Journal of Natural Gas Science and Engineering 45 (2017) 338–357

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Research on wellbore stress in under-balanced drilling horizontal wells considering anisotropic seepage and thermal effects

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ARTICLE INFO

Article history:
Received 7 October 2016
Received in revised form
28 April 2017
Accepted 29 April 2017
Available online 1 June 2017

Keywords:
Wellbore stress
Thermal effect
Anisotropic seepage
Under-balanced drilling
Horizontal well

ABSTRACT

Under-balanced drilling (UBD) is widely used in petroleum drilling engineering, and regarding wellbore safety, it is necessary to analyze stress distribution around the wellbore during drilling procedures. Aiming at seepage and thermal effects during UBD, a model of pore pressure distribution under anisotropic seepage of horizontal wells was derived using conformal transformation. Combined with elastic theory, a new model of seepage stress around wellbores has been constructed. Moreover, based on a heat transfer model solved by finite difference methods, this paper studied wellbore and formation temperature fields during horizontal drilling when heat sources (circulating pressure drops and mechanical friction) are considered. This study shows that both pore pressure and seepage stress are present in an elliptical manner under anisotropic seepage. The annulus temperature of the horizontal section is greater than the geothermal temperature, thus compressive thermal stress forms in the surrounding rock; in contrast, tensile thermal stress develops when heat sources are excluded. The two factors, therefore, should be considered sufficiently important. The heat sources with thermal effects and anisotropy of seepage, which are usually omitted, have been treated again, leading to more accurate results of horizontal UBD and providing a theoretical basis for subsequent wellbore stability analysis.

1. Introduction

Horizontal wells are helpful for connecting multi-oil layer reservoirs, as well as fracture networks, to enhance production. Because of the noticeable advantage of horizontal wells, they are widely used in oil and gas exploration and development. Under-balanced drilling (UBD) applied in horizontal wells can improve the rate of penetration (ROP), decrease reservoir damage and detect hydrocarbons more easily. There have been many studies of the wellbore stability of UBD (He et al., 2015; McLellan and Hawkes, 2001; Moos et al., 2010; Qiu et al., 2007), however, wellbore stability problems during UBD, which always maintains a hot focus, have not been effectively resolved. A comprehensive understanding of surrounding-wall stress is the foundation of wellbore stability analysis, and a number of studies have shown that temperature fluctuations and pore pressure changes around wellbores make a difference in the distribution of surrounding-wall stress. Some studies (Freij-Ayoub et al., 2003; Nguyen et al., 2009; Tang and Luo, 1998; Tao and Ghassemi, 2010) have indicated that stress distributions were different when temperature and seepage were considered.

Fluid seepage due to negative pressure produces additional stress during UBD; earlier researchers have mainly concentrated on isotropic seepage, such as He et al. (2015, 2014), who used a pore pressure distribution equation provided by Qiu et al. (2007) under isotropic seepage when they studied the wellbore stability of UBD. Although Tao and Ghassemi (2010) and Chen and Ewy (2005) analyzed thermal and seepage effects on wellbore stability, they did not weigh the anisotropic characteristics of seepage. However, a significant difference between horizontal and vertical permeability is generally observed in actual reservoirs, and this difference eventually leads to anisotropy of seepage.

Negara et al. (2015) stated that anisotropy is important when gas flows in shale since the direction of gas flow not only depends on pressure gradient direction but also relates to the optimal direction of permeability. The isobars of pore pressure around wellbores in homogeneous formations are concentric circles, while those for anisotropic flow are bunches of confocal ellipses (Fig. 1). The steady elliptical flow near a finite-length line source in an infinite reservoir was studied by Muskat (1938). Based on his work, Kucuk and

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http://dx.doi.org/10.1016/j.jngse.2017.04.030
1875-5100/

Brigham (1979) studied the unsteady seepage of infinite conductivity fracture wells with an elliptical boundary in anisotropic formation. Peaceman investigated anisotropic seepage and derived anisotropy seepage equations through coordinate conversion and conformal transformation, while, Peaceman (1983) provided a computing method for an effective radius. Freij-Ayoub et al. (2003) further studied formation damage skin factors and reservoir inflow models of horizontal wells with regard to anisotropy seepage.

With increasing well depth, a high temperature at the bore hole bottom leads to a remarkable thermal effect, which could affect wellbore stability. There have been many available investigations of wellbore and stratum temperature fields, as well as thermal effects. Regarding wellbore temperature fields, early works mainly deduced analytic models. For instance, the temperature field during drilling was analyzed in many studies (Holmes and Swift, 1970; Kabir et al., 1996; Karstad and Aadnoy, 1997; Ramey, 1962; Raymond, 1969; Spindler, 2011). Regarding temperature fields in the strata around wellbores, Carslaw and Jaeger (1959) provided theoretical solutions for temperature filed in semi-infinite and heat-insulated regions. A predictive model for formation temperature was proposed by Edwardson et al. (1962), and Arnold (1990) derived a heat transfer model in which formations and boreholes were coupled. Laplace transformation was used to calculate formation temperature in the studies by Hasan and Kabir (1991) and Wu et al. (2014). Numerical methods were also adopted to solve this problem, including FDM (Keller et al., 1973; G. Li et al., 2016; Marshall and Bentsen, 1982; Yang et al., 2013), FEM (Wołoszyn and Gołaś, 2013), and FVM (M. B. Li et al., 2015); in addition, an artificial neural network was recently introduced by Bassam et al. (2010) to approach static temperatures around wellbores. Relative research about temperature fields for different operational situations, such as drilling, killing wells, well workover, circulation loss, pipe drilling, coiled tubing service, well testing and production, etc., can be found in the literature (Aniket et al., 2012; Hasan and Kabir, 2012; Kabir et al., 1996; Kumar et al., 2012; Yang et al., 2013). Thermal stress emerges in the surrounding rock due to heat exchange between drilling fluid and the stratum. On the basis of the former scholars' achievements, it is possible to clarify the influence of thermal effects on stress distribution.

Although there has been some literatures separately paying close attention to seepage fields (stable/unsteady state, isotropic/anisotropic flow) and wellbore-stratum temperatures, regarding under-balanced drilling in horizontal wells, published reports have only seldom indicated that anisotropy of seepage and heat sources generated in heat exchange could be considered at the same time in the analysis of stress distributions around wellbores. This paper mainly aims at the horizontal segment of horizontal wells during UBD; in-situ stress around the wellbore is determined first, and then models of anisotropic seepage and seepage stress are derived, while temperature profiles and the distribution of thermal stress are examined. Finally, a model for surrounding-well stress distribution with anisotropy seepage and thermal effects is built. This essay lays the theoretical foundation for wellbore stability analysis when UBD is applied to drill horizontal wells.

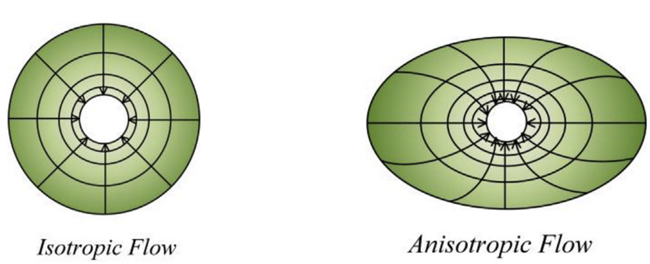

Fig. 1. Sketches of isotropic and anisotropic flow.

2. In-situ stress around wellbores during under-balanced drilling of horizontal wells

Excavation of the borehole breaks the balanced state of in-situ stress, and then the stress around the is borehole rearranged until a new balanced state is achieved, leading only to stress concentration at the borehole wall. In general, it is believed that in-situ stress consists of maximum horizontal principle stress (σ_H), minimum horizontal principle stress (σ_h) and vertical stress (σ_v).

Assuming that the formation is isotropic linear elasticity porous material when referring to mechanical properties, and it is a plane strain problem with small deformation, then linear superposition can be applied to study wellbore stress, indicating that the results of all factors act simultaneously, equal to that of superposing each factor's effects.

In-situ stress (σ_H,σ_h,σ_v), owing to the deviation angle and azimuth in wellbores, is required to be transformed. First, A selected coordinates (x', y', z'), of which the axes' orientations coincide with the directions of the in-situ principal stress (Fig. 2a), afterward transform the axes and ensure the z axis of the new coordinate system (x, y, z), along with the wellbore axis. This is a conventional treatment in analyzing In-situ stress around wellbore, detailed description of the coordinate transformation is presented in Appendix A. Simultaneously, the expression of stress distribution induced by in-situ stress in a cylindrical coordinate also is given in Appendix as Eq.(A-2).

3. Models of anisotropic seepage and corresponding seepage stress during under-balanced drilling of horizontal wells

3.1. Anisotropic seepage model of horizontal segments during UBD

The sketch of seepage filed in reservoirs and the zone closed to wellbores during horizontal UBD, as well as the geometry of the horizontal well, are shown in Fig. 3. To manage the problem of anisotropic seepage, a similar method applied by Furui et al. (2003) is employed in this study as well. Some assumptions are provided as follow.

1) Horizontal permeability k_H is identical on the horizontal plane, while it is different from vertical permeability k_v and does not vary with radial distance.
2) The horizontal borehole is located at the middle of a reservoir with uniform thickness, which is much larger than the wellbore size, and the borehole axis is parallel to the reservoir bed.
3) It is the radial flow within a region where r_t is the external boundary, and the pressure is constant at r_t. The fluid flow far away from the wellbore is the linear flow, and both the upper and lower boundaries of the reservoir are sealed; i.e., all of the fluid that experience linear flow eventually goes into the radial flow stage before entering the wellbore.
4) External factors, such as gravity, fractures, etc., which can affect seepage, are omitted.

Within the area of radial flow on Plane O, which is perpendicular to the borehole axis under the coordinate system as shown in Fig. 3, the seepage equation in this plane is as follows:

$$k_H\frac{\partial p}{\partial y^2} + k_v\frac{\partial p}{\partial z^2} = 0 \tag{1}$$

The boundary condition is:

$$\begin{cases} p = p_{wf} & (r = r_w) \\ p = p_t & (r = r_t) \end{cases} \tag{2}$$

where $r = \sqrt{y^2 + z^2}$, the external and inner boundaries are circular,