Introduction

Conductivity is the ability of a solution to transfer (conduct) electrical current. The value of the electrical conductivity depends on the ability for electrons or other charge carriers, to move within a liquid. Conductivity is generally shown in units of Siemens per centimeter, mS/cm (milliSiemens/cm) or µS/cm (microSiemens/cm).

The conversion of the units = 1 S/cm = 1,000 mS/cm = 1,000,000 µS/cm.

There are many instruments that can measure conductivity. One such device is a graphite probe, which measures conductivity by placing two plates of conductive material with known area and distance apart, in a water sample. A voltage potential is applied and the resulting current is measured. The value of the conductivity can be then be determined by the value of the current.

For solutions that have high conductivity a toroidal probe is often used. A toroidal probe consists of a pair of wire-wound metal toroids over-molded with corrosion-resistant plastic. One coil is the primary, and the other coil is the receiver. When the sensor is immersed in a conductive liquid, the device sends an alternating current of known value through the primary coil which creates a magnetic field and induces a current in the process liquid. This in turn, induces a current in the receiver coil which is directly proportional to the conductivity of the liquid.

Conductivity Theory

Conductance (G) is defined as the reciprocal of the **electrical resistance (R)** of a solution, between two electrodes.

$$G = 1/R$$
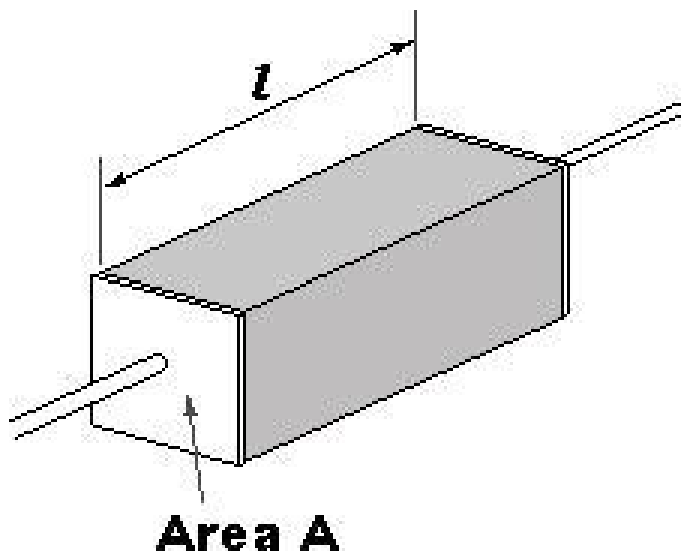
Area A

Often, it is necessary to relate the conductance to a specific length of material, as well as a constant cross sectional area. This is the ratio of the distance 'l' (between the electrodes), to the area 'A' of the electrodes. The ratio of 'l' and 'A' is called the **cell constant (K).**

$$K = l/A$$

K = cell constant (cm^{-1})

a = effective area of the electrodes (cm^2)

l = distance between the electrodes (cm)

Conductance and the cell constant are related in the equation below, and this is called Conductivity (σ). Electrical conductivity is the measure of a material to accommodate the transport of electric charge. The higher the value of the conductivity, the lower the resistance it provides to the flow of electric current.

$$\sigma = G \times K$$

σ = conductivity (S/cm)

G = conductance (S), where G = 1/R

K = cell constant (cm)

To obtain a conductivity value with the greatest accuracy, it is imperative that the correct cell constant is selected for the respective conductivity solutions.
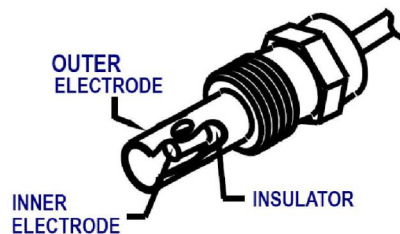
Measurement

Conductivity measurements are used routinely in many industrial and environmental applications as a fast, inexpensive and reliable way of measuring the ionic content in a solution. The measurement of conductivity is a typical way to monitor the properties of the water systems such as; sea water, river water, boiler water and in the purification of drinking water.


Examples of conductivity testing; boiler water (above) and waste water (below)

The electrical conductivity of a water solution can be measured by determining the resistance of the solution between two flat or cylindrical electrodes (inner and outer). These electrodes are separated by a fixed distance by moulding them onto plates within a graphite probe and by doing this, an accurate cell constant value can be obtained. To avoid polarization of the electrodes an alternating voltage is used. This stops any non-spontaneous reactions occurring on the surface of the electrode, resulting in inaccurate readings being recorded.

*An illustration of the two electrodes within a graphite probe.*
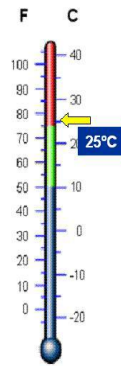
Conductivity measurements are strongly affected by the temperature of the sample. For example, the conductivity reading of a salt solution of sodium chloride typically increases by 2% for every degree Celsius temperature change, and thus the conductivity value of a salt solution at 15°C can be expected to be about 20% lower than the value at 25°C. Depending on the lab's standard operating procedure, conductivity readings may be temperature-compensated or not. It is important to note the temperature reading or the reference temperature with every conductivity reading recorded.

For low conductivity water solutions, the electrodes can be placed closer together (reducing L) to give cell constants of 0.1 cm^{-1}. This raises the conductance between the plates, and makes it easier for the electronic circuitry to obtain a result . As can be seen from the graph below, the graphite probe with a K = 0.1 (blue line), has a strong response when the conductivity is below 200 µS/cm. The probe, will therefore, have a low signal to noise ratio, and the results it obtains from the sample will be very accurate within this region. When the conductivity increases, the probes response per µS/cm will reduce. This will cause the signal to noise ratio to increase, resulting in a reduction in the accuracy of the probes measurements.

- **A probe with a cell constant of 0.1, is ideal to obtain an accurate result when the conductivity is between 0 to 200 µS/cm.**


Examples of graphite probes with varying K factor:- 0.1 (top), 1 (middle), and 10 (bottom)
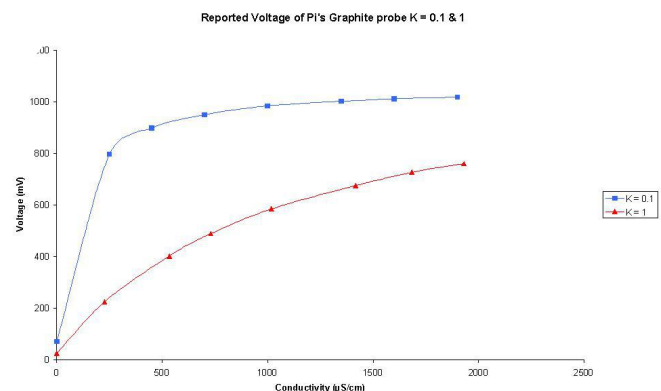
If the water has a moderate conductivity, it is best to use a probe with a K value of 1 (red line in the graph). Although it doesn't have high response the K=0.1 probe has in low conductivity solutions, it instead has a constant response from low to moderate levels of conductivity and the probe is able to give an accurate reading across a wide range of conductivity values, which can be indispensable if the conductivity of a water solution is unknown.

- **A graphite probe with a cell constant of 1 is ideal to obtain results when the conductivity ranges between 0 and 2000 μS/cm.**

For high conductivity solutions, the electrodes can be moved further apart (increasing L) to give a cell constant of 10.0 or more. More often, a plastic toroidal probe is used to determine the conductivity of these solutions.
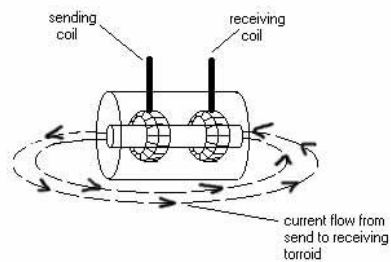
A diagram of the two currents created by the probe (above) and a picture of a toroidal probe (below).
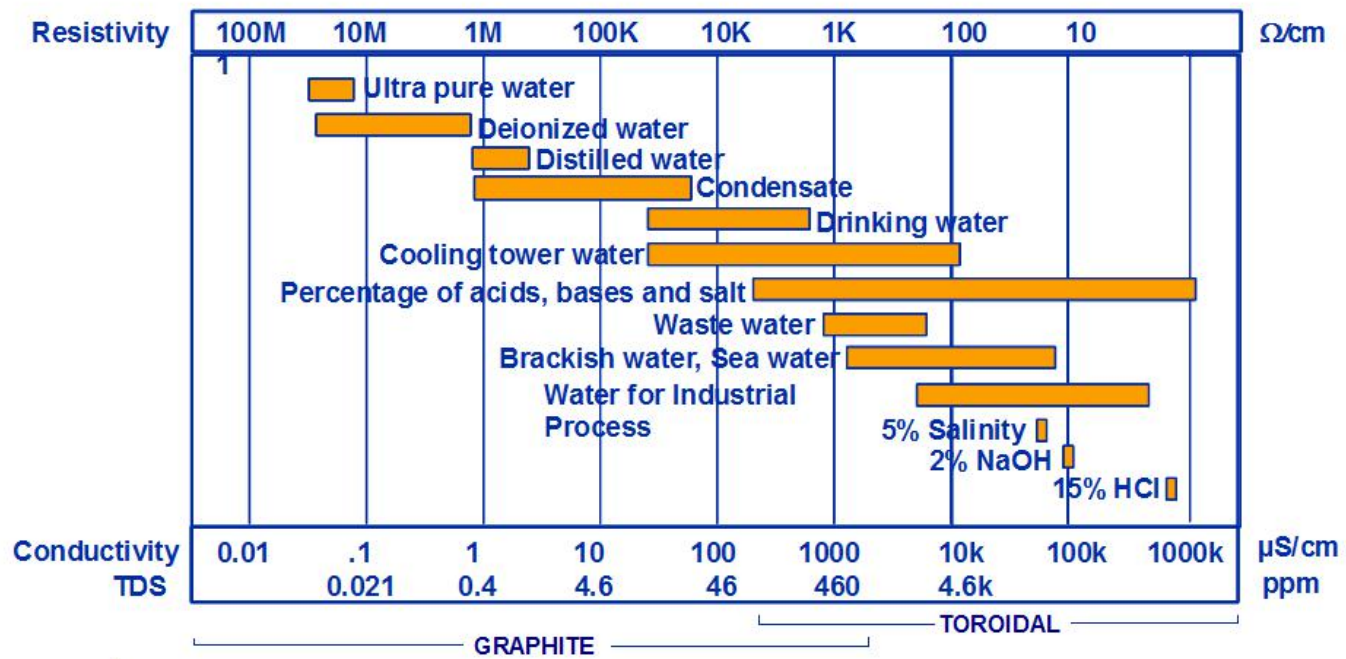

A laboratory study was undertaken by Pi to show the accuracy and the range of the toroidal probe using various concentrations of sodium chloride. Each sodium chloride concentration has a known value of conductivity; these values were compared to the values the toroidal probe recorded and the data was plotted in the graph below.
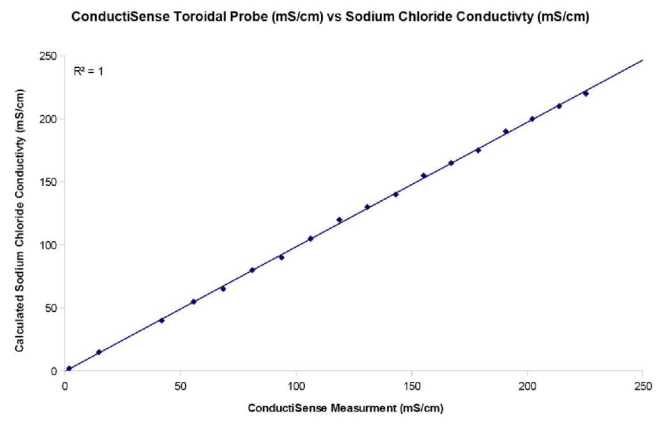
The maximum conductivity value a sodium chloride solution can produce is 230,000 μS/cm or 230 mS/cm before it becomes saturated solution i.e. no more sodium chloride will dissolve no matter how much is added. As can be seen from the graph above the toroidal probe accurately measured to this limit, and is capable of accurately measuring conductive solutions up to 2000 mS/cm, which is far beyond the range the graphite probes are capable of measuring.

Toroidal vs Graphite Contact Probe

- **A toroidal probe takes far greater space than a graphite probe, as it needs an three centimeters of conductive liquid surrounding the probe to ensure that current the receiver coil measures isn't compromised i.e. to keep the accuracy as high as possible.**

- **Graphite probes can be calibrated in place or in a separate container, whereas a toroidal probe must be calibrated in place to obtain the optimum results.**

- **The typical accuracy of a toroidal probe is ±20 μS/cm, which is a considerably larger error than that for the graphite probe, which is ± 5μS/cm.**

- **A toroidal probe can be used in fouling and coating environments, as well as being able to measure dirty, corrosive samples. A toroidal probe is therefore ideal to measure the conductivity of samples such as waste water and water used in industrial processes. This is in contrast to graphite probes, which must be used in clean, non-corrosive samples, (such as drinking water) in order to give accurate**

| Resistivity | 100M | 10M | 1M | 100K | 10K | 1K | 100 | 10 | | Ω/cm |

Ultra pure water
Deionized water
Distilled water
Condensate
Drinking water
Cooling tower water
Percentage of acids, bases and salt
Waste water
Brackish water, Sea water
Water for Industrial Process
5% Salinity
2% NaOH
15% HCl

| Conductivity | 0.01 | .1 | 1 | 10 | 100 | 1000 | 10k | 100k | 1000k | µS/cm |
| TDS | | 0.021 | 0.4 | 4.6 | 46 | 460 | 4.6k | | | ppm |

GRAPHITE — TOROIDAL

results. A table to which probe is suitable for a specific environment is given on the following page.

Total Dissolved Solids

Total Dissolved Solids (often abbreviated to TDS) is a measure of the combined content of all inorganic substances dissolved in a liquid. The TDS and the electrical conductivity are closely related, in that the more salts are dissolved in the water, the higher the value of the electric conductivity.

To convert the electric conductivity of a water sample (µS/cm) into the approximate concentration of total dissolved solids (ppm), the µS/cm is multiplied by a conversion factor. The conversion factor depends on the chemical composition of the TDS and can vary between 0.54 – 0.96. A value of 0.67 is commonly used as an approximation if the actual factor is not known.

[(TDS)ppm = Conductivity µS/cm x 0.67].

Since conductivity varies with temperature, it is necessary to correct the readings for changes in temperature. Most instruments contain circuits that automatically compensate for temperature and correct the readings to a standard 25°C.

References

1.http://books.google.co.uk/books?id=6jhELyGJOm0C&pg=PA491&redir_esc=y#v=onepage&q&f=false

2. http://www.ehow.com/how-does_5010026_conductivity-probe-work.html

3. http://epsppd.epfl.ch/Praha/web/98icpp_w/F002PR.PDF

4. http://www.radio-electronics.com/info/formulae/resistance/electrical-conductivity.php

5. http://www.eutechinst.com/techtips/tech-tips25.htm

6. http://infohouse.p2ric.org/ref/34/33027.pdf

7. http://sam.ucsd.edu/sio210/lect_2/lecture_2.html

8. http://water.epa.gov/type/rsl/monitoring/vms59.cfm

9. Ward, MR, Electrical Engineering Science, pp. 36−40, McGraw-Hill, 1971

10. http://www.lenntech.com/calculators/tds/tds-ec_engels.htm

11. http://www.ehow.com/how-does_5010026_conductivity-probe-work.html