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A study on casing deformation failure during multi-stage hydraulic fracturing for the stimulated reservoir volume of horizontal shale wells

Zhanghua Lian [a,*], Hao Yu [a], Tiejun Lin [a], Jianhua Guo [b]

[a] State Key Lab of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, China
[b] Research Institute of Gas Recovery Engineering, PetroChina Southwest Oil and Gas Field Company, Guanhan 618300, China

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ABSTRACT

Volume fracturing technique has effectively helped develop unconventional oil and gas reservoirs in recent years. At the same time, new problems of casing deformation failure occurred. Based on the drilling and well completion data, microseismic surveillance data, theories of fracture mechanics, rock damage mechanics and rock failure criterion, this paper established a finite element model of the formation of effective stimulated reservoir volume, including clustering perforation casing for X-1 h shale gas horizontal well, to address the problems. The research results indicate: 1) the stress deficit of zero stress areas and tension stress areas occurred within the range of stimulated reservoir volume during the process of volume fracturing. And, the state of this stress deficit, which would make clustering perforation casings of horizontal wells "hanging" in the formation to some extent, resulted in certain degree of deflection deformation radically and S-shape deformation axially. 2) the problem of casing deformation failure remains fundamentally unsolvable through simply improving casing grade and wall thickness to increase flexural strength. 3) the key to solve casing deformation failure is the reasonable spacing design of multi-stage fracturing. The methods and achievements in the paper provide theoretical supports for the popularization and application of shale stimulated reservoir volume and controlling the S-shape deformation failures of the horizontal multi-cluster perforation casing.

1. Introduction

In recent years, volume fracturing has become an effective technique for the development of unconventional oil and gas reservoirs (Wang et al., 2012, 2014a). Using volume fracturing measures, the stimulated reservoir volume (SRV) can be realized to achieve industrial production volume (Wang et al., 2015). In 2006, Mayerhofer et al. (2006) first mentioned the concept of the Stimulated Reservoir Volume (SRV). Later on, other experts in this field (Cipolla et al., 2009; Mayerhofer et al., 2010; Wu et al., 2011; Chen et al., 2012) developed the concept and revealed its basic contents, optimization design and the implementation methods. Meanwhile, Wu et al. (2011) clearly presented a new concept of volume fracturing technique, i.e. the technique can break up reservoirs to form complicated fracture networks, and "create" artificial permeability. This technique successfully breaks the traditional fracturing seepage theory model and greatly shortens the effective seepage distance and is especially applicable to the stimulation of highly brittle rock layer. Meanwhile, multi-stage and multi-cluster perforation modes are also applied (Wu et al., 2012). The SRV theory completely subverts the traditional fracturing theory (Wu et al., 2011). The volume fracturing technique no longer forms symmetry bi-wing fractures, but generates complex fracture networks. Also, this theory illustrates that fracture initiation and extensions are not a simple tension-fracture, but have completed mechanics behaviors with shear failure, leap and slip (Chipperfield et al., 2007). This volume fracturing was put into use for the first time in the multi-stage and multi-cluster SRV process of W201 well and W201-H1 well in Weiyuan, Sichuan Province, China, and good stimulation effect was obtained (Wu et al., 2012). After that, this technique was applied and developed in the SRV process of ultra-low permeability and tight oil reservoirs in Changqing oilfield, Jilin oilfield, Tarim oilfield, Southwest oil-gas fields and Sulige gas

* Corresponding author. State Key Lab of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, China.
E-mail address: milsu1964@163.com (Z. Lian).

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Nomenclature

Latin
D_{max} Maximum casing external diameter, mm
D_{min} Minimum casing external diameter, mm
d Damage factor, dimensionless quantity
E^0 The initial elasticity modulus (no damage), MPa
E Elasticity modulus after unit damage, MPa

Greek letter
σ_n Normal stress of cohesive element, MPa
σ_s, σ_t Tangential stresses of cohesive element, MPa
σ_n^{max} Critical stress of normal direction when the element loses efficacy, MPa
σ_s^{max}, σ_t^{max} Two critical tangential stresses when the unit loses efficacy, MPa
δ_m^{max} The maximum displacement in loading procedure, m
δ_m^f Displacement when element is completely damaged, m
δ_m^0 Displacement when element started to be damaged, m
ζ Casing section ellipticity, dimensionless

Abbreviation
ALE Arbitrary Lagrange-Euler
FEM Finite element modeling
LIB Lead impression block
MD measured depth
SRV the stimulated reservoir volume

field in China (Chen et al., 2007; Ye et al., 2013; Tang et al., 2013).

2. A new problem in volume fracturing-casing deformation failure

A new problem of casing deformation failure has occurred during multi-stage hydraulic fracturing of SRV. Due to the characteristics of big fracturing volume, excessive stimulated segments and big pumping delivery rate in the volume fracturing process, there will exist complicated mechanical behaviors such as shear failure, leap and slip around the horizontal casing and the change of in-situ stress field (Chipperfield et al., 2007; Hossain et al., 2007). All these problems will frequently lead to casing deformation failure and make it difficult to run subsequent completion tools. Consequently, normal well completion operations and stimulation treatments can't be performed, which would seriously influence stimulation effect (Chen et al., 2007; Hossain et al., 2007; Yang et al., 2013; Tang et al., 2013; Yu et al., 2014; Brantley et al., 2014).

Daneshy (2005) showed that during the fracturing operations, casing could fail under tension across the fractured interval either by de-threading of the collars of the casing or by tensile failure at perforations. He presented the main factors contributing to this failure are off-balance fracture growth, and pseudo-openhole environment; other contributing factors are borehole inclination with respect to the fracture plane, and the quality of the cement bond. Furui et al. (2010) developed a comprehensive liner-deformation model to analyze casing failure in fracturing and acidizing. Their computed results indicated that Their computed results indicated that fracturing and acidizing can lead to the compaction effect, borehole instability and casing deformation. Yu et al. (2014) constructed a three-dimensional finite element model of casing failure during the multi-layer fracturing of vertical wells. According to the comparison of MIT multi-arms logs after fracturing, casing failure is coefficient results of rock properties decrease, asymmetry treatment zones, high fracturing pressure and terrestrial stress field redistribution. Wang et al. (2014b) indicated that local buckling, crushing, connection failure and shear failure are the main modes of casing failure. The researches above have demonstrated the effect of traditional hydraulic fracturing on casing damage from different perspectives. However, studies on casing failure in multi-stage hydraulic fracturing of SRV are still relatively few.

In this work, we analyzed the information of a shale gas horizontal well in Sichuan, well X-h1, when serious casing failure occurred during its volume fracturing process. Based on microseismic monitoring data, areas affected by rock-cracking, tectonic map around casing, in-situ stress data, casing size and so on, using finite element analysis software, mechanical models for the research on the mechanism of casing damage of horizontal well volume fracturing could be established. Through finite element numerical modeling research and analysis under different conditions, we figured out the forms, reasons and mechanisms of the casing failure, and presented the related protection and control measures for the casing damage.

3. Finite element modeling (FEM) of horizontal section volume fracturing

3.1. Basic data of X-1 h well

X-1 h is a horizontal shale gas well in West China, with measured depth (MD) of 2649 m and horizontal section length of 1250 m, as shown in Fig. 1. In the horizontal section, casing dimension is 139.7 mm × 9.17 mm with a steel grade of P110. The material parameters of casing and cement sheath are shown in Table 1.

Twelve-stage volume fracturing was adopted in this well. Each stage of multi-cluster perforation had an effective length of 20 m and the spacing of adjacent fracturing sections was 80 m, as shown in Fig. 1. Each section was injected about 2000 m^3 fluids into the layer at the flow back rate of 9.8% and maximum pump pressure of 64 MPa. On the basis of microseismic information, some layers appeared repetitive volume fracturing, as shown in Fig. 2. After volume fracturing, during the process of drilling bridge plug, the block of Φ117 mm milling shoe at the depth of 2331.5 m evidenced the possibility of casing failure. The casing failure section was located in the fifth fracturing section, which was the biggest stimulated volume. Therefore, finite element (FE) model must contain all the information of this section.

3.2. Basic theory of rock damage and division of volume fracturing spread range

During each staged fracturing process, pump pressure would rise with the increase of delivery capacity, and fluid seepage pressure that forced on areas of volume fracturing would also go up, which changed the formation stress field. Whereas, the changing stress field could result in formation damage of stimulated areas and decrease of rock mechanical properties (Zhao et al., 2012). Based on microseismic principles, it can be considered that any signal of microseismogram is the initiation fracture of a microcrack that continues to expand (Dong and Gao, 2004). However, it is impossible to accurately depict the changes of rock mechanical properties that appeared after the generation of each microcrack. Therefore, it is assumed that the rock mass in the microseismic