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RESEARCH PAPER

Visualization experiments on polymer-weak gel profile control and displacement by NMR technique

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Abstract: The distribution and migration characteristics of weak gel in the core were observed by combining nuclear magnetic resonance (NMR) imaging technology with the core displacement experiment, and the oil displacement features of different polymer-weak gel combinations were examined with visualization experiments. Three combination patterns of polymer and weak gel were designed: waterflooding + polymer flooding (pattern 1), waterflooding + polymer flooding + weak gel flooding (pattern 2), and waterflooding + weak gel flooding + polymer flooding (pattern 3). The pressure variations, T_2 spectra, nuclear magnetic resonance images, oil displacement efficiencies under the different patterns were analyzed. The results show that the nuclear magnetic images can not only provide the direct information of weak gel distribution and migration characteristics inside the core, but also reflect the distribution characteristics of remaining oil; the T_2 spectrum characteristics indicate that both polymer and weak gel have the function of profile control and oil displacement, and the pattern 2 has the best profile control effect; of the three patterns, pattern 2 has the highest oil displacement efficiency of 78.84%, which is 18.33% higher than the displacement efficiency of water flooding in the initial stage.

Key words: weak gel; polymer; nuclear magnetic resonance (NMR); visualization displacement experiment; oil displacement efficiency

Introduction

Polymer and weak gel flooding are two effective chemical methods to enhance oil recovery (EOR)[1–4]. The lab experiments, including the etching and pack models, are the common methods to study the microscopic mechanism of polymer and weak gel flooding, and the fluid flow characteristics by means of microscope[5–9]. But relying on observation with optical microscope, these methods require the samples to have some transparency, so the samples must be very thin (3 mm), which limits the fluid flow along the thickness direction, and thus these methods can only simulate the fluid flow in the plane direction. As the traditional core displacement experiment doesn't allow direct observation of fluid flow inside the core, it can't be used to look directly into the working mechanism of fluid in micropores and fractures in the core. In view of this, many researchers have worked on developing visualized core displacement experiment method, and have developed the visual displacement apparatus mainly based on electronic computer X-ray tomography technique (CT)[10–11] and the nuclear magnetic resonance imaging (MRI)[12,13] technology. The former method can analyze rock properties quantitatively and pictorially, and characterize the pore structure intuitively, but can't distinguish the images of different fluids and the images of fluids and porous medium[10]. Whereas, the visual experiment method based on MRI can distinguish different fluids by restraining the relaxation time of the fluids because it only collect the signals of the fluid[12]. In this study, MRI and core displacement experiment are combined to analyze distribution characteristics and migration laws of weak gel in the core, and three different combination patterns of polymer-weak gel are designed and the oil displacement characteristics are analyzed.

1. Principle of visual core displacement method based on NMR

1.1. NMR relaxation of the fluid in the core

NMR relaxation contains transverse and longitudinal relaxation according to proton heading direction, which is closely related to the molecular structure and dynamic process of material and environment[14–15]. Since the test of longitudinal relaxation requires a long time and has fewer measuring points, transverse relaxation curve (T_2 spectrum) was tested in this study to analyze the physical properties of the core sample.

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When the core is filled with a single fluid, T_2 value is proportional to the pore size, and the signal amplitude is proportional to the volume of the fluid. Therefore, when analyzing T_2 spectrum, T_2 spectrum represents the size of pores in the core, the longer the relaxation time, the bigger the pore size, and vice versa; while the peak area of signal amplitude by relaxation time represents fluid volume in the core, the bigger the peak area, the larger the fluid volume inside pores[16]. Therefore, the fluid distribution in pores and fluid content variations in the core can be obtained by testing T_2 spectrum signal of the fluid.

1.2. Principle of MRI

Three mutually perpendicular and controllable linear gradient magnetic fields are applied on the target object to realize the spatial location and determine the direction of image slices by selecting layer, frequency and phase coding. NMR images include sagittal, transverse and coronal planes[12]. In this study, mainly sagittal plane (the vertical plane parallel to the axis of the core) and transverse plane (the plane perpendicular to the axis of the core) were captured.

The NMR signal spectrum taken initially contains some random external interferences, which results in light spots in the image. In this study, the post-processing program of NMR image is written, which can make the images clearly and correctly reflect the information of the sample by identifying fluid signal and interference, filtering jamming signal, unified mapping, adding pseudo color, etc.

2. Visualization experiments

First, the distribution characteristics and migration pattern of the weak gel in the core were observed by visual displacement experiment based on NMR. Next, three different combination patterns of the polymer-weak gel profiling and displacing were designed, namely water flooding + polymer flooding (pattern 1), water flooding + polymer flooding + weak gel flooding (pattern 2), water flooding + weak gel flooding + polymer flooding (pattern 3) to find out the pressure change, T_2 spectrum, NMR image characteristics and oil displacement efficiency of different combinations.

2.1. The apparatus

The visual displacement experiment apparatus based on NMR is shown in Fig. 1, which consists of a constant speed and pressure pump, hand pump, pressure vessel, core holder, NMR unit, control unit, and measurement unit, etc.

The main performance parameters of the NMR unit are shown in Table 1.

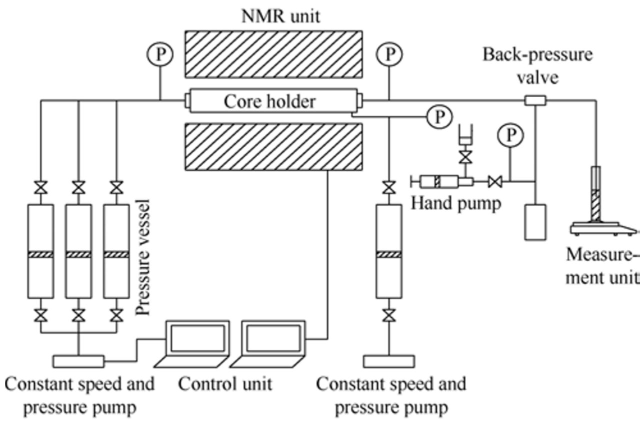

Fig. 1. Visual displacement experiment apparatus.

Table 1. Performance parameters of the NMR unit

Performance	Parameters
Magnet type	Permanent magnet
Magnetic field intensity	(0.52 ± 0.05) T
Magnetic field stability	≤ 300 Hz/h
Radio-frequency field	Impulse frequency: 1−30 MHz, the precision of frequency control: 0.1 Hz, pulse precision:100 ns
The transmission power of radio frequency	Peak output is greater than 300 W
Maximum sampling bandwidth	2 000 kHz
Imaging gradient	Strength peak is greater than 2.5 G/cm
The probe coil diameter	60 mm
The effective sample detection range	Sphere 60mm in diameter
Imaging quality	Image signal to noise ratio (SNR) is greater than 20 dB , image distortion is less than 15%, and the image uniformity is greater than 45%
Sampling frequency	50 MHz

Table 2. Parameters of the core

No.	Diameter/ cm	Length/ cm	Porosity/ %	Water permeability/ 10^{-3} μm^2
A-0	2.5	9.06	23.54	967
A-2	2.5	8.92	22.20	1531
A-3	2.5	8.98	22.30	1488
A-6	2.5	9.02	25.06	1582

2.2. The materials

Experimental materials: four artificial homogeneous cores, deuteroxide, cross-linking agent, $MnCl_2$, simulated formation water, and diesel oil, etc. The parameters of the core are shown in Table 2. The polymer was polyacrylamide with a relative molecular mass of about 25×10^6 and viscosity of 490 mPa·s (25 °C). The weak gel was crosslinking polyacrylamide and phenolic resin with a viscosity of 5040 mPa·s (25 °C).

2.3. The method and procedures

2.3.1. Distinguishing NMR signals of different fluids

In NMR tests, signals of different fluids can be distinguished according to relaxation time of different fluids. This study distinguished water, oil, polymer and weak gel signals.

2.3.1.1. Distinguishing the signals of water and oil

The NMR signals of water and oil cannot be clearly distin-