Analysis of the relation between glucose concentration in water and resonant frequency using the resonance model

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Abstract. Any material specifically has an electric and magnetic property which can be expressed in term of its permeability and permittivity values. Liquid material has some electrical properties such as permeability and permittivity. In a certain configuration, the values are presented in a form of capacitance and inductance value. In this study, we developed a liquid impedance measurement system using RLC model to measure the existence of a glucose concentration in water. The RLC model can show the resonant frequency value of the analyte which is affected by the capacitance and inductance values. We found that the higher concentration gave higher resonance frequency. The parallel resonance frequency of the system is nonlinearly related to the glucose concentration. The series resonance frequency of the system increased by 22.4 kHz per 1% glucose concentration.

1. Introduction

Impedance measurement systems in liquids have been developed as a method for detecting analytes. Any material especially liquid has electrical and magnetic properties that can be expressed in permeability and permittivity values. By the fact that the capacitance and inductance values are affected by the solution permittivity and permeability, detecting the impedance of a system containing the liquid can be related to the liquid properties. The purpose of this study is to analyze the relationship between glucose concentration in water and resonance frequency.

The electrical properties of a material can be analyzed by several methods of characterization. Characterization methods that utilize the impedance value of a material include the Electrical Impedance Tomography (EIT) method and the Electrochemical Impedance Spectroscopy (EIS) method. EIT is an image that estimates the distribution of electrical conductivity [1]. While EIS is an analytical technique used to detect changes in electrical properties through impedance values [2,3]. Electrical impedance occurs when an alternating current is applied to a circuit.

In electrical circuit systems, electrical impedance has resistive and reactive properties. Resistance is the result of electrical conductivity, whereas reactance exists when there are capacitance and inductance in the circuit. An impedance always exists in any electrical system in any form of an electrical circuit. It is also known that the electrical reactance, and then the electrical impedance value of the system is also frequency-dependent [4]. The capacitance value depends on the permittivity, and the inductance value depends on the permeability of the material in which the capacitive and inductive elements are formed. The permittivity, permeability, and conductivity of a material can be measured by constructing a certain geometric model [5]. The value related to the material under measured. For systems filled with liquids, impedance can be related to the liquid properties and the construction of the electrical elements [6].

The impedance characteristic depends on the electrical circuit design where the material under investigation was placed. The system construction may consist of capacitance, inductance, and resistance or part of them. Figure 1 shows the most used equivalent electrical circuit (EEC). The circuit consists of resistors, and constant phase elements (CPE) arranged in series, and capacitors arranged in parallel [7]. The constant phase elements contain the material, therefore its value depends on the material property.

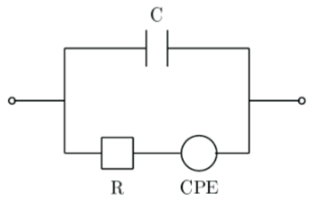

Figure 1. Schematic model of the equivalent electrical circuit (EEC).

The electrical circuit in Figure 1.1 can be formed using capacitive, inductive and resistive devices derived from glucose in water. The impedance value of a circuit can be measured using an impedance analyzer. It is known that permittivity (ε) decreases because glucose concentrations increase and conductivity increases due to increased glucose concentrations in water solutions [8]. Therefore we can expect that the impedance value of any circuit formed by a device containing glucose in water can be measured.

2. Method

2.1. The RLC circuit model

The main measurement system was a construction of the system to have a series and resonance frequency. A simple RLC circuit as shown in Figure 2 is used. The impedance of the system can be separated into two parts, which are the impedance from the parallel capacitor and impedance from the series resistance, inductance, and capacitance. The impedance value is expressed in equations (1) and (2). By using this simple R-L-C circuit, the liquid impedance can be measured by a simple calculation of the pure liquid impedance, where the resistance value is based on the analyte [9]. The resistance in this design is the resistance of the inductance wire. The resistance value should be constant.

$$Z_1 = Z_R + Z_L + Z_C \tag{1}$$

$$Z_{total} = \frac{Z_1 \, . \, Z_{C2}}{Z_1 + Z_{C2}} \tag{2}$$

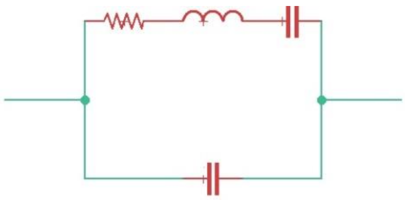

Figure 2. Equivalent circuit for Liquid Impedance Analyzer.

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2.2. Design of Liquid Impedance Analyzer

The basic design of the Liquid Impedance Analyzer developed is illustrated in Figure 3. This system consists of a liquid chamber, a coil, and a capacitor plate made of metal. The dimensions was chosen by considering the expected resonance frequency to fall within the measuring tool range and liquid sample volume. The liquid chamber used as an analyte container has a small size with a diameter of 3 cm and a height of 1.5 cm. The liquid chamber used as an analyte container has a small size with a diameter of 3 cm and a height of 1.5 cm. Then the coil is used as an inductor and the metal plate is used as a capacitor with a diameter of 3 cm. The system was realized using a 3D printing and presented in Figure 4. The wiring connection constructs the system to realize the circuit model in Figure 2.

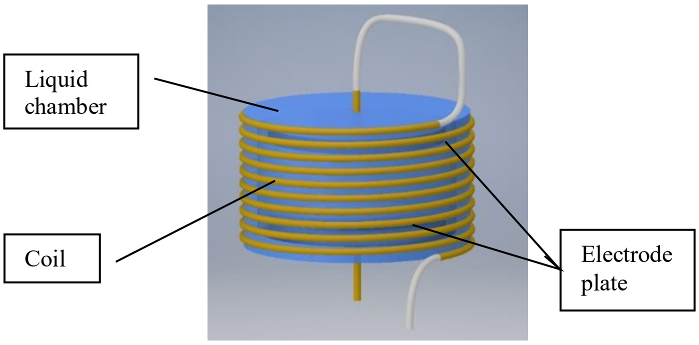
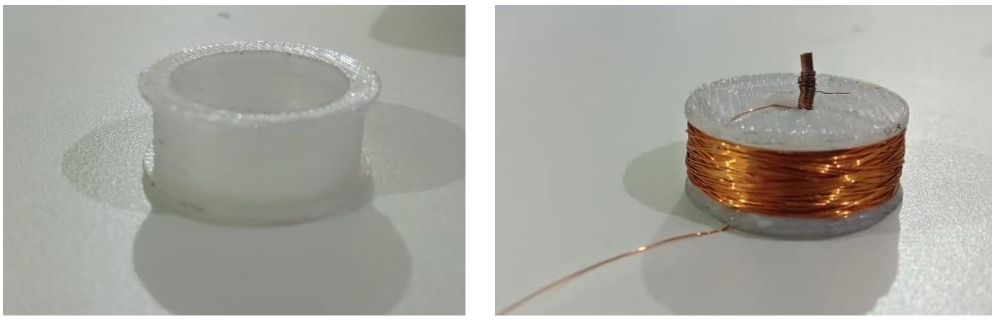


Figure 3. Liquid Impedance Analyzer chamber design.



(a) (b)

Figure 4. (a) Liquid Impedance Analyzer chamber without coil and electrode plate, (b) Liquid Impedance Analyzer with coil and electrode plate.

Resonance frequency and phase measurements are carried out by using a Bode 100 Impedance Analyzer. The Liquid Impedance Analyzer is connected to Bode 100 and data retrieval is done using Bode 100 software. The measurement process is shown in Figure 5.

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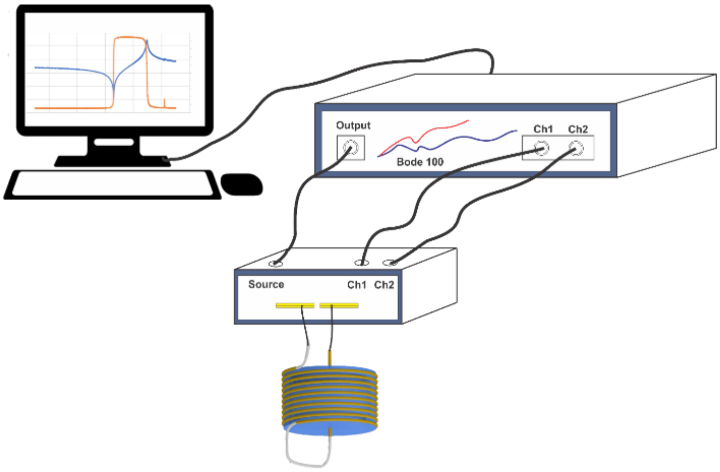

Figure 5. Resonance frequency and phase measurements process.

3. Result and discussion

In a previous study, a theoretical calculation shown the relationship between the impedance and phase spectrum of the resonant frequency for several variations of glucose concentration [9]. The simulation results showed that the higher glucose concentration shifted both of the series and parallel resonance frequency to a higher frequency. Whereas, the minimum impedance value at the series resonance frequency remained. Figure 6 shows the impedance curve of the system from the designed model taken using impedance analyzer Bode 100.

As the glucose concentration changed, the resonance frequency of the system shifted. The change of the resonance frequency indicated that the inductance and capacitance value of the system changed. As the physical dimension of the inductive part and capacitive part remains constant, the inductance and capacitance change is attributed to the change of the permittivity and permeability of the liquid placed in the measuring chamber.

Figure 6 shows the impedance spectrum of the analyte with varying glucose concentrations of 0%, 2.5%, 5%, 7.5%, and 10%. In water without glucose, the resonant frequency of 1.57 MHz for series and 2.11 MHz for parallel was measured. It can be seen that the resonance frequency of the analyte was increased with the increase in glucose concentration. The increase of resonance frequency value is not only occurred for series resonance frequency but also occurred for the parallel resonance frequency. However, there are differences in the results between measurements and simulations, which are located in changes of impedance value. In the simulation, a fixed impedance value was obtained, but the measurement shows a smaller impedance value for series resonance and a greater impedance value for parallel resonance.

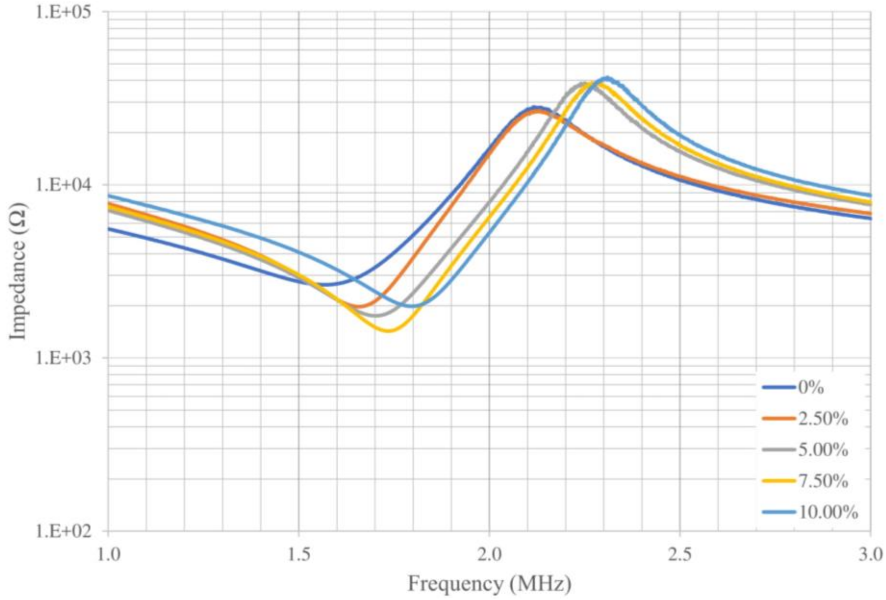

Figure 6. Impedance spectrum of the system at varying glucose concentration in water.

The change of impedance value in the series resonance is caused by the change of resistance value of the analyte. The smaller resistance value causes smaller impedance value at series resonance frequency as the reactance of the inductive part and capacitive part canceled each other. Other work with the different system also shown that the impedance value of the material was also influenced by the change of resistance values [2].

The phase spectrum of the system is presented in Figure 7. The data shows that the frequency where the spectrum at zero phases depends on the glucose concentration. However, the frequency at the zero phases and the frequency at minimum impedance is different. The different indicates that the resistance of the system was considered high thus affect the condition of minimum impedance and zero phases.

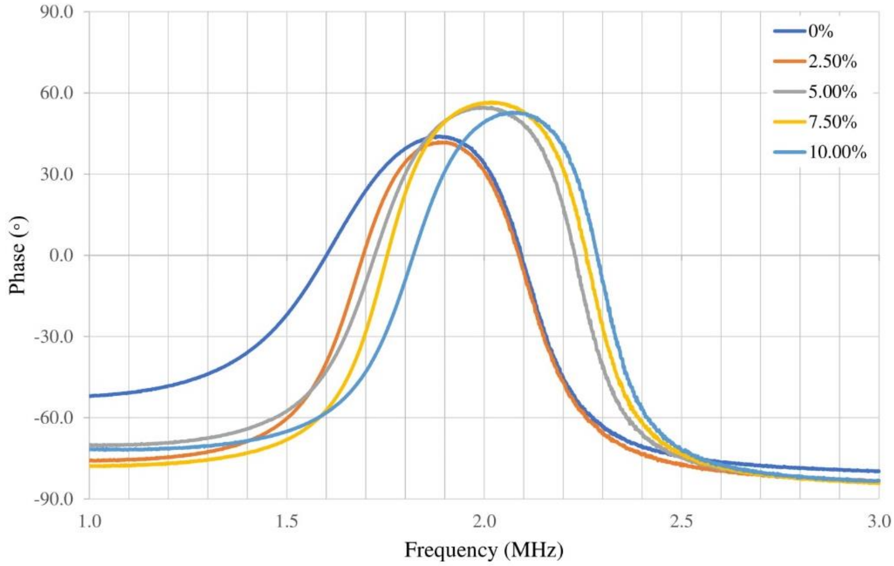

Figure 7. Phase spectrum of varying glucose concentration in water solution.

The relationship between the glucose concentration and resonance frequency of the analyte is depicted in Figure 8. The resonance frequency was taken at zero phases. The parallel resonance frequency is nonlinearly related to the glucose concentration. But the series resonance frequency can be taken as linearly dependent on the glucose concentration. The series resonance frequency at zero glucose is 1.573 MHz and at 10% glucose, the resonance frequency is 1.797 MHz. The frequency change is 22.4 kHz per 1% glucose concentration.

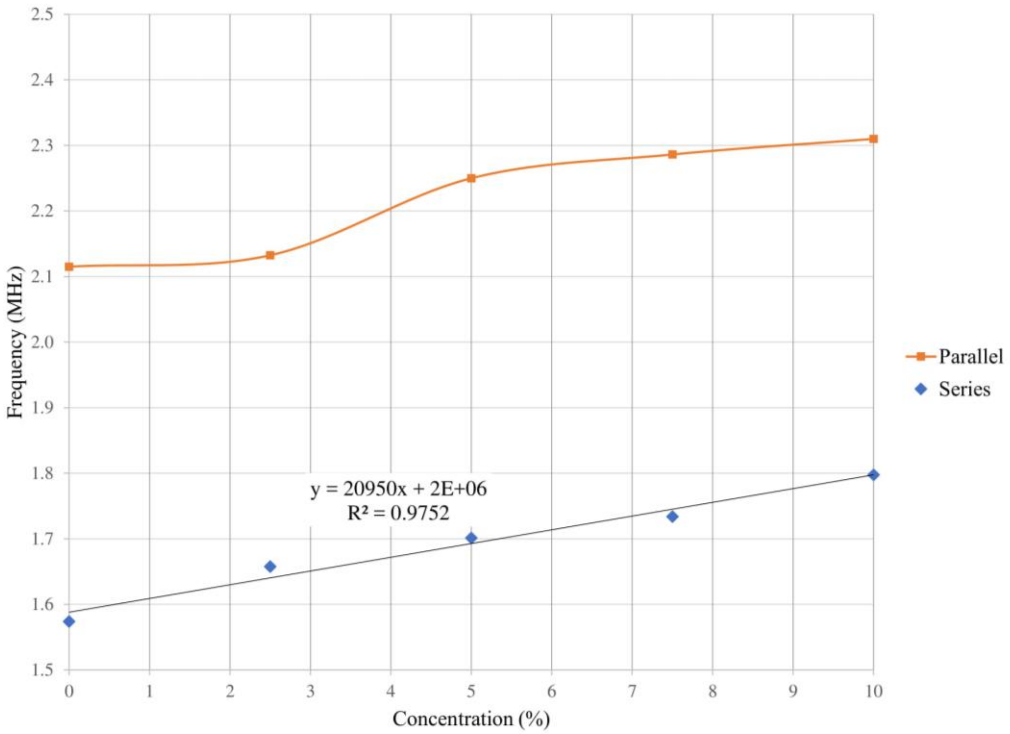

Figure 8. The relation between changes in resonance frequency to the percentage of glucose in water.

4. Conclusion
Glucose concentration in analyte affects the resistivity, permeability, and permittivity values of a substance. The change of the resonance frequency which is mainly caused by the change of permittivity and permeability value of the analyte increased significantly with the increased glucose concentration. The parallel resonance frequency of the system is nonlinearly related to the glucose concentration. The series resonance frequency of the system increased by 22.4 kHz per 1% glucose concentration.

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