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Pore-scale analysis of gas huff-n-puff enhanced oil recovery and waterflooding process

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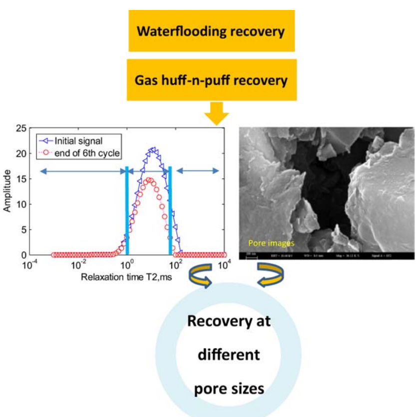
GRAPHICAL ABSTRACT



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ABSTRACT

Understanding the complex pore network and fractures are crucial to efficiently producing tight gas and oil reservoirs. A better understanding of gas flooding recovery mechanisms will lead to improved successes of EOR (enhanced-oil-recovery) practices in tight oil formations. In this paper, the gas huff-n-puff efficiency performance in tight oil formations is under surveillance by NMR technology. It is of our interest to estimate the recoverable or movable oil saturation by waterflooding and gas flooding at different types of pore sizes. Fortunately, NMR measurements provide an avenue for calculating the recoverable reserves in different types of pore system (micropores, mesopores and macropores). The NMR T_2 relaxation time closely correlates with the pore sizes. The NMR technique was used to analyze the mechanisms of gas flooding and waterflooding in shale formations from a microscopic scale view. In this paper, a series of nitrogen huff-n-puff experiments were conducted on tight cores and NMR was used in the whole huff-n-puff process to observe the gas flooding efficiency at different cycles. The NMR relaxation spectrum reveals that most of the oil production happened in the first few cycles, less oil is recovered in the subsequent cycles. The recoverable oil of this field falls into a range of 1–100 ms T_2 relaxation pore size system. Oil production only occurs in certain type of pores. Due to the nanometer or micrometer scales of the pores and pore throats, cycle depletion time has considerable effect on oil recovery from tight oil reservoirs in the first few cycles. The literature lacks a study of the NMR investigation of

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gas huff-n-puff effect in tight formations. The purpose of this current study is to illustrate the application of NMR technique in interpreting the effect of cyclic nitrogen injection in tight oil reservoirs.

Nomenclature

A	NMR signal amplitude
S_{wc}	Connate water saturation
S_{or}	Irreducible oil saturation for gas-liquid table
T_2	T_2 relaxation time

1. Introduction

Due to the prevailing of nano-scale pores in shale formations, gas flooding has the advantage to access the trapped hydrocarbons in nanopores compared to waterflooding. Experimental studies of CO_2 huff-n-puff EOR in shale oil core plugs include investigation of injection pressure, injection period, soaking time and the cycle efficiency [1–3]. Wan et al. [4] implemented a laboratory-scale evaluation of the nitrogen huff-n-puff in shale formations. Laboratory and numerical simulation results showed the role of diffusion mechanism in the mobilization and production of oil in very low permeability shale oil or gas reservoirs. The dispersive-convective flux through nano-pores during gas injection process in shale oil reservoirs is modeled. This paper extends the previous research work by using NMR spectrometer to investigate the recovery performance of cyclic gas injection in nanometer sized pores [4]. Better understanding of recovery mechanisms of water flooding and gas flooding will lead to improved successes of EOR projects in tight oil formations. In this paper, we will discuss the methods that can characterize the reservoir pore structures, reservoir heterogeneity and which type of pores mostly contribute to the ultimate oil recovery.

Advances in NMR logging use diffusion-based NMR methods to identify and characterize the fluids in hydrocarbon bearing reservoirs invaded by the oil-based mud filtrate [5]. Fluid analysis is made based on the contrasts in 2D distribution of relaxation times and molecular diffusion rates. NMR measurement of differences in the relaxation time at different water-saturation states provides an estimate of water saturation in chalk cores [6]. Freedman and Heaton compared the T_2 distribution for the partially oil-saturated rocks with the bulk oil. It was found that the NMR surface relaxation rate depends on the wetting phase saturation in mixed-wet rocks [7]. During NMR monitoring the process of water imbibition in shales, water firstly enters into the micropores (0.01–5 ms). After hydrocarbons in the micropores has been swept, water then infiltrates into less preferential mesopores [8]. Cracks were observed to appear on the surface of the shales when the core samples were in imbibition process [8]. Comparative measurements of the helium porosity with the NMR method, it shows that the helium porosity is higher than the NMR measured porosity [9]. The echo time exerts a strong influence on NMR measurements, and a longer echo time produces a smaller NMR porosity. NMR core experimental examination of the Haynesville shale also showed that the NMR measured effective porosity is lower than density porosity [10]. The NMR porosity measurement is affected by the pyrite concentration and kerogen content, which decreases with an increasing of pyrite. The measured average air permeability of the Haynesville shale cores is 0.268 mD, with an average porosity of 4.35%. The T_2 relaxation time distribution of the micropores ranges from 0.8 to 2 ms, in contrast, large pores corresponding to 2–200 ms. In addition to measure the pore size distribution, NMR techniques was used to assess the movable fluid saturation for 264 cores from the Yanchang Ordos basin [11]. The lithology of these cores is mostly comprised by lithic feldspar sandstone, whose permeability ranges from 0.11 mD to 2.8 mD. The T_2 cutoff value lies at about 5.34–20 ms. The average movable fluid percentage for a total of 264 core samples is 48.35%. The measured T_2 distribution is dominant by the bimodal distribution in ultra-low permeability reservoirs. The typical T_2 value of the cores falls in a range of 1–10 ms for the left peak and 10–100 ms of the right peak. In nanopores, the T_2 distribution measured in shales may not reflect an indication of the pore size distribution when the length scale of NMR diffusion is comparable to the relaxation time of pores [12–14].

NMR T_2 test and MRI were used to examine the oil mobilization in different pore sizes of tight matrix during CO_2 injection process [15]. Experimental results showed that oil mobilization by CO_2 injection in the tight matrix is affected by the exposure time. Oil mobilization in pores with radius smaller than 1 μm happens in a slow manner in which the oil recovery improves with an increase of exposure time. Gannaway presented a series of NMR experiments on Barnett shales [16]. NMR measurements were performed to characterize the pore network distribution in gas shales by conducting the $Mncl_2$ solution imbibition process after fully dodecane saturated. All the shale samples exhibited a unimodal T_2 distribution with a peak at 0.2 ms (clay bound water porosity) in their native state. By comparing the native state, dodecane saturated and $Mncl_2$ imbibed NMR distributions, the classification of effective porosity, inorganic porosity and organic porosity was discussed in the paper. It was found that displacement process took place at dodecane-filled pores (> 5 ms) in the $Mncl_2$ imbibition process and the clay-bound water filled pores at 0.2 ms was also displaced by water invasion. Recent studies indicate that significant T_2 relaxation time in Haynesville shales is smaller than a few milliseconds due to the fact that the high surface-to-volume ratios and the adsorption of methane on the pore surface result in large reduction of the relaxation times from their bulk values [23]. Studies on the Barnett gas shales by Songergold et al. also demonstrated an indication of a dominate range in pore body radius from 5 nm to 150 nm on the NMR spectra and most of the signal lies below 3 ms [25].

Tinni et al. presented a study of NMR responses in shale samples from Haynesville, Barnett, and Woodford [17]. Different brine-saturation pressures at 1000 psi, 2000 psi, 3000 psi, 4000 psi, 5000 psi, to 7000 psi were applied at the received state core plugs. The brine saturated cores show essentially one peak with T_2 values that range from 0.1 to 10 ms. For dodecane saturation after brine-saturated, an increase in amplitude at T_2 values from 1 to 100 ms is observed but there is no significant change of the water wet porosity peak. A broader distribution of T_2 relaxation time shifted to longer times is shown after dodecane saturation at exerted pressures which suggests that dodecane did not enter the water-wet pores but the hydrocarbon wet pores. NMR response in shale rocks is complicated by the presence of organic matter, maturity, and clay content [18,19]. The coexistence of different scale of pores (micro-pores and nano-pores) renders the interpretation process more difficult. The challenge of NMR interpretation in shales attributes to the heterogeneous distribution of pore sizes [20].

The NMR experimental design in cyclic gas injection avoids the perturbation of water signals without introducing the water component. In the cyclic nitrogen injection process, the only medium that

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