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Influence of stress sensitivity on microscopic pore structure and fluid flow in porous media

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ABSTRACT

At present, large quantities of experiments related to stress sensitivities on the macroscale have been conducted. Pore structure is complicated, especially in unconventional reservoirs of tight sandstone. As a result, stress sensitivity has a great influence on changing the pore space. This is of great significance for enhancing oil recovery to systematically study the stress sensitivity at the pore scale. In this paper, based on CT scanning technology, which can capture the real pore space characteristics of the core samples, and combined with a digital core and pore network model, the relationships between the effective stress and the pore structure are obtained. First, the theory and method of constructing the digital core and extracting the pore network model according to CT scanning are introduced. The 3D core image could be obtained after CT scanning, and the digital core is established after filtering and segmentation. The rock structure characteristics are obtained from analyzing the geometry-topology structure of the extracted pore network model, and the fluid flow analysis is conducted by numerical flow simulation. Second, the stress sensitivity experiments and analysis are conducted. Stress sensitivity experiments are performed in the carbon fiber core holder, and the core is scanned under a series of pressures. Digital cores and pore network models under a series of pressures are obtained, and the corresponding pore structure characteristics and fluid flow laws are analyzed. Last, these methods are employed in middle-high permeability sandstone and tight sandstone. The stress sensitivities of these sandstones are achieved and compared. In this paper, the stress sensitivity evaluation method at pore-scale is developed, which has the practical application of oilfield development.

1. Introduction

Stress sensitivity is the changing of permeability and pore structure resulting from the changing of the effective pressure, which has a great influence on fluid flow in porous media (Dvorkin et al., 1996). The storage and flow capability of the reservoir are determined by the pore structure of the porous media. Thus, it is necessary to analyze the effect of the stress sensitivity on pore structure and the fluid flow in porous media (Vairogs et al., 1971; Warpinski and Teufel, 1992). In this way, we can analyze the reasons that cause the stress sensitivity fundamentally, and reveal its nature. Particularly in tight oil reservoirs, formation pressure-sensitivity can affect oil production. Specifically, pressure-sensitive permeability affects both the permeability near wells and the production rates of pressure-sensitive reservoir. The permeability of the conglomerate decreases 85%–90% and the sandstone decreases 10%–20%, which means serious damage to the formation (Lei et al., 2007). The changing of the pore structure is an important reason that causes stress sensitivity. The simulation based on digital core can reveal the mechanism of stress sensitivity. In order to understand the mechanism of stress sensitivity better, it is necessary to combine microscopic and macroscopic scale (Yuan et al., 2015a). Rather, we must study this effect at the pore scale.

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In this paper, based on real core samples and the microscopic research method, the mechanism of the stress sensitivity influencing the fluid flow laws and the pore structure are studied (Yuan et al., 2015b).

Generally speaking, there are two methods to study stress sensitivity (Holt et al., 2005). The first is to use conventional experiments. Using physical experiments, the effective pressure influencing on the porosity and permeability of different types of reservoirs can be obtained (Li et al., 2013; Ruistuen et al., 1996); the other method is modeling and numerical simulation. In this method, coupled models of rock matrix deformation and fluid flow in porous media are developed (Cappa and Rutqvist, 2011; Rutqvist and Stephansson, 2003).

In the 1920s, some studies addressed how permeability changes with confining pressure. For elastic porous media, Terzaghi studied fluid flow in a deformable saturated medium (Terzaghi, 1925). Terzaghi proposed the one-dimensional consolidation theory, which considered saturated fluid flow consolidation, and obtained the effective stress formula. However, this formula is limited in real engineering applications due to its assumptions incompressible soil particles and fluid in the soil pores. After 1941, Biot developed the three-dimensional consolidation theory and extended it to apply to anisotropic porous media, motive power, stress analysis of dam foundation, soil consolidation, and so on (Biot, 1941, 1956). Some researchers developed their methods and mentioned that Biot's coefficient or fracture porosity would strongly affect the value of stress-sensitivity index (Zhu, 2013). Based on Boit's theory, Noorishad surmised that the stress field should be considered when we analyze flow in porous media, and the equations should be developed into constitutive relations with nonlinear deformation (Noorishad et al., 1982). He studied the relationship between stress and flow in porous media based on the developed equations. Bruno and Nakagawa studied the effect of pore pressure on rocks (Bruno and Nakagawa, 1991). Chen extended the conventional flow equation coupling of stress-strain, which can be used to calculate complicated reservoirs, such as fractured reservoirs (Chen et al., 1995). The porosity and permeability change with stress, but their changing rates are different. Compared with permeability, porosity has a smaller variation range. There are many conclusions based on the results of these experiments: with increasing confining pressure, porosity and permeability decrease. And, some other factors will influence permeability, including temperature, pore fluid pressure and stress loading methods.

Generally speaking, porosity and permeability both displayed classic stress sensitivity behavior (Lei et al., 2015). Each property followed a fairly rapid initial decrease at the beginning of the stress increasing process. Thereafter the property decline followed a slower decline with increasing stress. Porosity is a less stress sensitivity property than permeability (Farquhar et al., 1993). The reason is that the degree of formation compaction is greater in the low permeability reservoir, which means that with increasing effective stress, porosity will decrease slightly, but permeability will change substantially because of the deformation of the throats in porous media (Lei et al., 2007; McLatchie et al., 1958; Zhu, 2013).

Micro flow simulation is a type of technology based on the real digital core. The main work is that digital core can be reconstructed by physical experiments and numerical algorithms. Micro flow simulations can be conducted in the reconstructed digital rock. This is a new research method to study the influence of the stress sensitivity on microscopic pore structure and fluid flow in porous media. Some research have been conducted on microscopic structures of porous media under different effective stress conditions, however, these research are few and limited in application. At present, there are still some problems involved in stress sensitivity experiments: (1) Most stress sensitivity research is conducted on the macroscale, with few studies at the pore scale (An et al., 2016; Blunt, 2001). Because the pore structure change is an important source of stress sensitivity, it is necessary to study microstructure deformation, which results from changes in stress at the pore scale. This study can provide a better way to understand stress sensitivity at the microscopic scale. (2) The research equipment and process of pore structure change are imperfect. At present, most pore structure evolution research employ CT or SEM of samples removed from a pressure vessel, which cannot obtain the real pore structure in terms of confining pressure. We modify this experimental method, and attempt to obtain the real pore structure of core samples under different stress conditions. With the development of this technology and method, micro stress sensitivity research will be gradually improved based on digital rocks.

During the development of the reservoir, the formation is unavoidably influenced by stress, which deforms the pore structure. As a result, the physical properties of the reservoir are greatly influenced. Thus, the relationship between micro and macro characteristics can be obtained by studying the microscopic structure change in micro-scale experiments. The main content and procedure of this paper are as follows: (1) Reconstruct the digital core based on CT scanning; (2) Establish an evaluation method of stress sensitivity based on CT scanning images; (3) Analyze the stress influence on pore structure and flow ability; (4) Compare the stress influence degree on the middle-high permeability reservoir and low permeability reservoir.

2. The experimental process to study stress sensitivity

The diameter of the core sample is 10 mm, and the length of the core sample is approximately 15 mm–30 mm. A conventional core holder is usually made of stainless steel, but the core needs to be scanned by a CT scanner in this experiment, so the material that used to make core holder can be carbon fiber, PEEK material and other material that will allow X-ray through. In this study, we choose carbon fiber (tensile strength is greater than 73 MPa, density is 1.26–1.34 g/cm^3, and Brinell hardness is greater than 10) to make it. The core holder is specially made for this study and is shown in Fig. 1.

The CT scanner is MicroXCT-400 which is produced by Zeiss. The experimental procedures of stress sensitivity based on CT scanning are as follows:

(1) Put the core into the core holder. Scan it at the condition without confining pressure. Adjust the x-ray resource, detector and sample to obtain three-dimensional core images without confining pressure.

(2) Assemble the instruments: connect the hand pump, six-way valve and core holder together according to Fig. 2. It is more convenient and easier to use six-way valve compared with

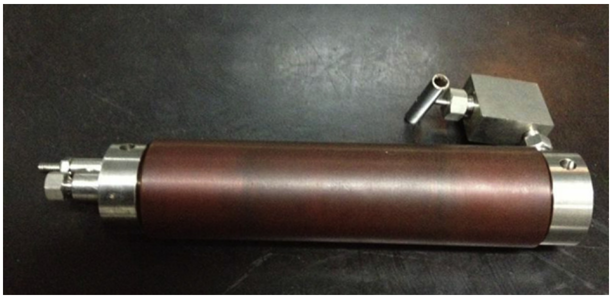

Fig. 1. Core holder made of carbon fiber.