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Development of Tetrapolar Conductivity Cell for Liquid Measurement Application

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Abstract: This paper deals with the development of a liquid measuring instrumentation using the popular tetrapolar electrode configuration. The system consists of four-electrode ring shape using Cromium metal plate and a small measurement. The developed instrument is calibrated with the help of prepared saline solution prepared in lab. A liquid of known parameter is placed inside the measurement cell and current is injected through excitation electrode with certain frequency and voltage drop is measured across electrode potential terminals. From this voltages and cell constant value, the conductivity, resistivity and impedance of the measured liquid could be determined with acceptable accuracy with more than 96 % compared to the standard measurement. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Tetrapolar, Four-electrode, Electrical conductivity, Ring shape.

1. Introduction

1.1. The Tetrapolar Electrode

In 1876, Lipmann has solved the problem raised in measuring electrolytic resistivity by using the tetrapolar method on his capillary electrometer. The issue rise in early 1800 on measuring resistivity of an electrolyte using a standard electrode pair in a container where electrode-electrolyte interface affected the measurement result contributed to inaccurate, unstable and error in the measurement [1]. Bouty, in 1844, introduced the tetrapolar or sometimes refer as four-electrode method which consists of four-electrode; two outer electrodes and two inner electrodes. The outer electrode is injected with a constant current and the inner electrode measuring the developed potential voltage [2]. The potential drop voltage could be used in determining the liquid or solid material electrical resistance or impedance. While electrical conductivity is the reciprocal of electrical resistivity which defined as ability of a material to conduct an electric current.

1.2. Conductivity Measurement Technique

Conductivity measurements are required in many application fields such as agricultural, manufacturing, environmental, biomedical and etc. Conductivity means how well a solution conducts electricity. It is also depending on the current frequency applied to the liquid or aqueous solution.

There are several method of measuring electrical conductivity namely; amperometric, potentiometric, inductive. The amperometric method, consist of many measurement techniques, usually use two electrodes spaced one centimeters on each other. Voltage is applied between these two electrodes and current is measured. This will determine the resistance in the spaced area. This technique is sometimes create an unstable current measurement and forms an electrode polarization. Another major disadvantage in this technique is the limitation to the wide range of conductivity measurement which relies to the specific cell geometry [3]. However, this disadvantages could be solve by introduce a four-electrode or tetrapolar electrode in potentiometric method. This method is more stable measurement by measuring the voltage drop in the inner electrode when outer electrode is applied a constant current. This method also is able to measure very high and ultra low ranges of electrical conductivity of materials especially in liquid form [4]. Although, both methods is very popular, the measurement technique are still need to be conduct in contact or invasive way to the material which make it limited and unsuitable to the certain application such as flammable and corrosive liquid or chemical reactions measurement application. These drawbacks could be solved by using another method of electrical conductivity measurement which is inductive method. This method is non-contact to the material using 2 torodial shape transformer. The material such as liquid containing ions passed the transformer and induced a current to the transformer and voltage could be measured and conductivity could be determined [5]. However, inductive technique requires a precision voltage and current ratio transformer. Furthermore, inductive coupled transformer is not suitable to apply on the small or microstructure applications. Despite all the methods explained is has a different techniques, the fundamental of measurement is still using Ohms law in common. There are many researcher and inventors have a high interest of the tetrapolar method in many fields and applications due to it is straight forward measurement, low cost equipment and device, reliable and having high repeatability and also less complexity in hardware set-up [6].

1.3. Electrode Geometrical

On the other aspect of instrumentation design, the shape, material, dimension and of electrode must be consider to provide less measurement error. P. Høyum et all, in their computational study of effect in tetrapolar electrode geometry shows that current shunting is significance reduced by changing the geometry of the pickup (sensing) electrode [7]. Another example using the tetrapolar configuration such as bioimpedance measurement application. Measurement is determined by geometrical configuration of the electrode system as well as the biological tissues. Most discussed that relationship of electrode type, position, dimension and current density are the most affected parameters in the measurement performance [8].

2. Methodology

2.1 Measurement Cell

The measuring cell or sometimes recognized as conductivity cell is where the fluid is placed into certain dimension to measuring the electrical conductivity where the liquid will be contacted to the measurement electrode in the cell. Theoretically, the conductivity cell is where a two 1 cm squared surface spaced by 1 cm length between each others. However, different geometries of this conductivity cell are characterized by their cell constant.

This project, the developed measurement cell is using standard Polycarbonate plastic with dimension of 4.78 mm of diameter, 0.0278 in2 in 1 ml/cc cylindrical shape tube. The cell is developed to be small capacity for liquid measurement purposed. The cell is 30 mm length. The minimum volume of liquid in the measuring cell is about 0.54 cm^3. The four-electrode are attached using epoxy adhesive glue to the inner cell body with certain dimension (length and area) between each electrode.

2.2 Electrode

Chromium plate material is selected in this project because of its low impedance electrode is a choice to minimizing electrode-electrolyte, corrosion problem raised. The electrode probe shape is circular/ring/band type and using four terminal sensing or tetrapolar configuration. The outer electrode of this configuration is proposed for the current excitation and the inner electrodes purposed for the measurement of voltage drop across the liquid in the measurement cell. Fig. 1 shows the electrode placement in the measurement cell.

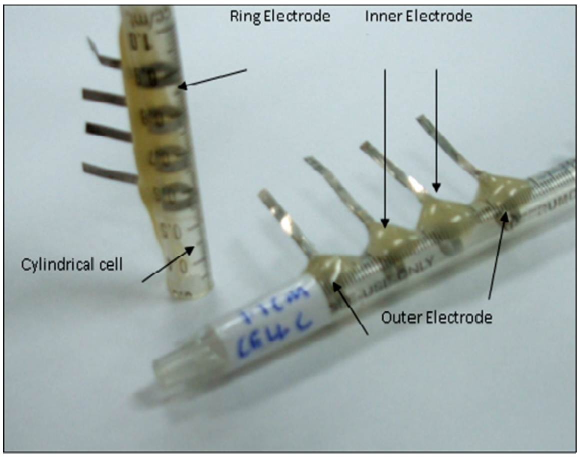

Fig. 1. The four-electrode placement in the measurement cell.

A signal was passed between the two input electrodes, and the potential difference between the measuring electrodes spanning the region of interest was measured. The resistivity between the measuring region electrodes computed from

$$\rho = \frac{V}{I} \times \frac{A}{L}, \quad (1)$$

where p is the resistivity of blood sample, V is the voltage measured between inner measuring electrode, I is the current through the outer input electrode, A is the cross sectional area of the cell and L is the length or distance between two measuring electrodes.

The impedance, Z value from the measurement cell can be calculated as

$$Z\angle\varphi = \frac{V(RMS)}{I(RMS)} \quad (2)$$

Since the impedance consist phase degree contributions of capacitors in blood electrical properties, it can be measure directly from oscilloscope by measure the phase delay.

Area of probe can be calculated depending on the cell shape and size. The cell shape is cylindrical type and hence the area of electrode can be compute as

$$Area\ , A = 2 \times \prod \times r \times L\ , \quad (3)$$

where $\prod$ is the ratio of the circumference to the diameter of a circle, approximately equal to 3.142, r is equal to the radius of cylinder cell and L is the thickness of the electrode. The electrode shape is depends on the cell which is cylindrical type. The area and length of the inner and excitation electrode are 0.243 cm^2 and 0.76 cm. Fig. 2 shows the electrode shape use in the measurement cell.

There a four electrode use in the cell measurement which is outer electrode for excitation and inner electrode for voltage measurement. Equation (1) shows that length, L between two inner electrodes as shows in Fig. 3.

2.3. Cell Constant

The cell constant, K is a ratio of electrode measured to the electrode area. The measured potential depends not only on the electrolyte resistivity, but also on the geometrical characteristics of the conductivity cell [9]. Thus, it is important to determine the cell constant in the measurement system. The potential voltage measured between the inner electrodes is equal to the product of the injected current I and the apparent resistance between these electrodes. The apparent resistance depends on the cell geometry and is related to the electrolyte resistivity, by the proportionality of

$$R = K \times \rho\ , \quad (4)$$

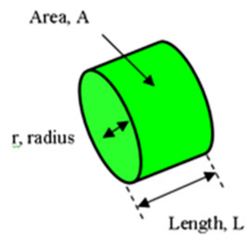

Fig. 2. Electrode ring shape dimension.

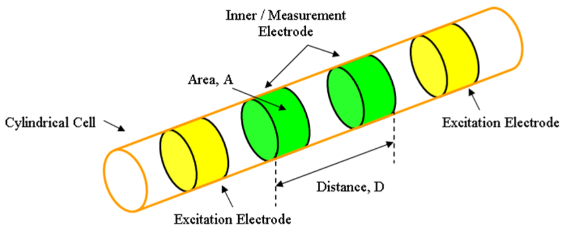

Fig. 3. The illustration of measurement cell designed with four-electrode ring shape.

where R is the apparent resistance and *K* is the cell constant. The proportionality cell constant, *K* is the parameters which characterize any conductivity measurement cell. The electrolyte resistivity is calculated from the measured potential as

$$\rho = \frac{V}{K \times I} \quad (5)$$

Therefore, to measure resistivity with the tetrapolar cell, it is only necessary to characterize the cell by determining the cell constant [8]. From equations (1) we can calculate the cell constant, *K* by means of cell length and area as

$$K = \frac{L}{A}, \quad (6)$$

where L is the distance or length of inner electrode and A is the area of electrode. To get an ideal cell constant, the K value should be 1. Hence, length, L and area, A should be equal as shows in equation (6) as shown in Fig. 3.

2.4. Cell Calibration

To ensure that the constant value from calculation on equation (8) is correct and also cell not effecting the measurement, it is best to practically measure the cell constant by calibrating the cell measurement. Calibration solution has been prepared using saline solution. Saline solution has been made from distilled water and mixed with Natrium Chloride (NaCl) to get the known resistivity value. The resistivity value of saline has been measure using CON510 (Oakton Instruments) conductivity meter. The resistivity of saline water is measured having of 67 Ω-cm or 0.014925 $S\text{-}cm^{-1}$ at temperature of 26 °C. Cell constant, K can be determine with conditions that current apply, I is known and using known resistivity, solution by using equation (1) and equation (5).

2.5. Procedure

The desired liquid measure temperature must need to be within 26-27 °C of room temperature. The current excitation electrode is connected to the constant current source circuit. The cell must be calibrated first with a known resistivity solution, as example a saline solution (NaCI) to acquire a cell constant, *K* value within the room temperature. This solution must fill the whole volume of measurement cell. When the *K* value is defined, the cell is ready to measure the desire liquid. A constant current source will provide an AC current of 1 mA with frequency of 15 kHz that inject to the measurement cell through current electrode and potential voltage differential will be measure using precision 6 digit digital voltmeter. This voltage is recorded and impedance of the measured liquid could be determined. Certain Frequency range (current source) could be change depending on the interest application. Fig. 4 shows the hardware for the experiment set-up.

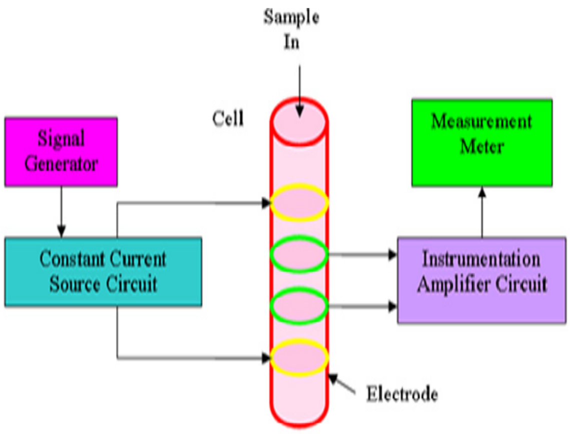

Fig. 4. The hardware setup during measurement.

3. Results and Discussions

The variations between actual measurement and measured using develop electrode in Fig. 5 and Fig. 6 show the differences are within ±5 kΩ for the calculated impedance value and ±0.5 for resistivity measurement over 10 seconds with frequency setup for 15 kHz. The reciprocal of electrical resistivity is conductivity, unit is Siemens per centimeter (S-cm^{-1}) shown in Fig. 7.

It has been identified and observed during measurement, certain factors are effecting the measurement such as cell constant value is effected by temperature coefficient, electrode depolarization-repolarization effect (electrolysis), electrode placement to the inner wall of measurement cell is not truly fixed, and the constant current source injected. Even the differences are acceptable, which showings below than 10 % from actual reading, this measurement still could be improved by neutralize all the error factors contribution.

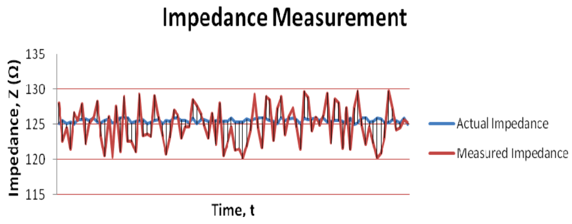

Fig. 5. The impedance measurement using developed method.

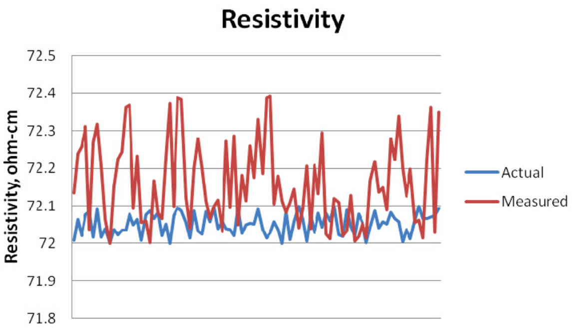

Fig. 6. The liquid resistivity measured.

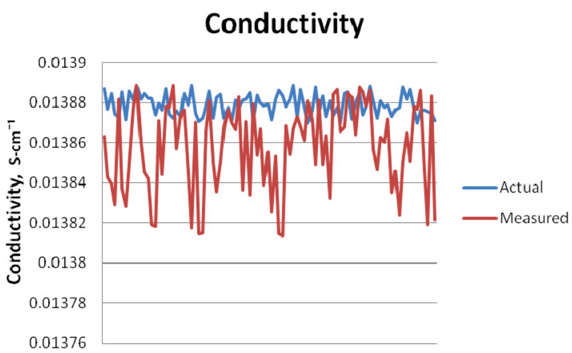

Fig. 7. The liquid conductivity measured.

4. Conclusion

The tetra-polar electrode measurement is established more than centuries ago used in many applications due to its high accuracy, cost-effective and simple model. The challenges using this method still need to be considered and overwhelmed. However, recent technologies developed help to manage these issues. Till date, there are many researcher interests in this method applied in many field and application.

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