Determining Saturation Using Electrical Impedance Tomography (EIT)

Robert W. Stacey, Kewen Li, and Roland N. Horne

Petroleum Engineering Department, Stanford University

Keywords

Electrical Impedance Tomography, EIT, saturation

ABSTRACT

Three-dimensional Electrical Impedance Tomography (EIT) is a measurement technique that has the potential to provide estimates of reservoir saturation at multiple scales from the calculated resistivity distribution. EIT in theory has the capability to image geothermal reservoir systems due to the contrast in resistivity between the liquid and vapor phases. Here in our initial laboratory investigation we have applied EIT to measure the saturation distribution within a core.

The initial EIT experiment presented here was on a Berea sandstone core with 48 electrodes attached in three rings of 16. The core was open to the atmosphere with saturation occurring by natural imbibition and desaturation occurs by evaporation. The voltage potential field is measured by applying a direct current pulse across the core and measuring the voltage potential at all electrodes, essentially applying the 4-wire resistance technique over all electrodes in turn. The result is a data set that embodies the resistivity distribution within the core, and by inversion the resistivity distribution is reconstructed, which allows for the inference of the cores saturation.

The data processing was accomplished by utilizing the EIDORS toolkit developed for MATLAB. The toolkit was required due to the nature of EIT being a nonlinear and an ill-posed problem. The procedure utilizes a finite element model for forward calculations and a regularized nonlinear solver for obtaining a unique and stable inverse solution. (Polydorides et al. 2002)

Initial tests on the core indicate that EIT is a viable alternative for measuring the saturation distribution within a geothermal rock core, and is capable of detecting saturation fronts in near real-time. Current efforts are focused upon calibrating the saturation inferred by EIT, and on increasing accuracy by examining the multiple aspects of the systems electrochemistry that may effect resistivity measurements.

Introduction

The measurement of the saturation distribution in a core using EIT was described in a paper by Van Weereld, et al. (2001). The paper showed that EIT techniques were able to image a two-phase system (oil and brine). However the authors did not convert resistivity images to saturation, or validate their results against other methods. Therefore we have developed a simple apparatus to investigate the feasibility of using EIT to measure saturation in a geothermal system.

Background

The theory behind EIT is that by imposing an electric current across an inhomogeneous medium, the distribution of the internal electrical resistance will result in a variation of voltage potential at the perimeter. Measurements of the variable voltage potential can be used to infer the resistivity distribution within the medium. This internal resistance distribution can be converted into water saturation based upon the resistance distinction between the two phases. Figure 1 is a diagram of a typical two-dimensional EIT experiment, consisting of 16 electrodes with an imposed current I across the core Ω, and measurement of the resulting potential V_1. The voltage potential is measured between all neighboring electrodes, before rotating the current drive electrodes and repeating the voltage measurement process.

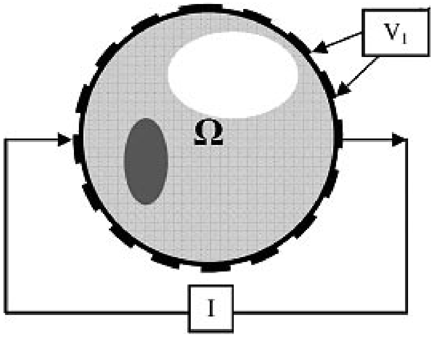


Figure 1. Diagram of 16 electrode EIT experiment. The potential V_1 is measured after a current I has been imposed across the core Ω. (Molinari 2003).

The governing equation for the voltage potential for a current imposed upon a core Ω is

$$\nabla \cdot (\sigma + \iota\varpi\varepsilon)\nabla\phi = 0 \tag{1}$$

Where σ is the electric impedance of the medium, ϕ is the electric potential, ϖ is the frequency, and ε is the electric permittivity. Under conditions in which low frequency or direct current is used ($\varpi \approx 0$), Equation 1 can be reduced to the standard governing equation for EIT (Molinari 2003):

$$\nabla \cdot (\sigma\nabla\phi) = 0 \tag{2}$$

The EIT inverse problem can be simplified down to a system identification problem. The cause and effect (injected current $\boldsymbol{I}$ and measured voltage $\boldsymbol{V}$) are known, but the physical system is unknown (impedance distribution σ). The nonlinearity arises in σ, as the potential distribution ϕ is a function of the impedance, $\phi=\phi(\sigma)$, and we cannot easily solve Equation 2 for σ (Molinari 2003). The ill-posed nature of the problem is clearly apparent when observing the diffusive nature of electricity, coupled with inherent measurement errors.

EIT Development

The EIT system can be separated into three parts; electrode configuration and connection, data acquisition, and data processing. The latter two have been investigated and developed in related fields, particularly the medical field. Polydorides (2002) in particular worked extensively in addressing the data processing issue of soft-field tomography, and has developed a MATLAB toolkit called EIDORS (Electrical Impedance Tomography and Diffuse Optical Tomography Reconstruction Software).

The EIDORS project has developed a community that promotes communication and sharing of software to further the development of EIT. The software, documentation, examples and available help were crucial in the data processing and data visualization stages of this project.

The issue of data acquisition has also been addressed. The Weerled et al. (2001) EIT experiment required data collection from 192 electrodes in near real-time, and did so successfully. However, the optimum order and procedure in collecting data has been debated by Molinari (2003) and Polydorides (2002), both of whom have modeled the system at hand extensively, but have published little physical experimentation. Polydorides (2002) has suggested that a 16 electrode ring is the optimum size based upon computational time, the noise imposed by additional electrodes, and the fraction of singular values that are useful.

Another method of interest suggested by Polydorides (2002) is a segmented electrode configuration. For example four electrodes across from one another would be turned on simultaneously, while the remaining electrodes measure voltage independently. Molinari (2003) and Polydorides (2002) have many suggestions on techniques to reduce computational time, increase resolution, and filter out noise, but all of this will be investigated when necessary later on in the project.

One of the major difficulties with EIT is in the electrode connection. In several papers (Van Weereld et al., 2001, Polydorides 2002, and Molinari 2003) it has been found that accurate, consistently geometric connections are difficult to obtain, and the practical limitations imposed by wiring limits the number that can be attached by hand (Van Weereld et al. 2001). Van Weerald's solution to this problem was to use a flexible circuit designed for the core specifically to ensure consistent size and distribution of electrodes while also creating a compact manageable system as compared to conventionally wired electrodes. However, initially a conventional wiring scheme has been selected here to begin investigating EIT.

EIT Apparatus

The primary idea behind the EIT apparatus, more specifically the electrode configuration, is that solid connections to the core sample must be made and the electrodes must be equidistant around the circumference of the core. This is in order to simplify the model used in solving the inverse problem. Design variations of the apparatus appear when trying to decide on a feasible number of electrodes, whether a flexible circuit is warranted and viable, and which design will be simple and reliable.

Electrode Design

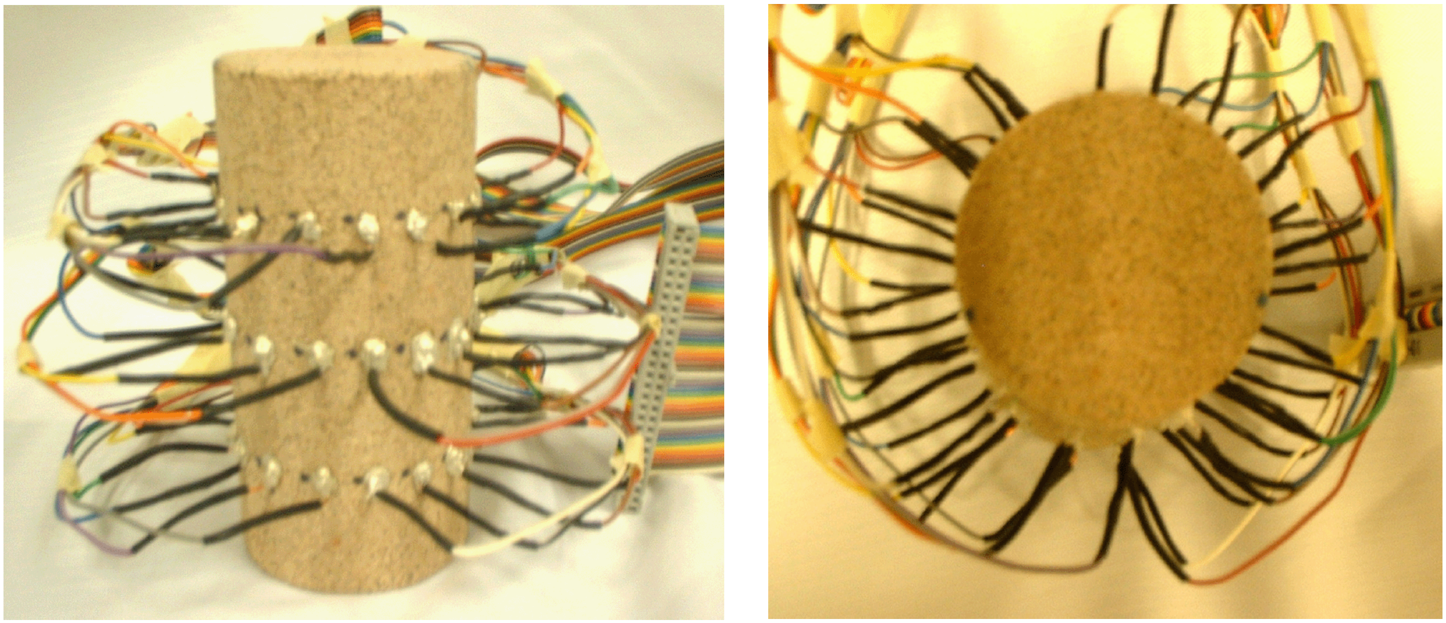
The electrode configuration decided upon for the initial experiment is simple enough to eliminate many unnecessary problems, such as system leaks, short circuiting, and poor connections. Yet the system is complex enough with 3 rings of 16 electrodes to fully test the data acquisition system and the MATLAB toolkit EIDORS in post processing. Figure 2 shows the design with 3 rings of 16 electrodes attached to the Berea sandstone core with conductive silver epoxy. The experiment works by imbibing water into the core by capillary forces. Therefore, no core holder is required, eliminating the issue of leak problems.

Data Acquisition System

The basic requirements of the EIT data acquisition system were found to be very similar to the cases of Polyrides (2002) and Weereld et al. (2001). The EIT system requires a computer with sufficient speed and memory to handle the data, a constant current source, and a matrix/multiplexer system that can manipulate the distribution of current signals to the array of electrodes. The system must have the capability of measuring the voltage potential at all electrodes, while applying a designated current across a select set of electrodes. The system must then change the set of electrodes applying current and measure the voltage potential at the remaining electrodes. It is obvious that under such a situation many measurements must be taken and a high speed switching system is necessary.

In our case with 48 electrodes, 2,304 switches needed to be made. (48 voltage measurements per current drive pair) An example of the numbering system for our core can be seen in Figure 3.

The switch matrix is set up in a 4x64 (1-wire) configuration, meaning that 64 external channels are crossed with four internal channels, giving the ability to access 64 electrodes voltages from four input channels. The present design uses 4x48



(Side View)

(Top View)

Figure 2. Side and top view of the preliminary design. 48 electrodes were attached to a Berea sandstone core using conductive epoxy.

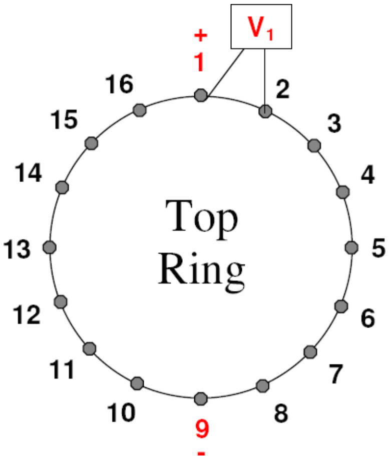


Figure 3. Numbering scheme for top electrode ring with current drive from electrode 1 to opposite electrode 9 and differential voltage measurement between electrode 1 and 2.

channels, 48 electrodes crossed with one current source, one ground, and two voltage measurement channels. The entire scan time for the core is approximately 40 seconds, which is mainly comprised of the settling time required to perform each measurement. This introduces the assumption that the saturation does not change significantly over the 40 second scan period.

Currently the total accuracy of our data acquisition system is unknown, but some limitations and tolerances are apparent. The voltage measurements are precise to several hundredths of a volt, and can measure up to +/- 10 V. The limitations of concern deal with the switching matrix capabilities; the applied current cannot exceed 400mA, the voltage may not exceed 30 V, and the switching rate is limited to 900 cycles/minute. These limitations were critical when designing test runs in order to protect the equipment and obtain accurate results.

A schematic of the EIT apparatus can be seen in Figure 4. The switch matrix and data acquisition (DAQ) card are controlled by an automated program developed in LABVIEW. The applied current and core saturation are manually set prior to the experiment, and the change in saturation is monitored by the scale. The data is then processed separately in the MATLAB program developed by the EIDORS project. During the calibration stage the resistivity meter is used manually to measure the real resistance along the core.

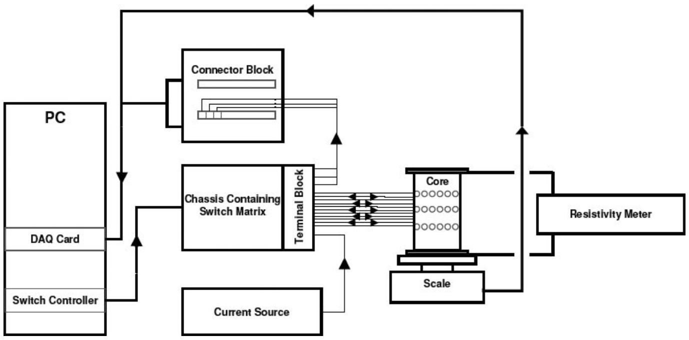


Figure 4. EIT system schematic. The PC cycles through the core by measuring the voltage potential at every electrode before changing the current source electrodes. The current is supplied by a DC current generator, while the voltage potential measurements are retrieved by the DAQ card. The scale and resistivity meter are used to calibrate the EIT measurements by providing the actual saturation and resistivity.

Data Processing

The data processing portion was accomplished with the EIDORS V3.0 toolkit. EIDORS is a MATLAB program package developed collaboratively by EIT research groups. The toolkit was required due to the nature of EIT being nonlinear and an ill-posed problem. It utilizes a finite element model for forward calculations and a regularized nonlinear solver for obtaining a unique and stable inverse solution. (Polydorides et al. 2002) The package is equipped with a mesh generator, several standardized EIT methods, a graphical output, and supports two-dimensional and three-dimensional systems.

The scheme utilized in our system was a forward solution solved with a mesh of 13,824 finite elements, and an inverse solution mesh of 1,536 elements. The program then calculated the linear inverse solution iteratively by using a weighted image prior of the homogeneous solution.

The major change implemented in reconstructing the resistivity image was omitting the positive and negative current electrode voltage measurements. These extreme voltages are caused by electrode skin effects (Bagotzky 1993), and were justified in their omission because we are interested in the internal resistivity distribution not the electrode resistivity. The final images reconstructed in EIDORS indicate the relative resistivity to the initial resistivity assigned for the forward solution, Figure 5 shows example images.

Experimental Procedure

Core Saturation

Prior to saturation, the core is heat dried under vacuum for four hours and the initial dry weight is recorded. The core is then deaerated by placing it in a vacuum flash, where it remains under vacuum at a pressure of ~100 millitorr for 5 hours to ensure pressure equilibrium within the core. After this period the core is saturated by opening a valve that allows the deaerated fluid into the chamber. The core then remains submerged for 24 hours to ensure complete saturation. The weight recorded after this saturation is set as the 100% saturation point for calculating the resistivity index. Both 0.5% NaCl and distilled water may be used in calibration test runs.

EIT Scan and Measurement Calibration

In these EIT experiments a scale and a resistivity meter are used to calibrate and quantify the accuracy of the EIT technique. Every 10 minutes the EIT system scans the core and records the core saturation. The real resistivity of the core is measured by using a resistivity meter with electrode plates at each end of the core. To minimize interference with the EIT voltage field, resistivity measurements are taken manually between EIT scans. The experiment continues until the resistivity distribution calculated by EIT becomes erroneous, which is speculated to be the point at which the connate water film becomes disconnected between an electrode and the core. This point has occurred at 15% and 11% water saturation in two of the experiments.

Experimental Results

Initial Tests

Initial tests, conducted to investigate the capabilities and limitations of EIT, were able to detect saturation changes in the core and the results were verified visually. The data acquisition time was approximately 40 seconds, with a post-processing reconstruction time of 74 seconds for images similar to those in Figure 5. An immediate problem appeared when scanning the core at very low saturations, <10%. At these saturations the differential voltages between electrodes went above the measuring capability of the system. The reason for this sudden spike in voltages is believed to be connate water becoming disconnected from the electrodes. Therefore this problem was addressed in two ways. First the voltage measurements at the current drive electrodes were omitted because the maximum voltage measureable by the system is 10V, and because of the difficulty due to the skin effect mentioned previously. Secondly, the EIT scans were limited to imaging when the saturation was sufficient to provide proper connectivity to the electrodes.

Therefore, in the series of tests shown in Figure 5, an initial saturation had to be present to allow imaging, as shown in Figure 5 (a). This initial saturation occurred by allowing distilled water to imbibe into the dry core for 3 hrs. Figures 5 b, c, and d show the step decreases in resistivity as the core was submerged in ionic water to the bottom, middle, and top ring respectively and then removed for imaging.

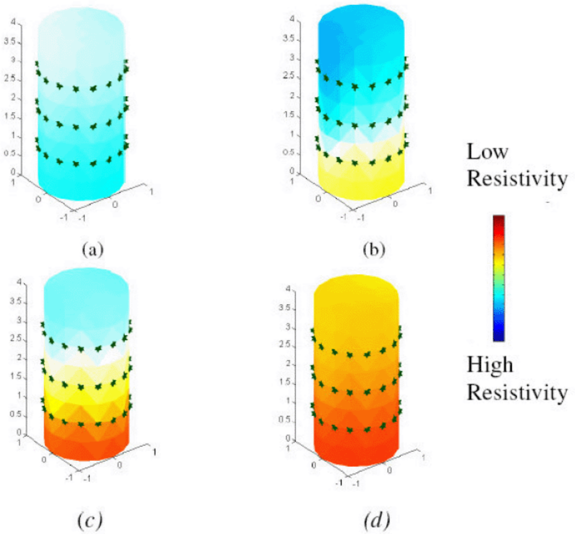


Figure 5. (a) Resistivity distribution after natural imbibition for 3 hrs. (b) Followed by submerging the column in water up to bottom ring. (c) Submerging to middle ring (d) Submerging to top ring.

EIT Calibration

Before using EIT to image multiphase flow systems, the technique needs to be calibrated to determine the corresponding resistivity-saturation relationship. The calibration is expected to follow the well-known Archie's equation for resistance and saturation, Equation 3. The equation indicates that with decreasing saturation, S_w, the resistivity index, I, increases, where R_0 is the core resistance at 100% saturation and R_t is the resistance measured.

$$I = {}^{R_t}\!\!\big/_{R_0} = {}^{1}\!\!\big/_{S_w^n} \qquad (3)$$

The calibration began with the core 100% saturated with 0.5% NaCl and the saturation decreased by natural evaporation. The EIT system scanned and recorded the core saturation every 10 minutes. In this initial trial experiment an unanticipated decrease in resistivity with decreasing saturation was observed until ~55% saturation, which contradicts Archie's equation.

Therefore in the second calibration experiment a resistivity meter was used to provide an accurate resistivity measurement for comparison with the EIT measurement, as shown in Figure 4. The resistance along the length of the core was measured at three different frequencies 100 kHz, 20 kHz, and 1 kHz. The results shown in Figure 6 indicate that the resistivity-saturation relationship for the core does indeed follow Archie's equation, with a logarithmic increase in resistance with decreasing saturation. It is clear that the decrease in resistivity with decreasing saturation is not a physical phenomenon of the core, but of the EIT system itself. Therefore further calibration and experimental refinement will be necessary before saturation distributions can be investigated quantitatively.

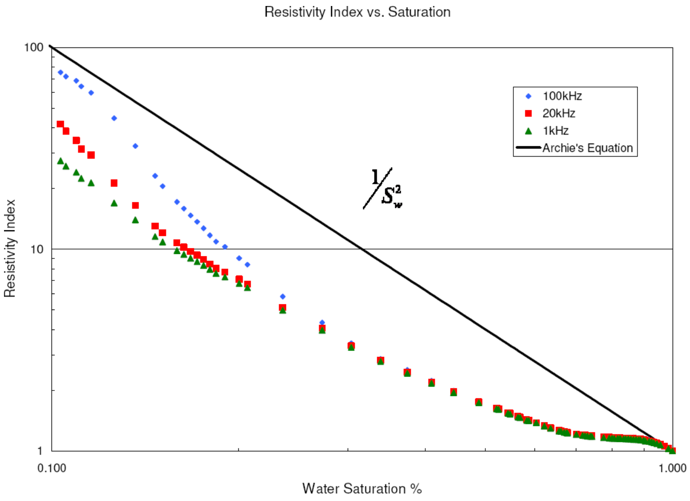


Figure 6. The resistivity index for the Berea sandstone core measured at 100 kHz, 20 kHz, and 1 kHz by the resistivity meter. The Archie curve is plotted with n = 2 for comparison.

Conclusions

The calibration of EIT system is still undergoing experimental confirmation. The contradiction to Archie's equation at high saturations demonstrates that there are multiple aspects of the system electrochemistry that need to be taken into consideration for EIT to provide accurate saturation measurements. Skin effects and polarized electrodes due to the DC current are two phenomena that may account for this deviation (Bagotzky 1993).

However, the initial qualitative tests on the Berea sandstone core indicate that EIT is a viable alternative for measuring the saturation distribution within a geothermal rock core, and is capable of detecting saturation fronts in near real-time. However, EIT does have drawbacks. The diffusive nature of EIT currently makes the reliable detection of sharp saturation fronts difficult, but not necessarily impossible. It is anticipated that with continuing advancements in the EIDORS project image resolution will increase.

The computational power required is also a problem to be addressed. The inversion process is computationally intensive. The process required ~1GB of RAM and ~74 seconds to complete the first inversion on a 3GHz processor, but only ~2 second for each subsequent inversion. It has been observed while working with the software that as the number of measurements and the mesh density increase, the time and memory required increase even more rapidly.

Future Work

The next step in development of the EIT technique is the saturation-resistivity calibration, because this is required before any quantitative experiments can be performed in regards to saturation distribution. Currently we are trying to understand the electrochemistry of the system and understand how it impacts the saturation-resistivity relationship. Upon the successful calibration of mean saturation and resistance, the saturation distribution inferred with EIT will be compared to the distribution measured by a traditional X-Ray CT scan.

In the future, with the uncertainties and limitations of the system understood, the technique may be applied in several areas at varying scales. In the laboratory, EIT may be applied to geothermal cores at reservoir pressures and temperatures to understand the pore scale physics within a geothermal reservoir. At the reservoir scale, a future possibility is to investigate the development of an in-situ EIT system, where boiling fronts may be monitored, residual saturation determined, and recharge systems investigated.

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