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Research Article

An optimal design of network-fracture acidification for ultra-deep gas wells in the Lower Permian strata of the western Sichuan Basin☆

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Abstract

The Lower Permian reservoirs in the western Sichuan Basin are ultra-deep with high temperature, high pressure and developed natural fractures. Leakage and contamination of drilling fluid is the main factor restricting reservoir stimulation effects, so the acidification will be the solution also as the first choice to enhance the gas recovery. In view of this, an acidification design was proposed to minimize the contamination skin factor to the highest degree. A model was first developed to calculate the critical pumping rate for opening natural fractures in deep beds. Then, the acidification model for the rock samples of natural fractures in the experimental scale was modified, and a model was established for predicting the effective penetration distance of acid and the fracture aperture in the conditions of wellbores. Accordingly, a skin factor calculation model for network-fracture acidification was developed. It is indicated that when the acid pumping rate is 5.0 m^3/min, all natural fractures around Well S1-1 can be opened, regardless of their dip angles. Besides, the advantage of high-rate acid injection emerges gradually when the injected acid is more than 100 m^3. Moreover, for minimizing the skin factor, the network-fracture acidification in Well S1-1 was optimized by pumping 210 m^3 acid at the rate of 4.5 m^3/min. According to the optimal design idea, network-fracture acidification has been successfully applied in Well S1-1, and a high-yield industrial gas flow was produced at the rate of 83.7×10^4 m^3/d. It is concluded that network-fracture acidification technology is a safest, most economical and effective mode for the stimulation of such ultra-deep reservoirs in the study area.

Keywords: Sichuan basin; West; Late permian; Ultra-deep gas well; Natural fracture; Network-fracture acidification; Skin factor; Optimal design

High-yield gas flow was successively obtained in the Lower Permian Maokou Fm and Qixia Fm in Jiulongshan, Daxingchang and Shuangyushi structures in the western Sichuan Basin. In particular, the high-yield gas flow obtained in Well Shuangtan 1 in the Shuangyushi structure in 2014 demonstrated huge prospects for natural gas exploration and development [1—3]. The Shuangyushi structure belongs to the front fold belt of Longmenshan at the northern margin of the upper Yangtze Craton, where the Lower Permian reservoirs are generally ultra-deep (>6000 m) with high temperature (>150 °C) and high pressure (bottomhole pressure >90 MPa) [1]. Natural fractures are developed in target reservoirs and a large amount of leakage of drilling fluid occurred in some producing intervals. The leakage and contamination are the main factors restricting reservoir stimulation. Acidification is a safe, effective and economical measure for the stimulation of such ultra-deep HTHP gas wells, the purpose of which is to completely remove the damage of drilling fluid, dredge the fracture network, minimize the reservoir skin factor and thus obtain relatively high gas well productivity [4].

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Based on the geological features of the Lower Permian reservoirs in the Shuangyushi structure, the authors proposed the an acidification design to minimize the contamination skin factor specific to fracture-type reservoirs, namely, the natural fractures are reopened to drive the acid fluid flow and react along the natural fractures so as to realize deep-penetration blockage removal and acidification. Accordingly, a calculation model was developed for the opening of natural fractures, the critical pumping rate for opening natural fractures in the Qixia Fm in the western Sichuan Basin was determined and a model was established for predicting the effective penetration distance of acid in natural fractures. Based on this distance and the fracture aperture after acidizing, a skin factor calculation model for acidification was developed and the acid treatment parameters were optimized.

1. Geological features of reservoirs

The Lower Permian reservoirs in the Shuangyushi structure include Maokou Fm and Qixia Fm, which are mainly composed of gray–dark gray dolomite and dark–gray black limestone. The reservoirs are mostly buried between 6800 and 7500 m, with formation pressure coefficient of 1.4–1.9, formation temperature of 150–159 °C, porosity of 1.2–8.8% and thickness of 20–40 m. Core observation and image logging interpretation indicate that there are natural fractures and vugs in the target reservoirs (Figs. 1 and 2), which serves as the major reservoir space.

Conventional logging interpretation and drilling shows indicate that there is severe drilling fluid leakage in the sections with natural fractures (Table 1). To open the natural fractures to eliminate the damage, dredge the natural fracture networks and realize the deep-penetration network fracture acidification of acid fluid is an economical and safe mode for the stimulation of such reservoirs [4,5].

2. Network-fracture acidification design to minimize the skin factor

Leakage and contamination of drilling fluid in fracture-type reservoirs have certain characteristics. For example, a large amount of drilling fluid leakage along the natural fracture networks blocks them, and the "non-radial" contamination zone covers a wide range and causes more severe formation damage than that in conventional pore-type reservoirs [6,7]. Since the natural fracture networks contribute the most to reservoir productivity, it is inevitable to reopen the natural fractures and dredge the natural fracture networks in the stimulation of reservoirs [7]. Practices have proved that conventional matrix acidification technology cannot effectively remove the contamination in the deep formation of such reservoirs. Conventional deep acid fracturing technique to make long fractures can reduce deep-formation contamination and connect the reservoirs far from the wellbore, but only communicate limited natural fractures, possibly leading to quick decline of production after acid fracturing. The volume acid fracturing technology for complicated acid fracturing networks with high liquid amount and a high pumping rate has gradually been applied in domestic fracture-type tight carbonate reservoirs in recent years [8]. However, the single-well acidification effect of the Lower Permian ultra-deep wells in the western Sichuan Basin in the earlier stage indicates that the wellhead pressure reached 95 MPa at an acid pumping rate of 3.0 m^3/min without obvious fracture shows in the formation, indicating relatively high engineering risks in high-pumping-rate volume acid fracturing technique.

Practices have proved that the network-fracture deep-formation acidification technology can effectively dredge the natural fracture network system of the reservoirs with natural fractures, so as to improve the flow conditions of formation and thus increase productivity [9]. Essentially in this technique, high injection rate is applied when engineering conditions permit, so as to increase the bottomhole pressure and open the natural fractures; the acid fluid flows into the reservoir in a non-radial form along the natural fractures and forces the acidizing fractures to expand in depth, so as to increase the permeability in the near wellbore zone, realize in-depth blockage removal, increase the gas drainage radius, minimize the skin factor and obtain high-yield gas flow (Fig. 3) [10]. In order to implement network-fracture acidification in the Lower Permian ultra-deep HTHP gas wells in the western

Fig. 1. Pictures of some coring sections in the Qixia Fm of Well S3.