

**INNOVATIVE SCHOOL-LEVEL QUANTITATIVE CHEMISTRY
EXPERIMENTAL TECHNIQUE (III)
A CONDUCTIVITY METER DESIGNED FOR MICRO-SCALE USE IN SCHOOLS**

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ABSTRACT

The paper is a continuation of Part (II) of the article [1] published in AJCE Vol 10 No.2, July, 2020. It also advocates the use of “DMM display” technique in which a single piece of instrument, a digital multi-meter (DMM), is used as a terminal display for more than one type of experiment. Sensor circuit design aims at providing a “unit-free” display situation in which students feel less threatening, i.e. a “user-friendly” situation for school-level experimentation. The designed electronic sensor, coupled with an innovative miniature conductivity probe, a combowell plate and a commercial DMM, is able to numerically display electrical conductivity of aqueous solutions ranging from non-conductive like deionized water as 0 to highly conductive such as 1M H₂SO₄ as 81, with a complete conductance calibrated at 100. The design allows digital display of conductivity measurement of aqueous solutions without the conventional reading unit of “μS/cm”. [*African Journal of Chemical Education—AJCE 11(1), January 2021*]

INTRODUCTION

The conductivity meter consists of a miniature probe made of two insulated nichrome wires (commonly known as heater wire), a home-made sensor (Fig. 1) that employs an electronic circuit to generate pulsing current for preventing electrolysis (Fig. 4) and a commercial digital multimeter (DMM). The conductivity meter is first calibrated by short-circuiting the two electrodes of the probe with a metal wire and by adjusting the calibration knob of the sensor so that the DMM, which is set at the 2000 mV range, displays a value of 100 mV. This is taken as the full-scale calibration of 100 and the knob is kept stationary for the rest of the experiment (Fig. 2). After this simple calibration procedure, the setup is ready for quantitative conductivity measurement.

FEATURES OF THE INSTRUMENTAL DESIGN

- (i) The “DMM display” technique employs commercial low-cost digital multimeter (DMM) to act as a common terminal display. Instruments employing the “DMM display” technique is very suitable for school level quantitative measurement of reaction variables such as pH, solution conductivity or colour intensity of aqueous solutions. Principle of measurement is based on probes for these reactions output electrical signals, which after suitable amplification, can be nicely handled in the DC millivolt range measurement by all kinds of DMM which provide at least an input resistance of 10 M Ω ensuring almost no loss of source signal.
- (ii) Commercial conductivity meters commonly use “ Ω S/cm” as reading unit. Meaning of the unit is usually not taught in school-level lessons. The design aims at doing away with such kind of reading units. When the conductivity probe is connected to the sensor which in turn connected to a DMM set at the 2000mV range, and by short circuiting the two electrodes

of the probe, the sensor outputs a pre-set maximum voltage of 100 mV and this value is treated as full conductance (i.e. 100). If a value of 29 mV is displayed when an unknown solution is tested, the electrical conductivity of this solution is looked upon as having 29/100 strength of full conductance (Fig. 3). This offers a “user-friendly” and less threatening situation for dexterity less competent school students.

- (iii) Circuit design gives an output voltage around 500 mV which can be attenuated to 385 mV (for details please go over page 7) and this means we can set the full scale to a higher voltage, say 300 mV, or a full scale of 300 instead of 100 (Fig. 22). The advantage of using this method is that one more digit of voltage can be displayed. For instance, using this way of calibration set at 300, a display of 123 can be achieved compared with a value of 41 employing the full-scale calibration set at 100 under the same condition. In other words, this method increases the sensitivity of measurement.



(Fig. 1) Miniature conductivity probe and sensor



(Fig. 2) Experimental setup for setting full scale by short-circuiting the probe with a thread of metal wire



(Fig. 3) A testing solution showing 29/100 conductivity



(Fig.4) Absence of electrolysis during conductivity measurement

- (iv) Primitive home-made school level conductivity tester using a 9V battery, a metallic probe and a single LED is incapable of quantitative investigation of solution conductivity and suffers from the drawback of electrolysis during measurement. Improvement using a bar-graph LED and a LM 3914 Dot/Bar Display Driver IC [2] can semi-quantitatively display solution conductivity by brightening or dimming an array of 10 LEDs [3], [4]. However, a true quantitative digital display should be able to display digits 0, 1 to 9 arranged in selected combinations. A readily available DMM suits the purpose nicely.
- (v) The design uses an Op-Amp relaxation oscillator to generate a single frequency alternating square wave signal source for electrical conductivity (Fig. 14). This way avoids electrolysis of the testing solution, as shown in Figure 4.
- (vi) The sensor employs a voltage follower circuit [6] for a unity gain output with no voltage inversion. This kind of buffered circuit is ideal for obtaining a stable, interference (noise) free and drift-free output voltage.

INSTRUMENT CONSTRUCTION

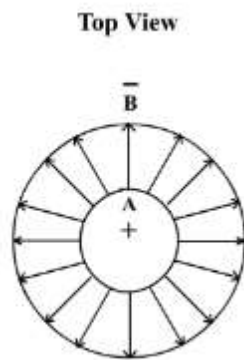
(A) *The probe*

One type of commercial conductivity probe (Fig. 5) is made in the form of concentric cylindrical metallic electrodes.

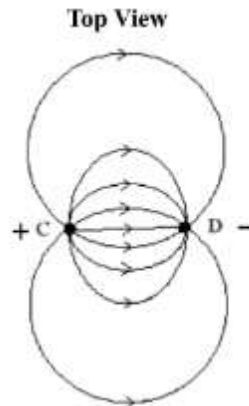


(Fig. 5) A commercial conductivity probe

The construction (Fig. 6) ensures even distribution of AC electric field developed between the 2 concentric cylindrical plates so that by measuring the conductivity of the solution, it is possible to calculate the solution's concentration. Instead of using concentric cylindrical plates, parallel rods (Fig. 7) can also be used, but the electric field developed between the parallel rods will not be even.



(Fig. 6) Evenly distributed electric field developed between 2 cylindrical electrodes A and B



(Fig.7) Unevenly distributed electric field developed between electrodes C and D in rod form

As shown in Figure 6, when immersed in solutions, electrical conductivity between concentric cylindrical plates A and B varies evenly and linearly with applied AC potential. Upon calibration, concentration of a testing solution can be calculated mathematically by conductivity

measurement (limited by a range of low concentration and at a fixed temperature, actual mathematical relationship involving all mobile ions of opposite charges is quite advanced, internet search). Commercial conductivity meter incorporates built-in electronic calculation mechanism and display final solution conductivity in “ $\mu\text{S/cm}$ ” unit. On the other hand, parallel rods C and D under the same condition form curved lines of electric field as shown in Figure 7. If the same calibration is attempted, mathematical calculation of concentration of a sample solution is difficult. However, graphically and not mathematically, a non-linear calibration line in this case is equally good for the determination of relative concentration of sample solutions. (Note: to avoid electrolysis, AC voltage should be used instead of DC voltage, and that is exactly the main job of the sensor).

Parallel rod type electrodes are much easier to construct than concentric cylindrical plate type electrodes. A simple mini-conductivity probe (so that it can be dipped into the small wells of a combo plate) is made by inserting two insulated nickel-chromium wire (i.e. wire used in electric heaters) into a small length of glass tubing, exposing a small section of the bare-wire end to act as testing area, and the rest of glass tube end region is sealed by epoxy cement, a connecting cable is attached to the other end of the bundled electrodes as shown in the following photos (Fig. 8 and 9). Nickel-chromium wire is selected as electrode because it is highly resistant to corrosion.



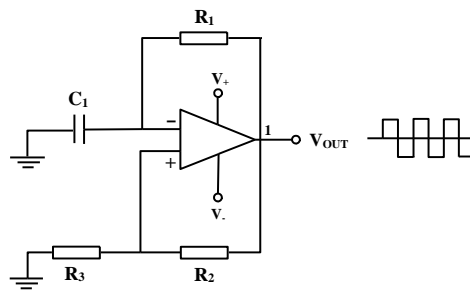
(Fig. 8) Size of the tip of the probe (compared with a toothpick)



(Fig. 9) Finished conductivity probe

(B) The sensor**(i) Relaxation oscillator**

The important part of the sensor circuit is a signal generator. Unless you are involved in academic studies of electronic circuits, amateur electronic hobbyists usually use the “black-box” approach to design circuits and ignore their advanced working principles. For this design, the “black-box” approach concentrates only on the input/output requirements. We have Op-Amp IC, capacitor and resistors at our disposal and we want to have a continuous chain of propagating AC electrical signals of frequency 5000 Hz. When your PC is connected to the internet, if you key in the keyword “*relaxation oscillator*” you will find the following typical relaxation oscillator circuit diagram in many available URLs (Fig. 10).



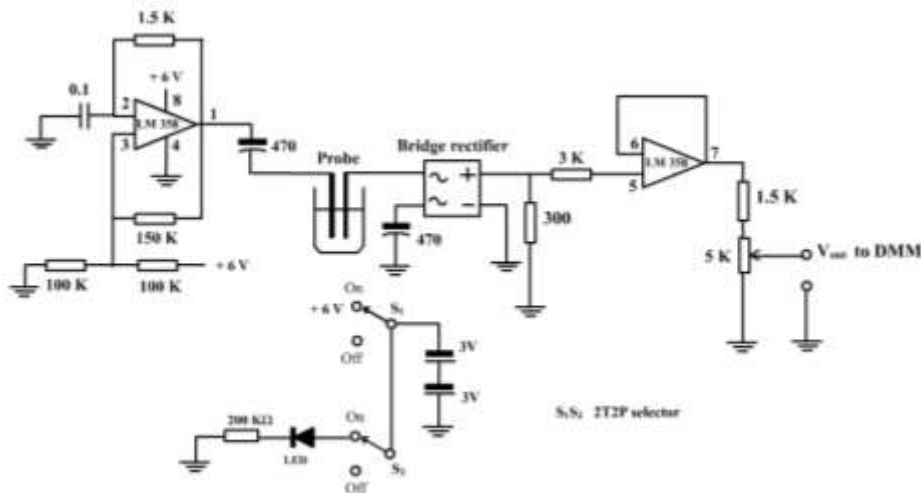
(Fig. 10) A typical relaxation oscillator circuit diagram

The generated frequency is represented by the following equation:

$$f = \left(\frac{0.5}{R_1 C_1}\right) \left(\frac{R_2}{R_3}\right) \text{ Hz}$$

All you need to do is to choose a certain combination of C_1 , R_1 , R_2 and R_3 to achieve the desired frequency. For example, if $C_1 = 0.1 \mu\text{F}$, $R_1 = 1.5\text{K}$, $R_2 = 150\text{K}$, $R_3 = 100\text{K}$, the generated frequency is calculated to be 5000 Hz. Usually C_1 is fixed as $0.1 \mu\text{F}$

(ii) Circuit diagram

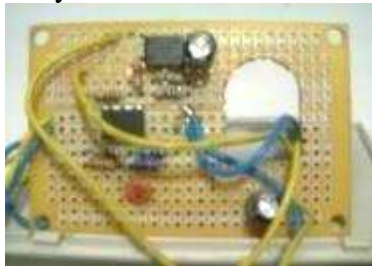


(Fig. 11) Sensor circuit diagram

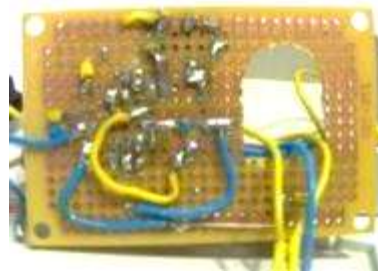
(iii) Circuit description

The sensor circuit (Fig. 11) seems complicated. However, it can be broken down into 3 basic parts: (i) left part of the circuit is a relaxation oscillator. It provides a chain of square wave signals by one half unit of dual Op-Amp LM 358 [5]. In short, a high frequency AC source. (ii) An AC rectification in the middle part, converting the AC signals to DC voltage and (iii) an unity gain voltage follower (i.e. input voltage equals output voltage, this kind of voltage follower design [6] reduces voltage error and noise caused by source loading) on the right by the other half unit of dual Op-Amp LM 358. Resulting output is fed to a DMM, set at the DC 2000 mV range.

The analogue circuit is traditional. The good point about it is that the idea works from first principle. Circuit board is used to solder various electronic components together at different junction points (Fig. 12 and 13). A similar design of home-made conductivity meter for school use was published in Chem. Educator 2019 [7].



(Fig. 12) Front view of soldered circuit board

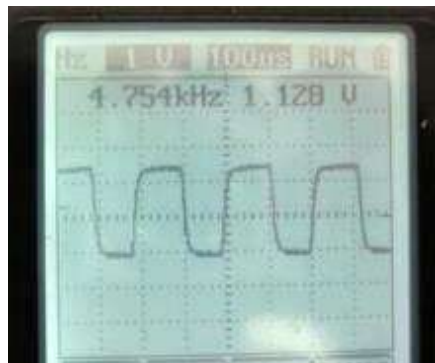


(Fig. 13) Back view of soldered circuit board

Frequency of the square wave is calculated as:

$$f = \left(\frac{0.5}{1500 \times 0.1 \times 0.000001} \right) \left(\frac{150}{100} \right) \text{ Hz} = 5000 \text{ Hz}$$

Oscillating voltage generated is measured across pins 1 and 3, not pin 1 and the ground. The reason is that LM 358 is a single power supply Op-Amp, negative supply voltage is not required and the ground is the – pole of the 6V supply voltage. A “pseudo” ground (in fact +3V w.r.t. ground) i.e. pin 3, for the oscillating part of the circuit has to be generated as the neutral reference of the propagating chain of oscillating voltage. It is done by short-circuiting the + and – poles of the 6V power supply (two button-type lithium 3V batteries connected in series) by two 100 K Ω resistors and tapping the middle of the resistor array as the neutral reference of the generated chain of square waves, as shown in the photo below (Fig. 14). A square wave pulse with a frequency of 4.8K Hz is detected and not the theoretical 5K Hz, this is due to % error of printed values indicated by the components.



(Fig. 14) Measured square wave frequency by a portable scope tapping at pins 1 and 3

The output of this AC signal generator (relaxation oscillator) is fed through capacitor 470 μ F to one end of the electrodes of the conductivity probe. The other end of the bundled electrodes of the probe (in which the probe is totally immersed in the testing solution) is connected to a full wave bridge rectifier and converts the AC voltage to a half-wave form which can be regarded as a crude positive DC voltage as the frequency of the generated AC signal is high. This voltage is fed through the 3K Ω resistor to the unity gain voltage follower formed by the other unit of dual Op-Amp LM 358. The output voltage of 500 mV through pin 7 is attenuated by a resistor ladder consisting of a 1.5K Ω resistor connected in series with a 5K Ω variable resistor and taps 385 mV by the 5K Ω variable resistor ($500 \times \frac{5}{1.5+5}$ mV or 385 mV). By adjusting the 5K Ω variable resistor, a full conductance (i.e. placing a metallic conductor between the ends of the probe) display of 100 mV, 200 mV and 300 mV can be achieved. The procedure is exactly the calibration for a FS of 100, 200 or 300. For experimentation, by setting at a FS of 100, if the sensor registered a voltage of, say, 40 mV for a testing solution, then this value represents 40/100 of the full strength of conductance, or simply 40 % strength. In this way, there is no need to use unit such as μ S/cm to indicate experimental results, thus demonstrating the usefulness of the “DMM display” technique.

Except when short-circuiting the probe for calibration, bottle-neck of current consumption is the small amount of high frequency AC current through the electrolytic solution. Owing to this factor, coupled with a buffered voltage follower sensor circuit and the use of a high input resistance DMM, the design offers a steady numerical output display overtime.

(iv) Complete sensor construction

The case of the sensor is a small plastic utility box measuring 100 mm (length) x 60 mm (width) x 25 mm (depth). Holes are drilled for accommodating the 5K $\square\square$ variable resistor, the pilot LED and the push-on/push/off mini-switch (Fig. 15, 16).



(Fig. 15) Utility box



(Fig. 16) Utility box with drilled holes of various sizes

Battery housing is designed as follows:

As the whole circuit draws little current, the power source is supplied by 2 button type lithium dry cells (CR 2032), each offering a voltage of 3V (Fig. 17). A special holder for such dry cells is used (Fig. 18), as they occupy limited space. Two such holders connected in series are held together by an acrylate strip with the help of a few drops of trichloromethane (Fig. 19). It is placed freely inside the plastic box with the rest of the instrument components holding it and making it quite stationary because the box is small enough (Fig. 21).



(Fig. 17) CR 2032 lithium button cell

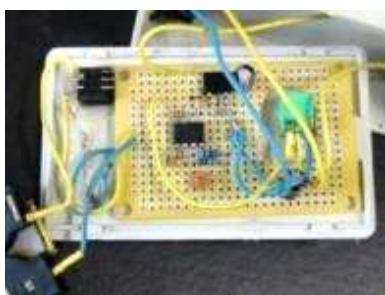


(Fig. 18) Button cell holder



(Fig. 19) Holder combination

The 5K $\square\square$ variable resistor is fixed onto the lid, completed by capping the axle with a turning knob. The soldered pre-assembled circuit board (you can do it yourself, if you have skills of soldering electronic components) is connected to various junction points of the circuit and is kept stationary by the wires joining the circuit board (Fig. 20). The output jack socket (to be connected to the DMM) and the input jack socket for the conductivity probe are fixed by hot glue to the bottom part of the utility box (Fig. 21).



(Fig. 20) Bottom view of the lid cover



(Fig. 21) Interior of the sensor box housing all components

Assembly of (probe + sensor + combo well-plate + DMM) for conductivity measurement is shown in Figure 3. The basic experimental requirement is that electrolysis of the testing solution should not be allowed to occur (Fig. 4).

SUGGESTED STUDENT EXPERIMENTS

Expt. 1 Micro-scale investigation of electrical conductivity of solutions

Objectives

- (i) To identify electrolytic or non-electrolytic solutions
- (ii) To identify strong or weak electrolytic solutions
- (iii) To propose a pattern for the relationship between conductivity of electrolytic solution and concentration

Experimental results

(A) Identification of electrolytic or non-electrolytic solutions

Table (1), using small wells of a combo plate

Small well no.		1	2	3	4	5	6	7	8
Substance		8 drops of deionized water	8 drops of 20% glucose solution	8 drops of 95% ethanol	8 drops of 1M ethanoic acid	8 drops of 1M sulphuric acid	8 drops of 1M sodium hydroxide	8 drops of 1M ammonia	8 drops of 1M sodium chloride
DMM reading/ mV	Full scale 300	0	2	2	15	243	222	14	184
	Full scale 100	0	1	1	5	81	74	5	61



(Fig. 22) Full Scale adjustment at 300 mV



(Fig. 23) Testing conductivity of solution

(B) Effect of dilution on strong electrolytic, weak electrolytic or non-electrolytic solutions

Table (2), using large wells of a combo plate

Substance	No. of drops of sat. NaCl	40	35	30	25	20	15	10	5
	No. of drops of deionized water	0	5	10	15	20	25	30	35
DMM reading /mV	Full scale 300	185	190	188	186	182	179	169	146
	Full scale 100	62	63	63	62	61	60	56	49

Table (3), using large wells of a combo plate

Substance	No. of drops of 1M NaCl	40	35	30	25	20	15	10	5
	No. of drops of deionized water	0	5	10	15	20	25	30	35
DMM reading /mV	Full scale 300	157	149	142	135	128	116	92	73
	Full scale 100	52	50	47	45	43	39	31	24

Table (4), using large wells of a combo plate

Substance	No. of drops of 100% ethanoic acid	40	35	30	25	20	15	10	5
	No. of drops of deionized water	0	5	10	15	20	25	30	35
DMM reading /mV	Full scale 300	2	2	10	14	21	22	22	18

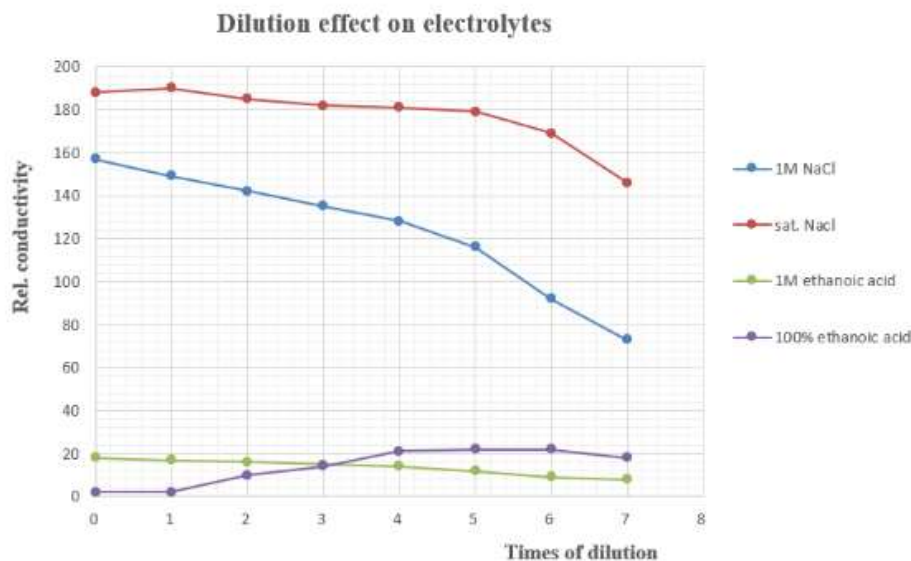
Table (5), using large wells of a combo plate

Substance	No. of drops of 1M ethanoic acid	40	35	30	25	20	15	10	5
	No. of drops of deionized water	0	5	10	15	20	25	30	35
DMM reading /mV	Full scale 300	18	17	16	15	14	12	9	8

Note: The “continuous variation method” is adopted for dilution which avoids volume change on adding deionized water.

Treatment of data

Manipulate all the collected experimental data by displaying, in each case, plots of relative conductivity vs times of dilution using a suitable spreadsheet software (Fig. 24).



(Fig. 24) Effect of dilution on the conductivity of strong, weak and non-electrolytic solutions

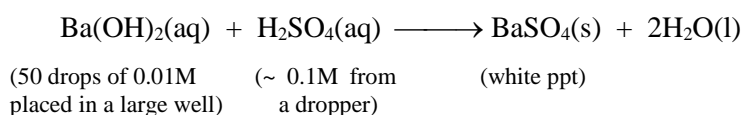
CONCLUSION

- (1) Electrolytes are substances that *conduct electricity* when dissolved in water. *Ionic or polar substances* are electrolytes.
- (2) Non-electrolytes are substances that *do not conduct electricity* when dissolved or partly dissolved in water. *Covalent or non-polar substances* are non-electrolytes.
- (3) Strong electrolytes are substances in which their aqueous solutions conduct electricity much better than weak electrolytes under *the same* conditions.
- (4) In general, electrical conductivity *decreases* with increase in dilution. However, with some soluble covalent compounds, such as *100% sulphuric acid*, conductivity *increases* with increase in dilution. This is due to *ionization* of covalent compounds on adding deionized water.
- (5) Electrical conductivity of aqueous solutions is due to *mobile* ions of opposite charges.

Expt. 2 Conductometric titration**Objectives**

- (i) To perform a micro-scale acid/alkali conductometric titration.
- (ii) To determine the concentration a provided sample of sulphuric acid by titration against 0.01M Ba(OH)₂(aq).

No. of drops of approx. 0.1M H ₂ SO ₄	0	1	2	3	4	5	6	7	8	9	10
Conductivity (FS 200 mV)	27	24	20	16	12	9	20	28	35	40	45



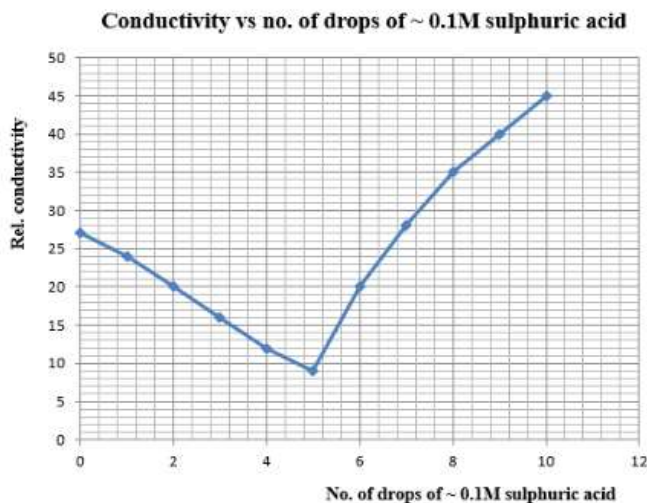
(Fig. 25) Calibrate the sensor by adjusting to 200 mV



(Fig. 26) Conductivity measurement during titration

RESULT AND CONCLUSION

By placing 50 drops 0.01M Ba(OH)₂(aq.) followed by 2 drops of phenolphthalein indicator solution into a large well of a combo plate, plot of relative conductivity vs no. of drops of ~ 0.1M H₂SO₄ added is shown below:



(Fig. 27) Titration curve

By inspecting the plotted graph (Fig. 27) and eye observation of disappearance of the red coloration, equivalence point of titration was reached when 5 drops of the acid had been added. Simple stoichiometric calculation showed that the given sample of sulphuric acid had a concentration of 0.1M.

For school level micro-scale conductometric titration experiment, concentration ratio of titrant : reactant to be titrated is normally kept at 10:1 . This is to avoid significant increase in total volume which could greatly affect ionic conductance.

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