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Building of a Low Cost Conductivity Meter and Its Application for Laboratory Practices

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Abstract: Following the line of a previous work, we have proceeded to the design and construction of a system based on a low-cost conductivity sensor and an Arduino microcontroller. This system has been conveniently calibrated and equipped with wired and wireless data outputs. The device thus constructed will allow to measure conductivities of both stationary and non-stationary systems.

Key words: conductivity, labs, conductivity meter, Arduino

1. Introduction

1.1 Electrolytic Conductivity

The conductivity of an electrolytic solution is a measure of its ability to conduct electricity. This measurement is used routinely in many industrial and environmental applications as a cheap, fast and reliable way of knowing the ionic content of a salt solution.

Conductivity is usually determined by measuring the resistance of a solution between two electrodes. As in a solid conductor, it will follow the law by which the resistance (R, ohms, Q) to the passage of current is directly proportional to the length (L) and inversely proportional to the section (A):

$$R[\Omega] = \rho \frac{L(m)}{A(m^2)} \tag{1}$$

where ρ (Ω · m) is the proportionality factor, "resistivity", characteristic for each substance.

The inverse of the resistance is the conductance, whose unit is the Siemens (S, Ω-1 or mho). Likewise, the inverse of resistivity is the "conductivity", κ ($S \cdot m^{-1}$).

The experimental measurement of resistance is based on connecting two electrodes in series with another known resistance and applying a potential difference also known, measuring the potential drop between the electrodes.

On the other hand, since conductivity depends on temperature, all conductivity measurements have to take this variable into account.

When conductivity measurement can be done continuously, it can be used to study the variation of ion concentration in a solution over time, which is especially valuable in non-steady-state or kinetic studies.

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1.2 Cell Constant and Temperature Dependence

To interpret the experimental measurements provided by the conductivity of a solution, the geometric characteristics of the measurement system ("cell") are usually grouped together, naming "cell constant" kc, as the ratio of the distance between the electrodes, L, to the cross-sectional area of those, A:

$$k_c = \frac{L}{A} \tag{2}$$

expressed in practice in cm^{-1}. Therefore, knowing this constant, the conductivity can be determined by measuring the resistance of the system:

$$\kappa \left[\frac{S}{cm}\right] = \frac{\kappa_c}{R} \tag{3}$$

As the measurement of conductivity requires the measurement of temperature, currently a NTC (Negative Temperature Coefficient) thermistor is incorporated into the conductivity measurement device, whose resistance decreases with increasing temperature. The temperature is determined by measuring the resistance of the thermistor applying the model based on the simplified Steinhart-Hart equation1:

$$\frac{1}{T} = \frac{1}{T_0} + B\left(\frac{R}{R_0}\right) \tag{4}$$

Where B is a constant of the order of 4,000 (in our case, 3.950), the temperatures are expressed in kelvin and R0 is the resistance of the thermistor at standard temperature, T0 (25 = 298.15 K).

In practice, the resistance of the thermistor is measured in the same way as that provided by conductivity: the thermistor is connected in series with another known resistance and a known potential difference is applied, measuring the potential drop across the thermistor.

2. Objectives

The main objective of this work is the construction of a conductometric system based on an Arduino microcontroller and a mixed conductivity and temperature sensor (Mallon E. & Beddows P., 2019; Ratcliffe, M., 2019; Smarter RET Program, 2019), following a line of work started previously (Jarabo F., García F. J. & Elórtegui N., 2018; Jarabo F., García F. J. & Marrero M. C., 2018) and that already began with didactic purposes more than forty years ago (Ayala A., Jarabo F., Macías J. J. & Guinea D., 1986; Macías J. J., Solá L., Rodríguez N. & Jarabo F., 1986).

The system thus built will undergo calibration with standard solutions and will be provided with data output both to a computer, via USB cable, and to Android platforms (mobile phones, tablets), via a Bluetooth link.

Once operational, the device can be used in the conductivity measurements of the laboratory practice "Mass balance in non-stationary regime", allowing its data processing in a fully computerized way.

During the second semester of this course, a unit of the new system will be made available to students, in order to assess the contribution to learning of this facility compared to the conventional one currently used.

3. Material and Method

3.1 Device Description

The device built for conductometric measurements is based on the low cost electroconductivity sensor with temperature compensation of XNQ Electric Company (13.86 euros). According to the manufacturer, the cell constant is 1,000 cm^{-1} and the NTC type temperature sensor has an internal resistance of 10 kΩ.

The sensor is controlled by an Arduino Uno R3 board (3.12 euros), the resistors and connections are made on a connections board (Prototyping shield, 1.07 euros) and communications are carried out with a Keystudio Bluetooth 4.0 board (8.62 euros). In addition, two 10 kΩ resistors are required, one 1 kΩ resistor and a push-button-switch (used to calibrate the conductivity meter). The connection plate has a built-in light diode whose resistance will also intervene in the operation. A schematic of the circuit is shown in figure 1, made with Fritzing (Fritzing.org). In Figure 2 actual system setup is shown.

3.2 Measurement Operations

The temperature measurement is carried out directly by means of the resistance of the thermistor, from which several values are taken (five is enough) and they are averaged. This value (R) is supplied to the simplified Steinhart-Hart equation together with the value of the resistance corresponding to 25°C (T = 298.15 K), which allows the calculation of the system temperature. The conductivity measurement can be done as a previous calibration value or as a real measurement, so is advisable to introduce a branch in the data flow provided by the sensor using the button-switch mentioned above. If the button is pressed, the collected data is sent to a calibration subroutine of the data acquisition program. This subroutine makes two temperature measurements in a 5 second interval to check if the difference between the two is less than 0.1°C. If the difference is greater, the cycle is repeated until the temperature stabilizes.

Once the temperature is stable, the conductivity measurement is carried out, the value is compensated with the temperature to normalize it to 25°C and the value of the cell constant, k_c is calculated, from the association of the external resistance and that of the fluid.

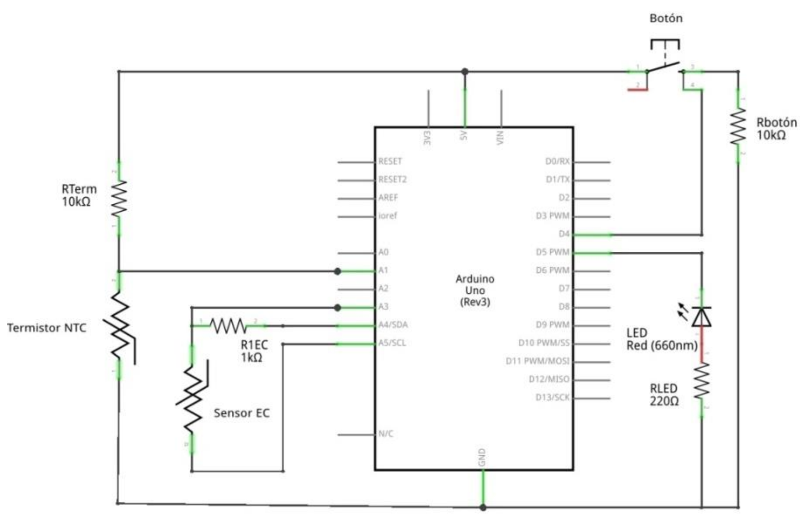

Figure 1 Schematic Setup of the Device

Even though you can use the cell constant provided by the manufacturer (k_c= 1.000 cm^{-1}), the calibration from a potassium chloride standard solution of 0.01 mol/l, with conductivity 1.415 mS/cm, it turns out to be k_c= 1.120 cm^{-1}.

Once the device has been calibrated, that is, the cell constant has been determined, direct measurements can be made. These include the measurements of temperature and its stability of 0.1°C and the use of the cell constant already obtained. The input signal from the sensor is converted into a voltage drop, which is compared to the supply signal. This voltage drop is related to the resistance of the cell and, knowing the cell constant with its conductivity, finally can be normalized to the standard temperature.

Note the operations carried out in this way make the measurement current pass through the solution only during the few instants (milliseconds) that it takes to measure, so that there is no heating of the solution caused by the passage of electric current or phenomena of polarization and electrolysis between the sensor electrodes. Otherwise, the formation of bubbles in the sensor could be observed with the naked eye and the rise in temperature caused by the passage of current could be noted, which would hamper the stability of the temperature required for the conductivity measurement.

Figure 2 System Assembly

3.3 Data Output

In addition to the output from the usual serial monitor, a data output has been prepared via Bluetooth to Android devices allowing the operation without the need for a computer connected to the Arduino board. To make this output, the Software Serial library is used, which allows us to divert the RXD and TXD pins of the Bluetooth module to the outputs that we determine, which in our case are pins 7 for RX and 8 for TX. In this way, the serial monitor output is also sent to Bluetooth and can be read either via USB cable (serial monitor) or wirelessly.

To receive the data sent by the Bluetooth module, you need an Android terminal capable of detecting Bluetooth LE (Low Energy) devices and an application that acts as a terminal. In general, recent Android devices have this ability. We have achieved a good performance using the Serial Bluetooth Terminal application, freely distributed on the Play Store. In the first use, this application may require a custom configuration ("custom" in the application) after detecting the device. In successive operations it will not be necessary.

The received data are stored in a text file whose location in the Android terminal folders can be found in the application settings (“settings”, “system”, “save folder”), allowing it to be located on an SD card.

4. Results

4.1 Application to Laboratory Practice

Once the conductivity and temperature measurement systems have been calibrated, the application to laboratory practical work is carried out “Mass balance in a non-stationary regime”. This practice has a dual objective. On the one hand, it is a question of determining the variation of the concentration of a solute versus time in a tank of constant volume when applying a stream of water. On the other hand, we proceed to verify the compliance with the equation resulting from the theoretical treatment of the practical case.

The laboratory practice involves a tank with a saline solution and an outlet feeded with a stream of fresh water. The inlet flow rate and the outlet concentration (through conductivity) are measured versus time. The ultimate goal is to obtain the time constant of the system, defined as the relationship between the tank volume, V, and the wash flow, Q:

$$\tau[s] = \frac{V}{Q}\frac{[m^3]}{[\frac{m^3}{s}]} \tag{5}$$

4.2 Using the Conductivity Meter

Conductivity measurements have been made versus time starting from a solution of 0.2 mol/l NaCl that is diluted with supply of fresh water until reaching its conductivity, using the conductivity meter built by us (hereinafter Xin), comparing the results with those obtained by reading with the commercial conductivity meter used till now (hereinafter, Hansa). As can be seen in Figure 3, there is a serious discrepancy between some data and others, mainly in the range above 5 mS/cm.

This discrepancy leads us to suspect that the Xin conductivity meter did not provide a linear behavior of the data.

Therefore a calibration of the conductivity meter using the Hansa apparatus as a standard with a set of six NaCl solutions between 0.05 and 3 mol/l was carried out. The results obtained are shown in Figure 4, where it can clearly be seen that the Xin conductivity meter deviates from linearity, which is not the case with the Hansa.

Data obtained from this calibration allow us to get a calibration equation for the Xin conductivity meter, “normalizing” its results compared to the commercial sensor. This operation can be carried out in the data processing spreadsheet or, even better, by inserting it into the Arduino code, so the data output of the conductivity meter directly provides normalized data, which will be almost identical to that of the Hansa commercial conductivity meter, as shown in Figure 5.

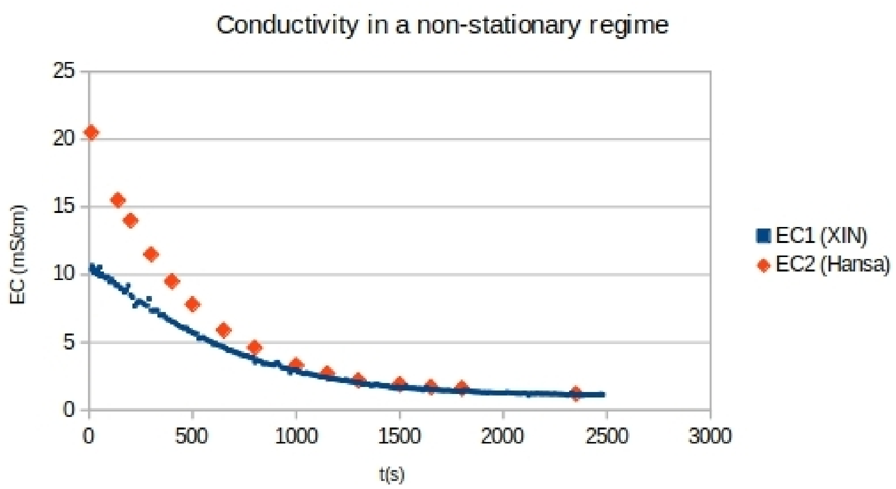

Figure 3 Discrepancy Between Both Conductivity Meters

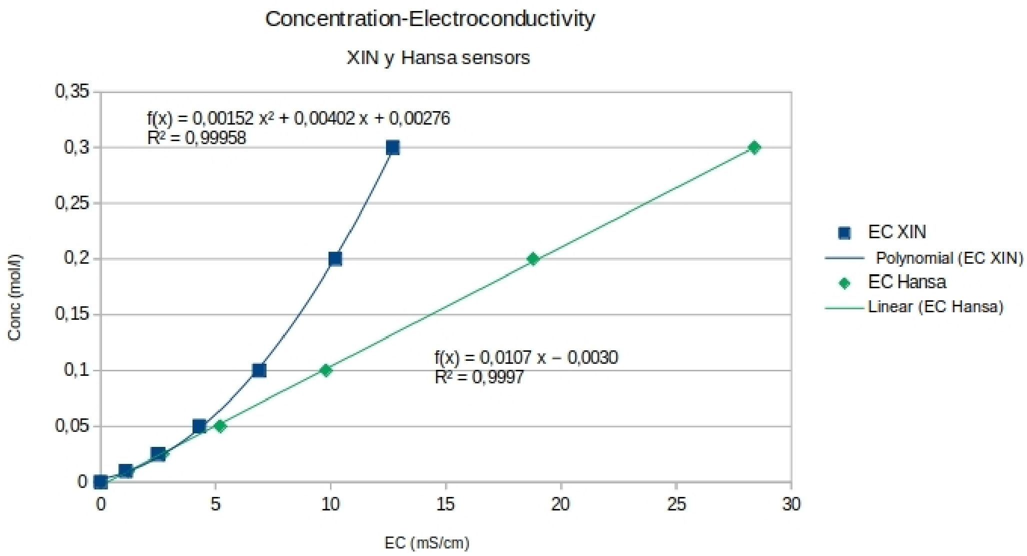

Figure 4 Comparison of Both Conductivity Meters

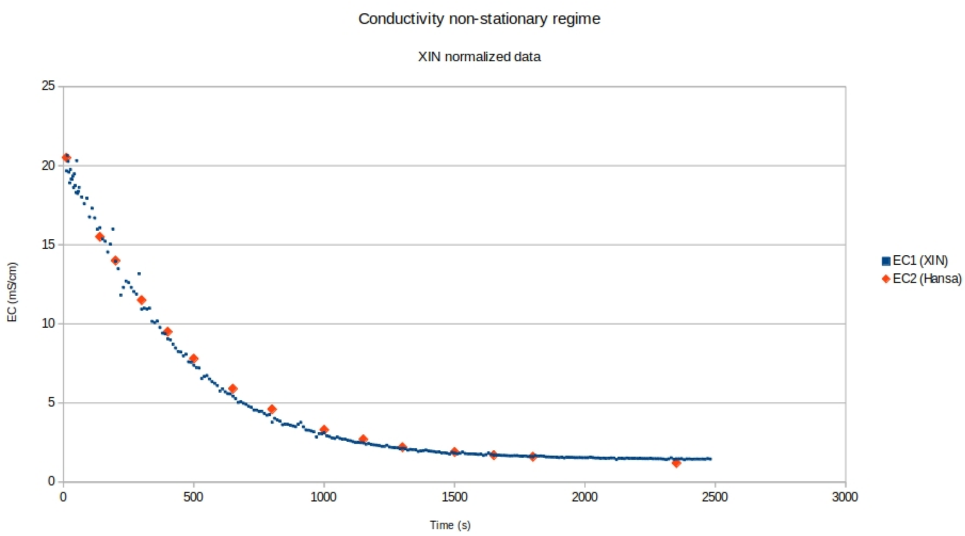

Figure 5 Behavior of the Calibrated Conductivity Meter

4.3 Contextualization of the System

Once the measurement system has been designed and built, it will be necessary to implement it in the laboratory practice that is currently being carried out, in order to evaluate it and determine the educational improvements it provides. Results are not yet available regarding improvements in student learning, since these practices are carried out during the second semester. However, it is expected that this will be the case, since the following aspects related to Chemical Engineering are provided for students in the second year of the Degree in Chemistry:

- From the pedagogical point of view, the commercial conductivity meter as a measuring device is totally opaque and as such is used in other disciplines; However, the proposed approach clearly makes it possible to distinguish that the real measurement is a potential difference, which later becomes a resistance, a conductivity and finally, in a concentration.
- All this makes it possible to relate the variables that appear in the equations (concentration) with those

that are measured experimentally and their dependence on the environment (temperature).

- Chemical Engineering sensors are frequently designed to meet specific needs, which allows us to see the convenience of using measuring instruments of our own design, especially when this can be carried out with current technology, at very low cost.
- Mass balances imply knowledge of the properties of fluids and, therefore, the importance of their continuous measurement compared to discontinuous measurements that are carried out in other subjects of the Degree in Chemistry.
- Instrumentation calibration, both laboratory and process, continues to be an essential technique, which must be considered in all experimental areas.
- It helps to deepen in the measurement and control of variables by software, through the digitization of continuous measurement parameters and their conversion to data readable by a spreadsheet; furthermore, the data collection period can be easily controlled.
- It is clear the need of representing the data obtained in different scales (linear, logarithmic) to obtain important parameters of the system (time constant), thus making progress in the use of spreadsheets.

5. Conclusions

The assembly and fine-tuning of electrical conductivity measurement systems in liquid solutions has made it possible to verify that currently very low-cost laboratory practices related to Chemical Engineering can be designed and assembled (in the case studied, less than 30 euros). Although, at the moment the specifications of these low-cost sensors do not cover a wide range of measurements without losing linearity, the use of classic laboratory devices for their calibration allows their proper use while requiring the handling of concepts (graphics, calibrations) that are being lost in the usual practice of teaching.

From the educational point of view, we consider that the introduction of automatic measurement technologies to the usual systems involved in Chemical Engineering approached in the laboratory practices should help to better deepen the understanding of the concepts that are approached and exercised in said practices.

Doing so allows a glimpse of the immediate future using modern low-cost measurement elements that enables the practice material to be extensively renewed and involve students in handling new data acquisition and analysis technologies in their most basic studies.

6. Recognition

This work is part of the educational innovation project "Application of Arduino technology to reinforce knowledge in Fluid Mechanics", granted by the Vice-Rector's Office for Teaching of the University of La Laguna for the 2018–2019 academic year.

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