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Numerical simulation of directional propagation of hydraulic fracture guided by vertical multi-radial boreholes

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ABSTRACT

The conventional hydraulic fracturing is not effective in the target oil development zone (remaining oil or gas, trap reservoir, etc.) with available wellbores located in the azimuth of non-maximum horizontal in-situ stress. The technology of directional propagation of hydraulic fracture guided by vertical multi-radial boreholes was innovatively developed. In order to verify the technology, a 3D extended finite element numerical model of hydraulic fracturing promoted by vertical multi-radial boreholes was established using Abaqus Software, and the influence of horizontal in-situ stress differences, azimuth, diameters, spacing, and lengths of radial boreholes, rates and viscosities of fracturing fluids, Young modulus and Poisson's ratio of rock, and reservoir permeability on propagation of hydraulic fracture guided by radial borehole row were comprehensively analyzed. Moreover, the term ‘Guidance factor (G)’ was introduced for the first time to effectively quantify guidance of radial borehole row. Finally, the guidance of the above ten factors is comprehensively evaluated through gray correlation analysis. The results showed that the directional propagation of hydraulic fracture is realized through scientifically arranged vertical radial borehole row, and ‘G’ reflects the real guidance strength of radial borehole row to hydraulic fracture. The azimuth of radial borehole row increases by 75°, G increases by 18 times. Horizontal in-situ stress difference increases by 9 MPa, G increases by 95%. The borehole diameter increases by 4 cm, G decreases by 54%. The borehole spacing increases by 0.5 m, G increases by 18%. The borehole length increases by 10 m, G decreases by 40%. Young's modulus of reservoir rock increases by 20 GPa, G decreases by 23%. Poisson's ratio increases by 0.1, G increases by 57%. Permeability of reservoir increases by 100 times, G increases by 3.3 times. Injection rate increases by 9 m^3/min, G decreases by 63%. Both excessively high and low viscosities are adverse to guidance of radial borehole to hydraulic fracture, and 50 mPa s fracturing fluid creates best guidance to propagation of hydraulic fracture. The gray correlation analysis showed that the influences (from strong to weak) of the above factors on guidance of radial borehole were listed as follows: azimuth of radial borehole > injection rate of fracturing fluid > horizontal in-situ stress differences > Young's modulus of rock > viscosity of fracturing fluid > borehole diameter of radial borehole > radial borehole spacing > reservoir permeability > length of radial borehole > Poisson's ratio. This study provided theoretical evidence for directional propagation of hydraulic fracture promoted by radial borehole, and it predicted the guidance of radial borehole to hydraulic fracture in a certain extent, which is helpful for planning well-completion and fracturing operation in technology of hydraulic fracturing promoted by radial borehole.

1. Introduction

The radial borehole (also known as radial well) refers to a horizontal borehole with radius far less than that of conventional drilling, and its borehole is formed mostly by hydraulic jet or drilling, with length between 10 m and 100 m and borehole diameter between 25 mm and 50 mm (Dickinson et al., 1992; Li et al., 2000; Gong et al., 2016; Ursegov et al., 2008). Combination of radial borehole and hydraulic fracturing is an innovative technology to effectively develop the low-permeability, thin-layer, and fractured

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reservoir, water-flooded ‘dead oil area’, and lithologic trap reservoir (Megorden et al., 2013; Wu, 2012). The main role of radial borehole is to guide the direction of hydraulic fracture and enhance deep penetration of fracture. Since the azimuth of radial borehole in target zone may not be close to the azimuth of maximum horizontal in-situ stress and strong reservoir anisotropy (Clarkson et al., 2016), it is possible that the hydraulic fracture does not propagate along the orientation of single-radial borehole to target zone, the orientation of fracture transfers, and transverse fracture forms, which creates unsatisfactory stimulation result and limits the application of technology.

Directional propagation of hydraulic fracture in case of single-radial borehole not effectively guiding the propagation of fracture needs to overcome the original in-situ stress and reservoir anisotropy and improve the guidance of radial borehole. Based on this theory, a method was presented that radial borehole rows are vertically displaced along wellbore with certain spacing, and all radial borehole rows extend toward target development zone (Fig. 1). To realize the artificial control of directional propagation of hydraulic fractures along well row orientation, increment of drainage area, and effective communication of target zone, the interference between radial drilling holes should be used to overcome control of in-situ stress and interference from anisotropy.

At present, many authors have conducted research on the spatial stress theory related with guidance of multi-holes to control fracture propagation (Gui, 2005; Bashkirov and Vityazev, 1996), which shows that the axis plane of hole is main stress plane, superposition of tensile stress in axis plane of borehole creates maximum tensile stress in borehole wall of axis plane, and it reaches the tensile strength of fractured formation firstly. Thus, the radial crack is initiated firstly in borehole wall of hole axis plane, and it grows as expansion stress increases. Liu and Liu (2013) published an article about adding multi-directional perforation to wellbore and creating slot in coal bed through high-pressure hydraulic jet, which initiates cracks in shear failure zone around crack tip. Then, another direction of fracture is created in next fracturing operation. Xia et al. (2013) published an article about guidance of hydraulic fracture, which suggests placing the directional drilling around fracturing hole, and it is thought that in order to prevent hydraulic fracture from diversion or propagation towards adjacent reservoir, it needs propagation of fracture along plastic coal formation, namely that hydraulic jet slotting creates continuous plastic zone in coal bed and communicates the plastic zone resulted from slotting fracture.

At present, the study is limited to initiation of fracture guided by directional perforation. A prediction model of initiation of hydraulic fracture guided by directional perforation was established by Zhu et al. (2015) who analyzed the influence of directional perforation on initiation pressure of hydraulic fracture and fracture form. A true tri-axial hydraulic fracturing experiment was conducted by Lei et al. (2015) who studied the influence of perforation spacing and horizontal in-situ stress differences on propagation of hydraulic fracture, and it is thought that more perforation holes and smaller in-situ stress difference benefit propagation of fracture along perforation direction. The experiment of hydraulic fracturing in tight sandstone was conducted by Fallahzadeh et al. (2015) who found that both borehole and perforation affect initiation mechanism of tight reservoir, and it is thought that perforation affects the geometrical morphology of hydraulic fracture in immediate vicinity of wellbore. Moreover, it was found by Chen et al. (2010) through massive fracturing experiments that the change of directional perforation angle and horizontal in-situ stress differences influences propagation of hydraulic fracture. The experiment of hydraulic fracturing directional perforation was conducted by Hong et al. (2014) who studied guidance of perforation number to hydraulic fracture, and it is thought that sufficient guidance holes create effective crack, which promotes initiation and guidance of hydraulic fracture. However, because of large differences between radial well (borehole) and directional perforation hole in length, hole diameter and spacing, there are large differences between radial borehole and directional well in guidance to hydraulic fracture. At present, there is no study about guidance of radial borehole to propagation of hydraulic fracture.

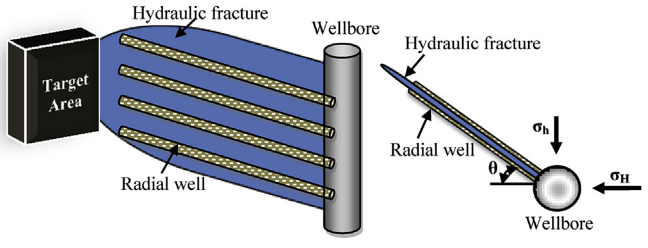

Fig. 1. Schematic diagram of hydraulic fracture directed propagation guided by radial wells.

Based on the extended finite element theory, a 3D numerical model of propagation of hydraulic fracture guided by radial borehole row with fluid-structure interaction was established (Gunde et al., 2010; Fries and Belytschko, 2010; Dong and Ren, 2011; Gordeliy and Peirce, 2012; Wang et al., 2014; Dolbow et al., 2000; Moës and Belytschko, 2002; Sheng and Li, 2014) by Abaqus Software. It reveals influences of horizontal in-situ stress differences, azimuth of radial borehole, borehole diameter of radial borehole, radial borehole spacing, length of radial borehole, injection rate and viscosity of fracturing fluid, Young modulus and Poisson's ratio of rock, and reservoir permeability on guidance of radial borehole row to propagation of hydraulic fracture, and provides reliable scientific basis for effective operation of guidance of radial borehole to directional propagation of hydraulic fracture. Thus, by solving the problems that the hydraulic fracture only extends along the direction parallel to horizontal maximum in-situ stress, which causes available wellbores fail to develop remaining oil and trap reservoir, and that complex multi-fractures tend to generate in immediate vicinity of wellbore, which makes it hard to realize deep penetration of fracture, it improves the result of fracturing operation and recovery efficiency of oil field. Furthermore, the study has important reference value in other unconventional reservoirs where the guidance of multi-radial boreholes to propagation of hydraulic fracture is operated to stimulate reservoir volume and enhance control of fracture shape in geothermal systems (Hofmann et al., 2014; Zhang et al., 2014).

2. Numerical simulation of propagation of hydraulic fracture

2.1. Introduction to model

2.1.1. Simulation of initial fracture

The enrichment functions are introduced to finite element approximation to simulate initial fracture, and the discontinuity of fracture is described by the enrichment functions related with additional degree of freedom. The displacement vector function u characterizing entire division is written as (Guo et al., 2011):

$$\mathbf{u} = \sum_{I=1}^{N} N_I(x)\left[\mathbf{u}_I + H(x)\mathbf{a}_I + \sum_{\alpha=1}^{4} F_\alpha(x)\mathbf{b}_I^\alpha\right] \tag{1}$$

where $N_I(x)$ is shape-function of general nodal displacement, $\mathbf{u}_I$ is continuous part of solution to displacement, both $\mathbf{a}_I$ and $\mathbf{b}_I^\alpha$ are