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Optimizing the particle size distribution of drill-in fluids based on fractal characteristics of porous media and solid particles

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ABSTRACT

Drill-in fluid loss will lead to severe formation damage, and the particle size distribution (PSD) of lost circulation material is one of the most essential factors to control the drill-in fluid loss and protect the formation. In this paper, a fractal model for optimal solid PSD in drill-in fluids is developed for porous reservoir protection. The proposed model presents the following features: It demands particle size should be determined based on the "d_{90} Rule", it requires the average capillary pressure curve to characterize the whole porous reservoir, and it allows for the microstructure characteristics of porous media and solid particles. The core dynamic damage experiments to verify this fractal model are carried out. Experimental results indicate that the loss of drill-in fluids designed by the proposed fractal model can be controlled within 10 min, and the permeability recovery rate after dynamic damage is above 90%, which means that formation damage is mitigated and well-controlled by the proposed fractal model. It is preliminarily proved that the proposed fractal model is of great validity and more suitable for formation damage control.

1. Introduction

Prevention of reservoir damage is an extremely important measure while exploring, drilling, developing oil and gas reservoirs (Amanullah et al., 2011). Formation damage induced by the invasion of drill-in fluids will severely obstruct the timely discovery, accurate evaluation and efficient development of oil and gas reservoirs (Bennion, 2002; Kalantariasl and Bedrikovetsky, 2014; Kang et al., 2014a, 2014b; You et al., 2015). Correspondingly, drill-in fluids are supposed to be prevented from invading into the formation as much as possible for mitigating the formation damage and protecting the formation (Civan, 2007; He and Stephens, 2011; Kang et al. 2012, 2014a, 2014b; Ezeakacha and Salehi, 2018). It is a key technology to carry out formation damage control (FDC) measures effectively by designing reasonably performance of drill-in fluids, which includes the particle size distribution (PSD) and the concentration of solids, the rheological property of drill-in fluids, etc. (Mei et al., 1996; Smith et al., 1996; Suri and Sharma, 2001; Mohamed, 2011; Savari et al., 2011; Kumar et al., 2013; You et al., 2014; Xu et al., 2017a, 2017b). Especially, optimal PSD of solid material, matching with the pore size distribution of formation, is essential to prevent the drill-in fluids from invading into the formation, which has attracted a lot of interest (Kaeuffer, 1973; Abrams, 1977; Luo and Luo, 1992; Dick et al., 2000; Vickers et al., 2006; Xu et al., 2017a, 2017b).

Several design guidelines have been proposed to optimize the sized-material PSD of drill-in fluids to maximize the sealing efficiency and minimize the formation damage, including 1/3 Rule, Ideal Packing Theory (IPT), d_{90} Rule, etc. Abrams (1977) first proposed the "1/3 Rule", which reveals that the particle size of the bridging material should be at least equal to or lightly greater than 1/3 of the pore size of reservoir rocks, and the solid volume concentration of drill-in fluids should be at least 5%. Based on the "1/3 Rule", Luo and Luo (1992) developed the "2/3 Bridging Rule", which indicates that the best bridging effect will be achieved when the size of rigid particles is equal to 2/3 of the pore size of reservoir rocks, and the solid volume concentration of drill-in fluids should be at least 3%. Kaeuffer (1973) provided the IPT method transferred from the paint industry to practical application in petroleum industry, which suggests that the ideal packing effect would take place at which the cumulative volume fraction of the temporary plugging agents is directly proportional to the square root of the particle size. Subsequently, the IPT method was systematically developed and elaborated (Dick et al., 2000; Vickers et al., 2006). Hands et al. (1998) developed the "d_{90} Rule" that d_{90} of PSD should be designed to equal to the largest pore size, which is better applied to the in-situ application and more suitable for protecting the pores with larger size. Due to the introduction of PSD design guidelines

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mentioned above, numerous experimental investigations have been conducted to better improve the pore/fracture plugging efficiency (Kefi et al., 2010; He and Stephens, 2011; Chellappah and Aston, 2012; Razavi et al., 2016; Xu et al., 2018). These methods, however, simply emphasizing that the solid particle size would match with rock pore size, mostly overlook an intrinsic issue that it is the distribution characteristics of both rock pore structure and solid particles affecting the plugging efficiency. Consequently, formation damage issues caused by drilling fluid loss still occur frequently (Kang et al., 2014a, 2014b).

The microstructure characteristics of porous media (PM) are the important-internal factors to control the degree and types of formation damage (Xie et al., 2011). Thus, in order to mitigate the formation damage caused by drill-in fluid loss, it is the possibly best way to make sure a good match between the size distribution characteristics of solid particles and rock pores. According to fractal geometry theory, the complexity and features of solid particles and PM-reservoir pores can be characterized by fractal dimension (FD) (Mandelbrot and Wheeler, 1983; Katz and Thompson, 1985; Yu and Li, 2001, 2004).

In summary, in order to overcome the above-mentioned drawbacks, it is more essential to develop a fractal model for the optimal solid PSD in drill-in fluids for porous media, which accounts for the complexity and characteristics of the whole reservoir pores and sized solid material. It is noted that the information of pore fractal characteristics of a reservoir would be obtained by the average capillary pressure curve (Angulo et al., 1992).

In this work, based on the size-distribution fractal characteristics of rock pores and solid particles, a new rule to optimize the PSD is proposed. This paper is organized as follows. First, we build the fractal models of reservoir capillary pressure and particle size. Then, we illustrate the procedure to optimize the solid PSD for minimizing formation damage. After that, we conduct core damage experiments, show the results and discuss differences of results obtained by three different methods. Finally, we summarize our conclusions.

2. Methodology

2.1. Fractal model for capillary pressure

According to the fractal geometry theory, the number of pores whose size is equal to or greater than size r of pores with fractal characteristics have a power-law relationship with size r as follows (Katz and Thompson, 1985; Krohn, 1988):

$$N(>r) = \int_{r}^{r_{\max}} P(r)\mathrm{d}r = ar^{-D_c} \tag{1}$$

Eq. (1) describes the scaling relationship of cumulative pore population with FD of pore size distribution.

The probability density function of the number of fractal pores can be obtained by deriving Eq. (1):

$$P(r) = \frac{\mathrm{d}N(>r)}{\mathrm{d}r} = \alpha' r^{-D_c-1} \tag{2}$$

Where $\alpha' = -aD_c$. According to probability theory, the probability function $P(r)$ should satisfy the following relationship (Yu and Li, 2001):

$$\int_0^{\infty} P(r)\mathrm{d}r = \int_{r_{\min}}^{r_{\max}} P(r)\mathrm{d}r = 1 \tag{3}$$

Eq. (3) indicates that $r_{\min} < < r_{\max}$ must be satisfied for a porous medium with fractal features, otherwise the porous medium is non-fractal.

The cumulative pore volume $V(<r)$ whose size is smaller than size r can be calculated by following expression:

$$V(<r) = \int_{r_{\min}}^{r} P(r)\cdot\alpha r^3\mathrm{d}r = \alpha''\left(r^{3-D_c} - r_{\min}^{3-D_c}\right) \tag{4}$$

Where $\alpha'' = \alpha'\alpha/(3-D_c)$, α is a constant related to the shape of pores ($\alpha = 1$ for cubic-shape pores, $\alpha = 4\pi/3$ for spherical-shape pores).

The total pore volume of PM can be calculated by displacing size r with $r_{\max}$ in Eq. (4):

$$V_{\mathrm{total}} = \alpha''\left(r_{\max}^{3-D_c} - r_{\min}^{3-D_c}\right) \tag{5}$$

Thus, the cumulative pore volume percentage whose size is less than size r can be derived by the following equation:

$$S = \frac{V(<r)}{V_{\mathrm{total}}} = \frac{r^{3-D_c} - r_{\min}^{3-D_c}}{r_{\max}^{3-D_c} - r_{\min}^{3-D_c}} \tag{6}$$

Generally, for the fractal PM, the maximum pore size is much larger than the minimum one (i.e., $r_{\max} > > r_{\min}$), Eq. (6) can be simplified as:

$$S = \left(\frac{r}{r_{\max}}\right)^{\lambda} \tag{7}$$

Where $\lambda = 3\text{-}D_c$.

Assuming that the fractal PM is consisted of cylindrical cubes with radius r, the required capillary pressure P_c for fluid entering the pores should obey the Young-Laplace equation:

$$P_c = \frac{2\sigma\cos\theta}{r} \tag{8}$$

Substituting Eq. (8) into Eq. (7) leads to the capillary-pressure fractal model:

$$S_w = \left(\frac{P_e}{P_c}\right)^{\lambda} = \left(\frac{P_e}{P_c}\right)^{3-D_c} \tag{9}$$

Taking the logarithm of both sides of Eq. (9):

$$\ln(S_w) = (D_c - 3)\ln(P_c) + (3 - D_c)\ln(P_e) \tag{10}$$

It can be seen from Eq. (10) that there is a linear relationship between ln (S_w) and ln (P_c), and the slope of the straight line ln (P_c) versus ln (S_w) is (D_c-3). This relationship is the key criteria to judge if a porous medium satisfies fractal characteristics (Zheng et al., 2017), and to obtain the FD by fitting the experimental data.

2.2. Fractal model for particle size distribution

According to fractal theory, the particle number whose size is equal to size d of particles with fractal characteristics have a power-law relationship with size r as follows (Hyslip and Vallejo, 1997; Zhang, 2002; Chu et al., 2017):

$$n(d) \propto d^{-D_p} \tag{11}$$

The particle cumulative mass whose size is greater than d can be expressed by:

$$M(>d) \propto \int_{d}^{d_{\max}} m(d)\ \mathrm{d}\ n(d) \tag{12}$$

In addition, the mass of a single particle can be obtained by:

$$m(d) = \rho V(d) = \rho\frac{4}{3}\pi d^3 \propto d^3 \tag{13}$$

Taking Eq. (11) and Eq. (13) into Eq. (12), Eq. (12) can be derived as:

$$M(>d) \propto \int_{d}^{d_{\max}} d^{2-D_p}\ \mathrm{d}\ (d) \tag{14}$$

Finally, the particle cumulative mass $M(>d)$ whose size is equal to or greater than d can be calculated by integrating Eq. (14):

$$M(>d) = \alpha\left(d_{\max}^{3-D_p} - d^{3-D_p}\right) \tag{15}$$

The total particle mass can be obtained by substituting the minimum size $d_{\min}$ into Eq. (15):

$$M = \alpha\left(d_{\max}^{3-D_p} - d_{\min}^{3-D_p}\right) \tag{16}$$