

Understanding conductivity in practical terms

By Frederick J. Kohlmann and Bhupen Patel

This paper describes the theory of conductivity and how it is measured, looking in detail at the individual components, the types of conductivity measurements available, the importance of specific items related to the measurement and the proper methods for calibrating, cleaning and care of the conductivity sensor.

What is water?

We cannot begin our discussions of electrolytic conductivity without first discussing water. Water is the most precious commodity on this earth. Without water, life as we know it would cease to exist. Water is life.¹ Drinking water is essential to human life. It is also in short supply in many areas of the world, and wars have been fought over the rights to claim clean drinkable water.

Our world as it exists would not be possible without water. Water in liquid state, is the very reason we seem to be all alone in the universe. The Earth is at the exact correct distance from the sun, 93,000,000 miles away, in order to keep water in a liquid state, not frozen, and not in a gaseous form. We are in what scientists refer to as “The Goldilocks Zone”. If the Earth were only five percent closer to the sun, it would be a barren desert wasteland. Ten percent further away from the sun, and the Earth would be a frozen mass.

In the news, it was reported that the astronauts on the international space station, for the first time, drank recycled urine. A new system, combines urine and moisture from the air, moves it to a large tank where the water is boiled off and the vapor collected. The contaminants, the brine in the urine are thrown out. The water vapor goes through filters, much like those found on homeowners’ taps on Earth, and then is ready for consumption.

Life without water for astronauts working in space would not be possible. Making a water purification system in outer space is essential to life as well as cost and space savings for NASA. Imagine the costs associated with launching missions just dedicated to “water tankers” that would re-supply the space station with water. Water is essential to life.

One estimate is that over 70% of the world is covered with water from its five oceans and other large bodies of water. Saltwater, found in the oceans, accounts for 97% of all surface water and none of it is drinkable due to its high salt content. Fresh bodies of surface water account for < 1%. Less than 2% of all water (used for drinking) is found underground.

One analogy goes like this: if all the water in the world were compressed to fit into a one gallon jug, fresh water would account for only three tablespoons. The water accessible by humans would come out to only one tablespoon.

Water is known as the universal solvent. It is aggressive and over time, whatever it comes in contact with, gets dissolved or eaten away. Pure water is even more vigorous.

Water comes in three states; liquid, solid (ice), and vapor (steam). For the purpose of this paper, we are only concerned with the liquid state.

Water can either be a good conductor of electricity or a bad conductor. We all know not to use an electrical appliance near or in the bath tub as this could lead to electrocution. The conduction of the water itself, plus the added impurities of the soaps makes this water a perfect conductor. Ultra pure water has limited impurities, so it is a poor conductor of electricity.

The term (definition of) conductivity

Simply put, water or any aqueous solution has the ability to conduct an electrical charge. This conduction of charge is referred to as Conductivity or Resistivity (Resistance). Conductivity is the inverse or reciprocal of resistance. The strength or efficiency of that charge is determined by the charged atoms, particles (ions) that are dissolved in solution. For instance; pure water, water that has no impurities and therefore very little dissolved ions is a relatively poor conductor of an electrical charge. Seawater on the other hand has a multitude of dissolved minerals and as such has a great ability to conduct an electrical charge. The more dissolved material, the greater or more efficient the conductance. (The conductance is directly proportional to the amount of total dissolved solids (TDS) in water).

Strong electrolytes dissociate nearly completely (in diluted solutions), and thus, there are many charge carriers present which equates to a high conductivity. One might think of hydrochloric acid, sulfuric acid or sodium hydroxide.

Weak electrolytes on the other hand, dissociate only partially, thus there are not many charge carriers available which equates to low conductivity. Think of acetic acid, citric acid or ammonia.

MHOs vs. Siemens

Traditionally, conductivity is measured in Siemens/cm. Just as we are used to defining temperature in degrees F (Fahrenheit), conductivity practitioners use the term Siemens.

Many years ago, the measurement community at large, changed the terminology used to define/talk about conductivity. The term changed from MHOs/cm to Siemens/cm. (One MHO, as you may have guessed is the reciprocal of one OHM, an electrical resistance measurement).

Conductivity is expressed in microSiemens/cm ($\mu\text{S}/\text{cm}$) or millionths of a Siemen. It can also be expressed as milliSiemens/cm (mS/cm) or 1/1000 of a Siemen. Resistivity is measured in terms of megohm-centimeters for measuring in high purity water applications, with a typical range of 0-18.3 megohms \cdot cm ($\text{M}\Omega \cdot \text{cm}$).

Care must be taken as the written term mS/cm may be confused as microSiemens, and μS confused for milliSiemens, when in fact they are interposed.

μ = micro
m = milli

One can convert milliSiemens (mS) to microSiemens (μS), by multiplying mS by 1000. For example, $0.10 \text{ mS} = (0.10 \times 1000) \mu\text{S}$, or $100 \mu\text{S}$.

As the conductivity of a solution goes up in value, so do the contaminants within the solution. That is to say, the dissolved ions (contaminants) are also increasing.

Pure water = few dissolved ions
Seawater = an abundance of dissolved ions

Let's look at a scale of Conductivity value vs. solution (see Figure 1).

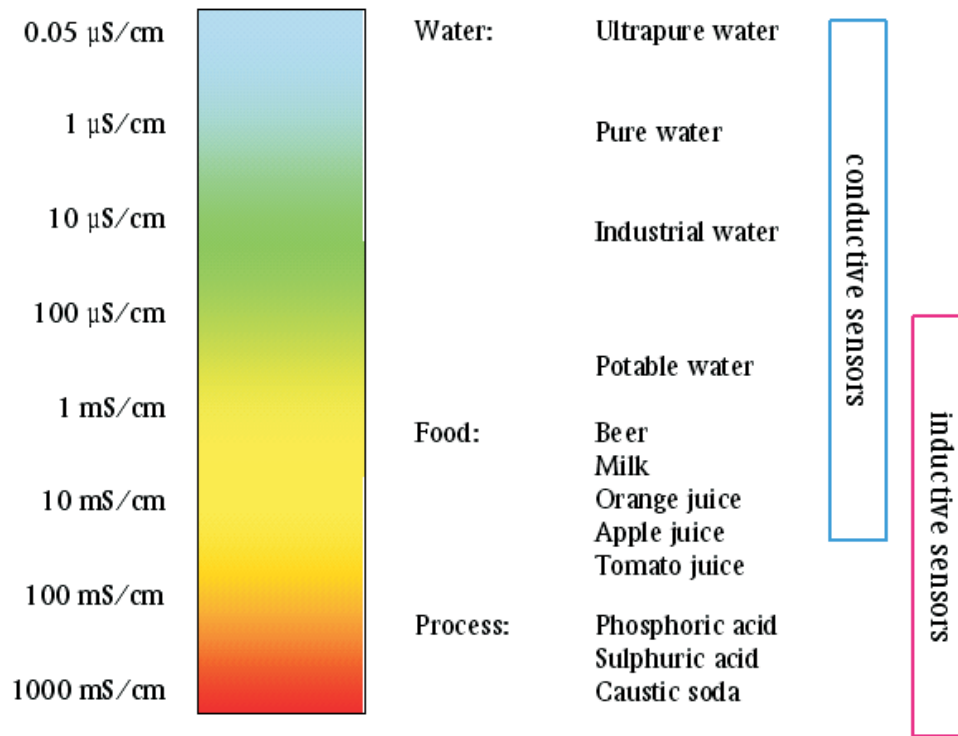


Figure 1: Ranges of conductivity in liquids

Why is conductivity measured

Conductivity is measured as a means to control deposits, scaling, chemical additions, purity and chemical interfaces just to name a few. Gas and coal fired boilers use conductivity measurements to make sure the heated water has a solids concentration below some set limit. If not, corrosion could occur (making the boiler less efficient). Condensate return to the boiler is also monitored for leakage so that process solutions do not enter the higher purity water in the boiler and cause damage.

The chemical peeling of fruits and vegetables use varying concentrations of acids or bases for peeling the skins of fruits and vegetables. The strength of this solution is often measured with either pH or conductivity depending on the process, in order to maintain a constant strength of the solution. Too strong, and more than the skin is peeled away, and too weak a solution, skins remain on the product and passed onto the consumer.

Various plating and cleaning operations in the metal industry rely on conductivity to alert operators of carry-over of soaps and cleansers when moving metal pieces from one tank to another. When the conductivity of a certain tank reaches a threshold, the tanks need to be either diluted (add more water) or strengthened (adding more chemical) depending on the application. Conductivity is a good way of measuring the purity or strength of these chemical baths.

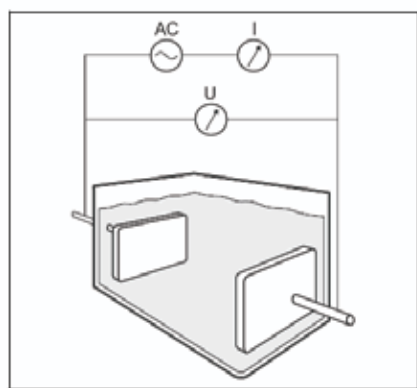
Reverse Osmosis systems take brackish, or grey, or sea water and turn it into drinkable water by forcing the water through very fine filters under pressure. Conductivity measurements are used to measure the raw water and the finished (polished water) to determine the quality of the water being made, and when the filters are in need of back-flushing or replacement.

Cooling towers use fresh water to circulate in a system and cool down processes (removal of the heat loading). As the water evaporates and existing water becomes more saturated with contaminants, a valve opens and drains or blows down the tower while at the same time, adds fresh water until a pre-determined conductivity value is reached. If this were not done, contaminants would build up to the point that the cooling effectiveness of the tower would be lost, and chemical and biological reactions would render the tower useless. Ultimately, the processes within the plant that depended on the cooling tower's ability to cool, would shut down.

Chemical scrubbers, the types that typically destroy odors in processes and keep them from inflicting a noxious odor to the surrounding community, use conductivity as a means to control odor. These scrubbers force product up a tower of some sort, and from the top of the tower, reign down a dissipating chemical reagent to cause a reaction whereby the outgoing product has been rendered neutral. This chemical reagent is collected in a sump and returned to the top of the scrubber to go through the cycle once more. Conductivity measurements make sure the strength or consistency of this chemical is kept within a strict value in order to be an effective neutralizer. Too little strength and the noxious fumes return. Too much strength of this reagent means wasted monies, and possible damage to the scrubber's internal parts or an adverse chemical reaction.

How do conductivity sensors work?

The conductivity of liquids is measured with two electrodes immersed in the medium. An AC voltage is applied to these electrodes which generates a current in the medium. The electrical resistance or its reciprocal value, the conductance G , is calculated according to Ohm's law. The specific conductivity κ is determined using the cell constant k that is dependent on the sensor geometry. That signal is then displayed on the conductivity transmitter.



Conductive measurement of conductivity

AC Power supply
I Current meter
U Voltage meter

Figure 2. Conductive measurement of conductivity

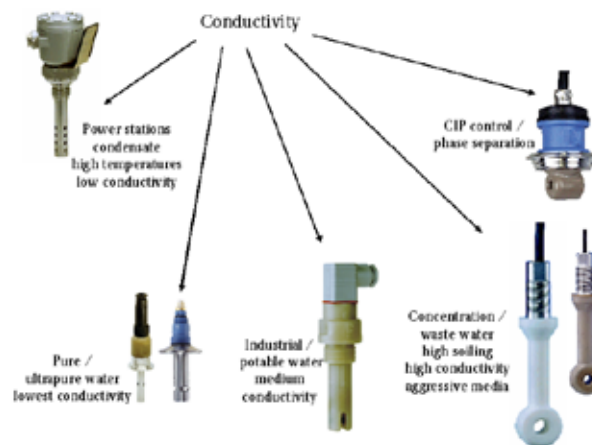


Figure 3. Different conductivity sensors

Figure 2 is meant as only a graphic indication of the sensor plates and relative geometry. In practice, the sensors look more like those shown in Figure 3.

The reason engineers decided to use sensors that work using an AC voltage rather than a DC voltage is due to something called polarization. Since AC voltage is an alternating current, and DC voltage is a direct current, DC would tend to have the media's positive ions build up on the negative sensor electrode and the positive ions build up on the negative sensor electrode, thereby polarizing the electrodes and inhibiting the electrode's contact with the media to be measured. Think of this as a buildup of ions that coats the electrodes and does not allow current to pass. AC voltage on the other hand, alternates between the sensor electrodes whereby the ions will not be drawn to any particular electrodes for any given amount of time.

Contacting conductivity sensors and cell constants

A contacting style conductivity sensor is typically made up of a sensor body which houses two electrodes which are then immersed into the solution to be measured, and which are insulated from each other. The electrodes are made from materials such as stainless steel or titanium, or other conductive materials. The electrodes are specifically sized and spaced apart in such a fashion as to result in what is known as a cell constant (k). For example, a cell constant of 1.0, has two electrodes, each one being 1 square cm in area and spaced 1 cm apart².

The cell constants are mated to their corresponding analyzer/detector, and the frequency and voltage that is applied to the sensor is pre-programmed by the manufacturer for the specific requirements of the measuring range. Not all manufacturers use cells with similar cell constants.

In theory, a conductivity sensor with a cell constant of 1.0 measuring pure water with a conductivity of 1.0 $\mu\text{S}/\text{cm}$, would have a resistance of 1.0 $\text{M}\Omega$. As conductivity might increase, the $\text{M}\Omega$ reading would decrease. More ions (=) better conductance (=) less resistance.

The smaller the measurement range in terms of conductivity (higher resistance) the greater the surface area needed to capture the reading. The higher the conductivity (lower resistance), the smaller the surface needed. Differing ranges equal differing cell constants.

Contacting conductivity sensors are used for the ranges of ultra pure water to mildly concentrated solutions of acids and caustics. The general rule of thumb is, if the solution is clear it can be measured with a contacting style sensor. If it is not clear, step up to an inductive style sensor. (Note: Many acid and caustic solutions are in fact clear, but have very high concentrations, and as such are not recommended for contacting style conductivity sensors. So in this case, the rule of thumb is not applicable).

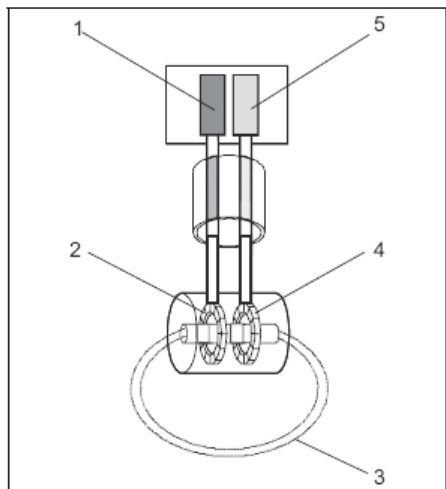
Typical conductivity ranges and associated cell constants

Range	Cell Constant (k)
0-0.04 $\mu\text{S}/\text{cm}$ to 20 $\mu\text{S}/\text{cm}$	0.01
0-0.1 $\mu\text{S}/\text{cm}$ to 200 $\mu\text{S}/\text{cm}$	0.1
0-0.1 mS/cm to 20 mS/cm	1.0

Toroidal/inductive/electrodeless conductivity sensors

An inductive conductivity sensor is one that uses two coils or transformers encapsulated in a sensor body to measure a signal generated through the media being that is to be measured. A generator (1) generates an alternating magnetic field in the primary coil (2) which induces a current in the medium (3). The strength of the induced current depends on the conductivity of the medium and thus the ion concentration of the medium. The current flow in the medium generates another magnetic field in the secondary coil (4). The resulting current induced in the coil is measured by the receiver (5) and processed by the analyzer to determine the conductivity.

Since the electrodes that actually do the measuring (the transformers/coils) are encapsulated into the sensor, they never become fouled like traditional contacting style conductivity sensors. As long as solution is allowed to flow through the hole in the center of the sensor, a measurement can be made. Even thick, viscous coating materials can be measured with a sensor of this design. The outer housing of the sensor is made up of materials that are impervious to the solutions being measured. Typical body wetted parts are PEEK® or PFA. Other parts like flanges and O-ring seals are made from 316 L SS, and CHEMRAZ™ materials. Consult with the manufacturer for details on chemical compatibility.



Inductive conductivity measurement

1. Generator
2. Primary coil
3. Current flow in the medium
4. Secondary coil
5. Receiver

Figure 4. Inductive sensor

Benefits of inductive conductivity measurement

- No electrodes, therefore no polarization
- Accurate measurement in media or solutions with a high soiling degree and a tendency to deposition
- Complete galvanic separation of measurement and medium

Since the electrodes (unlike those of a contacting style sensor) are not directly in contact with the medium being measured, there is no electrical contact of the medium back to the analyzer electronics. This is referred to as galvanic isolation and prevents things like ground loops from hampering the measurement.

Now one might ask, well if this sensor has all these great features, why not use it all the time? The first reason is that the inductive properties of the sensor make it viable for measurements of higher conductivity values. This ranges from approximately 100 $\mu\text{S}/\text{cm}$ up to approximately



Figure 5. Typical inductive conductivity sensor

2000 mS/cm. Anything under 100 $\mu\text{S}/\text{cm}$, and the readings are somewhat noisy due to the inherent electronic effects of the coils. The second reason is cost. These sensors can be two to three times the cost of more traditional contacting style conductivity sensors.

However when it comes to materials that would tend to coat, foul or attack standard contacting style conductivity sensors, the inductive sensor has clear advantages.

TDS (total dissolved solids)

When salt crystals (solids) added to water, the salt crystals dissolve in water adding more ions and solids that is now considered dissolved. TDS (total dissolved solids) is a test method for water quality³. In general there are two kinds of solids, water soluble and water insoluble. The soluble solids are further categorized by strong ionizing, moderate ionizing and weak ionizing solids. Strong ionizing salt solids such as sodium chloride, carbonates of magnesium, and calcium, and other soluble solids also represent hardness of water. Since these salts are ionizing, they will add to the conductivity of water. In the water world, this increase of ionic activity can be measured by conductivity. The conductivity is proportional to the dissolved solids present in the water. Table 1 below explains the relationship between TDS and conductivity in context of water hardness.

One of the most well-known applications of conductivity measurement is in the reverse osmosis (R.O.) process of water treatment. In this process the ions are removed from water. Permeate will have very low conductivity as compared to the feed water. The conductivity measurement provides a much needed performance evaluation of the RO systems.

Conductivity $\mu\text{S}/\text{CM}$	Temp. C	TDS mg/L	Degree of water hardness
150	4-7	70	Very soft
300	7-15	150	Soft
400	15-25	240	Mild hard
550	15-25	290-300	Moderate Hard
740	32-45	380	Hard water
800 and higher	45	450 and higher	Very hard water

Table 1. Conductivity and TDS Correlation

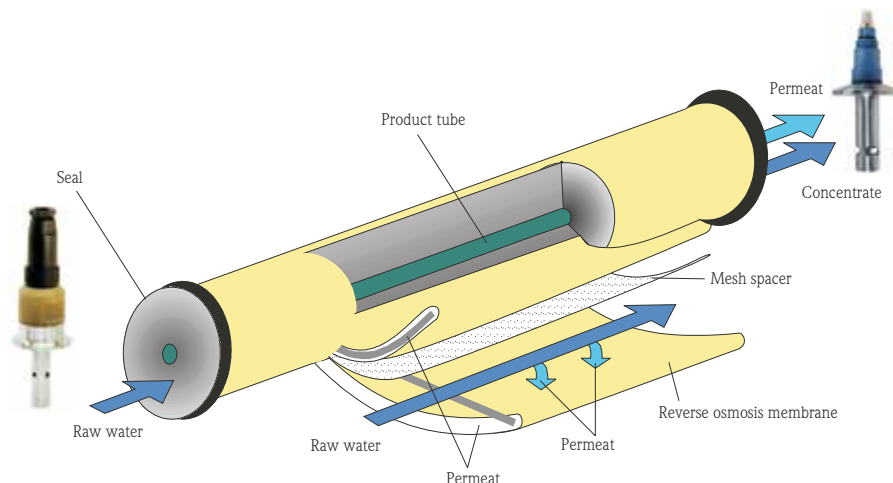


Figure 6. Reverse Osmosis membrane

Temperature considerations

In order to obtain accurate conductivity measurements, accurate determination of temperatures must also be done. Since temperature coefficients of common solutions vary from 1 to 3 percent, the conductivity measurement system should include automatic temperature compensation to adjust conductivity readings to a 25° C reference.⁴ As presented in Table 1, conductivity must be reported along with the temperature of the fluid. The temperature effect is almost like a volume expansion of gas as temperature increases at a constant pressure. The volume is also reported with the temperature. In similar fashion, conductance increases in many cases, however it will decrease if the temperature is making the water loss. As the temperature increases, the ionic activity increases. As a result, the same number of ions will move around faster. Due to this increased movement, the conductivity increases with temperature. For these reasons the concept of a reference temperature allows us to compare conductivities of different products. Generally, the reference temperature is 25° C or 20° C, and solutions change in a linear fashion from approximately 1.5 to 7% per degree C. The conductivity analyzer measures the temperature and the conductivity, then converts the reading to a reference temperature using a temperature correction factor stored in the analyzer. When selected, this reference temperature is processed by the analyzer, and correctly displays the conductivity value on the analyzers display. Temperature correction can be linear, non linear or no correction. To make accurate readings it is imperative to have a temperature reading at the same time the conductivity is measured.

The temperature effect on conductivities of water soluble chemicals such as acid, alkalis, and salts differs greatly from one compound to another. To overcome this, the temperature correction is used in conjunction with alpha (α), which is the known temperature coefficient of the solution. To calculate the temperature coefficient α , measure the conductivity of a solution at different ranges of temperature. The temperature and conductivity is then plotted on a graph. The slope value of this change in conductivity is divided by the conductivity at a reference temperature.

Application guide – which sensor style to use when

Conductivity measurements are widely used in F&B, steam, water treatment, chemical processing, refineries, electroplating and surface finishing, biodiesel, and in the ethanol industry. The specific applications are related to concentrations of chemicals, CIP operations, purity of water, phase separations, beer identifications and quality control. The list is long.

As discussed earlier, there are two types of conductivity cells, direct contact and inductive or toroidal. For successful and accurate conductivity measurement, it is important to know what technology to apply for different situations. Figure 3 gives us some general ideas about applications. In general, the measurement range, the solution or the process liquid, temperature, pressure and flow velocity are key factors in determining the appropriate sensor. Since each application is unique in its own way, generalizing based on some commonality may not be appropriate for accurate readings.

As a rule of thumb, higher conductivity solutions ranging from 100 to 2000 mS/cm would require the inductive technology. One can think of it this way: Clear liquids (other than strong acids and bases) should be able to be measured with contacting style sensors. For all other liquids, use the inductive sensors. This is just a general rule however. Liquids with medium to low conductivities can also be measured with the inductive method. The characteristics of the inductive sensor are such that the process fluid is not in direct contact with the measuring part of the sensor. It is insulated with PTFE, PVDF or PEEK. Therefore, use of inductive sensors with corrosive material is very well established.

For applications in potable water, wastewater, and WFI (water for injection), contacting conductivity sensors are used more frequently than inductive sensors due to the relatively low range of conductivity. In PCP (personal care products) specially designed contacting conductivity sensors can be used to measure ACH (aluminum chlorohydrate), sodium fluoride (NaF) or salt in paste type semi solid materials.

Calibration - inductive style sensors

The inductive sensor has fixed operating materials (as previously discussed) therefore periodic calibration should not be necessary. However calibration checks may be performed if desired to make sure the electronics have not changed or drifted, or that materials have plugged the center hole of the sensor causing a change in the readings. This single point calibration can be accomplished two ways, either electronically by means of fixed resistors or via the use of calibration solutions or grab samples.

Using a fixed resistor:

Determine the value you want the analyzer to display. For instance, if the unit is ranged 0-5000 $\mu\text{S}/\text{cm}$, and you want to verify 2500, the formula is as follows:

$$\frac{1,000,000 \times \text{cell constant}}{\text{value needed}}$$

For a cell constant of 15 and a conductivity value needed of 2,500 $\mu\text{S}/\text{cm}$ substituting these numbers into the formula:

$$\frac{1,000,000 \times 15}{2,500} = 6,000 \text{ ohms}$$

Obtain a 6,000 ohm resistor and connect it with a loop of wire such that the resistor goes through the center hole of the sensor.



With the resistor connected, one should see the instrument display the correct value. If we now want to see half the reading shown, it is a simple matter of doubling the resistance. 1250 $\mu\text{S}/\text{cm}$ = 12,000 ohms.

Calibration – for both contacting and inductive style sensors

Single point wet calibrations can be performed on either contacting or inductive conductivity sensors. The use of a calibration standard such as a 1000 $\mu\text{S}/\text{cm}$ solution or performing a grab sample calibration are the two most common approaches. For a solution calibration, consult your manufacturer's information on either purchasing a calibration solution or making one yourself, as often times there is a recipe included with the documentation on how to manufacture a solution using common chemicals and pure water. For this calibration, one mixes up the solution or purchases the stock solution, immerses the sensor into the solution and waits for the sensor to come to equilibrium with respect to the conductivity value and the temperature. When the readings have stabilized, perform the single point calibration according to the manufacturer's instructions.

For the grab sample calibration, this is done by taking a sample of the process flowing past the sensor, analyzing it and then adjusting the sensor/analyzer to equal the sample taken. This must be done fast and accurately in order to obtain overall accurate readings. Many things come into play when this type of calibration is performed. Time may change the reading as well as changes in temperature which are not accounted for. If these two factors are not controlled or understood, the calibration will be inaccurate.

Installation tips

Sensors of both styles, inductive and contacting, are usually mounted in a flowing stream within a pipeline, in a trough, or in an open or sealed tank of some sort. Not only is it important to select the proper sensor, it is equally important to select the proper installation and orientation of the carefully selected sensor. Improper installation will lead to erroneous readings, which in many cases create a perception that the sensor is not working properly, or that it is not reliable, etc. To avoid some of these frustrations, a few of these installation precautions are presented here.

1. The sensor must be fully immersed in the liquid. This is best fulfilled by mounting the sensor at the bottom of a tank or in upstream applications.
2. Install the sensor at least 3 to 5 ft. away from the discharge site of the pump to minimize any pulsation effects which may alter the readings when using inductive conductivity sensors.
3. If the sensor is installed on the discharge side, insure the drain pipe is full at all times during the measurement.

4. Sometimes this requirement is in conflict with the self-draining requirement in pharmaceutical installations. Therefore, careful considerations need to be made.
5. Since temperature is very important in the measurement of conductivity, when measuring hot or cold fluids, make sure the sensor is not exposed to ambient temperatures as an error will result. Make sure the sensor is at the same temperature as the process to be measured.

Figure 7 presents the typical installation diagrams.

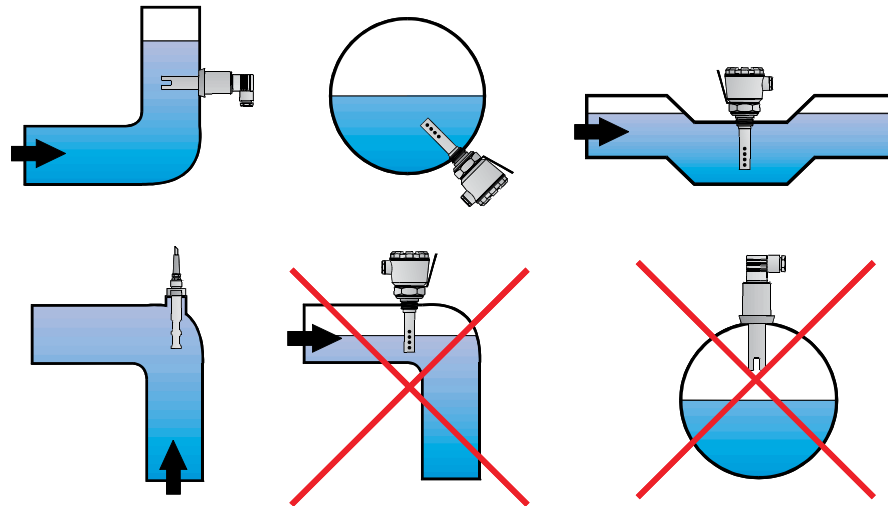


Figure 7. Typical installations

Care and maintenance of conductivity sensors

Maintenance requirements of the contacting style and inductive style conductivity sensors are somewhat different. However common themes to both sensors are: Inspect interconnect cables and junction boxes for damage. Frayed ends, cuts or nicks in the cable or moisture on the terminal strips of the junction box or analyzer are detrimental to the measurement, or at least may affect the accuracy of the measurement. Keep cable lengths to a minimum, especially on contacting style sensors. Consult the manufacturers' instructions for maximum lengths, usually defined based on the range being measured.

Analyzers have their own maintenance considerations, the most important of which (see analyzer manuals for more details) is keeping condensation out of the instrument.

Typically, inductive style sensors need little to no maintenance. A quarterly inspection of the sensor and cable and the periodic wipe-down of the sensor may be all that is required. As long as solution flows around and through the center of the cell, a measurement is possible. Debris caught in the center hole may plug the flow of solution, thereby hampering the reading.

For contacting style sensors, the sensor itself is fixed in space. That is to say that the electrodes are fixed in size and in distance from each other such that nothing changes. Given clean fluids to measure and no physical harm coming to the sensor, it could last forever. However, should the geometry of the sensor change due to it being dropped or coming into contact with abrading fluid, the geometry of the sensor changes and then so too does the (k) factor. As an example, when scale forms on the electrode it is a sure indication that scale is also forming elsewhere in the system, for instance in a boiler, and advice on the boiler water treatment should be obtained without delay. The sensor may be easily cleaned, but the boiler on the other hand, is a completely different situation.

Recommendations:

- Remove the probe once a quarter and clean it with tap water; if scale is observed use diluted cleaning agents
- Clean the end of the electrode with fine emery cloth for contacting conductivity sensors
- Clean the PTFE probe tip and sleeving with a cloth or a soft bristle brush
- Ensure that the probe tip is flush with the end of the electrode before refitting the probe

In general, clean the sensors as follows:

For oily and greasy films, clean with detergent (grease solvers, such as alcohol or acetone). Dawn® dishwashing liquid is another alternative.

Warning!

When using the following cleaning agents, make sure to protect your hands, eyes and clothing. Consult a chemist or plant safety personnel to be sure you are using the proper chemicals for cleaning and not generating a hazardous chemical reaction – either from the cleaning solutions or in combination with the chemicals left on the sensor (process chemicals) and the cleaning chemicals.

For lime and metal hydroxide deposits, dissolve layers using dilute hydrochloric acid (3%) and then rinse carefully with a large volume of tap water.

For deposits containing sulphide (from flue gas desulphurizing or sewage treatment plants) use a mixture of dilute hydrochloric acid (3%) and thiocarbamide (usual commercial grade) and then rinse carefully with a large volume of tap water. For deposits containing proteins (food industry) use a mixture of dilute hydrochloric acid (0.5%) and pepsin (usual commercial grade) and then rinse carefully with a large volume of tap water.

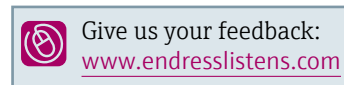
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Endress+Hauser, Inc.
2350 Endress Place
Greenwood, IN 46143
Tel: 317-535-7138
888-ENDRESS (888-363-7377)
Fax: 317-535-8498
info@us.endress.com
www.us.endress.com

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