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Productivity equation of fractured horizontal well in a water-bearing tight gas reservoir with low-velocity non-Darcy flow

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ABSTRACT

Based on the features of tight gas reservoirs and considering the existence of threshold pressure gradient (TPG), a new mathematical model was established for low-velocity non-Darcy flow in water-bearing tight gas reservoirs. Calculation method of control areas is also presented. Productivity equations of vertical fractured well and horizontal fractured well in tight gas reservoirs are obtained with TPG. Influential factors were analyzed to provide theoretical basis for the effective development of tight gas reservoirs. According to the numerical results, with the increase of pressure drawdown, both the volumetric flow rate of gas well and control area grow first and then gradually becomes stable. The influence of TPG on the volumetric flow rate of gas well is great and cannot be neglected. For fractured horizontal well, gas well production increases with the increase of flow conductivity capacity and half-length of hydraulic fractures. For certain length of the borehole, when the fracture spacing increases and the number of the fractures decreases, the control area and the volume flow rate of the gas well decreases. Consequently, there is an optimum allocation among drawdown pressure, fracture half-length, fracture conductivity and fracture spacing to achieve maximum production.

1. Introduction

Tight sandstone gas resource is abundant and widely distributed. It is one type of unconventional natural gas reservoirs, and becomes more and more important for natural gas supply in the world (Dazhong et al., 2012; Dai et al., 2012). There are some features of tight gas reservoirs such as low-permeability less than or equal to 0.1 mD, low porosity, narrow throat and plenty of associated water (Desbois et al., 2011; Clarkson et al., 2012). Many researchers and scientists have shown that, natural gas flows through the water-bearing tight sandstone in terms of low-velocity non-Darcy flow, and there exits threshold pressure gradient (Friedel and Voigt, 2006; Yuan et al., 2013; Mahdiyar et al., 2011; Guo et al., 2012; Freeman et al., 2013). It is difficult to make nature gas flow without fracturing in tight gas reservoir because of low permeability and high water saturation (Littke et al., 2008; Zou et al., 2012). The production capacity prediction of fractured well is very important for development.

Based on the tight gas reservoir flow characteristics, productivity evaluation for horizontal fractured well has been frequently studied through numerical simulation which is time consuming and complex (Ruyan et al., 2003; Lei et al., 2007; Manrique and Poe, 2007; Clarkson and Beierle, 2011; Yunsheng et al., 2012; Bonyadi et al., 2012; Qiu et al., 2013). There are also some empirical expressions for horizontal well productivity which were obtained by combining ideal model with the numerical calculation (Ostojic et al., 2012; Qin et al., 2013). However, there has been a distinct lack of analytical expressions for productivity evaluation of horizontal fractured well considering low-velocity non-Darcy flow.

Therefore, based on features of tight gas reservoirs, a mathematical model considering the low-velocity non-Darcy flow has been established. Pressure distribution formulae of planar radial flow are derived and the calculation method of control areas is also presented. Productivity equations for both vertical and horizontal fractured well in tight gas reservoirs are obtained. Influential factors were analyzed to provide theoretical basis for effective development of tight gas reservoirs.

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2. Mathematical models and productivity equation

2.1. Volumetric flow rate of a vertical well

The flow in tight gas reservoirs is constrained by the molecular interaction between the rock pore and fluid. Fluid cannot move until the driving pressure overcomes the threshold pressure. Combined with the current experimental research achievements of threshold pressure gradient (Millheim and Cichowicz, 1968; Gil et al., 2001; Alvarez et al., 2002; Song et al., 2011), non-Darcy motion equation is established:

$$\vec{v} = \frac{k}{\mu}(\nabla p - G) \tag{1}$$

Due to the existence of threshold pressure gradient in tight gas reservoirs, there must be periphery areas of reservoir uncontrolled so that productivity capacity might be affected. Therefore, the evaluation of the effective control area due to threshold pressure gradient is the key for the development of tight gas reservoir. Our previous work has made in-depth research on effective drainage of the tight gas reservoirs (Zhu et al., 2011), and obtain the pressure distribution formula under the condition of the steady-state flow of tight gas reservoir:

$$p^2(r) = \mu\overline{Z}[-C_1E_i(G_cr) + C_2] \tag{2}$$

Where

$$C_1 = \frac{p_e^2 - p_w^2}{\mu\overline{Z}[E_i(G_cr_w) - E_i(G_cr_e)]}; \quad C_2 = \frac{1}{\mu\overline{Z}}p_w^2 + C_1E_i(G_cr_w)$$

Making differential calculation of Formula (2) for, we obtain the pressure gradient equation:

$$\frac{\mathrm{d}p}{\mathrm{d}r} = \frac{1}{2p(r)}\frac{C_1}{re^{Gr}} \tag{3}$$

When the driving pressure gradient of tight gas reservoir reaches the TPG, that is, $dp/dr = G$, the critical value r, namely the control radius is obtained, and $r_w \le r_c \le r_e$ (Zhu et al., 2011). For homogeneous single vertical wells drilled in the tight gas reservoirs, the control area is circular. Assuming formation pressure is p_e, the control radius is r_c, the well radius is r_w, the bottomhole pressure is p_w, and reservoir is homogeneous with equal thickness, as shown in Fig. 1, the equation of the productivity capacity of the vertical well is shown as follows:

$$Q = \frac{T_{sc}Z_{sc}}{TZp_{sc}}\frac{\pi kh}{\mu}\left[\frac{p_e^2 - p_w^2}{\ln r_c - \ln r_w} - 2r_cGp_e\right] \tag{4}$$

Where $G_c = G\cdot C_\rho$, G is the threshold pressure gradient, Pa/m; C_ρ is isothermal compressibility of the gas; p_e is the boundary pressure, MPa; p_w is the wellbore pressure, MPa; r_w is the wellbore radius, m; r_e is the radius of pressure drainage, m; μ is the gas viscosity, mPa·s; $\overline{Z}$ is the average gas compressibility factor.

2.2. Volumetric flow rate of fractured vertical well

Due to low permeability of tight gas reservoir and high water saturation, fracturing is applied to improve gas recovery. Fig. 2 shows a sketch map for a fractured vertical well in tight gas reservoirs.

For a fractured vertical well, the area controlled by gas well can be divided into three zones, Zone I, Zone II and Zone III, as shown in Fig. 3. Zone I refers to the radial flow area around the end of the fracture. Zone II represents the planar parallel flow around the fracture. Zone III is the linear flow in the fracture.

Based on the characteristics of fractured wells in tight gas reservoir, assumptions of volumetric flow rate are shown as follows: (1) Gas reservoir is homogeneous with the same thickness. Upper and lower boundaries are impermeable. Reservoir extends to infinite in the horizontal direction. The initial reservoir pressure is the same everywhere; (2) fluid is compressible in single-phase and flows in terms of planar flow with constant coefficient of compressibility and viscosity; (3) the width and height of the fracture are constants and the fracture height has the same thickness as the reservoir.

2.2.1. The area of planar radial flow

In Zone I, the gas flow is non-Darcy and planar radial. Then the production rate is obtained using Equation (1)

$$Q_{m1} = vA\rho_g = \frac{k}{\mu}(\nabla p - G)\cdot 2\pi rh\cdot\frac{T_{sc}Z_{sc}\rho_{gsc}}{p_{sc}}\frac{p}{TZ} \tag{5}$$

The boundary conditions are:

$$\begin{cases} r = r_c, & p = p_e \\ r = r_w, & p = p_m \end{cases}$$

Integral Formula (5) and substituting the boundary conditions, we obtain the flow rate expression:

$$Q_{v1} = \frac{T_{sc}Z_{sc}}{TZp_{sc}}\frac{\pi kh}{\mu}\left[\frac{p_e^2 - p_m^2}{\ln r_c - \ln r_w} - 2r_cGp_e\right] \tag{6}$$

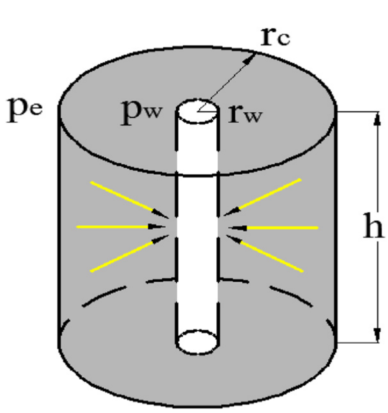

Fig. 1. A schematic of planar radial flow of single vertical well.

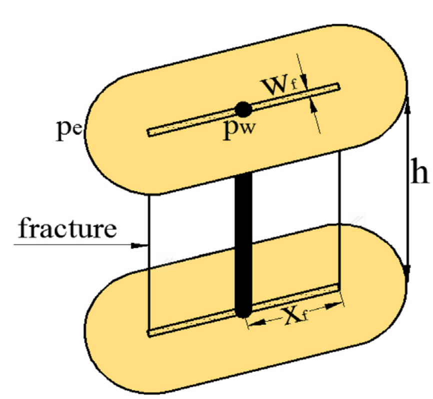

Fig. 2. A sketch map of fractured vertical well in tight gas reservoirs.