unlike the paper (Luo and Wang, 2012; Wang et al., 2011), Guo et al. (2012) used fundamental solution of the point source function in the Laplace domain to obtain the bottom hole pressure response function. Cai et al. (2008) studied the typical curves of wells with vertical fractures in double-porosity reservoirs. Although the derivations of analytical solution are a little different, the conclusions are the same: the upwarping feature of the type curves appears during med-late time period due to the existence of TPG. Xu et al. (2007) pointed out that the boundary layer fluid was one of the main factors causing the nonlinear seepage law of low permeability reservoirs based on experiment of flow in micro tubes of 2.5 μm and 1 μm radii.

The most common form of the corrected Darcy's law is (Prada and Civan, 1999):

$$\begin{cases} \mathbf{u} = -\dfrac{K}{\mu}\left(\nabla p - \dfrac{\nabla p}{|\nabla p|}\lambda\right) & |\nabla p| > \lambda \\ \mathbf{u} = 0 & |\nabla p| < \lambda \end{cases} \tag{1}$$

where $\mathbf{u}$ is the flow velocity in m/s, μ is the fluid viscosity in Pa.s, K is permeability in m^2, ∇p and λ are pressure gradient and TPG in Pa/m respectively. In Eq. (1), λ is regarded as absolute TPG.

Based on the complicate distribution of pore throat size in the low permeability reservoirs, researchers proposed the concept of pseudo threshold pressure gradient (pseudo TPG, λ_{pseudo}). The low permeability formation has a wide range of pore throat size. The viscous forces in the large pore throats are small and fluid easily overcomes the viscous forces to flow. For the smaller pore throats, the viscous forces are relatively larger and thus fluid needs to overcome larger forces to flow. Therefore, when the pressure gradient is small, the fluid mainly flows through the pores with large throats, and when pressure gradient increases slowly, the fluid gradually flows through the pores with smaller throats, and total flow rate increases correspondingly. When pressure gradients exceed the largest TPG, the flow begins to obey Darcy's law.

Therefore, the smallest pore throat determines the maximum TPG, denoted as λ_{max}; the largest pore throat determines the minimum TPG (min TPG), denoted as λ_{min}. If λ_{min} is equal to zero, it means that TPG does not exist in the largest pore throat. If λ_{min} is large than zero, it means that TPG exists in the largest pore throat.

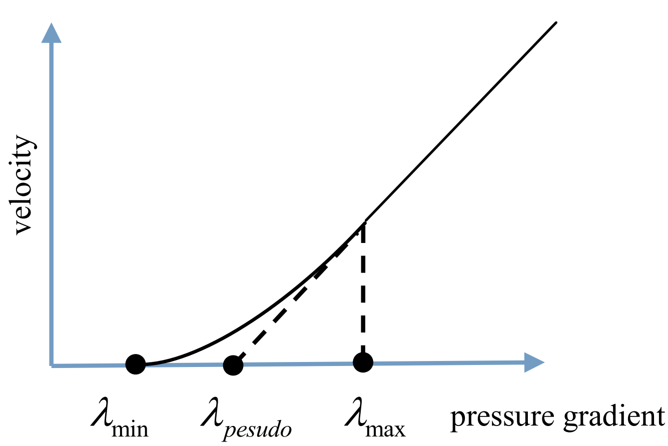

Fig. 1. Darcy' law with pseudo TPG. Flow flux vs. pressure gradient shows that when TPG exists, the linear relationship does not pass through the origin, but intercepts the pressure gradient axis at the pseudo TPG.

Fig. 1 presents a typical non-Darcy flow curve (Shi et al., 2009; Yu et al., 2012; Zeng et al., 2012) in ultra-low permeability reservoirs, which no longer follows Darcy's law. The flow curve is a combination of a straight line and a concave curve. When the pressure gradient is greater than maximum TPG (λ_{max}), the velocity–pressure gradient curve is a straight line, and its extrapolation has an intersection "λ_{pesudo}" with the pressure gradient axis, which is defined as pseudo threshold pressure gradient (pseudo TPG). When the pressure gradient is less than λ_{max}, the velocity–pressure gradient relationship is a concave curve, and its intersection with the pressure gradient axis is min TPG(λ_{min}).

When pseudo TPG exists, the flow in the porous media can be expressed as:

$$\begin{cases} \mathbf{u} = -\dfrac{K}{\mu}\left(\nabla p - \dfrac{\nabla p}{|\nabla p|}\lambda\right) & |\nabla p| > \lambda_{max} \\ \mathbf{u} = f(K, \mu, \nabla p, \lambda) & |\nabla p| < \lambda_{max} \end{cases} \tag{2}$$

Where $f(K, \mu, \nabla p, \lambda)$ is a nonlinear function. When the pressure gradient is greater than λ_{max}, flow follows Darcy's law.

Many models were proposed to describe function of $f(K, \mu, \nabla p, \lambda)$. Deng et al. (2001) modeled Eq. (2) by a function with 3 parameters. Xiong et al. (2009) used nonlinear flow segment and quasi-linear flow segment to model the nonlinear function. Li et al. (2008) used a quadratic function of ∇p to model the nonlinear flow. Shi et al. (2009) used throat density distribution function to calculate the pressure gradient and to establish the nonlinear function.

During the application study of TPG, some researchers use superposition principle to solve Equation Eq. (1) to study the pressure transient response during shut-in period. These studies show that TPG is the reason that the slopes of curves of dp and dp' are large than zero at med-late time (Cai et al., 2008; Wang et al., 2011; Guo et al., 2012; Luo and Wang, 2012). However, the result is doubted because the equation incorporating TPG is not homogenous and superposition principle cannot be used to solve the flow model incorporating absolute TPG (Li et al., 2015).

Some researchers use numerical simulation to study non-darcy flow behaviors. Yu et al. (2012) used the effective permeability of low permeability reservoir to describe non-darcy flow in low permeability reservoirs, and performed an integrated study on an actual low permeability reservoir. Yin et al. (2011) used dynamic permeability for low-permeability reservoirs to study the effect of pseudo TPG on the pressure distribution of low-permeability reservoirs. Wu et al.(2013) established a model with TPG and other nonlinear mechanisms to describe flow in unconventional gas reservoirs. However, the effect of TPG on pressure transient response is not discussed in the three papers.

Although many papers study the absolute TPG and pseudo TPG, no papers use the numerical simulation to study the pressure transient response for the flow model with pseudo TPG.

In this paper, we aim to fill this gap to study the effect of pseudo TPG on pressure transient behaviors for vertical wells in low permeability reservoirs. We firstly proposed a correlation of nonlinear function, and then we developed a fully implicit numerical scheme to solve the nonlinear equation. Thirdly, buildup pressure data of two vertical wells were interpreted to show correctness of the proposed correlation incorporating pseudo TPG. Finally, sensitive studies were conducted.

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