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Effect of spacing, concentration of NaCl solution, and biasing of graphite electrodes towards conductometric sensor response

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ABSTRACT

An electrical conductivity (EC) sensor is a conductometric sensor used to measure a solution's ability to transmit electrical charges. However, EC sensing accuracy and stability are not consistent due to many factors, such as gap spacing between electrodes, concentration of the solution, and electrical biassing. This study investigates the influence of the gap spacing between electrodes, the concentration of the solution, frequency, and voltage input applied to the EC sensor electrode on EC sensor measurement and provides insights into the relationship between these parameters and the sensor's performance using the voltage divider rule which is the simpler way to measure the conductivity of the solution. From this investigation, gap spacing between the electrodes, the concentration of the solution, frequency below 50 Hz, and voltage input have been found to directly affect the EC sensor measurement. However, there is no significant change in EC sensor measurement regarding the frequency applied to graphite electrodes when the frequency is above 50 Hz. The findings of this study highlight the complex interplay between the physical setup parameters and EC sensor measurement.

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1. INTRODUCTION

An electrical conductivity (EC) sensor is one of the chemical sensors that is used to measure the ability of a solution or material to conduct electric current [1]. This sensor works on the conductometric principle, which measures the conductivity of the material or solution. Typically, this sensor consists of two electrodes immersed in the water or solution being tested [2]. A small electrical current is passed through the solution between the electrodes, and the resistance of the solution will be measured to determine the conductivity of the solution, which is expressed in units of Siemens per meter (S/m) or Siemens per centimeter (S/cm) [3]. This electrode needs to be powered up by an alternating current (AC) supply only because the ions in the solution will accumulate on the electrodes, and the electrodes will become polarized when the direct current (DC) supply is used [4].

This means that the positive and negative ions in the solution move toward the anode and cathode, respectively, and accumulate there [5]. This can lead to increased resistance at the electrode, which will decrease the current and lead to an inaccurate measurement reading. Therefore, DC supplies are not suitable to be used for long periods for conductivity measurements. Instead, AC is used, as it periodically reverses the polarity of the electrodes, preventing electrode polarization and keeping accurate measurements over more extended periods.

The ions in the solution are extremely important in determining the conductivity of the solution during EC sensor measurement [6]. The ions in the solution go through several steps when a voltage is applied across the electrodes of the EC sensor [7]. Firstly, the ion mobility process, the ions in the solution become mobile because of the electric field created when voltage is applied. Increasing the voltage applied will increase the electric field in the solution. The positively charged electrode will attract negatively charged ions (anions), whereas the negatively charged electrode will attract positively charged ions (cations). Next, ion migration process. As the ions travel in the direction of the corresponding electrodes, they will produce an electric current, which is a flow of charged particles.

The amount of electrical current that flows through the solution is proportional to its conductivity [2]. However, EC sensing accuracy and stability are inconsistent due to many factors. The accurate measurement of EC is the most important aspect that needs to be carefully considered of various factors, including the physical setup of the EC sensor. The physical setup refers to the arrangement of the electrodes, which is the distance between the electrodes, the concentration of the solution, and the electrical biasing [5]–[8]. These parameters can significantly impact the performance and accuracy of the EC sensor measurement. Changes in electrode spacing, voltage input biasing, frequency applied to the graphite electrode, and concentration of the solution can influence the electrical properties of the solution being measured.

Based on Muslan *et al.* [5] who investigated the conductivity of the solution at different concentrations of solution using an EC sensor electrode said that the concentration of the solution will affect EC sensor measurement due to the presence of the ion in the solution. The number of ions in the solution will increase as the concentration does, which will improve the conductivity of the solution. From this paper, it has been concluded that the conductivity of the EC sensor increases when the concentration of the solution increases [5]. This statement also be proven and supported by Widodo *et al.* [9], which also investigated the relationship between conductivity and concentration.

The types of materials that will affect the EC sensor reading depending on their material properties have been evaluated by Song *et al.* [10]. The types of solution used, the concentration of the solution, the voltage level applied towards the electrode, and electrode immersion time before taking the measurement reading setup were constant. The types of materials that will affect the EC sensor reading depending on their material properties have been proven in this paper. This is due to material properties. Certain materials, such as metals and highly conductive materials, have high electrical conductivities that make it easier for electric current to flow through the solution effectively [10]. Electric current may be limited by other materials, such as insulators or materials with low conductivity.

Asgari and Lee [11], investigations on the effect of the temperature of the solution on EC sensor measurement were done at different temperatures, from 5-50 °C. The conductivity of the solution will increase when the temperature of the solution increases, as has been concluded in this paper and supported by Scoggins and Iersel [12], which has been done at different temperatures from 10-40 °C. This is due to ion mobility. An increase in the temperature of the solution will increase the mobility of the ions to move freely and effectively, which can also lead to an increment in the conductivity of the solution [13]. The conductivity of the solution will increase when the temperature of the solution increases.

Finally, Atkinson and Sophocleous [14] investigated the frequency applied to the electrode. A difference frequency of 1-5 kHz was used to observe the effect of frequency on EC sensor measurement. From this paper has been concluded that in a solution with a constant conductivity of 1 mS/cm, varying the square wave driving signal's frequency had no significant effect on the measured output voltages from the sensor. Variations in concentration of the solution and frequency above 50 Hz parameters have already been investigated by previous researchers, but variations in gap spacing between cylindrical graphite electrodes, voltage input, and frequency below 50 Hz parameters have not yet been investigated. Previous researchers only discussed the effect of concentration, temperature, electrode material, and frequency on EC sensor performance, regardless of the gap spacing between electrodes. This study looked into the effects of the gap spacing between electrodes, concentration of solution, frequency, and the voltage input applied towards EC sensor performance, while previous studies investigated the effect of the concentration of solution, the electrode materials, frequency, and temperature. The previous research did not explicitly address its influence on the gap spacing between electrodes and the voltage input towards EC sensor performance as it affects the distribution of the electric field and the overall sensitivity of the sensor. By considering this additional variable, can gain a more comprehensive understanding of how different parameters influence conductivity measurements and improve the accuracy of EC sensor readings.

This paper aims to analyze the effect of the physical setup (gap spacing between electrodes, the concentration of the solution, frequency, and voltage input applied to the EC sensor electrode) on EC sensor performance. The result of this paper can help other researchers and the community know the importance of physical setup for the accuracy of EC sensor measurement and be more careful in setting the physical setup before conducting the experiment.

2. RESEARCH METHOD

2.1. Measurement setup

This work investigates the effect of physical setup (gap spacing between electrodes, the concentration of the solution, frequency, and voltage input applied to the EC sensor electrode) on EC sensor performance. A simple circuit needs to be constructed to measure the EC sensor's voltage output shown in Figure 1. In this work, a simple connection was used to measure EC sensor measurements that consist of a function generator, a series of resistors, two electrodes of graphite (sensing electrode and reference electrode), and an oscilloscope. A function generator is an electronic device that is commonly used to supply a wide range of waveforms, such as sine waves and square waves, and an oscilloscope is a device that provides a graphical representation of voltage signals over time.

In this paper, a function generator is used to supply the sine wave AC signal voltage to the sensing graphite electrode, and an oscilloscope is used to measure the voltage across the electrode. Series resistance was added between the function generator and sensing electrode to apply voltage divider rules that set the accuracy of the measurement. This approach method has been used and verified by Muslan *et al.*[5]. The series resistance in an EC sensor measurement circuit plays an essential role in determining the accuracy and reliability of the measurement [5]. It is used with the voltage divider rule to measure the voltage drop across the sensing element of the EC sensor.

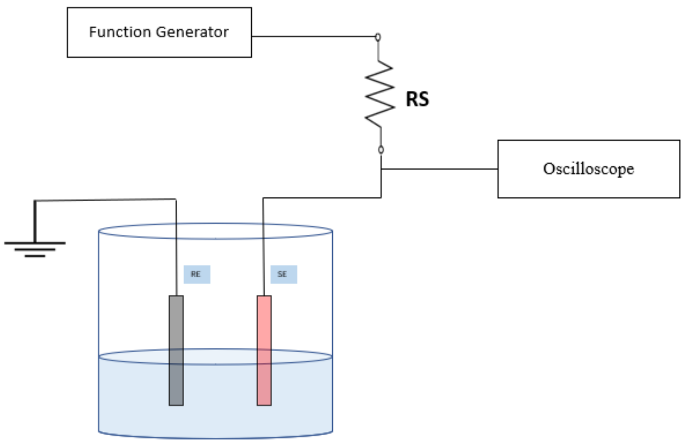

Figure 1. Connection used for EC sensor measurement

2.2. Theoretical analysis

This work uses voltage divider rules to measure the voltage across an EC sensor. According to the voltage division rule, the voltage across any series component in a series circuit is determined by multiplying the value of that component's resistance by the total supply voltage and then dividing that result by the series circuit's total resistance. The voltage across the EC sensor electrode, $Velec$, can be derived as shown in (1).

$$Velec = \frac{Re}{Re+Rs}(Vin) \tag{1}$$

Where Re is the resistance in solution, Rs is the series resistance value, and Vin is the voltage input applied towards the EC sensor electrode. Thus, conductivity is defined as the reciprocal of a solution's resistance between two electrodes and can be expressed as shown in (2) [15].

$$G = \frac{1}{Re} \tag{2}$$

The Siemens (S), originally known as the mho, is the fundamental unit of conductivity. The sensor's actual measurement range is based on the cell geometry [9], [16], [17]. Specific conductivity units are used to represent standardized data to compensate for differences in electrode diameters [17]. Since this paper uses a cylindrical electrode, the area of the electrode can be expressed as shown in (3) [13].

$$A = 2\pi rh + 2\pi r^2 \quad (3)$$

Where r is the radius of the electrode and h is the height of the electrode. The measured conductivity (G) is multiplied by the electrode's cell constant to determine the specific conductivity [16].

3. RESULTS AND DISCUSSION

3.1. Gap spacing between electrodes

Gap spacing between electrodes is the distance between electrodes. In this work, a gap spacing electrode parameter that varies from 1 to 5 cm was investigated for its effect on EC sensor measurement under the different ionic concentrations of the solution, which are 0.5, 1, 2, and 3 M of sodium chloride (NaCl) solution. Figure 2 shows that the gap spacing between solutions is inversely proportional to the conductivity of the solution. When the gap spacing between the electrodes in an EC measurement increases, the conductivity of the solution will decrease. This phenomenon arises due to the fundamental relationship between the electric field strength and ion mobility in the solution. A wider gap spacing between the electrodes results in a weaker electric field in the solution [16]. As a result, the electric field strength is inversely proportional to the gap distance. This weakened electric field exerts less force on charged ions present in the solution which will affect their movement [18]. In addition, ions encounter a longer distance to travel within a less potent electric field, which affects their ability to carry electric charge effectively. Consequently, the electric current flowing between the electrodes decreases, directly correlates with a decrease in the solution's conductivity [19]. In summary, increasing the gap spacing between electrodes will weaken the electric field, which will reduce ion mobility and lead to a lower measured conductivity. This study investigated a comprehensive gap spacing between 1-4 cm only, However, additional and in-depth research may be required to confirm its effect on EC sensor performance, particularly regarding the gap spacing above 4 cm.

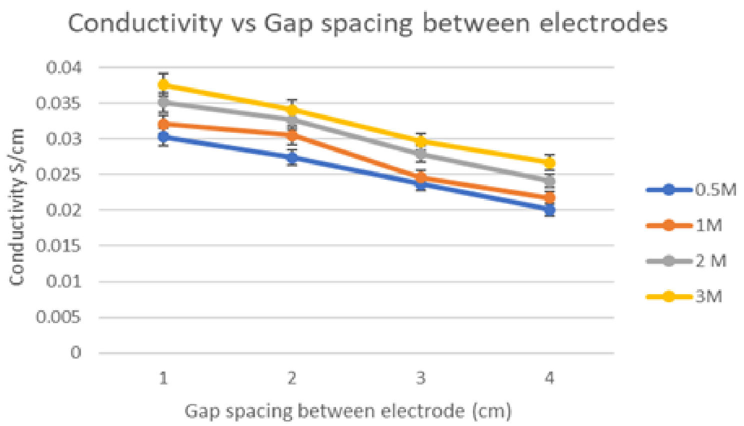

Figure 2. The relationship between gap spacing electrode and conductivity of the solution under different concentrations of NaCl solution

3.2. Voltage input level

Figure 3 shows the relationship between the voltage input level applied to the EC sensor electrode and the conductivity of the solution under difference gap spacing. When the voltage input to an EC measurement system increases, the conductivity of the solution is slightly increasing. This relationship can be explained by the fundamental principles of EC. The voltage applied across the electrodes will generate an electric field within the solution. This electric field exerts a force on charged ions that are present in the solution to move. When the voltage increases, the electric field strength will increase, resulting in a more significant force acting on the ions [17]. Consequently, ions move more readily through the solution, leading to a higher electric current flow. This increment in current flow is directly proportional to the conductivity of the solution. Essentially, the increased voltage will enhance ion mobility which will allow ions to carry electric charge more efficiently, resulting in high conductivity. This phenomenon underlines the essential role of voltage in influencing the conductivity measurement, providing valuable insights relationship between the voltage input and the conductivity of the solution.

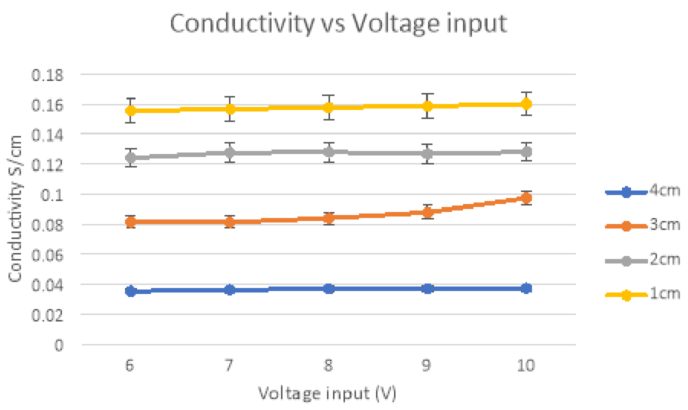

Figure 3. The relationship between voltage input and conductivity of the solution under different gap spacing between electrodes

3.3. Frequency applied to electrical conductivity sensor electrode

Figure 4 shows the relationship between the frequency applied to the EC sensor electrode and the conductivity of the solution under different gap spacing which are 1, 2, 3, and 4 cm. The graph shows that the increment in frequency does not significantly affect the conductivity of the solution. This statement has also been proven by Atkinson and Sophocleous [14], who found that in a solution with a constant conductivity of 1 mS/cm, varying the square wave driving signal's frequency had no significant effect on the measured output voltages from the sensor and conductivity of the solution. This is because NaCl solution is an ionic solution with better conductivity qualities; its electrical impedance tends to remain constant in the frequency range above 50 Hz [9].

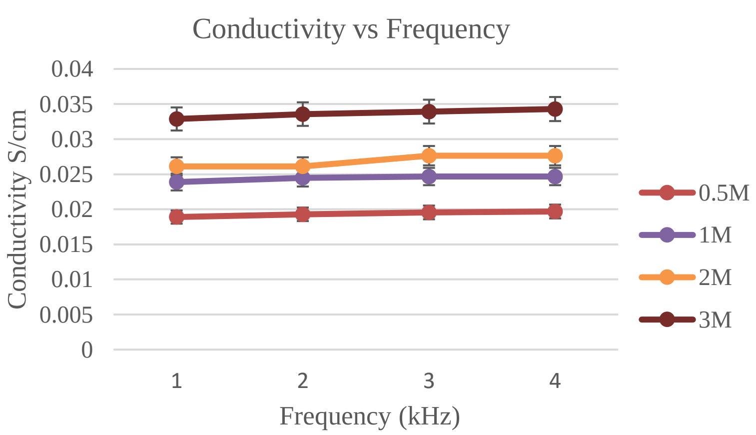

Figure 4. The relationship between the frequency applied to the EC sensor electrode and the conductivity of the solution under different gap spacing

The NaCl solution has a mostly resistive structure at high frequencies, whereas its capacitive characteristics are only detectable at low frequencies [9]. This statement has also been proven in this paper, where the frequency varies from 20-50 Hz. Figure 5 shows that the conductivity of the solution increases due to the impedance decreasing as the frequency increases, where the range of frequency is below 50 Hz [9]. Because the NaCl solution is capacitive at low frequencies and has a very high capacitive resistance value due to the double layer effect, impedance decreases significantly at those frequencies, which increases the conductivity of the NaCl solution [9]. When the frequency is below 50 Hz, the frequency has a significant impact on capacitive reactance, which can affect the impedance of the solution and the conductivity of the solution. The higher the frequency, the lower the capacitive reactance, which will increase the conductivity [15], [20]. Recent observations indicate that the frequency does not have a significant effect on EC sensor performance. In this paper findings offer definitive proof of that statement, however when the frequency is below 50 Hz, it affects the EC sensor performance.

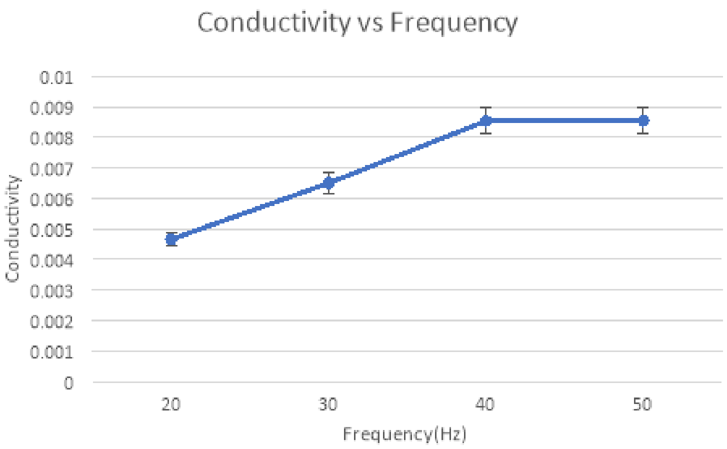

Figure 5. The relationship between the frequency applied to the EC sensor electrode below 50 Hz

3.4. Concentration of NaCl solution

Figure 6 shows the relationship between the concentration of the solution from 0.5-3 M and the conductivity of the solution under variation of voltage input. The figure shows that a higher concentration of NaCl solution will increase the conductivity of the solution. This result has been supported by Widodo *et al*. [9], also found that conductivity is proportional to the NaCl solution's concentration. Higher ion concentrations will produce a greater density of charge carriers [21]. As a result, when an electric field is applied, these ions can move more readily, leading to a higher current flow through the solution [22]–[24]. Consequently, the conductivity of the NaCl solution increases since conductivity is a measure of the ability of the solution to allow an electric current to flow through it [3], [6], [22], [25]. This study investigated a comprehensive concentration of NaCl from 0.5-3 M only, However, additional and in-depth research may be required to confirm its effect, particularly regarding the solution above 3 M.

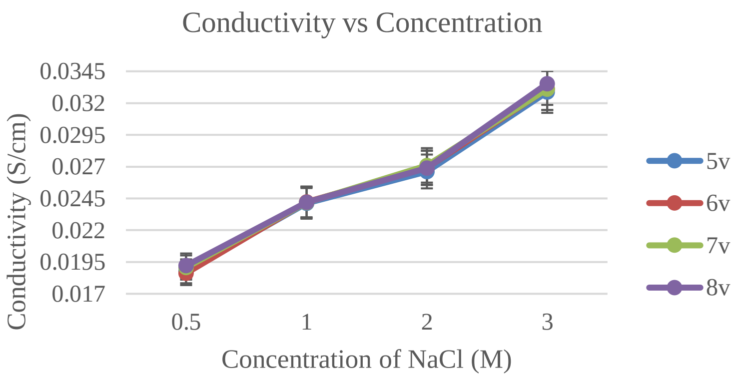

Figure 6. The relationship between the concentration of NaCl solution and the conductivity of the solution under different voltage inputs applied to the EC sensor electrode

4. CONCLUSION

This work focused on the effect of physical setup on EC sensor measurement. Physical setups investigated in this paper are gap spacing between the electrode, concentration of the solution, frequency, and voltage input applied to the EC sensor electrode. From this investigation, gap spacing between the electrode, concentration of the NaCl solution, and voltage input has an impact on EC sensor measurement. This is due to the changes in the mobility of ion move and the resistance in solution. When the concentration of the solution and voltage input applied increases, it makes resistance in the solution decreasing that will make it easier for ions to move effectively. However, there is no significant change in EC sensor measurement regarding the frequency above 50 Hz applied to electrodes. This is because the NaCl solution has a mostly resistive structure at high frequencies, whereas its capacitive characteristics are only detectable at low frequencies. In low frequencies, capacitive characteristics become dominant. This has been proven in this paper that when a frequency below 50 Hz has been applied towards the EC sensor electrode, the conductivity increases as the frequency increases. This is because when frequency increases, the impedance in the solution became decreasing that will allowing more charge to flow through the solution. Generally, the influence of electrode setup (gap spacing between electrodes), the concentration of the solution, and electrical biasing (voltage input and frequency applied to EC sensor electrode) towards EC sensor performance have been analyzed and investigated in this paper. The result of this paper can help other researchers and the community know the importance of physical setup for the accuracy of EC sensor measurement and be more careful in setting the physical setup before experimenting.

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