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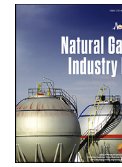

Research Article

Numerical simulation and field application of diverting acid acidizing in the Lower Cambrian Longwangmiao Fm gas reservoirs in the Sichuan Basin☆,☆☆

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Abstract

The Lower Cambrian Longwangmiao dolomite gas reservoirs in the Sichuan Basin are characterized by well-developed natural micro-fractures and dissolved pores and cavities. Due to the strong heterogeneity of reservoirs and the serious damage of drilling and completion fluids, acid placement is difficult, and especially the acidizing stimulation of long-interval highly deviated wells or horizontal wells is more difficult. In this paper, the diverting mechanism and rheological behavior of viscoelastic surfactant (VES) based diverting acid was firstly investigated, and the diverting acid with good diversion performance and low secondary damage was selected as the main acid. Then, based on the experimental results of its rheological behaviors, an empirical model of effective viscosity was fitted and a two-scale wormhole propagation model was coupled. And accordingly, a mathematical model for the acidizing of self-diverting acid was established to simulate the pH value, Ca^{2+} concentration, effective viscosity and wormhole shape under the effect of diverting acid in long-interval highly deviated wells that are non-uniformly damaged. Finally, gelled acid and 5% VES diverting acid were compared in terms of their etched wormhole shapes, flow rate distribution and acid imbibition profiles. It is shown that the diverting acid can obviously improve the acid imbibition profile of strong-heterogeneity reservoirs to intensify low-permeability reservoir stimulation. In view of the strong heterogeneity of Longwangmiao dolomite reservoirs and the complexities of drilling and completion fluid damage in the Sichuan Basin, a placement technology was developed for variable VES concentration diverting acid in horizontal wells and long-interval highly deviated wells completed with slotted liners. This acid placement technology has been practically applied in 8 wells and their cumulative gas production rate tested at the wellhead is 1233.46×10^4 m^3/d. The average production stimulation ratio per well is up to 1.95. It provides a support for the efficient development of the Longwangmiao giant gas reservoir.

Keywords: Sichuan Basin; Early Cambrian; Longwangmiao Fm gas reservoir; Dolomite; Diverting acid; Rheological behavior; Matrix acidizing; Numerical simulation; Field application; Highly-efficient development

1. Introduction

The Lower Cambrian Longwangmiao Fm gas reservoirs in the Moxi block of the Sichuan Basin are the largest monolithic carbonate gas reservoirs ever discovered in China [1,2]. They are composed of dolomite and contain microfractures and

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millimeter−centimeter-sized dissolution pores. With strong heterogeneity, these reservoirs are dominantly fractured-cavity reservoirs and fracture-pore or pore reservoirs locally [3]. They are more than 4500 m in depth, and characterized by low porosity (2.48−8.91%, with an average of 5.19%), medium to low permeability (0.01−10.00 mD), high temperature (140.21 °C), high pressure (pressure coefficient of 1.64) and acidity (with H_2S content of 5.00−11.68 g/m^3 and CO_2 content of 21.50−48.83 g/m^3).

Drilling fluid loss or influx during the overbalanced drilling is serious. The permeability damage of matrix rock sample is 98.20% and the permeability damage of fracture rock sample is 82.23−89.23% [4,5]. Thus, it is urgent to carry out acidizing stimulation in order to fully relieve the damages of drilling and completion fluids and release the natural flow of gas [6,7]. However, in long-interval highly deviated wells and horizontal wells, the characteristics of drilling fluid damages are complex, and the depth and extent of damages of drilling and completion fluid in flux are significantly heterogeneous. In addition, the reservoirs have natural strong heterogeneity. With consideration to these factors, acid placement is particularly important for the stimulation of long-interval highly deviated wells and horizontal wells. Viscoelastic surfactant diverting acid is a kind of polymer-free acid liquid system. Its viscosity increases and then decreases with the acid−rock reaction. It can realize self-diversion [8]. The system is widely used in matrix acidification of carbonate reservoir [9−12].

2. Steering mechanism

2.1. Viscosity variation mechanism

The key viscoelastic surfactants commonly used for diverting acid are zwitterionic surfactants or cationic quaternary ammonium surfactants. Taking zwitterionic surfactants for example, they exhibit various charge characteristics at different pH values. When the pH value is lower than the isoelectric point, its anion group ionization is weak and it shows cationic characteristics. In this case, the surfactant molecules are distributed in the form of monomer, so the fresh acid has low viscosity and mainly enters the intervals with high permeability or low damage that has high acid absorption ability. With the increase of pH value, the ionization degree of anionic groups increases, the anionic properties increase and the cationic properties decrease. The neutral characteristics begin to appear from the isoelectric point, the charge effect is weakened, and the surfactant molecules are spherical or short rod-like micelles. Under the cross-linking of divalent cations (Ca^{2+} and Mg^{2+}) generated by the acid−rock reaction, spherical or short rod-like micelles entangle with each other to form wormlike micelles with a spatial network structure. Then the viscosity of the system increases sharply and the high-permeability zone is temporarily blocked, forcing the subsequent acid to enter the low-permeability zone or high-damage zone [8]. With the further reduction of H^+ concentration, or when encountering the crude oil, natural gas and other hydrocarbon substances in the reservoir, worm-like micelles change into spherical micelles, resulting in automatic gel breaking and viscosity reduction, which is conducive to residual acid flowback (Fig. 1).

2.2. Rheological behavior

The rheological behavior of diverting acid changes with the acid−rock reaction process, which is the root cause for diverting. It is found that acid concentration or pH value, VES concentration and Ca^{2+} concentration are the main factors that affect the viscosity of the diverting acid, and the effect of Mg^{2+} and Na^+ is relatively small [13].

In simulating the spent acids of diverting acid at a specific time during the acid−rock reaction, HCl acid solution was first added according to the setting concentration of hydrochloric acid and surfactant was added at a suitable concentration. According to the acid−rock reaction metrology relationship, acid−rock reaction product $CaCl_2$ calculated [14] by the consumption of acid (the difference between the amount of 20% fresh acid and the amount of residual acid) was added to determine its apparent viscosity in the 170 s^{-1}. The apparent viscosity curves of the residual diverting acid at a mass concentration of 5% under different VES concentrations are shown in Fig. 2. The apparent viscosity of the diverting acid at a VES concentration of 5% varies with pH and Ca^{2+} concentration, as is shown in Fig. 3.

Using the empirical rheological model of diverting acid proposed by Liu et al. [15], the empirical model of the rheological behavior of diverting acid can be fitted as follows.

$$\mu_{\text{eff}} = \mu_0 + \mu_{\max} f(\text{pH}) f\left(\text{Ca}^{2+}\right) f(\text{VES}) \tag{1}$$

$$f(\text{pH}) = \frac{\text{erf}(b \cdot \text{pH} - c) + 1}{W_1} \tag{2}$$

$$f\left(\text{Ca}^{2+}\right) = \exp\left[-\left(\frac{C_{\text{Ca}^{2+}} - C_{\text{m,Ca}^{2+}}}{W_2}\right)^2\right] \tag{3}$$

$$f(\text{VES}) = \exp\left[-0.5\left(\frac{C_{\text{VES}} - C_{\text{m,VES}}}{W_1}\right)^2\right] \tag{4}$$

where, μ_{eff} represents the effective viscosity, mPa·s; similarly, μ_0: the apparent viscosity of fresh diverting acid, which is set to be 5.68 mPa s; $\mu_{\max}$: the maximum apparent viscosity of the diverting acid, which is set to be 126.52 mPa s; C^{2+}_{Ca}: the mass concentration of $CaCl_2$; $C^{2+}_{\text{m,Ca}}$: the $CaCl_2$ mass concentration corresponding to the maximum apparent viscosity of the diverting acid, which is set to be 25%; C_{VES}:the VES mass concentration; $C_{\text{m,VES}}$: the VES concentration corresponding to the maximum apparent viscosity of the diverting acid, which is set to be 5%; W_1, W_2, W_3, b and c respectively represent the fitting parameters (W_1 = 1.85, W_2 = 14, W_3 = 1.756, b = 1.2, c = 1.5, dimensionless).

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