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RESEARCH PAPER

Multistage interwell chemical tracing for step-by-step profile control of water channeling and flooding of fractured ultra-low permeability reservoirs

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Abstract: To monitor the dynamic variations of sweep area and formation parameters during the process of multiple slugs step-by-step profile control, the multistage interwell chemical tracing technique was proposed and tested in field, in line with the features of the step-by-step profile control in fractured ultra-low permeability reservoirs and the basic principle of chemical tracing test. According to the design scheme of step-by-step profile control and the characteristics of water channeling and flooding in fractured ultra-low permeability reservoirs, this study worked out times-design method for interwell tracing, optimized the selection principle of chemical tracer and calculation formula of tracer dosage, and set up the parameter optimization forecasting method of step-by-step profile control based on multistage interwell tracing. The application results of the method show multistage interwell chemical tracing can reflect dynamic variation of fractured parameters effectively, and the monitoring results match with the dynamic production testing results, demonstrating good adaptability of the method.

Key words: fractured reservoir; ultra-low permeability reservoir; step-by-step profile control; multistage interwell tracing; dynamic monitoring

Introduction

In fractured ultra-low permeability reservoirs featuring tight matrix, complex and variable fracture systems and strong heterogeneity, water channeling pathways are likely to occur during waterflooding, causing severe water channeling and flooding of the reservoir[1–4]. At present, multiple slug step-by-step profile control is a major treatment to tackle serious water channeling and flooding in this kind of reservoir[5–6], and the real time dynamic monitoring is taken to ensure the effectiveness of it. As one important means for monitoring the dynamics between different wells, a complete theory system on chemical inter-well tracer monitoring has been established, and gradually accepted in field practices[7–17]. Previously, the reservoir was treated as a series of non-communicating layers in different kinds of interpretation methods (analytical method, numerical method and semi-analytical method)[11–17], but the basic hypothesis of the above methods is not suitable for the interpretation of fractured ultra-low permeability reservoir[2–3]. Meanwhile, the sweeping range and parameters of the formation during the process of step-by-step profile control dynamically change with the time, the traditional inter-well tracer monitoring, lacking continuity and dynamicity, can't effectively monitor the dynamic variation during the step-by-step profile control[7–10].

Multistage inter-well tracer monitoring for the step-by-step profile control of water channeling and flooding of ultra-low permeability reservoir has been proposed in this study, which allows real-time monitoring of plugging situation, fracture parameters, and dynamic sweeping of injection water of various levels of channeling pathways, optimization and prediction of control parameters, and improvement of effectiveness of step-by-step profile control at last. The multistage inter-well tracer monitoring for the step-by-step profile control of water channeling and flooding of ultra-low permeability reservoir can provide an important basis for parameter optimization and effect evaluation and prediction of the step-by-step profile control.

1. Design of tracer test times

Multistage inter-well chemical tracer test for step-by-step

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profile control is the precondition to ensure smooth running of tracer monitoring and step by step profile control[18]. The design of tracer monitoring times should not only consider the cycle of tracer monitoring and step by step profile control, but also avoid the influence of injected gel slugs on tracer monitoring results.

Based on the injection scheme of step-by-step profile control, the injection sequence of gel slugs and tracer slugs and tracer monitoring times must be worked out. What the tracer monitored is the distribution of injected fluid under certain pressure, but the injection of gel slug would cause pressure fluctuations inevitably. Considering the crosslinking time of gel and retardance of pressure propagation, the injection of gel slug will have a little influence on tracer monitoring results, if a gel slug is injected when the tracer of last time reached the peak concentration. Assuming the number of injected gel slug is E and the times of injected tracer is F, in order to ensure all works can be completed within the time T, the sum of injection time of all slug, gelling time and tracer monitoring time should be equal or less than time T, then:

$$\sum_{e=1}^{E}\left(\frac{V_e}{Q}+a_e\right)+\sum_{f=1}^{F}\left(\frac{V_f}{Q}+t_{\mathrm{p}f}\right)\le T \tag{1}$$

where

$$t_{\mathrm{p}f}=\max t_{\mathrm{p}ji} \tag{2}$$

Assuming the production well j has i fracture belts and each belt has multiple fractures. The fracture belt i is equivalent to a flowing tube cluster consisting of n_{ji} tubes in D_{ji} diameter, then:

$$t_{\mathrm{p}ji}=\frac{\pi {s_{ji}}^2\left(\sum_{i=1}^{N_j}\frac{n_{ji}{D_{ji}}^4}{s_{ji}}\right)\left(\sum_{j=1}^{M}\sum_{i=1}^{N_j}\frac{n_{ji}{D_{ji}}^4}{s_{ji}}\right)}{4Q{D_{ji}}^2\left(\pi\sum_{i=1}^{N_j}\frac{n_{ji}{D_{ji}}^4}{s_{ji}}-4{D_{ji}}^2 f_j V_e\right)} \tag{3}$$

where

$$f_j=m_j\bigg/\sum_{j=1}^{M}m_j \tag{4}$$

2. Tracer selection principle and calculation of tracer dosage

Selecting different tracers for different times and calculating tracer dosage at every stage are the most important part of scheme design of the multistage inter-well chemical tracer monitoring for step-by-step profile control of water channeling and flooding of fractured ultra-low permeability reservoir[18–19].

2.1. Evaluation and screening principle of multistage interwell chemical tracer

In the screening of traditional tracers used in one-time monitoring, only the physicochemical properties of the tracer, reservoir rock properties, the properties of formation water and injected water, economy, security and environmental protection etc need to be considered, while in picking tracers for multi-stage interwell monitoring, besides all the factors mentioned above, the interaction between different times of tracers and physicochemical properties of the tracer and injected gel also need to be considered. To effectively avoid the interference of different times of tracers, at least two types of tracers should be chosen, and the method of multistage alternative injection should be adopted. In addition to the evaluation of heat resistance, compatibility between tracer and injected water, compatibility between tracer and formation water, rock adsorption of tracer and reservoir damage, multistage tracer screening must evaluate the compatibility between the tracers and gel adsorption of the tracers[18]. The selected multistage chemical tracers should have the biggest maximum absorption wavelength difference and lower gel adsorption.

2.2. Calculation of multistage interwell tracer dosage

Based on the characteristics of water flooding in fractured ultra-low permeability reservoirs, the injected water mainly flow along the fracture systems with the lowest resistance, and tracer in injection water can monitor the fracture systems. Therefore, under the condition of Brigham-Smith water flooding[11,19], the formula of five-point pattern chemical tracer dosage is adapted to the calculation formula of interwell chemical tracer dosage that can be used in fractured ultra-low permeability reservoirs:

$$m_{\mathrm{T}}=4.442\times10^{-6}\phi_{\mathrm{f}}\bar{h}\frac{\rho_{\mathrm{o}}f_{\mathrm{ws}}}{\rho_{\mathrm{o}}f_{\mathrm{ws}}+\rho_{\mathrm{w}}B_{\mathrm{o}}\left(1-f_{\mathrm{ws}}\right)}\frac{d}{a}C_{\mathrm{s\,max}}L^{1.735} \tag{5}$$

The formula above is applicable to calculate tracer dosage of five-point well pattern. For other types of well pattern, only the conversion coefficient of maximum recovery concentration between ground and reservoir needs to be changed[18].

Water cut can be calculated from dynamic production data of each production well by formula (5). Due to the complexity of fracture porosity calculation, the fracture porosity of the first stage tracer monitoring before step-by-step profile control is usually calculated mainly according to the fracture density and fracture parameters in the research area, thus calculation formula of the first stage tracer dosage can be expressed as follows:

$$m_{\mathrm{T1}}=4.442\times10^{-6}\frac{lwh_{\mathrm{f}}\rho_{\mathrm{f}}H}{V}\bar{h}\frac{\rho_{\mathrm{o}}f_{\mathrm{ws}}}{\rho_{\mathrm{o}}f_{\mathrm{ws}}+\rho_{\mathrm{w}}B_{\mathrm{o}}\left(1-f_{\mathrm{ws}}\right)}\times \frac{d}{a}C_{\mathrm{s\,max}}L^{1.735} \tag{6}$$

Fractures of various levels are plugged step by step, fracture porosity and water cut decrease gradually with the ongoing of step-by-step profile control. Based on the last tracer interpretation results, the fracture volume can be worked out, and then the corresponding fracture porosity can be calculated. Therefore, tracer dosage calculation formulas of different interwell chemical tracer injection times can be deduced:

$$m_{\mathrm{T}f}=4.442\times10^{-6}\frac{\phi_{\mathrm{f}}V-\sum_{e=1}^{k}V_e}{V}\bar{h}\frac{\rho_{\mathrm{o}}f_{\mathrm{ws}}}{\rho_{\mathrm{o}}f_{\mathrm{ws}}+\rho_{\mathrm{w}}B_{\mathrm{o}}\left(1-f_{\mathrm{ws}}\right)}\times$$