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ELECTRICAL IMPEDANCE TOMOGRAPHY (EIT) METHOD FOR SATURATION DETERMINATION

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ABSTRACT

3D Electrical Impedance Tomography (EIT) is an alternative to the traditional CT scan technique that has been used to measure saturation distribution within a rock core. The primary motivation for investigating EIT is the applicability to high pressure, high temperature geothermal reservoir conditions, which would require a metal core holder, therefore eliminating the use of the CT scan technique. Secondary advantages of the EIT technique are that it is an inexpensive, practical, compact, and safe alternative to the CT scan.

The initial EIT device presented here instrumented a Berea sandstone core with 48 electrodes attached in three rings of 16. The core is open to the atmosphere and saturation occurs by natural imbibition. The resistivity measurements are conducted by applying a direct current pulse and using the 4-wire resistance technique over all electrodes. This resulted in a data set that embodies the resistivity distribution within the core. Processing of this data set results in the reconstruction of the resistivity distribution, which is the saturation distribution.

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

It was found that EIT can detect changes in the core's resistivity distribution quickly and with relatively good accuracy. However, currently the diffusive nature of EIT makes the reliable detection of sharp saturation fronts difficult, but not impossible. Therefore future efforts are being applied to increase resolution and quantify accuracy.

INTRODUCTION

The concept of measuring the saturation distribution in a core using ERT 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 techniques shown in the paper did not convert resistivity images to saturation, or validate their results against other methods. Therefore we have developed an apparatus to investigate the feasibility of using EIT to measure geothermal core saturation.

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.

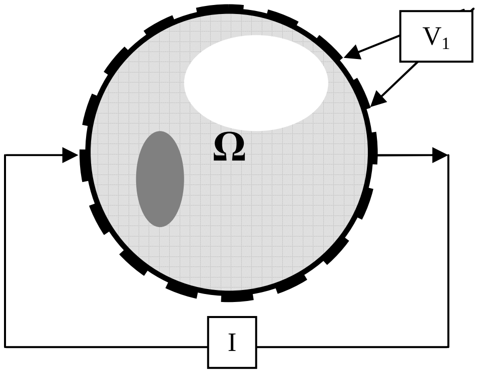


Figure 1. Diagram of 16 electrode EIT experiment. The potential V_1 is measured after a current I has been imposed across the core Ω. (Molinari 2003)

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

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

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

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

The EIT inverse problem can be simplified down to a system identification problem. The cause and effect (injected current ***I*** and measured voltage ***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 researched and developed in similar 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 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 stage.

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 latter on in the experiment.

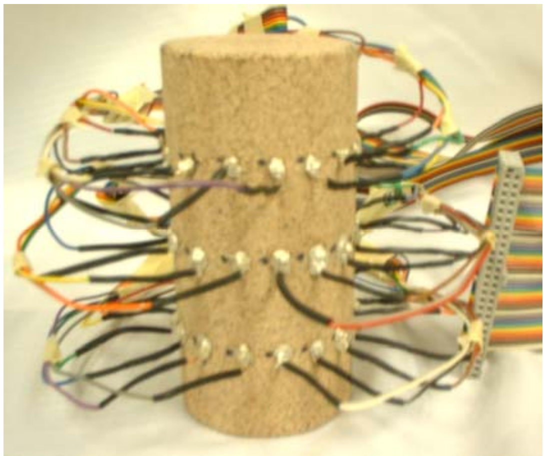
One of the major difficulties with EIT is in the electrode configuration and connections. In several papers (Van Weereld et al., 2001, Polydorides 2002, and Molinari 2003) it has been found that accurate, consistently geometric connections are difficult to obtain, and the practical limitations imposed by wiring limits the number 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, in our experiments a conventional wiring scheme has been selected initially to begin investigating the EIT.

EIT Apparatus

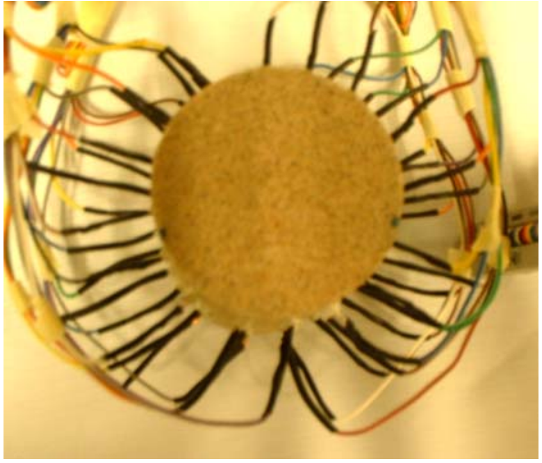
The primary idea behind the EIT apparatus, more specifically the electrode configuration, is that solid connections to the core sample must be made and the electrodes must be equidistant around the circumference of the core. This is in order to simplify the model used in solving the inverse problem. The 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 able to eliminate many problems, such as system leaks, short circuiting, and poor connections. Yet the system is complex enough with three 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 three rings of 16 electrodes attached to the Berea sandstone core with conductive epoxy. This system has been tested by placing the core in varying depths of water and allowing water to imbibe naturally by capillary forces. During this time the data acquisition system records the voltage potential data for post-processing, resulting in the reconstruction of the internal resistance distribution. The accuracy of the experiment is qualified by visual observations of the saturation front.



(Side View)



(Top View)

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

Data Acquisition System

The basic requirements of the EIT data acquisition system were found to be very similar to the cases of Polyrides, and Weereld. 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 handle the array of electrodes. Essentially, 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 need to be made. (48 voltage measurements per current drive pair) For this purpose, a National Instruments SCXI-1130 switch matrix was selected. An example of the numbering system for our core can be seen in Figure 3.

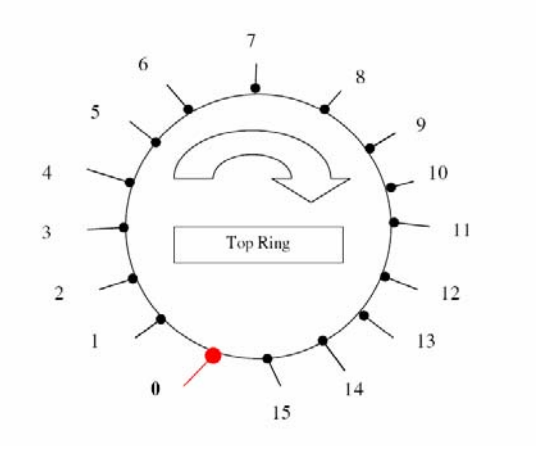


Figure 3 Numbering scheme for top electrode ring.

The SCXI-1130 is configured in a 4x64 (1-wire) configuration, meaning that 64 channels are crossed with four channels, giving the ability to access 64 channels from four channels. The present design uses 4x48 channels, 48 electrodes crossed with one current source, one ground, and two voltage measurement channels. The entire scan time for the core (approximately 12 seconds) is comprised mainly of the settling time required to perform each measurement. This introduces the assumption that the change in saturation is not significant over the 12 second scan period.

Currently the total accuracy of our system is unknown, but some limitations and tolerances are known. The SCB-68 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, that the applied current cannot exceed 400mA, and that the voltage may not exceed 30 Vac, and that the switching rate is limited to 900 cycles/minute. These 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 DAQ card are controlled by an automated program developed in LABview. The current source and core saturation are manually set prior to the experiment. The acquired data are then processed separately in the MATLAB program developed by the EIDORS project.

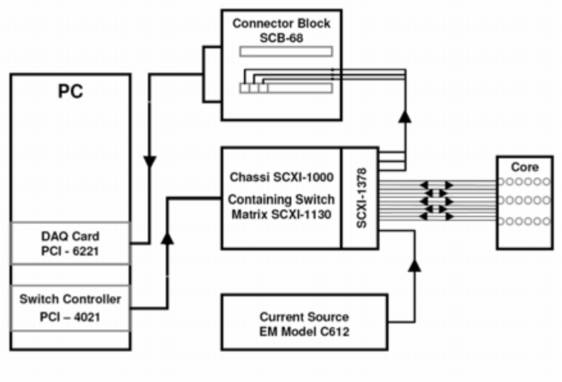


Figure 4. EIT system schematic. The PC cycles through the core by measuring the voltage potential at every electrode before changing the current source electrodes. The current source is supplied by a constant current generator, while the voltage potential measurements are retrieved by the DAQ card.

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 non-linear and an ill-posed problem. It utilizes a finite element model for forward calculations and a regularized non-linear 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 2D and 3D 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 (Bockris et al. 1993), and were justified in their omission because we are interested in the internal resistivity distribution not the electrode resistivity.

The reconstructed images that resulted indicate relative conductivity to the homogeneous conductivity assigned for the forward solution.

EXPERIMENTAL RESULTS

With the EIT technique we have detected saturation changes in the core, and have visually verified these results, Figure 5. Figure 5 a-d show a series of tests conducted to investigate the abilities and limitation of EIT. It was found that the data acquisition time is approximately 12 seconds, with a post-processing reconstruction time of 74 seconds for images as seen in Figure 5, using a 3 GHz Pentium-4 computer for the inversion..

A clear problem discovered early on was that of imaging the core at very low saturations. At low saturations the connate water becomes disconnected from the electrodes, therefore requiring voltages in excess of 150V to maintain a constant current of 0.05mA. Voltages at this level are beyond the handling capability of the SCB-68, and the switching matrix. Therefore this problem was addressed in two ways. First the voltage measurements at the current drive electrodes were omitted due to the skin effects previously mentioned, and because the SCB-68 cannot measure over 10V. Secondly, the core is limited to imaging when the saturation is 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, Figure 5 (a). Figures 5 b, c, and d show the step decreases in resistivity as the core was submerged to the bottom, middle, and top ring respectively and then removed for imaging.

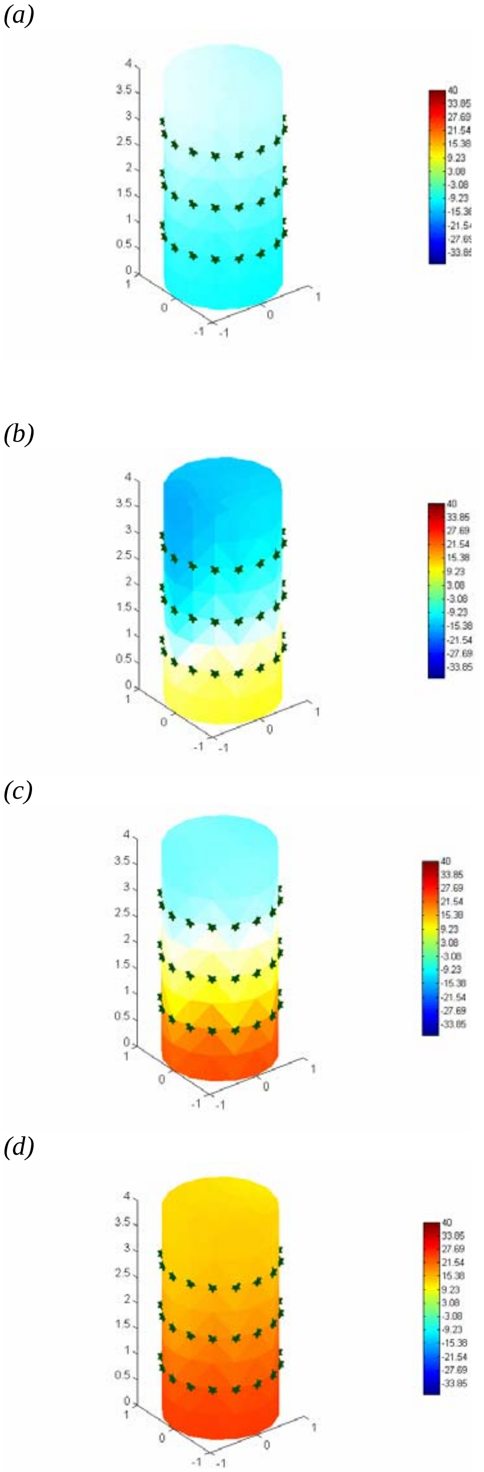


Figure 5 (a) Resistivity distribution after natural imbibition for 3 hrs. (b) Followed by submerging the column in water up to bottom ring. (c) Submerging to middle ring (d) Submerging to top ring.

RESULTS AND DISSCUSSION

From these initial atmospheric tests on the Berea sandstone core it appears that EIT is a viable alternative for measuring the saturation distribution of geothermal rocks. It was found that EIT can detect changes in the core's resistivity distribution quickly and relatively accurately. The accuracy statement is based upon visual observations, not on quantitative tests as are planned for the future. Therefore the EIT technique appears to be an inexpensive, practical, compact, and a safe alternative to the CT scan for measuring core saturation distribution.

However, EIT comes with downfalls. It has been found as anticipated that the diffusive nature of EIT currently makes the reliable detection of sharp saturation fronts difficult, but not necessarily impossible. With continuing advancements in the EIDORS project image resolution is anticipated to become clearer. Another issue to note with EIT is the computational power required. The reconstruction of these images required ~1GB ram, a 3GHz processor, and ~74 seconds to complete the inversion, and the time and memory required increases dramatically with an increase in the number of measurements and mesh density.

FUTURE WORK

One of the immediate goals for the project is to convert resistivity measurements to saturation. The accuracy of the EIT technique will then be quantified by comparing saturation measurements to measurements obtained by mass balance calculations and the traditional CT scans. In calibrating the EIT saturation measurement it is also planned to conduct a sensitivity analysis on the inversion algorithm itself.

Following successful saturation calibrations, the next major step is to apply the EIT technique to high pressure and temperature reservoir conditions. The experiment would include phase transport in a geothermal core, just as in typical core experiments. These upcoming experiments are anticipated to provide new insight into the core scale mechanics of geothermal reservoirs.

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