Feasibility study of application of nanoparticles in complex resistivity (CR) reservoir monitoring

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Summary

An ability to understand and control reservoir behavior over the course of production is necessary for optimization of reservoir performance and production strategies. This goal can be achieved by geophysical monitoring of the propagation of the fluids within the reservoir. Electromagnetic (EM) methods represent an important technique of geophysical monitoring of the reservoirs, because they can distinguish between hydrocarbons and saline water based on their differing resistivities. The induced polarization (IP) effect represents another important electrical characteristic of the reservoir saturated by different fluids - the complex resistivity (CR) of the reservoir rocks. This paper considers an application of nanoparticles for reservoir monitoring in order to enhance the electrical conductivity contrast and the IP responses associated with the oil-water interface within the reservoir. We have conducted the measurements of the CR of reservoir rocks in order to examine the effect of adding in water solutions the organic, PEDOT-PSS, and inorganic, Fe_3O_4, Fe_2O_3, NiO, and Al_2O_3, nanoparticles. The results of this study demonstrate that the application of the organic and inorganic nanoparticles may change significantly the resistivity of the reservoir rocks and produce a significant spectral IP effect.

Introduction

An ability to predict and to control the position and movement of oil-water interface is very important for monitoring the production from the hydrocarbon (HC) reservoirs. The idea of utilizing nanoparticles for monitoring and even for facilitating of the oil production has been developed in a number of publications (e.g., Rahmani et al, 2013, Heagy and Oldenburg, 2013; Hubbard et al., 2014). Several types of nanoparticles were explored in view of possible HC application. For example, magnetic nanoparticles were used by Lesin et al. (2011) to study their effect on the viscosity of liquid suspensions with fractal aggregates in petroleum colloidal structures. The paramagnetic nanoparticles were tested as aqueous dispersions in reservoir rock for enhanced oil recovery and evaluating oil saturation (e.g., Yu et al., 2010, Armani et al., 2013). These studies attempted to utilize the concept of enhancing MRI imaging with the use of paramagnetic nanoparticles for accurate determination of oil saturation and the oil-water interface.

This paper presents the results of the lab study of the electrical properties of Saudi Arabian's reservoir rocks with the goal to examine the effect of application of nanomaterials for enhancing the EM and spectral IP responses from the reservoir rocks saturated by different fluids.

In this study, we have tested organic (conductive) and inorganic (semiconductive) nanoparticles. We have used poly (3, 4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT-PSS) as an example of organic nanoparticles, and Fe_3O_4, Fe_2O_3, NiO, and Al_2O_3**,** as examples of inorganic nanoparticles. The experiments were conducted with reservoir and artificial rocks, which were saturated by salt water and brine solutions. We used the rock samples and brine from the Arab D reservoir, provided by Saudi Aramco. All rock samples were saturated with brine from the same well in a vacuum system. We have conducted complex resistivity (CR) measurements for each sample at different saturation stages at 27 frequencies over a range from 0.005 Hz to 1000 Hz using the CR measurement system described in Zhdanov et al. (2012, 2013). The CR system is operating in frequency domain in order to avoid errors related to the conversion from time to frequency domain.

The goal of this research is to investigate a possibility of developing a nanoparticle-assistant EM monitoring system based on the complex resistivity (CR) measurements, which can be used for monitoring the changes in the location of the oil-water contact within the reservoir by tracing the spectral IP responses.

Measurements of the complex resistivity of reservoir rocks saturated by brine and organic nanoparticles

We have analyzed first the Arab D rock sample #180 saturated in brine, and in a mixture of 90 % of brine and 10% of PEDOT-PSS mother solution of nanoparticles (NP). Figure 1 presents the corresponding CR spectra for sample #180. This sample has porosity of 27.44% and permeability of 1104 mD.

Figure 2 presents the CR spectra for sample #112 saturated in distilled water (DW) and in pure PEDOT-PSS mother solution (100% of NP). This sample has porosity of 25.32% and permeability of 730.9 mD. One can see from these plots that the addition of organic nanoparticles results in dramatic decrease of the real part of the resistivity, while the imaginary part of the resistivity remains practically unchanged.

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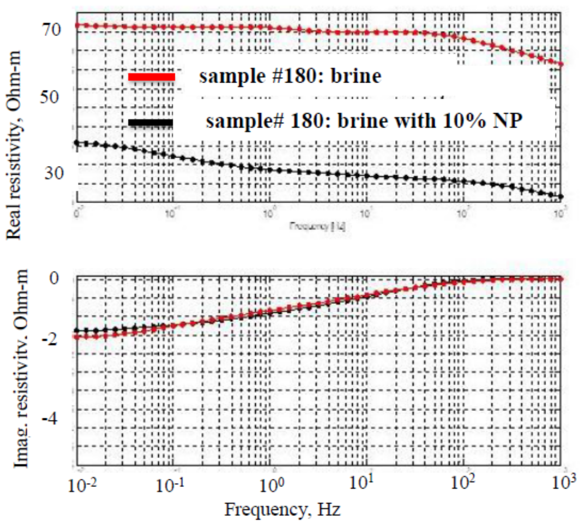

Figure 1 Plots of the CR spectra for high porosity sample #180. The red dotted lines show the CR for the rock sample saturated in brine. The black dotted lines present the CR spectra for the same sample saturated in 10% volume mixture of PEDOT-PSS mother solution with 90% volume of brine. The upper panel shows the real part of the resistivity and the bottom panel presents the imaginary part.

Complex resistivity measurements of artificial rocks saturated by brine and inorganic nanoparticles

In the next set of the lab experiments we used artificial rocks saturated by brine and inorganic nanoparticles. We prepared a 6% suspension of Fe_3O_4 nanoparticles in partly saturated by brine sand cartridges. Figure 3 summarizes the CR spectrum of undoped (10% of brine plus sand mixture) and doped (10% of brine plus sand plus 6% of Fe_3O_4 nanoparticles) artificial rocks. In this figure, we compare the CR spectra of suspension of Fe_3O_4 nanoparticles in brine placed in cartridges and the same liquids placed in partly (10%) saturated sand cartridge. One can see from this figure that the addition of inorganic nanoparticles results in the change of both the real and imaginary parts of the resistivity of the rock sample.

We have also investigated the effect of different inorganic nanoparticles on the CR spectrum. Figure 4 presents the CR spectra of partly (10%) saturated sand cartridge, which was doped by equal 6% percent solutions of various nanoparticles -- Fe_3O_4, Fe_2O_3, NiO, and Al_2O_3. One can see that Fe_3O_4 nanoparticles have the most profound effect on the complex resistivity of the samples.

Finally, we have studied the effect of different amounts of doping of Fe_3O_4 nanoparticles on complex resistivity in partly (10%) saturated sand cartridges (Figure 5). We can see that the increase of concentration of inorganic nanoparticles results in an increase of the real part of resistivity of the rock sample, and, at the same time, produces a stronger IP effect, manifested in the minimum of the imaginary resistivity. One can observe also a shift of the IP minimum toward the lower frequency of the CR spectra for the higher concentrations of the Fe_3O_4 nanoparticles. This property of inorganic nanoparticles can be employed in order to enhance the IP effect in the reservoir rocks saturated by brine and to use it as a marker of the oil-water contact for reservoir monitoring.

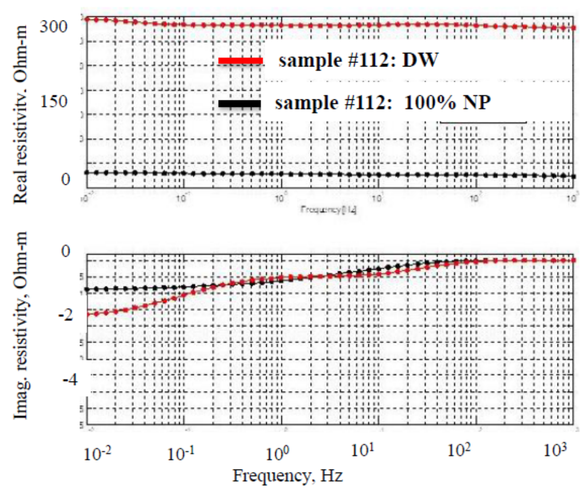

Figure 2. Plots of the CR spectra for high porosity sample #112. The red dotted lines show the CR for the rock sample saturated in distilled water, while the black dotted lines present the CR spectra for the same sample saturated in 100% mother solution of organic nanoparticles. The upper panel shows the real part of the resistivity and the bottom panel presents the imaginary part.

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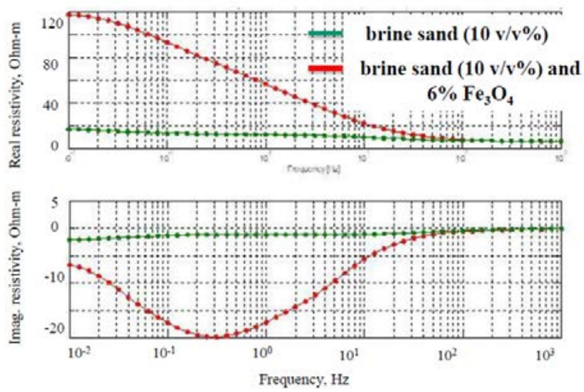

Figure 3 Plots of the CR spectra of artificial rocks saturated by brine and inorganic nanoparticles. The green doted lines show the CR for the sand cartridge partly (10%) saturated by saltwater (brine). The red dotted lines present the CR spectra for the same sand cartridge saturated in brine solution with a 6% suspension of Fe_3O_4 nanoparticles. The upper panel shows the real part of the resistivity and the bottom panel presents the imaginary part.

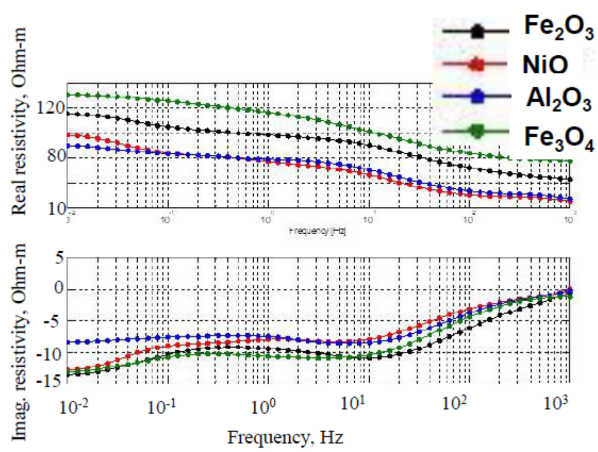

Figure 4 Plots of the CR spectra of artificial rocks partly (10%) saturated with different nanoparticles solutions (Fe_3O_4, Fe_2O_3, NiO, and Al_2O_3). The upper panel shows the real part of the resistivity and the bottom panel presents the imaginary part.

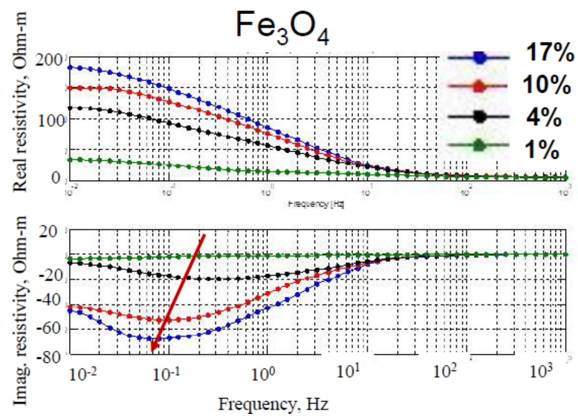

Figure 5 Plots of the CR spectra of artificial rocks saturated by brine and inorganic Fe_3O_4 nanoparticles of different concentrations. The dotted green, black, red, and blue lines correspond to 1%, 4%, 10%, and 17%, respectively, of volume concentration of Fe_3O_4 nanoparticles. The upper panel shows the real part of the resistivity and the bottom panel presents the imaginary part. The red arrow indicates a direction of the IP minimum shift at the higher concentrations.

Analysis of experimental results

The experimental results presented above demonstrate that, the CR responses of the real and artificial rock samples can be changed significantly by saturating the rock samples with different solutions of organic and inorganic nanoparticles. Figures 1 and 2 show the effect of doping of the rock cores by organic nanoparticles, which have smaller resistivity compared to inorganic nanoparticles. The real resistivity of the rock samples saturated by brine with 10% nanoparticles decreases dramatically with respect to that of original brine (the upper panels in Figures 1 and 2). The imaginary resistivity responses for the rock samples saturated by pure brine and the brine with nanoparticles look very similar (the bottom panels in Figures 1 and 2).

Figures 3 through 5 illustrate the effect of saturating the artificial rocks with the solutions containing inorganic nanoparticles, which have a larger resistivity compared to organic nanoparticles. In these experiments, we observe the change in the CR spectra of artificial rocks, which consists of increasing the magnitude of both real and imaginary parts of the resistivity. This phenomenon reflects the higher resistivity of Fe_3O_4 nanoparticles compared to brine. Remarkably, the pick of the negative IP response in the imaginary part of the resistivity is located around 0.2 Hz, which is a typical frequency used in borehole-to-surface

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electromagnetic (BSEM) deep HC reservoir monitoring (Marsala et al., 2011a, 2011b).

The final set of lab experiments was aimed at studying the CR response of the artificial rocks saturated with the solutions of different nanoparticles and with different concentrations. Figure 4 compares the CR responses of the rock samples with Fe_3O_4, Fe_2O_3, NiO, and Al_2O_3 nanoparticles, which are commercially available and are relatively cheap. It should be noticed that, while all CR spectra of tested nanoparticles have a very similar shape, especially for the real part of the resistivity, adding the Fe_3O_4 nanoparticles induces the largest change of both the real and imaginary parts of the resistivity. The other nanoparticles show the lower responses, but, potentially, they can also be used in monitoring the flow of the injected fluids.

Figure 5 presents a clear picture of the increase of the CR response with larger concentration of Fe_3O_4 nanoparticles. Interestingly, the strong IP minimum of the imaginary resistivity is moving toward the lower frequency with the higher concentration of Fe_3O_4 nanoparticles. This may be an indication that Fe_3O_4 nanoparticles form the larger colloids at the higher concentrations of nanoparticles. This observation correlates well with the known dependence of the position of the IP minimum from the grain size, which was experimentally demonstrated long time ago by Ostrander and Zonge (1978). A similar effect was recently explained theoretically on the basis of the generalized effective medium theory of the IP effect (GEMTIP) by Zhdanov (2008).

Conclusions

We have demonstrated that the application of the organic and inorganic nanoparticles may change significantly the resistivity of artificial and Saudi Arabian's carbonate reservoir rocks and produce a significant spectral IP effect. The results of this study open a possibility of developing a principally new method for monitoring the fluid movement in the reservoir by using the IP effect associated with the nanoparticles. For this monitoring, a conventional IP method and equipment can be used, which is capable of recording the IP responses from the reservoir saturated by brine and nanoparticles solutions. The future progress might be achieved using GEMTIP modeling and inversion, which is capable to determine the petrophysical characteristics of the reservoir rocks based on spectral IP data (Zhdanov, 2008, 2009).

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EDITED REFERENCES

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