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Numerical simulation of the influence of stimulated reservoir volume on in-situ stress field

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ABSTRACT

In recent years, the stimulated reservoir volume is a new developing technology applied to the effective exploitation of low permeability shale gas reservoirs. Despite of its superiority and potential, the geostress field is under a complex mechanical environment during the volume fracturing process due to excessive stimulated stages, large fracturing volume, high injection capacity, and increasing dense areas of microseismic events. Based on the drilling and completion data and microseismic monitoring data of Sichuan shale gas horizontal well X201-H1, the three-dimensional finite element model of volume fracturing is established, combining fluid-solid interaction mechanics with the basic theory of rock damage mechanics. According to the established model, the finite element analysis on different fracturing conditions is carried out, which finally results in the stress distribution of near-wellbore area after each staged fracturing operation. The results show that: 1) The change of pore pressure caused by volume fracturing can generate induced stress field, which leads to the re-orientation of in-situ stress field and even the appearance of tension stress areas and zero stress areas within the region of volume fracturing stimulation. 2) The existence of stress field interference in different stages of fracturing operations leads to the change in the magnitude and direction of stress field after each staged fracturing. Research methods and results of the paper will provide guiding significance to the optimization design of staged fracturing of horizontal wells to some extent.

1. Introduction

As the core technology in the stimulation operations of shale gas reservoirs, volume fracturing technology has been widely applied in recent years (Wang et al., 2012, 2014a; Zhang et al., 2015a). The volume transformation technology of shale gas in the USA can be divided into 4 stages, i.e. large-scale hydraulic fracturing in vertical wells, large-scale slip hydraulic fracturing in vertical wells, staged fracturing technology in horizontal wells and casing completion and staged fracturing technology in horizontal wells (Mayerhofer et al., 2010). In 2006, Mayerhofer et al. (2006) first used the concept of Stimulated Reservoir Volume (SRV) and then experts in the field including Wu et al. formulated the concept and revealed its basic connotation, optimization design, and implementation method. Meanwhile Wu et al. (2011) clearly proposed the new concept of "volume transformation technology". The volume fracturing (transformation) technology was first applied in the staged multi-cluster volume transformation operation in W201 and W201 − H1 in Weiyuan, Sichuan, both achieving good effects (Wu et al., 2012). Then, it came into use and development in the volume transformation of ultralow permeability and tight oil reservoirs in Changqing Oilfield, Jilin Oilfield, Tarim Oilfield, Southwest Oil and Gas Field and Sulige Gasfield in China (Tang et al., 2013; Chen et al., 2007). In 2013, volume fracturing technology began large-scale development and was employed in the Jiaoshiba shale gas field in the Sichuan Basin, China (Wang et al., 2014b).

Geostress is a kind of objective existence, generated by the combination effect of buried depth, lithological character, pore pressure, rock structure and tectonic pattern. In volume fracturing, geostress field will decide whether complex fracture network and effective seepage channel can be formed. Researches on in-situ stress and fracturing have been conducted from various perspectives. Using the boundary element model developed on displacement discontinuity method, Cheng (2009) analyzed the in-situ stress field redistribution and fracture mechanics for multiple

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parallel fractures through simplifying the mechanical properties. And they presented that tensile stress occurs near the areas beyond the fracture tips for both the maximum and minimum horizontal stresses. Through 3D finite element numerical modelling, Roussel and Sharma (2011) calculated in-situ stress distributions around uniform pressure fractures, and proposed the understanding and quantification of the mechanical stress interference generated during the stimulated of horizontal wells is crucial to improving reservoir drainage in shale gas reservoirs. They also obtained the relationship between the re-orientation of geostress and the propagation of subsequent fractures. Zhao et al. (2014) established a mathematic model with a complex fracture network to investigate how the fracture network forms and changes with different parameters, including rock mechanics, in-situ stress field distribution, fracture properties and frac treatment parameters. And their simulation results indicated that smaller difference of in-situ stresses is sufficient condition for fracture network development. Wu and Olson (2015) described a novel fracture-propagation model to simulate multiple hydraulic fracturing and perform sensitivity analysis of in-situ stress field, coupling fracture deformation with fluid flow in the fractures. Zhang et al. (2015b) studied the change of in-situ stress field after fracturing using theoretical analysis and numerical simulation based on "Texas Two-Step" model. The results indicated that fractures generated by hydraulic fracturing will cause stress re-orientation, change principal stress difference and therefore change the mechanical condition of fracture network. Through numerical simulation based on cohesive zone method, Wang et al. (2016) elucidated the in-situ stress difference has a significant influence on the extent of the stress interference zone and the local in-situ stress in the near-tip region is redistributed during fracture propagation.

However, the geostress field was in complex mechanical environments in the volume transformation process due to the volume fracturing characterized by excessive stimulated stages, large fracturing volume, high injection capacity, and increasing dense areas of microseismic events (Lian et al., 2015). This paper discusses the horizontal shale gas Well X201-H1 in Sichuan. Based on its drilling and completion data, microseismic monitoring data, and in combination with such fundamental theories as the fluid-solid interaction mechanics and rock damage mechanics, the 3D finite element model of volume fracturing of Well X201-H1 was established. The finite element simulation analysis of the first 4-stage fracturing was conducted. Finally, the influence rule of volume fracturing of shale gas on the geostress field was obtained, providing the basis for the optimal design of staged fracturing technology in horizontal wells.

2. Concept of volume fracturing technology

Volume fracturing technique is a new technology, aiming at the effective development of unconventional oil and gas reservoirs. It employs staged multi-cluster perforation shown in Fig. 1. First, tensional cracks are developed perpendicular to the minimum horizontal principal stress, forming principal compressional fractures perpendicular to the bedding plane (Wu et al., 2011). Under appropriate stress conditions, natural fractures and bedding effects, extension directions of principal fractures vary, which connects fracture convergence formed by the cracking of weak bedding planes and natural bedding planes. So complex fracture networks are formed and the contact area between crack sides and rock matrix is increased. The technology breaks up the reservoir and forms a complex map cracking, creating "artificial" permeability. It breaks through the traditional mode of fracture percolation theory, significantly reducing the effective fluid flow distance (Wu et al., 2012; Wang et al., 2015). In addition, it achieves the 3D fracturing transformation of unconventional hydrocarbon reservoirs. The proposal of "volume transformation technology" subverted the classic fracturing theory. The crack formed after volume transformation is no longer double wing symmetrical crack, but a complex map cracking. Initiation and propagation is not only tensile damage of fractures, but also such complex mechanical behaviors as shearing, slipping, leap, etc. (Chipperfield et al., 2007).

Staged multi-cluster perforation is employed in the volume fracturing technology. Staged multi-cluster fracturing employs interference among cracks to induce crack re-orientation, thus creating a complex map cracking (Liu and Zhang, 2011). The purpose of shale gas fracturing is to establish a larger map cracking independent of the traditional fracture half length, and increase the stimulated volume of shale reservoirs as much as possible (Zhang et al., 2011). However, induced stress field generated in volume fracturing changes the value and direction of in-situ stress field, resulting in the geostress field in complex mechanical environments. Stress interference between fracturing clusters leads to the constant change of induced stress field, enhancing the complexity of the geostress field. The direction change of geostress field and the value decrease are in favor of the formation of a complex map cracking through volume transformation. In contrast, the increase of local geostress improves the initiation pressure in the region, and affects the extension and expansion of fractures in a natural fracture zone, making it difficult to form induced fractures and affecting the stimulation effect (Pan et al., 2014; Zhao et al., 2012). Therefore, study on the change of geostress field which focuses on the change of induced stress field during volume fracturing is important to guide the rational clustering design.

3. Pore pressure induced stress field theory

The state of formation stress field includes far field geostress field and near-wellbore stress field. The initial geostress field does not change when it is far away from the borehole and it is defined as

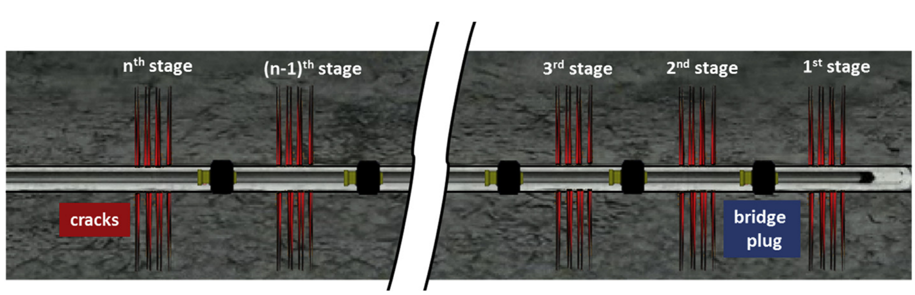

Fig. 1. Schematic diagram of staged multi-cluster perforation fracturing.

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