17th Brazilian Congress of Thermal Sciences and Engineering
November 25th-28th, 2018, Águas de Lindóia, SP, Brazil

ENCIT-2018-XXXX
LOW-COST EIT SYSTEM DESIGN BASED ON THE SOFTWARE EIDORS

Bruno Furtado de Moura
Universidade Federal do Espírito Santo, Av. Fernando Ferrari, 514 - Goiabeiras, Vitória - ES, 29075-073, Brasil
bfurtado.moura@gmail.com

Francisco Sepúlveda Palma
Universidad de Santiago de Chile, Av Libertador Bernardo O'Higgins 3363, Santiago, Chile
francisco.sepulveda.p@usach.cl

Wellington Betencurte da Silva
Universidade Federal do Espírito Santo, Alto Universitário, s/n, Alegre, ES, 29500-000, Brasil
wellingtonufes@gmail.com

Rogério Ramos
Universidade Federal do Espírito Santo, Av. Fernando Ferrari, 514 - Goiabeiras, Vitória - ES, 29075-073, Brasil
rogerio.ramos@ufes.br

Márcio Ferreira Martins
Universidade Federal do Espírito Santo, Av. Fernando Ferrari, 514 - Goiabeiras, Vitória - ES, 29075-073, Brasil
marcio.martins@ufes.br

Abstract. *Electrical impedance tomography (EIT) is widely studied when dealing with multiphase flow. This method presents a technical advantage over others, as it is a non-intrusive and radiation-free technique. It allows to quantify specific flow patterns, flow measurements, along with others applications. Basically, it consists of setting electrodes in the limits of a body and obtain electrical measurements such as voltage and impedance, these measurements together with mathematical models allow to reconstruct an image of the interior. This image is calculated by the algorithms of inverse problems, such as Gauss-Newton minimization regularized by the Tikhonov technique, this combination allows to estimate the distribution of conductivity within the domain and thus indirectly the distribution of the multiphase fluid. In this work, the software Electrical Impedance Tomography and Diffuse Optical Tomography Reconstruction Software (EIDORS) together with a developed low-cost EIT system is used to reconstruct the conductivity distribution of a domain.*

Keywords: *Electrical impedance tomography, imaging, EIDORS, Inverse problem, Finite element method*

1. INTRODUCTION

The electrical impedance tomography (EIT) is a technique that is widely studied nowadays. Through the application of electrical current in adjacent pattern, it is possible to obtain a reconstructed image of the conductivity or permissivity. In this image, due to the differences in the conductivity or permissivity in the media, one could visualize the flow pattern, identifying different phases or bodies in the domain in question. The application of the electrodes is non-intrusive and low-cost, which makes this technique extremely attractive. Those techniques are employed in biomedical applications (Bodenstein et al., 2009) and industrial applications (Sharifi and Young, 2013). Specifically in industrial applications, it has been appreciated in different types of multiphase flow, as ascending and horizontal flows (Parvareh et al., 2010), different purposes as flow measurement (Meng et al., 2010) and phase distribution monitoring (Kourunen et al., 2011).

The data acquisition is realized through the use of electrodes around the surface of the domain, normally between 16 and 32 electrodes. In an application which the reconstruction is planar, the electrodes are all in the same plane, however if the reconstruction must be tridimensional, various planes of electrodes are set. An electrical current is injected within the domain through the first pair of electrodes and an electrical field is formed in this domain. In that manner, the corresponding electrode measures and register the voltage in a computer. This is done until all electrodes of the pattern is used as working electrode. A specific number of measurements is registered in that manner. These measurements are then utilized in the inverse problem (Graham, 2007).

In this work, a reconstruction is performed with the aid of the software Electrical Impedance Tomography and Diffuse Optical Tomography Reconstruction Software (EIDORS). The software uses the finite element method for the forward problem and the regularized Gauss-Newton to solve the inverse problem. A low-cost EIT equipment is developed in this work, which is used to obtain the data utilized to minimize the regularized solution.

2. MODELLING THE PROBLEM

2.1 The forward problem

Let be a domain Ω with a conductivity σ with a potential u on the electrodes which are applied a current. The equation that represents the phenomena is described as (Holder, 2004):

$$\nabla.(\sigma \nabla u) = 0, \qquad x \in \Omega \tag{1}$$

In order to express completely the model, boundary conditions must be set. In this work, the Complete Electrode Model is used, which involves the consideration of a contact impedance in the electrodes. Thus,

$$u + z_l \sigma \frac{\partial u}{\partial n} = U_l, \qquad x \in e_l, \qquad l = 1,2,\dots,L \tag{2}$$

$$\int \sigma \frac{\partial u}{\partial n} dS = I_l, \qquad x \in e_l, \qquad l = 1,2,\dots,L \tag{3}$$

$$\sigma \frac{\partial u}{\partial n} = 0, \qquad x \in \partial\Omega \backslash \bigcup_{l=1}^{L} e_l \tag{4}$$

where u is the potential distribution, n is the normal of the boundary $\partial\Omega$, z_l is the contact impedance, dS is the infinitesimal area and L is the number of electrodes.

Additionally to those conditions, in order to ensure existence and the uniqueness of the solution, it is necessary to add the model the law of conservation of charge

$$\sum_{l=1}^{L} I_l = 0 \tag{5}$$

And to set a reference point

$$\sum_{l=1}^{L} U_l = 0 \tag{6}$$

2.2 The finite element method

Firstly, in order to apply the method, the domain Ω is fractionated in simplices, turning the domain into a finite number of elements Ω_k. In two dimensions a simplex is a triangle. The mesh is then formed by the sum of those simplices, which will have k simplices and N vertices, which are called nodes. To approximate the potential on the mesh, it is used functions which are linear on each simplex, and continuous across the face, called basis function. After applying the weak form to Equation (1), a system of equation must be solved (Holder, 2004):

$$AU = I \tag{7}$$

where $I = (\mathbf{0}, I)^T$, $\mathbf{0} \in \mathbb{R}^{1xN}$, $I = (I_1, I_2, \dots, I_L)^T \in \mathbb{R}^{1xL}$ is the vector containing the injected currents. The matrix A is formed by

$$A = \begin{pmatrix} B & C \\ C^T & D \end{pmatrix} \tag{8}$$

where

$$B(i,j) = \int_{\Omega} \sigma \nabla\phi_i \cdot \nabla\phi_j dxdy + \sum_{l=1}^{L} \frac{1}{z_l} \int_{e_l} \phi_i \phi_j dS \qquad i,j = 1,2,\dots,N \tag{9}$$

$$C(i,j) = -\frac{1}{z_l}\int_{\text{ej}} \phi_i dS \quad i = 1,2,\dots,N, j = 1,2,\dots,L \tag{10}$$

$$D(i,j) = \begin{cases} 0 & i \neq j \\ \frac{|e_j|}{z_j} & i = j \end{cases} \quad i,j = 1,\dots,L \tag{11}$$

And ϕ is the basis function and $|e_j|$ is the length in 2D of the electrode.

2.3 The measurement protocol

In order to express the Neumann boundary condition to the system, one should adopt a protocol of injection and acquisition of measurements. In an EIT equipment, different strategies to inject current have been proposed in the literature. The adjacent protocol is the most common pattern. The first pair of electrode injects a current into the system. The successive pairs of electrodes that are not currently injecting proceeds measuring the voltage. The injection continues to the next pair of electrode and then to the respective remaining pairs measure the potential until all measurements are finished. The procedure for an 8 electrodes case is described and can be seen in Figure 1.

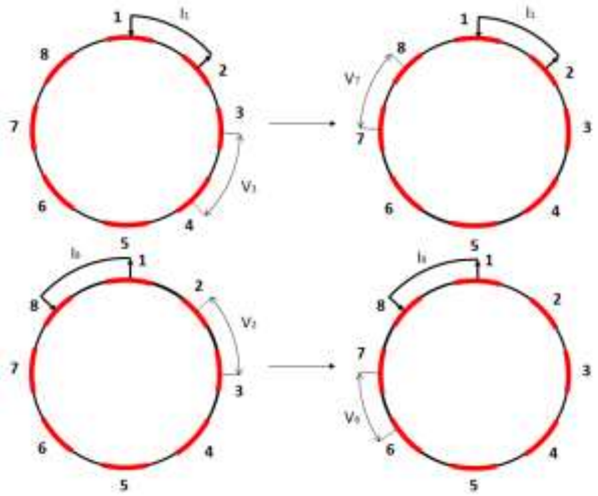

Figure 1. Schematic explaining the adjacent pattern.

Firstly, the current is injected in the pair 1 of electrode and measured in the pair 3, as the second electrode do not measure. It continues to measure in the subsequent pairs. The injected electrode is changed to the next and as it reaches to the 8 electrode pair, the measurement proceeds from electrode pair 2 until it reaches the last measuring electrode pair, the pair 6.
For the first the inject current vector $I_1 = [1,-1,0,\dots,0]^T$, where $I_c = [I_1, I_2, \dots, I_L]^T \in \mathbb{R}^{LxL}$ and the measurement matrix $M_{1,1} = [0,0,1,-1,0,\dots,0]^T$ where for each current pattern $M_{p,1} = [M_{1,1}, M_{1,2}, \dots, M_{1,M}]^T \in \mathbb{R}^{LxM}$ where M represents the number of measurements.

2.4 Inverse Problem

Consider an equation that has an input parameter and, as this parameter is chosen, an output is given. The inverse problem is to do the exact opposite path. To obtain of the parameter given the output. In the case of EIT, the problem is to obtain the conductivity parameter given the potential field. This problem is ill-posed and non-linear.
An ill-posed problem is defined when at least one of three conditions are not satisfied: existence, uniqueness, stability. To the solution to be well-posed a solution must exist, the solution must be unique and the solution must not have large variations when small changes.
To obtain a solution, one must minimize $\|Z - V\|_2^2$, where Z is the observations and V is the forward calculations (Lionheart, 2004). To overcome the ill-posedness, the equation must be regularized. The Tikhonov regularization is utilized that the term that must be minimized is

$$F(\sigma) = \|Z - V\|_2^2 + \lambda^2 \|L(\sigma - \sigma^*)\|_2^2 \tag{12}$$

where λ is the regularization term, L is the regularization matrix, σ is the estimated conductivity and σ^* is the prior information of the conductivity.
Applying a linearization, the sigma vector can be obtained as

$$\delta\sigma = (J^T J + \lambda^2 L^T L)^{-1}(J^T(Z - V) + \lambda^2 L^T L(\sigma^* - \sigma)) \tag{13}$$

$$\sigma_{k+1} = \sigma_k + \delta\sigma \tag{14}$$

where J is the jacobian, k is the step.

2.5 Jacobian

When using methods based on optimization it is normal the need of Jacobian of the model. It is basically to calculate the derivative of the voltage measurements based to the conductivity parameter. It could be also called of sensitivity maps as the rows of the matrix compute the sensitivity of the media. There are two forms to compute the Jacobian. The more optimized with the least time of computation is the measurements fields (Polydorides, 2002), which is

$$J_{(d.m,n)} = \frac{\partial U_l^{(d,m)}}{\partial \sigma_n} = -\iint_{\Omega_n} \nabla u(I^d) \cdot \nabla \mathrm{u}(\mathrm{I}^{\mathrm{m}}) dxdy \tag{15}$$

where m is the measurement and d is the current pattern, n is the simplex.
Thus, to evaluate the Jacobian, one must obtain from the finite element method the value both gradients of the basis function multiplied by the electric potentials solved when using the current pattern and the electric potential solved when using the measurement field as explained in the Section 2.3.

3. METHODOLOGY

The acquisition used in this work consists of three programs and an equipment that measures the voltage in each pair of electrodes. The first software is the acquisition system by the Arduino digital-analog converter. An algorithm was developed to perform the acquisition according to the adjacent pattern.

The second part of the software is about transferring the data to the Matlab environment. In this way, in the third part, the data can be processed normally using the free software EIDORS. This software is a set of functions written for Matlab that uses the equations in Section 2 to simulate the voltage measurements for a given injection pattern. With simulated measurements and experimental measurements, the Gauss-Newton method can be applied to recover the electrical conductivity of the medium.

The hardware consists of the main parts shown in Figure 2.

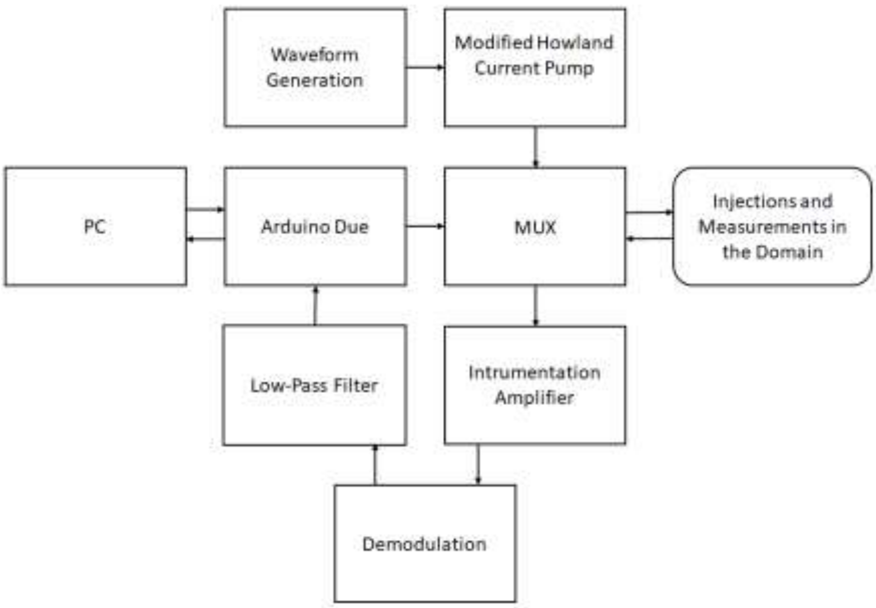

Figure 2. Flowchart of the EIT system.

These are the waveform generator, which effectively provides the wave with a suitable frequency and voltage. The frequency which is chosen is 20 kHz. The modified Howland current source is a system that injects a constant current from an applied voltage. The current applied by the current source is 1 mA. The multiplexers, which are controlled by the Arduino, have the function of controlling the way the currents and voltages are injected and measured, respectively, in the different pairs of electrodes used in a measurement cycle. The instrumentation amplifier receives the voltage values from the multiplexer and its signals are transformed into a differential measurement and amplified by a value of 40.22. After that, the wave goes through a demodulation process through an RMS converter that turns the sine wave into a DC value. It then passes through a low-pass filter to eliminate noise that diminishes signal quality. All these measurements are then read by the Arduino digital-analog converter and obtained in a specific order. Those measurements are transmitted to the PC and processed through the free software program EIDORS.

4. RESULTS AND DISCUSSION

The equipment goes through all hardware stages: function generator, current source, multiplexers, domain, instrumentation amplifier, IC RMS-to-DC converter, low-pass filter, Arduino, PC. In the PC, it passes through all the softwares: acquisition of Arduino, transformation of data from Arduino to Matlab, EIDORS.
In order to calibrate the equipment, a full gain curve in the equipment is created. Basically two voltage dividers were assembled with the first resistor of the voltage divider equal 10 kΩ and the second resistors being 1100 Ω and 2530 Ω respectively. The input voltage at these voltage dividers was varied for the purpose of evaluating the differences between these voltages amplified, which are also varied. The differences between the values obtained were then evaluated with respect to the digital output of the system, according to Figure 3. It can be seen that the gain of the equipment was greater than the value of the instrumental amplifier and that the output is linear.

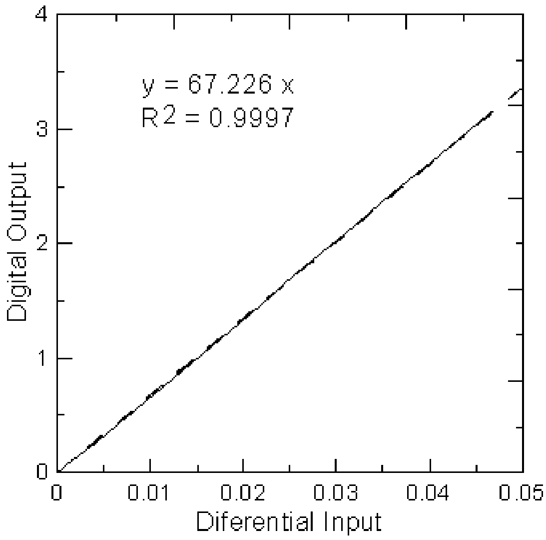

Figure 3. Calibration curve of the equipment.

To reconstruct the image, the signal, measured in V, is then obtained for the 208 possible measurements for the adjacent pattern. For a homogeneous system composed only of water, it is possible to compare the experimental signal obtained through the use of the acquisition equipment mounted in the present work, the left in Figure 4, with the simulated model signal from the EIDORS free code software, the right in Figure 4.

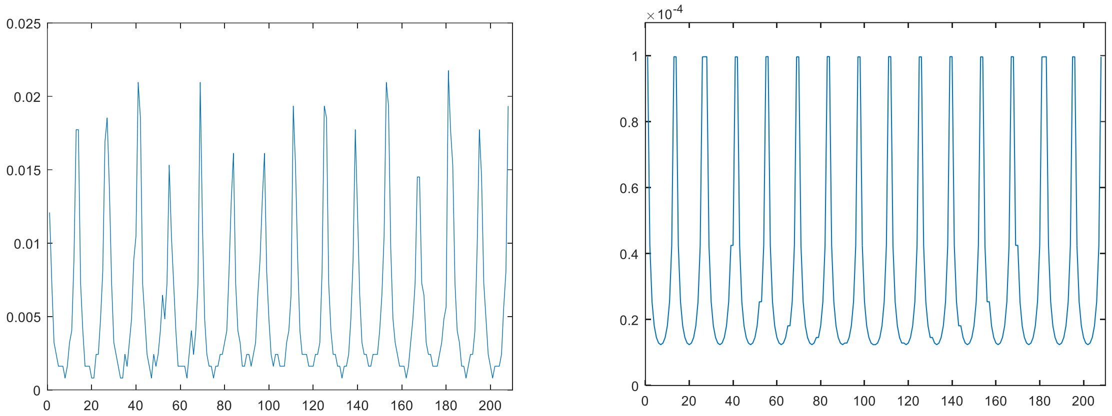

Figure 4. Experimental measurement left and modelling result right for a homogeneous media.

Note that there is a 'U' pattern in the measurements obtained by the Arduino digital-to-analog converter. It can be seen that the experimental results vary between a voltage of 20 mV and 1 mV after converting the amplified signal into the real signal. The default is in accordance with the simulation with the EIDORS package.

The signal was measured after passing through the low-pass filter and, from that point, the signal-to-noise ratio of the system (SNR) was analyzed. This is given by the relation shown:

$$SNR = 20 \cdot \log \frac{|E(V_i)|}{Std(V_i)} \tag{16}$$

where $|E(V_i)|$ is the average of the voltage measurements read by the digital-to-analog converter, $Std(V_i)$ is the standard deviation of the measurements. The signal was measured for each electrode 100 times during the first acquisition cycle. As the first cycle have 13 measures, the test thus has 1300 experimental points. Figure 5 shows the measurements for the first cycle.

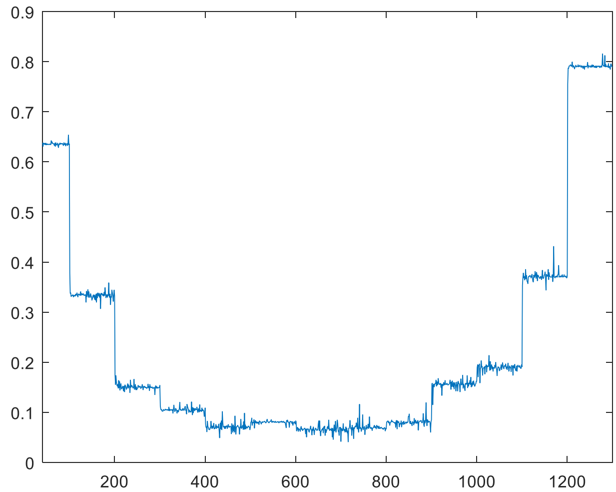

Figure 5. Measurements utilized to calculate the SNR of the equipment.

There is a small noise in the measurements. From these values, the SNR was calculated using Equation 16. The average SNR value for the equipment is 64.31 dB.

From the measurements, the difference between the simulated and the experimental is calculated and the conductivity value at each point of the mesh is minimized. For the cylindrical specimens, the following conductivity results are obtained at each point, shown in Figure 6. It is notable that the hardware in conjunction with the software can properly estimate the forms in the domain. The blue region in the graph corresponds to the non-conductive body. For both a body and two bodies, it was possible to reconstruct conductivity in the domain.

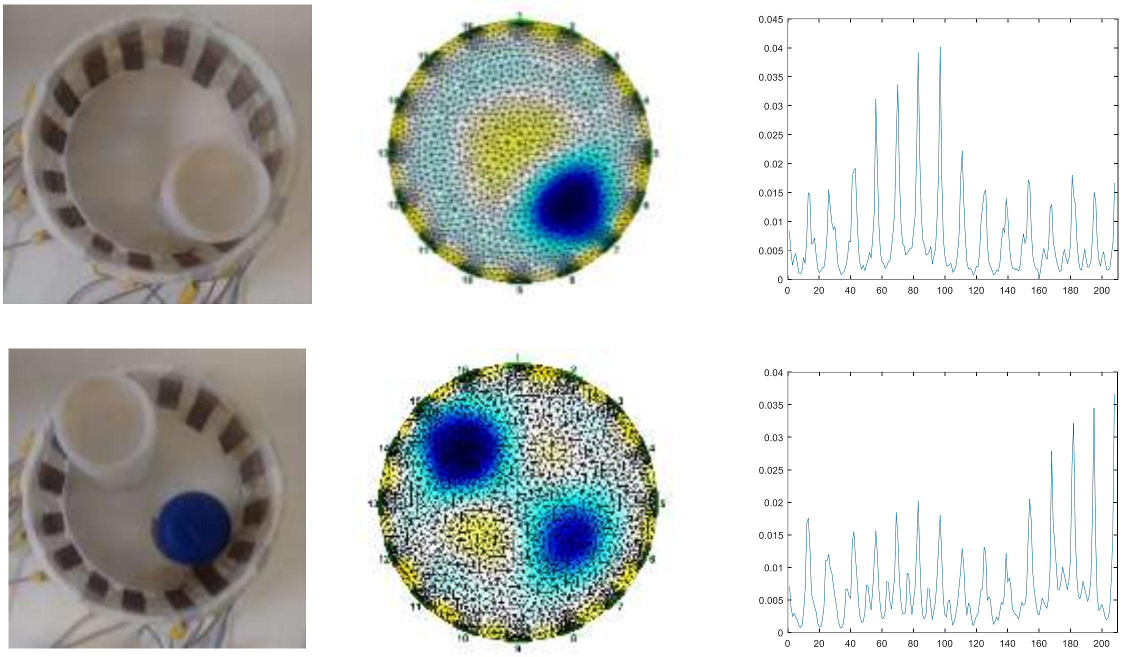

Figure 6. Body in the media, the reconstructed image and the signal for this case.

5. ACKNOWLEDGEMENTS

The authors would like to thank to the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) and Petrobrás for supporting the research.

6. REFERENCES

Analog Devices, 2017, Integrated Circuit True RMS-to-DC Converter. AD536A.

Bodenstein, M., David, M., Markstaller, K., 2009, *Principles of electrical impedance tomography and its clinical application.* Critical Care Medicine, Volume 37.

EIDORS: Electrical Impedance Tomography and Diffuse Optical Tomography Reconstruction Software, 2017. <http://eidors3d.sourceforge.net/news.shtml>

Graham, B. M., 2007, *Enhancements in Electrical Impedance Tomography (EIT) Image Reconstruction for 3D Lung Imaging*, Ph.D. thesis, University of Ottawa.

Holder, D. S., 2004, *Electrical Impedance Tomography: Methods, History and Applications*, CRC Press.

Kitchin, C., Counts, L., 2006, *A Designer's Guide to Instrumentation Amplifiers*, Analog Devices.

Kourunen, J., Niitti, T., Heikkinen, L. M., 2011, *Application of three-dimensional electrical resistance tomography to characterize gas holdup distribution in laboratory flotation cell*, Minerals Engineering, Volume 24.

Lionheart, W. R. B., 2004, *EIT reconstruction algorithms: pitfalls, challenges and recent developments*, Physiological Measurement, Volume 25.

Mahnam, A., Yazdanian, H., Samani, M. M., 2016, *Comprehensive study of howland circuit with non-ideal components to design high performance current pumps*, Measurement, Volume 82.

Meng, Z., Huang, Z., Wang, B., Ji, H., Li, H., Yan, Y., 2010, *Air–water two-phase flow measurement using a Venturi meter and an electrical resistance tomography sensor*, Flow Measurement and Instrumentation, Volume 21.

Parvareh, A., Rahimi, M.,Alizadehdakhel, A., Alsairafi, A., 2010, *CFD and ERT investigations on two-phase flow regimes in vertical and horizontal tubes*, International Communications in Heat and Mass Transfer, Volume 37.

Polydorides, N., 2002, *Image reconstruction algorithms for soft-field tomography*, Ph.D. thesis, University of Manchester.

Sharifi, M., Young, B., 2013, *Electrical Resistance Tomography (ERT) applications to Chemical Engineering*, Chemical Engineering Research and Design, Volume 91.

Texas Instruments, 2003, *High-Speed CMOS Logic 16-Channel Analog Multiplexer/Demultiplexer*, SCHS209C.

Texas Instruments, 2017, *TL07xx Low-Noise JFET-Input Operational Amplifiers*, SLOS080N.

7. RESPONSIBILITY NOTICE