# $CO_2$ Sequestration Electromagnetic Imaging Based on Nanoparticle Contrast Agent and Casing Excitation

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**Abstract.** We proposed a casing excitation method and one nanoparticle-enhanced electromagnetic IP technology to improve the detection depth and resolution of $CO_2$ sequestration electromagnetic monitoring. The highly conductive nanoparticles are selected to be mixed with the supercritical $CO_2$ for the low-resistance environment, otherwise the high-resistivity nanoparticles are selected. The complex resistance measurement is performed on different mixing methods to test the effect of nanoparticle-enhanced electromagnetic IP. By injecting the excitation current through the ground-connected metal completion casing and arranging the array of receivers away from the casing, the excitation current can be passed down deeper into the vicinity of sequestration reservoir along the metal casing without opening the well, so the resistivity contrast image of the deeper layer can be obtained. The resistance contrast between the supercritical $CO_2$ and the reservoir environment is improved by the nanoparticles, and the electromagnetic induction polarization response is greatly improved, thereby improving the electromagnetic detection resolution. The high-resolution imaging capability will offer more effective monitoring of $CO_2$ plume migration during geologic sequestration.

**Keywords:** $CO_2$ sequestration · Nanoparticle-enhanced · Electromagnetic monitoring · Steel-casing excitation

## 1 Introduction

The ability to predict and to control the position and movement of the $CO_2$ plume is very important for geologic sequestration. The conception of using nanoparticles for monitoring and even for facilitating oil production has been developed in the geophysical literatures (e.g., Heagy and Oldenburg [1]; Leroy et al. [2]; Hubbard et al. [3]; Burtman et al. [4]). Many types of nanoparticles have been studied in view of possible HC applications. For example, magnetic nanoparticles were used by Lesin et al. [5] to explore their effect on the viscosity of liquid suspensions with fractal aggregates in petroleum colloidal structures. Similar researches were conducted in Iran [6]


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and China [7]. The paramagnetic nanoparticles were reported as aqueous dispersions in reservoir rock for enhanced oil recovery and for evaluating oil saturation (e.g., Yu et al. [8]; Leroy et al. [2]). 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. However, the monitoring of $CO_2$ plume migration during geologic sequestration using Nanoparticle enhanced imaging method is not reported in literatures so far.

Using steel well casing to distribute an electrical current into the subsurface to monitor fracture propagation has become an increasingly interesting subject in a number of publications (e.g., Börner et al. [9]; Hibbs [10]; Weiss et al. [11]). Transmitting current through the well casing, the subsurface near the well will be energized, and measurements of the resulting electric fields on the surface are very sensitive to the electrical conductivity of the energized subsurface. If the injected fluid is sufficiently electrically conductive, the bulk conductivity of the energized region near the well casing may be lowered enough to cause a measureable anomaly at the surface.

From our lab study of the electrical properties of a $CO_2$ geologic sequestration reservoir in Ordos Basin, we have found that the application of organic and inorganic nanoparticles can change significantly the resistivity of the supercritical $CO_2$ of the artificial and the tested reservoir samples and produce a significant spectral IP (induced polarization) effect. And through both numerical modeling and field testing we found that the well casing excitation method is sensitive to the injection of supercritical $CO_2$ to the deep sequestration reservoir.

## 2 Nanoparticle-Enhanced IP

The application of nanoparticles for $CO_2$ geological sequestration monitoring assumes that nanoparticles can uniform mix and stable exist with migrate with supercritical $CO_2$. Nanoparticle enhanced $CO_2$ squestration reservoir monitoring should be more efficient for reservoir monitoring than in the case of injected supercritical $CO_2$ without nanoparticles. A possibility of changing the chargeability of the injected liquid by adding the nanoparticles is based on the fact that the IP phenomenon is related to the charge accumulation on the surface of the particles. Nanoparticles are particles between 1 and 100 nanometres in size. One of the interesting and sometimes unexpected properties of nanoparticles, which make them suitable for increasing the IP effect, is largely related to the large surface area of the material filled with nanoparticles. Indeed, a solid cube of a material 1 cm on a side has 6 $cm^2$ of surface area. At the same time, when that single cubic centimeter of volume is filled with 1-nanometer-sized cubes—1021 of them, each with an area of 6 $nm^2$—their total surface area comes to 6000 $m^2$! This effect of the increased surface area provided by nanoparticles makes them a very powerful source of the IP phenomenon.

We test nanoparticles as Fig. 1. We consider the Organic NP and Inorganic NP.

In our lab, the experimental process, experimental device, as shown in the Fig. 2.

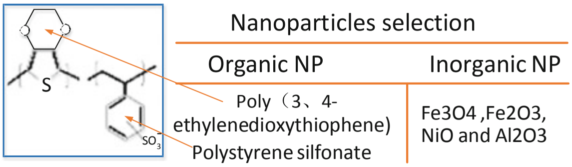


**Fig. 1.** Selected organic and inorganic nanoparticles

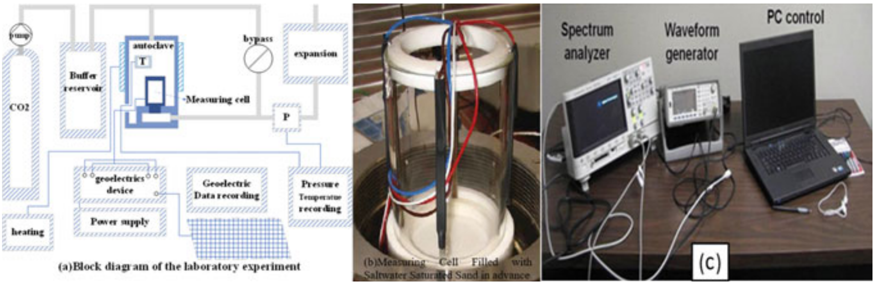


**Fig. 2.** Set-up for simulation of $CO_2$ sequestration on a laboratory scale

As show in Fig. 3, the effect of different amounts of doping of $Fe_3O_4$ nanoparticles on the complex resistivity in partly (10% v/v) saturated by saltwater and supercritical $CO_2$ cartridges, the plot shows 1% of volume doping (green line), 4% of doping (black line), 10% of doping (red line), and 17% of doping (blue line). The upper panel shows a log of the real part of the complex resistivity (CR), while the lower panel presents a log of the imaginary resistivity.

In these experiments, we observe the change in the CR spectra of artificial $CO_2$ geological sequestration reservoir, which consists of increasing the magnitude of both the real and imaginary parts of the resistivity. This phenomenon reflects the higher resistivity of $Fe_3O_4$ nanoparticles compared to brine and $CO_2$. Remarkably, the peak of the negative IP response in the imaginary part of the resistivity is located at around 0.2 Hz, which is a typical frequency used in borehole-to-surface Electromagnetic deep HC reservoir monitoring [12, 13]. The significant change in resistivity brings a significant IP effect, which eventually leads to a great improvement in the resolution of electromagnetic monitoring for the migration of $CO_2$ plume enhanced by paramagnetic nanoparticles.

## 3 Well Casing Excitation—Top Casing Source

A special borehole source, the current flows up the casing and is returned by a simple connection to the top of the casing as illustrated in Fig. 4. This configuration is termed a Top Casing Source (TCS) and has the significant benefit that all required equipment is deployed at the ground surface.

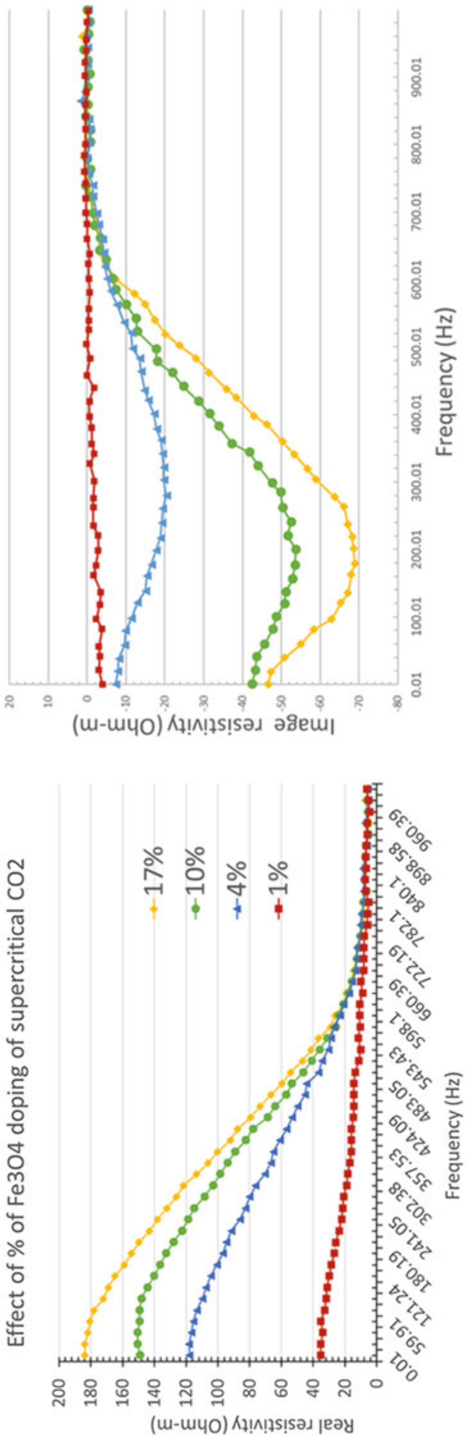


**Fig. 3.** The effect of different amounts of doping of $Fe_3O_4$ nanoparticles on the complex resistivity

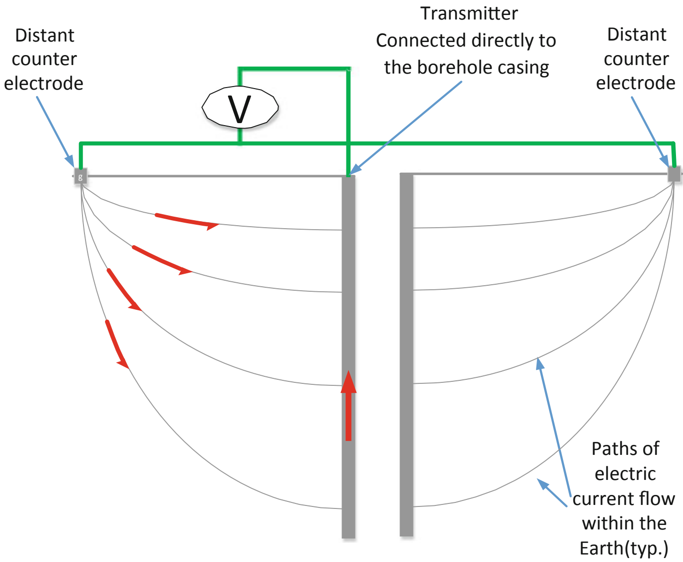


**Fig. 4.** TCS with the electrical connection at the top of the casing. Arrows show the direction of current flow in the casing at the same instant of the transmitted current waveform

An example of the electrical connection to the wellhead is shown in Fig. 5. A TCS is clearly very easy to configure and has the obvious advantage that the well does not need to be opened. It is also clearly suitable for long-term monitoring and permanent installation. As shown in Fig. 6, one reservoir is at a depth of 2000 m. Change in surface E-field for three positions of the boundary between the injecting well and the $CO_2$ plume relative to the field for the same boundary at 500 m from a well.

Since we usually has more accurate prior data of the sequestration reservoirs before $CO_2$ injection and the injection well and the observation well are ready, we can deploy our TCS conveniently, while monitoring the electromagnetic response and reservoir imaging data before $CO_2$ injection can be used as a reference for our follow-up monitoring datum.

## 4 Case Study

For a $CO_2$ geologic sequestration reservoir in Ordos Basin, The traditional electromagnetic (EM) monitoring method has not used the electromagnetic induction polarization enhancement of the nanoparticles. The result of using the completion casing as the excitation source is the result of the three dimensional (3D) inversion of the electromagnetic field. As shown in Fig. 7. The right image is the result of the nanoparticles enhanced by 25% $Fe_3O_4$. It is obvious that the electromagnetically induced intensification is significantly enhanced and can be tracked more. $CO_2$ tail feathers are migrated in a wide range.

**Fig. 5.** Photograph of a TCS connection to a wellhead for a pilot survey

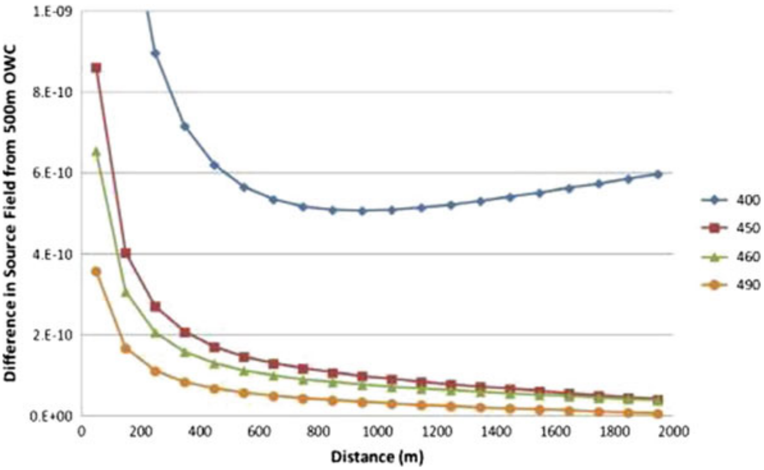


**Fig. 6.** Change in surface E-field

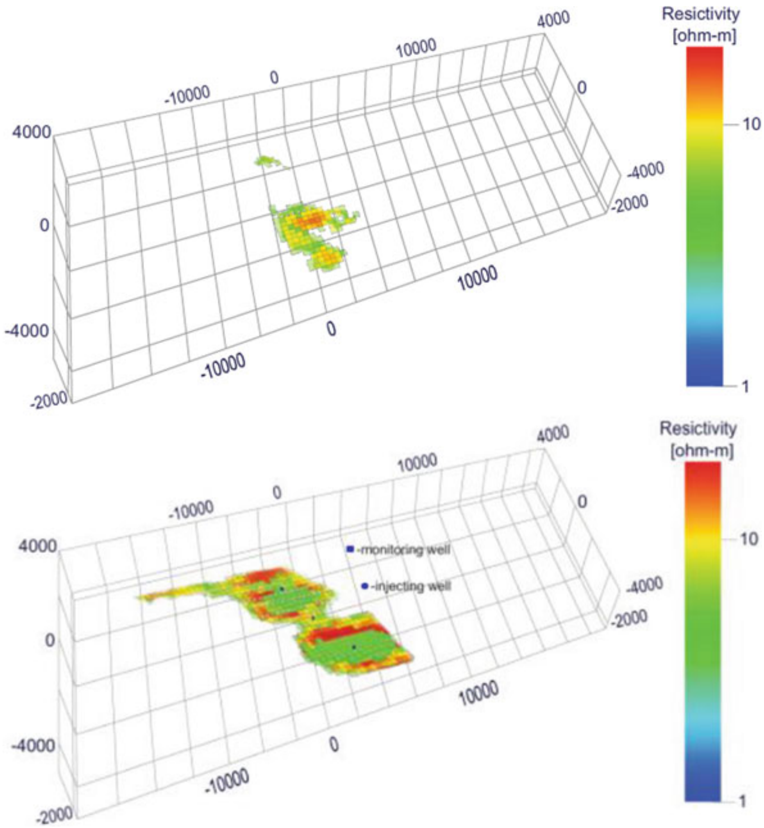


**Fig. 7.** 3D EM inversion result for $CO_2$ geological sequestration, the up picture using a traditional method and down picture using CTS method

## 5 Conclusion

The magnetic enhancement technology of nanoparticles is a significant increase in the IP utility of the critical state of $CO_2$. By selecting the suitable type and the appropriate proportion of the nanoparticles to obtain the maximum electromagnetic effect of $CO_2$, the resolution of the $CO_2$ injection process and the migration trajectory of the tail feathers can be significantly improved. The TCS system can inject the detection current into the storage reservoir, especially near the $CO_2$ injection port, so that it can be closer to the observation target. At the same time, the magnetic increase of the nanoparticles is more beneficial to detecting the path of the current to trace the $CO_2$ injection path and its migration path in the reservoir. The critical state $CO_2$ rapid imaging monitoring technology based on the electromotive force of the cannula has solved the problem of insufficient depth and low resolution of electromagnetic monitoring in deep geological storage of $CO_2$. At the same time, TCS technology makes it possible to deploy long or permanent electromagnetic monitoring system without opening the well cap.

The implementation of this technology not only widens the application range of geophysical controlled source electromagnetic methods, but provides a safe and reliable monitoring and evaluation technology for the safe implementation of $CO_2$ deep sequestration.

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