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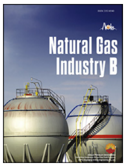

Research article

A new post-frac evaluation method for shale gas wells based on fracturing curves☆

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Abstract

Post-fracturing evaluation by using limited data is of great significance to continuous improvement of the fracturing programs. In this paper, a fracturing curve was divided into two stages (i.e., prepad fluid injection and main fracturing) so as to further understand the parameters of reservoirs and artificial fractures. The brittleness and plasticity of formations were qualitatively identified by use of the statistics of formation fracture frequency, and average pressure dropping range and rate during the prepad fluid injection. The composite brittleness index was quantitatively calculated by using the energy zones in the process of fracturing. It is shown from the large-scale true triaxial physical simulation results that the complexity of fractures is reflected by the pressure fluctuation frequency and amplitude in the main fracturing curve, and combined with the brittleness and plasticity of formations, the fracture morphology far away from the well can be diagnosed. Well P, a shale gas well in SE Chongqing, was taken as an example for post-fracturing evaluation. It is shown that the shale beds are of stronger heterogeneity along the extension directions of horizontal wells, and with GR 260 API as the dividing line between brittleness and plasticity in this area, complex fracture systems tend to form in brittleness-prone formations. In Well P, half of the fractures are single fractures, so it is necessary to carry out fine subsection and turnaround fracturing so as to improve development effects. This paper provides a theoretical basis for improving the fracturing well design and increasing the effective stimulated volume in this area.

Keywords: Shale gas well; Post-frac evaluation; Prepad fluid injection; Main fracturing; Brittleness; Fracture complexity; Quantitative evaluation; SE Chongqing

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Shale matrix has extremely low porosity and permeability, and contains abundant adsorbed gas; therefore, shale gas is characterized by a long recovery life and a long production cycle [1−4]. In a shale gas block of SE Chongqing, the costs of well drilling, completion and fracturing are high, ranging from RMB 7000 × 10^4 to 9000 × 10^4 yuan, and the stable gas production is 1 × 10^4−2 × 10^4 m^3/d. In order to control the costs, many supporting measures (e.g. conventional logging, fracture morphology monitoring and tests of gas production profile) have been less-frequently implemented [5−7]. The post-fracturing evaluation method based on a mature software model can provide multiple solutions and requires interpretable data. For instance, the G function analytical method based on the pressure decline curve after the pump is stopped requires the pressure test data after a long period of pump stop; the interpretation can't be achieved if the time of pressure test in field is short. Therefore, the reliability of post-fracturing evaluation results is directly related to the evaluator's

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experience [8−10]. How to further accurately understand shale formation based on limited data has been a conundrum for researchers. The authors proposed a new method that can invert the reservoir parameters and qualitatively evaluate fracture morphology of post-fracturing based on fracturing curves. With this method and through full use of the data of stimulated wells, the fracture and reservoir parameters can be re-understood. Taking a shale gas well, Well P, in SE Chongqing as an example, the post-fracturing evaluation was performed, providing theoretical basis for further amelioration of fracturing design and improvement of effective stimulated reservoir volume.

1. Overview of stimulated wells

Well P in a shale gas block of SE Chongqing was obliquely drilled to 4190 m in the Lower Silurian Longmaxi Fm, with a horizontal section of 1260 m. A total of 22 intervals were fractured, with 2−3 clusters per interval. The maximum displacement of fracturing maintained at 13.0−14.5 m^3/min, the mean pressure of fracturing ranged from 60 to 70 MPa, total fluid volume reached 46542 m^3, and total sand volume was 2108 m^3.

According to the gradient of instantaneous initial shut-in pressure (*ISIP*) in formation and the existence of formation leakage (leakage zone encountered in the first 6 intervals), the fracturing pressure curve can be divided into four types: Type 1, Intervals 1−2, leaking formation, *ISIP* = 0.021−0.023 MPa/m; Type 2, Intervals 3−7, leaking formation, *ISIP* = 0.016−0.017 MPa/m; Type 3, Intervals 8−13, non-leaking formation, *ISIP* = 0.018−0.022 MPa/m; Type 4, Intervals 14−22, non-leaking formation, *ISIP* = 0.023−0.026 MPa/m. As shown in Fig. 1, Well P shows higher crustal stress at about 100 m to the toe side, and gradually-increased crustal stress to the heel side.

2. Identification of formation brittleness and plasticity

In the process of fracturing of a shale gas well, fractures are continuously initiated and propagated as prepad fluid is injected into the formation. Brittleness and plasticity of shale formation were identified depending on pressure dropping range and rate at the fracturing pressure points.

2.1. Characterization of formation fracturing

Interval 5 of Type 2 in the fracturing curve (Fig. 2) was selected to analyze the formation fracturing pressure characteristics in the prepad fluid stage trapped by the red rectangular dash circle. This interval presents a leaking formation with low crustal stress. In the process of displacement increase and a state with larger displacement, the formation was fractured, showing clear pressure dropping range of 2.1−5.2 MPa and rate of 1.68−6.67 MPa/min at three points. The large pressure dropping range and rate after fracture initiation indicates good brittleness, large fluid loss, and good existence of natural fractures in the formation.

Similarly, the formation fracture frequency, mean pressure dropping range and rate in the displacement increase stage were counted for 22 intervals in Well P (Table 1). In Intervals 1−6, abundant natural fractures existed, and pressure dropping range and rate were high; several periods of obvious fracturing occurred in the process of displacement, implying that the formation is brittleness-prone. In Intervals 7−11, pressure dropping range and rate were low, 2−3 periods of minor fracturing occurred at relatively low displacement, implying that the formation is plasticity-prone. In Intervals 12−22, due to higher crustal stress, pressure dropping rate decreased to some extent, and the frequency of obvious fracturing decreased, implying that the formation has medium plasticity and brittleness.

2.2. Quantitative evaluation of formation brittleness and plasticity

For plastic shale formation, the pressure is almost constant after fracturing, but continual deformation results in large energy consumption. For brittle shale formation, the pressure drops rapidly after fracturing, and the energy consumption is relatively small. With the method proposed in Ref. [11], the energy zone at fracture initiation in the process of fracturing

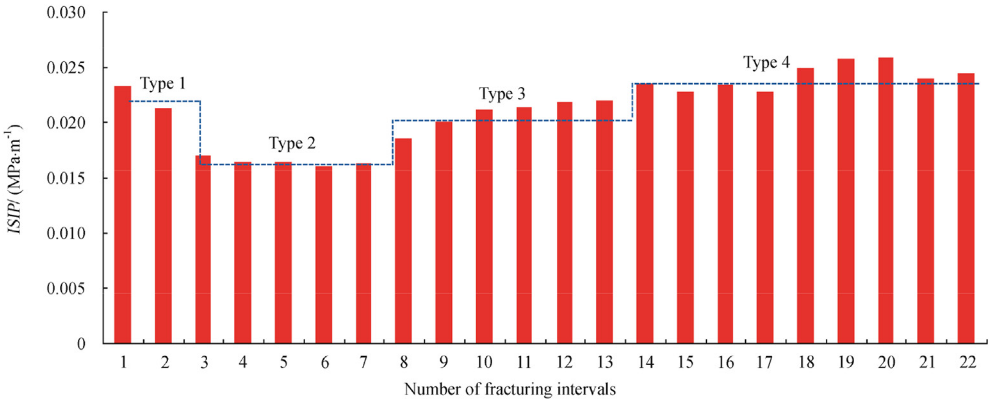

Fig. 1. Division of fracturing pressure curve for the given well.