

## Investigation of electrical conductivity of different water liquids and electrolyte solutions

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### Abstract

In this study one of the most important physical parameters identifying conductance of liquid solutions is investigated. Electrical conductivities of pure, distilled, municipal, industrial and river water liquids along with those of different electrolyte solutions are computed at room temperature (25 °C). Obtained results for ultra pure, pure distilled, municipal, industrial, well and river water liquids with different impurities are compared at such a given temperature. A similar study is performed for different electrolytes and related results. In addition electrical conductivity of water liquid is compared with that of a typical NaCl electrolyte solution and interesting results for differences in conductance values are discussed.

**PACs:** 61.20.Gy; 61.20.Ne; 61.20.Qg; 72.15.Cz; 72.15.Eb

**Keywords:** Water, conductivity, impurity, electrolyte

### 1. Introduction

Water is one of the most important matters in the nature and widely used for different purposes in a variety of applications. One goal has been to find different procedures to obtain high quality ultra pure water liquids for medical or other sensitive applications. Some researches have focused on the procedures and mechanism in order to refine the water by ionization, distillation, or other processes in order to obtain ultra pure water liquid. A variety of methods has been developed to measure and test the refined products in order to specify the purity of the produced refined water. For example the electrical conductivity of the solution has been one of the important physical quantities in this respect and many probes and devices such as conductive sensors have been devised [1-3]. Such probes are used to measure conductivity or conductance of solutions at the given concentration and temperature. For many applications water solution is grouped into ultra pure, pure, and regular water depending on the percentage of impurities [4-7].

Water substance can be in form of vapor, liquid, or solid phase. Pure water is a clear, colorless, and odorless liquid that is chemically made up one oxygen and two hydrogen atoms. This powerful substance is a good medium for many reactions, which is used as a universal solvent. Physical and chemical properties of water results from strong attraction that hydrogen atoms have for each other in water molecules. Al-

though pure water is a poor conductor of electricity, but natural impurities found in water can transform it into a relatively good conductor. Salts and other contaminants in water can dissociate into components called ions. In most cases, ions in water are considered as impurities especially when referring to pure water, while in other aqueous solutions such as hydrochloric acid or sodium hydroxide, the ions define the actual chemical deposition.

### 2. Theory of Electrical Conductance

Generally water molecules are in continuous motion, even at low temperatures and when two water molecules collide, a hydrogen ion is transferred from one molecule to the other. The other molecule that loses the hydrogen ion becomes negatively charged hydroxide ion. The molecule that gains the hydrogen ion becomes a positively charged hydrogen ion and this process is commonly called the self-ionization of water. In fact at room temperature (25 °C), each concentration of hydrogen ions and hydroxide ions is only of the order of  $1 \times 10^{-7} \text{M}$ , and as a result this dissociation allows a minute electrical current to flow. The current flow is in the range of conductivity of 0.05  $\mu\text{S}/\text{cm}$  at room temperature. It is important to note that the amount of  $(\text{H}^+)$  and  $(\text{OH}^-)$  ions are approximately equal and this solution is described as a neutral solution.

In other aqueous solutions, the relative concentrations of these ions are unequal and one ion is increased by one order of magnitude while the other one shows some decrease, but the relationship is constant and the ion product is always constant given by  $K_w$ ,

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which is called the ion-product constant for water. Electrical conductivity of solutions has been studied for several reasons such as studying the process of salvation, association and transparent properties of ions in different solvent media. Such processes depend on the charge, radius, and hydrate numbers of ions and the nature of solvent. Electrolytic conductivity is a measure of ability of a solution to conduct an electric current and is defined by the specific conductance or term conductivity. Conductivity is the inverse of electrical resistivity, which defined as the measure of the ability of a solution to resist an electric current flow.

Water is a polar solvent with an uneven distribution of electron, and the application of electric field causes one portion of the molecule to be somewhat positive and another part negative (polarization effect). In an external DC electric field, the dissolved electrolyte substances are free to move and positive charged particles move towards negative electrode while negative charged particles migrate toward the positive electrode. The migration of the charged particles causes the electric current flow in liquid. Such DC polarization can be eliminated by using AC voltage at 60 Hz or higher frequencies and in practice by increasing the cross sectional area of the electrodes.

The mechanism of electrical conduction through a liquid is different in comparison with a solid. In solid, when a potential is applied to a solid conductor, the flow of current is instantaneous, and is virtually proportional to the applied potential. In addition, different types of materials conduct electrical charges with different efficiencies. In metals, there are free electrons, which are available for conduction even at a very low temperature. One major difference of a metal with semiconductor and isolator materials is that metal resistance increases as the metal heated because of the decrease in electron mobility. Conversely, the resistance of semiconductors and insulators decreases with increasing temperature because the number of charge carries increases. Therefore, in semiconductor and in particular in insulators, more activation energy is needed to excite electrons to be available to conduct a charge.

The conductivity of a solution relates to the total dissolved solid (TDS) and amount of the suspended solids (SS) or insoluble solid in a water sample. Total dissolved solid includes solid particulates such as ions, inorganic substances, salts, and metals. Total solid (TS) is defined as the sum of TDS and SS. In laboratory analysis measurement of these parameters are made by filtering and weighing to determine SS, then drying and weighing to determine TDS. In analysis of water the conductivity measurements are classified for the Ultra-pure, high-purity and pure water samples, which show accordingly an increase in the conductivity value (0.053 to 10  $\mu\text{S}/\text{cm}$ ). There are some look up tables that can be used to convert between conductivity, resistivity and TDS in pure and

ultra-pure water.

The electrical conductivity of a conductor is given by the relation

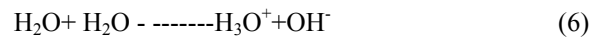
$$\kappa = nqu, \quad (1)$$

where  $n$  is the density of charge carrier,  $q$  is the species charge, and  $\mu$  is the charge particle mobility defined by the ratio of the applied electric field to the charge carrier velocity. The electrical conductivity of a semiconductor crystal is given by

$$\kappa = (ne\mu_e + pe\mu_h), \quad (2)$$

where  $n$  and  $p$  are the concentration of electrons and holes, respectively.  $\mu$  as defined is the mobility for the electron and hole, accordingly.

For pure water ionization the possible colliding reaction is



and the  $K$  factor is defined by the ratio of species concentrations

$$K = \frac{[\text{H}_3\text{O}^+][\text{OH}^-]}{[\text{H}_2\text{O}][\text{H}_2\text{O}]}, \quad (7)$$

where one can write

$$K[\text{H}_2\text{O}]^2 = [\text{H}_3\text{O}^+][\text{OH}^-], \quad (8)$$

and the term in the left hand side of Eq.(8) is always constant defined by  $K_w$ .

$$K_w = [\text{H}_3\text{O}^+][\text{OH}^-], \quad (9)$$

which is in most practical cases a constant. The conductance of electricity is a usual way to measure the mobility of ions and conductivity meters are used for this purpose. Conductivity is measured in unit of (S/m) and the molar conductivity is a common expression for solutions, which is the conductivity per unit of concentration ( $\text{Sm}^2/\text{mol}$ ). Conductivity meters measure and display conductivity or resistivity of a sample solution at a given temperature. By using a standard solution (KCl) the constant  $K$  (S/cm) for a given cell probe is obtained.

By using the equality of the electric force and the friction force on ions for finding the velocity of ions for the electrolyte a general formula for the conductivity is given by [8,9]

$$\kappa = \frac{e^2 N_A}{6\pi\rho} \sum_i \frac{(Z_i C_i)}{r_i}, \quad (10)$$

where  $C_i$  is the fractional concentration. Here  $e$  is the electric charge,  $r$  is the ionic radius,  $N_a$  is the Avoga-

dro number,  $Z$  number of involved ions and  $\rho$  is the ion viscosity. The electrical conductivity of water electrolyte in concentration equilibrium condition can be obtained by the multiplication of the  $K_w$  and the possibility factor for the ion generation in the ion migration process:

$$\kappa = K_w \exp\left(-\frac{\Delta G}{RT}\right), \quad (11)$$

which can be written as

$$\kappa = \frac{e^2 N_A}{6\pi\rho} \sum_i \frac{Z_i}{r_i} \exp\left(-\frac{\Delta H}{2RT}\right) \exp\left(\frac{\Delta S}{2R}\right), \quad (12)$$

where the equality of

$$\Delta G = \Delta H - T\Delta s, \quad (13)$$

is plugged into Eq. 11 for  $G$ , which defines the Gibbs free energy (kJ/mol). Here  $H$  is the enthalpy,  $s$  entropy,  $T$  temperature, and  $R$  the universal gas constant. For computations the radius used in Eq. 12 is not only the radius of the ion but also shows the dimension of the ion itself plus the effective radius of the polar solvent that surrounds that particular ion. Such an effective radius is called hydrodynamic radius of ions. By using the hydrodynamic radius of ions in (12) the conductivity becomes:

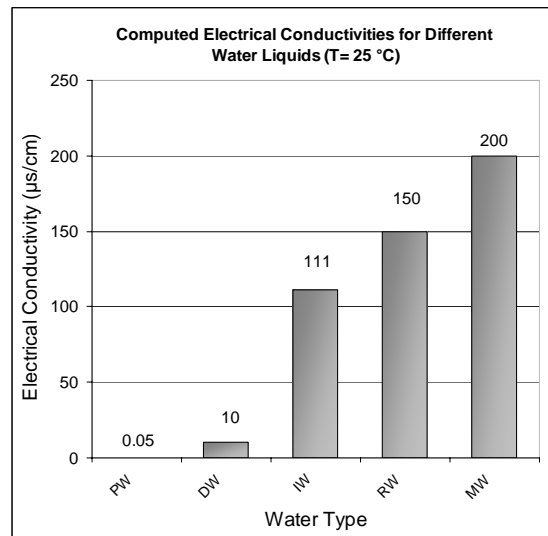
$$\kappa = \frac{e^2 N_A}{6\pi\rho} \left(1/r_{H_3O^+} + 1/r_{OH^-}\right) \exp\left(-\frac{\Delta H}{2RT}\right) \exp\left(\frac{\Delta S}{2R}\right), \quad (14)$$

### 3. Computation Results

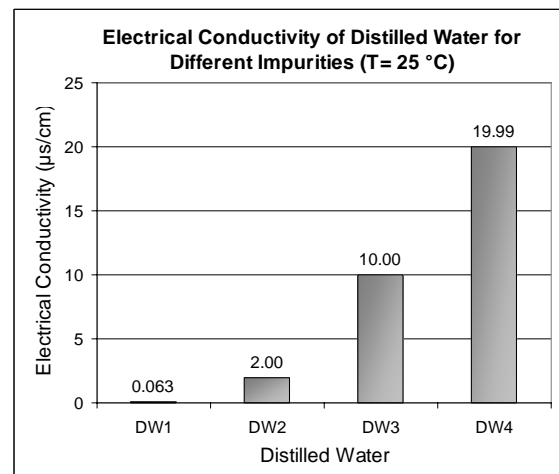
Based on the developed theoretical formulation different programs written in visual basics are executed in macro option of the Excel program. The written program code is user friendly and can be run easily on a PC using the usual Microsoft window operating system compatible with the office program. Based on the developed algorithms different programs are written that easily outputs the conductance values according to the given input parameters. Four different water samples are considered for the first study and the computed results for the electrical conductance are reported. The input parameters for water samples in written programs are the impurity; total dissolved solid, density, viscosity and the temperature. For electrolytes in the written programs the input values are the concentration and the temperature values.

Fig. 1 shows the computed results for different water liquids including the pure, distilled, municipal, industrial, rivers and well waters. Samples indicated as PW (Pure Water), DW (Distilled Water, 5 ppm), IW (Industrial Water, 100 ppm), RW (River Water, 100 ppm) and MW (Municipal water, 100 ppm). As can be seen the electrical conductance ranging from a low

value of 0.0539  $\mu\text{S}/\text{cm}$  (pure water) to 200.0  $\mu\text{S}/\text{cm}$  for the municipal water resource. The value of the electrical conductance is given for the room temperature of 25° C for all samples.



**Fig. 1. Computed electrical conductivities for different water liquids. Samples indicated as PW (Pure Water), DW (Distilled Water, 5 ppm), IW (Industrial Water, 100 ppm), RW (River Water, 100 ppm) and MW (Municipal Water, 100 ppm).**



**Fig. 2. Variation of electrical conductivity of distilled water as a function of impurity. Impurities for samples are DW1 = 0.03, DW2 = 1, DW3 = 5 and DW4 = 10 ppm.**

In the next study variations of electrical conductivity in respect to the impurity concentration for the distilled water are investigated. Fig. 2. shows the variation of electrical conductivity of distilled water as a function of impurity. Impurity concentration is varied from 0.03 ppm to 10 ppm for the distilled water. Samples indicated as DW1 = 0.03 ppm, DW2 = 1 ppm, DW3 = 5 ppm and DW4 = 10 ppm are considered for this computation. As can be seen the electrical conductivity ranging from a low value of 0.0639  $\mu\text{S}/\text{cm}$  (DW1) to 19.99  $\mu\text{S}/\text{cm}$  for the high impurity 10 ppm

municipal water resources(DW4). The values of the electrical conductivities are given for the room temperature of 25° C for all samples. As can be seen in Fig. 2, electrical conductivity shows increase by increasing the amount of the foreign impurity at the given temperature.

In Fig.3 variation of electrical conductivity of municipal water as a function of impurity is shown. Here typical concentration is increased from 100 ppm to 500 ppm for the municipal water samples. As can be seen in Fig. 3, electrical conductivity indicated by numbers 1, 2, 3, 4 and 5 for different samples. As shown in Fig.3, electrical conductivity shows an increase by increasing the amount of the foreign impurity. For example for the same room temperature of (25 °C), the electrical conductivity for 100 ppm is about 200  $\mu$ S/cm while it is increased to about 1000  $\mu$ S/cm for the impurity concentration of 500 ppm.

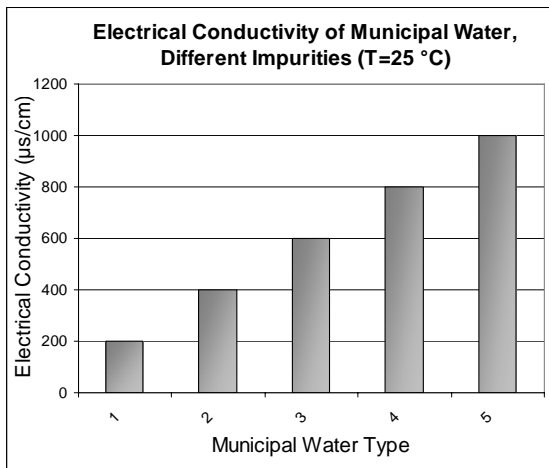


Fig. 3. Variation of electrical conductivity of municipal water as a function of impurity. Five samples indicated by numbers 1,2,3,4, and 5 show impurities of 100, 200, 300, 400, and 500 ppm, respectively.

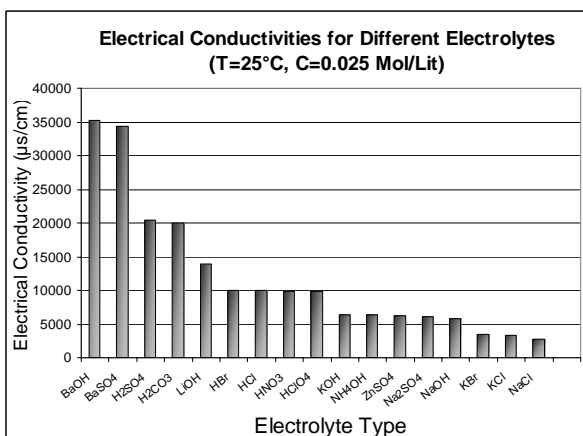


Fig. 4. Computed electrical conductivities for different electrolyte solutions.

In the second study electrical conductivity for seventeen different electrolyte solutions are computed and the results are discussed here. Results for the elec-

trical conductance at room temperature (25 °C, typical concentration of 0.025 Mol/Lit) are presented in Fig. 4. As can be seen the electrical conductivity ranging from a low value of 2807.57  $\mu$ S/cm (for NaCl) to the highest value of 35227.12  $\mu$ S/cm for the BaOH solution. All the values of the electrical conductivity are given for the room temperature and a molar concentration of 0.025 Mol/Lit.

Fig. 5 shows the variation of electrical conductivity of H<sub>2</sub>SO<sub>4</sub> electrolyte as a function of molar concentration (Mol./Lit). In this study concentration is increased from 0.025 Mol/Lit to 1 Mol/Lit for the H<sub>2</sub>SO<sub>4</sub> electrolyte sample. As can be seen in Fig. 5, electrical conductivity shows an increase by increasing the amount of the electrolyte concentration. For example for the same room temperature of (25 °C), the electrical conductivity for 0.025 Mol/Lit is about 20464.24  $\mu$ S/cm, for 0.5 Mol/Lit is about 338747.68  $\mu$ S/cm while it is increased to about 602230.85  $\mu$ S/cm for the electrolyte concentration of 1 Mol/Lit.

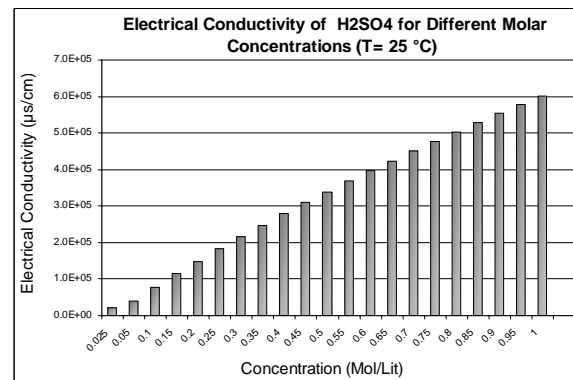


Fig. 5. Variation of electrical conductivity of H<sub>2</sub>SO<sub>4</sub> as a function of molar concentration.

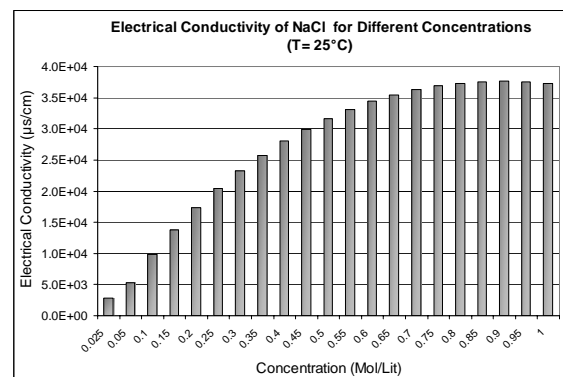


Fig. 6. Variation of electrical conductivity of NaCl as a function of molar concentration.

In Fig. 6 variation of electrical conductivity of NaCl electrolyte as a function of molar concentration (Mol./Lit) is presented. In this study concentration is increased from 0.025 Mol/Lit to 1 Mol/Lit for NaCl electrolyte. Similar to the previous case electrolyte concentration is varied and as can be seen in Fig. 6, electrical conductivity shows a notable increase by increasing the concentration of the electrolyte. For

example, at the same room temperature of (25 °C), the electrical conductivity for 0.025 Mol/Lit is about 2807.57  $\mu\text{S}/\text{cm}$ , for 0.5 Mol/Lit is about 31677.92  $\mu\text{S}/\text{cm}$  while it is increased to about 37242.09  $\mu\text{S}/\text{cm}$  for the electrolyte concentration of 1 Mol/Lit. Comparing the results for the NaCl and that of  $\text{H}_2\text{SO}_4$  electrolyte it is noted that at the same temperature and concentration,  $\text{H}_2\text{SO}_4$  electrolyte has a much higher electrical conductance.

In Fig. 7 comparison of the electrical conductivity of water liquid (distilled and municipal) and a typical electrolyte solution (NaCl, 0.025 Mol/Lit) is given at room temperature (25 °C). As can be seen the NaCl electrolyte solution has a conductance value of 2807.57  $\mu\text{S}/\text{cm}$  much higher than that of typical distilled water (19.99  $\mu\text{S}/\text{cm}$  at 10 ppm) and municipal water (1000  $\mu\text{S}/\text{cm}$  at 500 ppm).

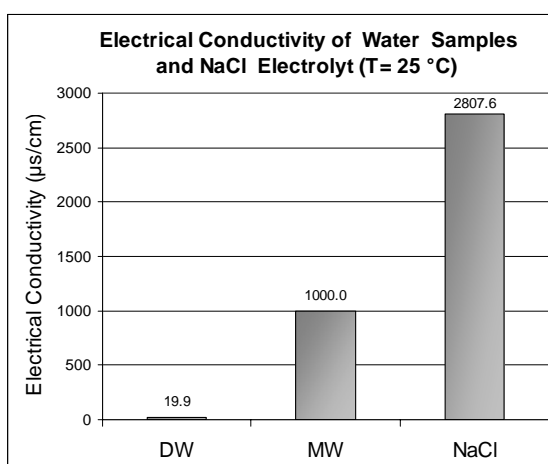


Fig. 7. Comparison of the electrical conductivity of water and NaCl electrolyte (0.025 Mol/Lit) at room temperature (25 °C). Distilled water with 10 ppm and municipal water with 500 ppm impurities considered.

The physical reason for such a high conductance value can be described as following. In ionic compound, entire ion may diffuse to conduct electricity, though these ions may have very low mobility. Applying a potential to a liquid conductor causes current to flow through solution by dissolved particles (ions) that have electrical charges. Usually dissolved ions move slower than electrons, depending on their geometry, potential, and the temperature of solution. Generally smaller ions move through a solution more rapidly than larger ones. As discussed, in water the hydrogen ion ( $\text{H}^+$ ) and the hydroxyl ion ( $\text{OH}^-$ ) are extremely mobile due to their geometry and size of ions relative to each other in comparison with the  $\text{Na}^+$  and  $\text{Cl}^-$  ions in NaCl aqueous solutions. As a result, NaCl shows a much higher conductance value in comparison with that of water liquid. Same argument about higher value of electrical conductivity in comparison with the water liquid can be given for other electrolytes.

As described there is a relationship between the conductivity and concentration of electrolytes. Differ-

ent solutions with different conductivities do not always show a direct relationship proportional to concentration of salts or solids in solution. In dilute solutions, an increase in concentration causes a linear increase in conductivity provided that there are no interactions between the solution and the dissolved electrolyte. When these conditions are met, the dissolved electrolyte is said to be completely dissociated. An example is sodium chloride. Thus, investigating concentration versus conductivity provides an important physical property of solution. As shown in Fig. 5, sulfuric acid ( $\text{H}_2\text{SO}_4$ ) can be completely dissociated and its conductivity is directly proportional to its concentration. For this solution the  $\text{H}_2\text{SO}_4$  dissociates to form ( $\text{H}^+$ ) and ( $\text{HSO}_4^-$ ) ions and for the given low concentration as shown in Fig. 5, a gradual increase of electrical conductivity with the concentration is noticed. As can be seen in Fig. 6, a similar pattern is noticed for the NaCl electrolyte.

#### 4. Conclusions

A theoretical model for computation of electrical conductivity of water and electrolytes are reported in this study. Based on the developed algorithms different programs are written that easily outputs the conductivity values according to the given input parameters. The written programs offer potentials for variation study of such a quantity as a function of different parameters. Parameters such as substance temperature and impurity play important roles in the determination of the electrical conductivity and results for the concentration variation for given substances are given in this study.

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