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Using 3D Electrical Resistance Tomography for Packed Bed Column Monitoring

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ABSTRACT

Electrical Resistance Tomography (ERT) is a scanning technique that has been widely used in various industrial processes. By injecting low frequency signal into measuring samples, ERT technique is able to obtain the conductivity distribution information of the sample. The conductivity information can be an important indicator for process conditions, for example, mixing conditions, material composition and contamination detection. In the past, ITS Plc has successfully implemented 2D ERT technology into the packed bed applications such as chromatography column monitoring. Column chromatography is a widely used technology in chemistry for purifying/separating chemical compounds. It is often an expensive process and the packing cannot be used after certain amount of cycles, due to degradation of the packing. In the life sciences sector which are regulated a conservative approach must be taken to ensure quality and purity of production. The lack of information in columns and their expense makes ERT an attractive technique for monitoring the packed beds and column conditions. By monitoring the column conditions effectively, the user can determine assess its performance and quality, to prevent unnecessary loss and maintain quality and yield. Conventional 2D multi-plane ERT can provide cross sectional distribution information about the conditions. However the result might not be very representative due to the lack of inter-plane information. In this paper, multi-plane 3D ERT modelling is proposed as it is believed that 3D ERT can provide further axial information about the process, which is very critical because of the geometrical features of the pack bed. A 4x16 ERT sensor is used in this paper to demonstrate the difference between 2D and 3D ERT. Both the theoretical and experimental results will be presented in this paper.

Keywords Process Tomography, Electrical Resistance Tomography, 3D Reconstruction, Pack Bed Applications.

1. INTRODUCTION

Packed beds are typically consisting of vertical cylindrical container filled with packing materials that improve the surface contact of two phases in processes. It can be applied in a chemical reactor, distillation process or chemical purification chromatography applications. Due to the nature of the packed bed structures, the process takes place within the packing is often inaccessible and the packing material will wear out after certain amount of process cycles due to material degradation.

A high performance of a packed bed usually refers to how evenly the flow is distributed through the packed bed reactor, which in turn is dependent on the packing structures. Therefore, monitoring the flow pattern throughout the packed bed becomes critical to ensure a better control of the process. By monitoring packed bed processes, the user can further understand the chemical processes in a more complete manner, e.g. liquid flow distribution and mixing processes. In addition, the cost of replacing a packed column is often very expensive; it is therefore very useful to keep track of the packed bed condition, so the packing replacement will only take place when it is needed.

Several studies on packed column monitoring have been carried out such as liquid collecting method [DANG-VU 2006], tracing method [INGLEZAKIS 2001] and conductance probe method [TSOCHATZIDIS 2002]. Nevertheless none of these methods can offer the information in real time. For example, liquid collecting method has been used widely to investigate the flow distribution because of its simplicity, however the analysis result can only be revealed when the chemicals are collected at the end of the process. In order to obtain the information at the same time as the reaction takes place, electrical resistance tomography (ERT) technique has been proposed for this packed bed monitoring applications [DOAN 2011]. ERT is an instrumentation technique that is sensitive to the electrical conductivity properties of sampling materials. By attaching an electrode array on the peripheral of the measuring object, its conductivity information within the sensing region can be obtained through a series of current excitation and potential measurement processes. In many chemical processes, often the chemicals are electric conductive, which makes ERT a suitable

technique for this particular monitoring task. In the previous studies, 2D ERT tomogram has been the standard technique for packed column monitoring and quantifies the chemical processes along both the radial and axial direction without disturbing the flow profile [LEE 2010, RUZINSKY 2007, BOLTON 2004]. However each 2D tomogram can only provide the cross-sectional information in radial direction. If there is any chemical reaction take place in the inter-plane region, or the reaction profile is unsymmetrical along the axial direction, the results obtained from 2D ERT can be erroneous and misleading.

To overcome this issue, the authors propose using 3D ERT to improve the situation. 3D electrical tomography has been studied by many researches [DAVIDSON 2004, JAVAHERIAN 2014, WANG 2014] but there has not been much investigation into utilising ERT for packed bed applications. The advantage of 3D tomography is that it includes extra inter-plane voltage measurements into the reconstruction process, hence the conductivity change around the inter-plane region can also be detected. As the result, the unsymmetrical flow profile in the packing column can also be detected and reconstructed correctly. In this paper, the 3D ERT forward and inverse methods will be discussed and simulated. A quad plane ERT sensor is also used for concept validation. Several experiments have been conducted to simulate the packed bed environment in laboratory scale and demonstrate that 3D ERT is capable of monitoring packed bed condition in a full-field manner.

2. FORWARD MODELLING

A typical 3D ERT sensor consists of two or more planes of electrodes. During the measurement, one electrode is injected with sinusoidal current, and its adjacent electrode is connected to earth to create a current path. The potential difference between the rests of the electrode pairs are used for receiving signal. In ERT, the relationship between the conductivity distribution $\sigma(x)$ and the boundary electrical potential $u(x)$ are given by the following Poisson equation (1):

$$\nabla \cdot \sigma(x)\nabla u(x) = 0 \quad (1)$$

And the boundary conditions are set by the current injected into an electrode pair τ_l with contact impedance z_l :

$$V_l = u(x) + z_l \sigma(x) \frac{\partial u(x)}{\partial n} \quad (2)$$

$$I_l = \int_{\tau_l} \sigma(x) \frac{\partial u(x)}{\partial n} d\tau \quad (3)$$

$$\sigma(x) \frac{\partial u(x)}{\partial n} = 0 \quad (4)$$

In the equation (2), $u(x)$ is the electric potential on different surfaces of the sensing electrodes and V_l is the constant voltage on the l -th electrode. Equation (2) is the boundary condition of the driving electrode pair, and equation (3) is for the boundary without electrodes.

After defining the boundary conditions, the electrostatic values for all the voxels can be calculated for each of the excitation electrode pair. And the sensitivity map (also known as Jacobian matrix) can then be computed. The sensitivity map gives the relationship between the change of the sensor measurement and the change of the electrical conductivity of the measuring object. The formulation of sensitivity maps are discussed in [Zhang 2013; Lionheart 2004], the generalised equation is indicated below:

$$\int_{\tau} \delta E_1 \times H_2 \cdot n d\tau = \int_{\Omega} -i\omega\delta\mu H_1 \cdot H_2 + (\delta\sigma + i\omega\delta\varepsilon)E_1 \cdot E_2 d\Omega = 0 \quad (5)$$

Where the left-hand side represents the sensitivity by surface integral at boundary τ , and the right hand side is the volume integral over the perturbation region Ω .

When the forward problem is computed, the sensitivity maps are modelled (Equation 9) using MATLAB. The generated sensitivity map can be exported to csv format for further processes. Figure 1 shows the computed sensitivity map result for a 4 planes ERT system. The 3D mesh is generated by the NetGen software, and the sensor diameter and electrode sizes are both defined based on the true multi-planes ERT sensor dimension.

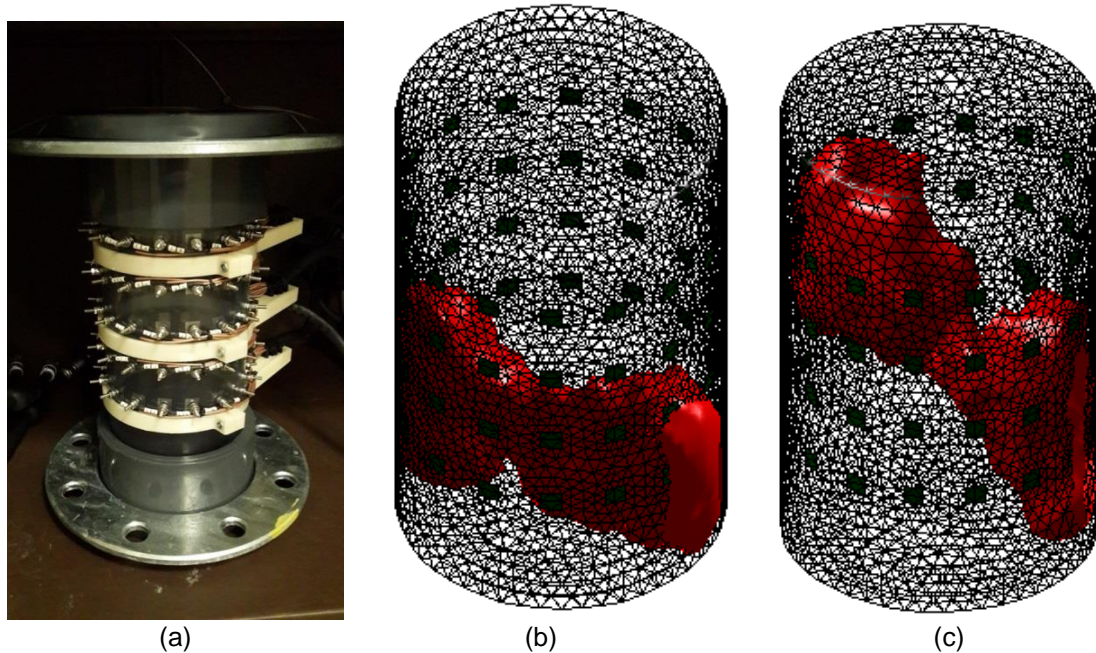


Figure 1: (a) A multi-plane ERT sensor and its corresponding 3D sensitivity distribution between (b) electrode pair 1-2 and electrode pair 8-9; (c) electrode pair 1-2 and electrode pair 55-56.

3. IMAGE RECONSTRUCTION

3.1. Reconstruction Algorithm

To expand the 2D system to 3D, not only the forward model calculation become more complicated, but the image reconstruction processes also require more computational resource. For example, to increase the electrode numbers from 16 to 64, the number of independent trans-measurement will also increase from 104 to 1952. Furthermore, in single step Gauss Newton reconstruction method, the matrix multiplication $A^T A$ will consume tremendous amount of memory. In order to avoid such a huge computational overload, a modified Wiener filter is applied into the single step method, so the multiplication $A^T A$ can be avoided.

$$x = A^T (AA^T + \lambda R)^{-1} b \quad (6)$$

Where A is the sensitivity matrix computed from Section 2, b is the relative voltage change, x is the relative conductivity change, λ is the regularisation parameter and R is the regularisation matrix. The principle of this alternative inverse solver is discussed in [ADLER 2007, DAI 2007]. By using Equation 10, the $A^T A$ multiplication can be avoided; hence the memory size and the computational time required for inverse solver can be reduced dramatically.

Due to the nature of electric field distribution, it is known that the central region of the sensor will have the weakest sensitivity. For 3D tomography reconstruction, due to the increase of inter electrode pair distance, the sensitivity at the centre region of the phantom will be even weaker. To enhance the central sensitivity, the Newton one step error reconstruction (NOSER) algorithm is applied to reconstruct all tomograms for all the data acquired from the experiments in this paper [CHENEY 1990, DAI 2007]. In the next section, some simple experiments using a quad-plane ERT sensor will be conducted to validate the forward model, inverse algorithm and sensor performance.

3.2. Reconstruction Validation

In order to validate the sensor performance and model calculation, some simple experiments were conducted. The ERT sensor used in the test has a cylindrical geometry with 10cm diameter and 5 planes of electrode rings. The inter-plane distance is 3.0 cm and each ring contains 16 electrodes which are equally located around the sensor. In the tests, only the bottom 4 planes are used, in order to match our 4x16 ERT model computed in Section 2.

The ERT instrument p2+ system (developed by Industrial Tomography Systems PLC) is used for data acquisition. The p2+ system is a current driven ERT system which can excite sinusoidal current

ranges from 0.1mA to 75mA. And it can support a maximum of 128 channels sensor, which is very suitable for 3D applications which often involved with large number of sensor array electrodes.

The sensor is initially filled with tap water. For the first two tests, non-conductive plastic rods are inserted into the sensor in diagonal and upright positions (Figure 2 and Figure 3). In Figure 4, a conductive pipe is configured into a spiral shape and put into the sensor. Both contour method and slice method are used to visualise the reconstructed 3D tomogram. From all the figures, one can see the tomogram can successfully determine the true conductivity distribution of the real scenario.

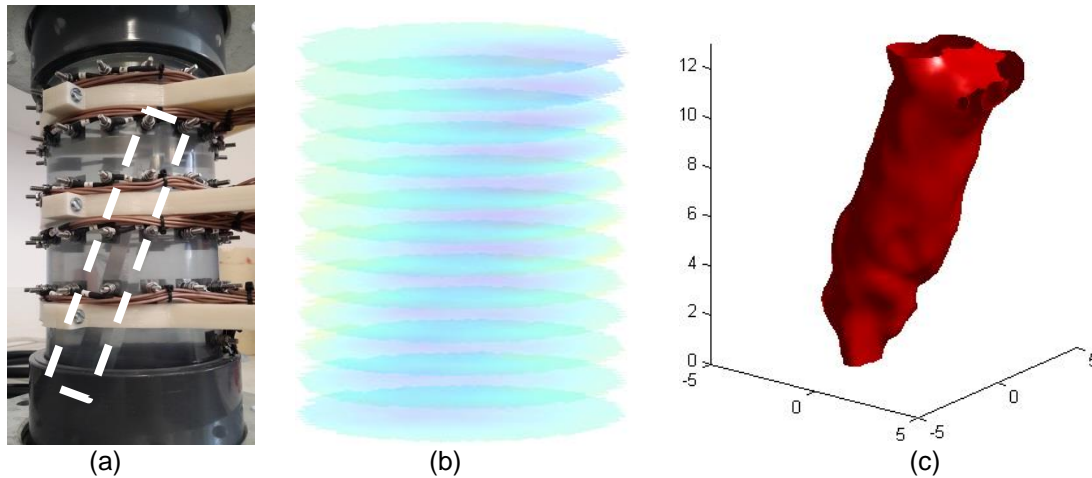


Figure 2: One non-conductive plastic stick is inserted diagonally in an ERT sensor.

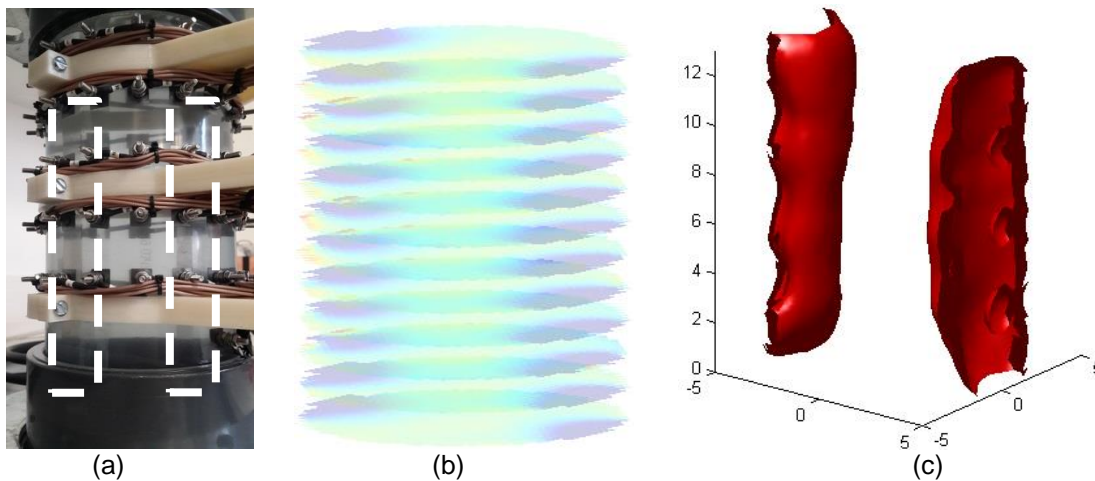


Figure 3: Two non-conductive plastic sticks are inserted upright at the opposite positions in an ERT sensor

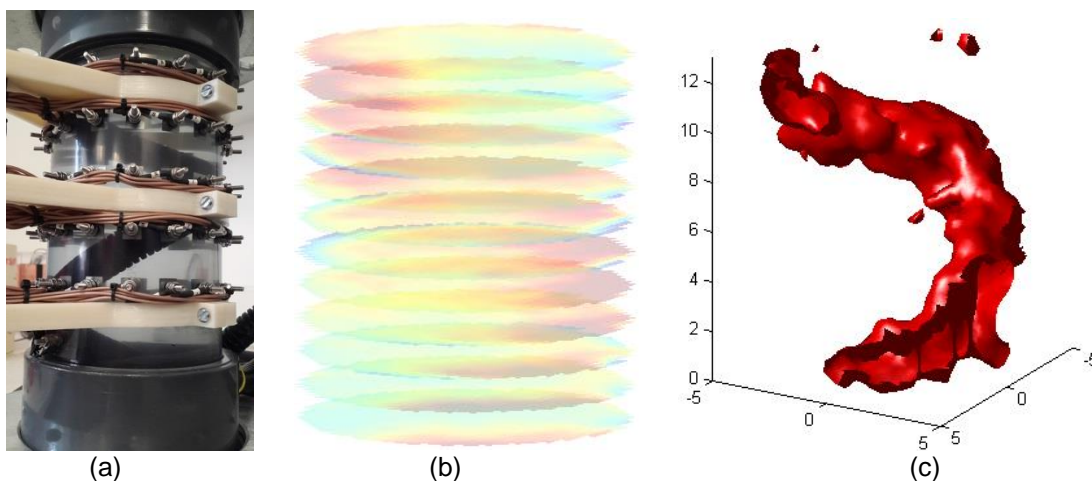


Figure 4: One conductive spiral tube is inserted in an ERT sensor

Besides capturing the true conductivity distribution in all figures, Figure 4 further demonstrates the importance of capturing the axial information, which can only be achieved by performing 3D full-field reconstruction. When there is non-symmetrical element occur inside the sensor, it will be relatively difficult to extract true process information based on multiple 2D tomograms. Figure 5 shows the reconstruction result when the same spiral tube is placed in the ERT sensor.

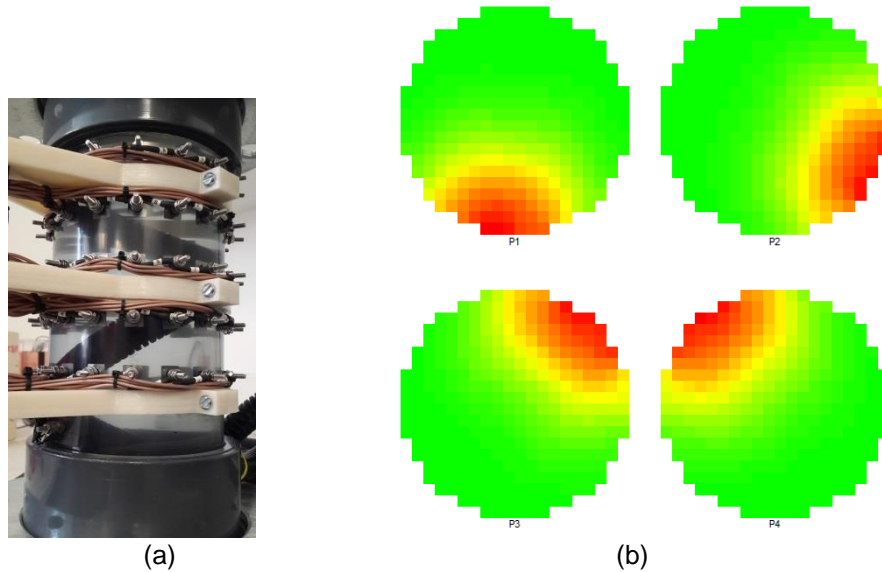


Figure 5: The 2D ERT reconstruction results when detecting a spiral shaped object.

4. PACKED BED EXPERIMENTAL RESULTS

To further validate the concept of applying ERT for packed bed column monitoring process, more experiments are conducted to evaluate the ERT performance under a laboratory based packed bed setup. In process industries, packed bed materials can be hollow tubes, pipes, specifically designed structured packing or some randomly filled small objects. In this paper, 1.5 cm diameter glass pebbles (Figure 6 (a)) are used for packing materials. To simulate a packed bed environment, the ERT sensor is filled with water and 2kg of glass pebbles (see Figure 6(b)). Because ERT is useful when detecting relative conductivity change, the additional packed bed in the sensor shall not affect the system performance significantly. By subtracting the measurement signal ($V_{\text{water}} + V_{\text{packing}} + V_{\text{chemical}}$) by the reference signal ($V_{\text{water}} + V_{\text{packing}}$), the reconstruction result will only show the conductivity perturbation caused by the process change, provided that the packing remains the same.

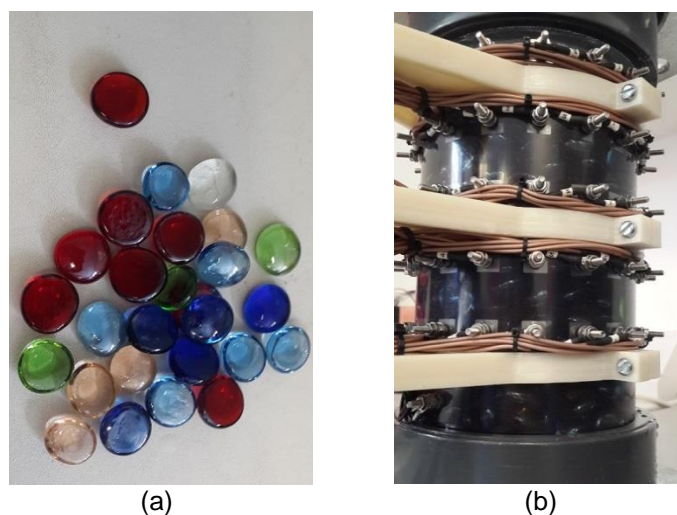


Figure 6: (a) The glass pebble used for simulating packed bed column and (b) the packed bed system setup.

To evaluate the ERT's capability to capture the process in a packed column, diffusion experiments are conducted in this paper. The multi-plane ERT sensor is first filled with glass pebbles and water. After taking a set of voltage reference, red food colouring dye is then added at the top of the packing.

Because of the packing effect and the higher dye density, the red dye is expected to diffuse through the packing towards the bottom of the sensor. In the first experiment, 2ml of red dye is added gradually at the side of the sensor. Because red dye has a higher conductivity than water, ERT sensors can be used to sense the conductivity change within the sensing region. Figure 7 shows the reconstruction result of the red dye diffusion process.

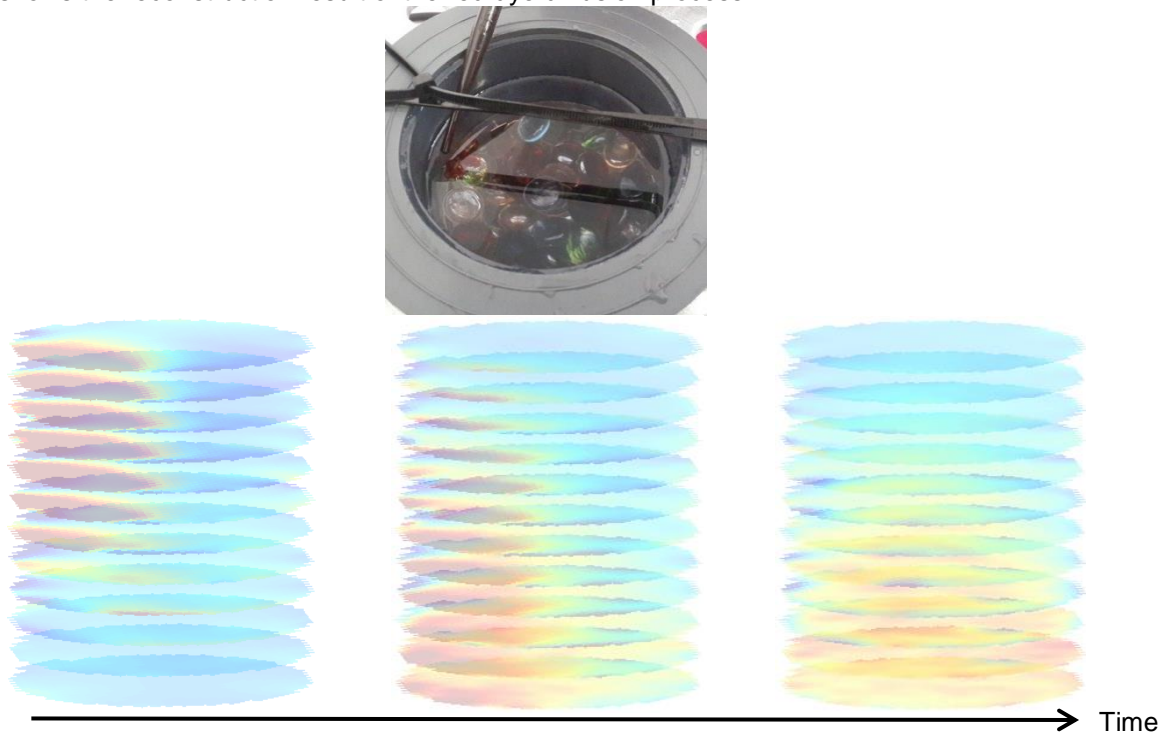


Figure 7: Red dye diffusion tomograms when red dye is dripped down at the side of the sensor.

In the second experiments, instead of adding the red colouring dye at one location, 5 ml of red dye is homogeneously dripped on the entire water surface. ERT is again used to monitor the red dye diffusion process. Figure 8 shows the reconstruction result of the red dye diffusion process.

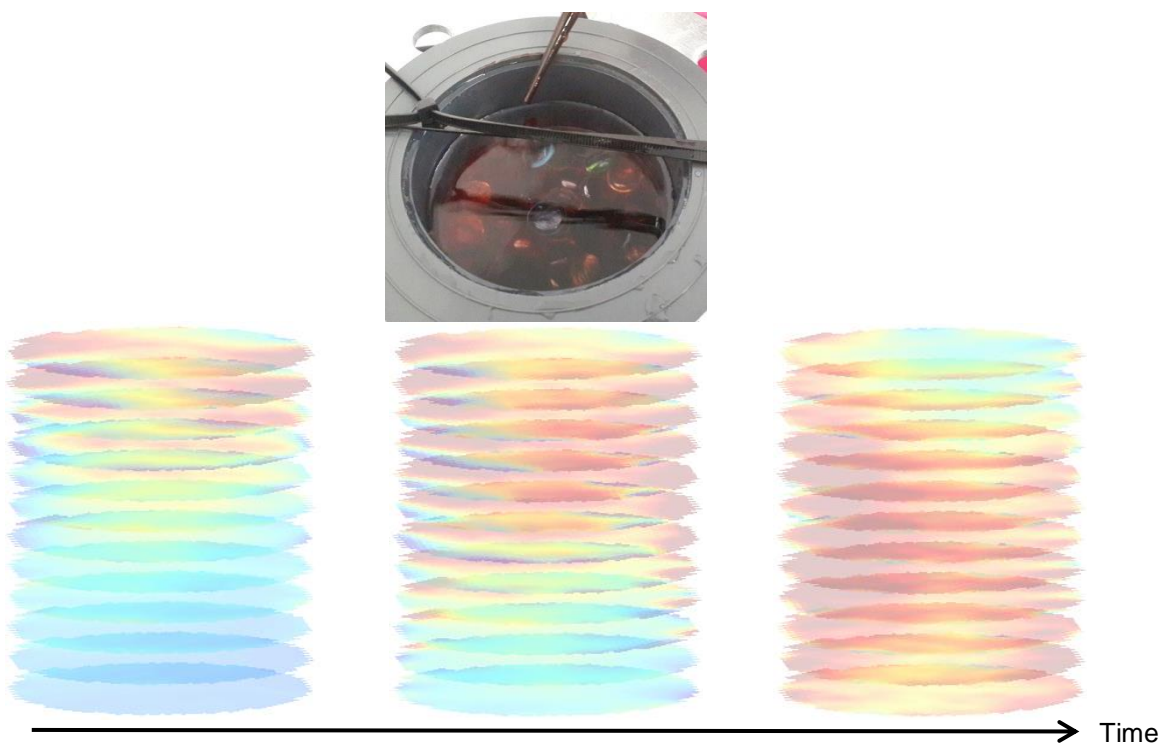


Figure 8: Red dye diffusion tomograms when red dye is distributed equally on the top water surface.

In the first experiment (Figure 7), the red dye first settles down towards the bottom because of its higher density, and then the dye starts to be diffused through the radial direction. In the second experiment (Figure 8), since the red dye is already evenly dripped on the top water surface, it is expected that the red dye will only gradually diffuse along the axial direction. Not much diffusion can be noticed in radial direction.

From both

Figure 7 and Figure 8, it can clearly be seen from the tomogram that ERT can successfully capture the conductivity change in the water because of the red dye. Although the packing is presented in the ERT sensor, it does not cause significant signal disturbances. For the packing setup, the sensor is filled mainly by the non-conducting materials. It is worth knowing that when using an ERT system for packing monitoring, a lower operational frequency is recommended, so the current signal can have a deeper penetrate depth into the packing column.

5. CONCLUSION

In this paper, the authors have demonstrated the advantage of 3D ERT in terms of capturing electrical property changes in axial direction. The potential of applying 3D ERT technology into packed bed monitoring applications is also verified. By using the ITS p2+ system, the quad-plane has successfully capture the red dye diffusion process within the glass pebble packing and the reconstructed volumetric tomogram can correctly determine the conductivity variation due to the addition of the red dye. More analysis will be required to determine the accuracy of the 3D tomograms; however this will be the subsequent studies.

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