**Hebron University**

**Faculty of Graduate Studies**

**Chemistry Department**

# Effect of Temperature and Salt Addition on the Conductivity of Sodium (polystyrene sulfonate) Aqueous Solutions

**By:**

**Saida Fawzy Asfour**

**Supervisor:**

**Dr. Ahmed Ayyad**

**Co-supervisor:**

**Dr. Fahed Takrori**

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## Committee Decision

**We, the undersigned, approve the Master's Thesis of Saida Fawzy Asfour.**

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**This thesis was successfully defended on May, 2022 and approved by:**

| **Committee Members:** | | **Signature** |
|---|---|---|
| Supervisor | Dr. Ahmad Ayyad | د.احمد عياد<br>………………… |
| Co-supervisor | Dr. Fahed Takrori | ………………… |
| Internal Examiner | Dr. Mahmoud Deheidel | ………………… |
| External Examiner | Dr. Rasha Ghunaim | …Rasha… |

# Contents

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## Dedicate

Dedicated to the soul of my dear father Fawzy, may God have mercy on him, and make this humble research in the balance of his good deeds, to my dear mother, may God give her long life, and to my dear husband Mousa, companion of the path and life partner and to my lovely children Baraa Mai and Qassam, may God bless them all.

# Abstract

In this work I have studied the conductivity of sodium (polystyrene sulfonate) (NaPSS) aqueous solutions as a function of NaPSS concentration in the range 0.15 g – 2.0 g NaPSS in 100 ml of distilled water and in sodium chloride solutions at concentrations in the range of 0.1 M - 0.4 M and temperature in the range of 278 K – 328 K. The conductivity is found to increases with increasing NaPSS concentration both in pure water and in salt solutions. It is also found that the conductivity increases with increasing either NaCl concentration or temperature. The interesting findings here is the additivity rule: that the conductivity of the polyelectrolyte ($k_{ps}$) in the salt solution is the sum of its conductivity ($k_p$) in pure water plus the conductivity of the salt ($k_s$) holds only at low NaPSS concentration and deviates at higher NaPSS concentrations. This additivity rule holds better the higher the temperature and the higher the salt concentration. What is more interesting is that the contribution of NaPSS to the conductivity of the solution is more in pure water than in salt solution and that its contribution is higher the lower the NaCl concentration in salt solutions. This latter behaviour is only found at high NaPSS concentration while it is inverted at low NaPSS concentration. These findings will certainly contribute to a better understanding of the complex behaviour of the conductivity of polyelectrolytes in aqueous solutions.

## نبذه مختصره

تم في هذا البحث دراسة الموصليه الكهربائية للمحاليل المائية للمركب الالكترولايتي المسمى متعدد ستايرين سلفونات الصوديوم (NaPSS), عند تراكيز ودرجات حرارة مختلفة اضافة الى اجراء ذات القياسات بوجود تراكيز مختلفة من كلوريد الصوديوم, وقد وجد ان هناك زيادة في قيم الموصلية الكهربائية مع زيادة تركيز مركب NaPSS سواء المحاليل التي احتوت على المركب الالكترولايتي لوحده او بوجد ملح كلوريد الصوديوم, كما ان هذه الموصلية شهدت زيادة في قيمها مع رفع درجات الحرارة وهو امر مرتبط بزيادة حركة الايونات نتيجة لهذه الزيادة اضافة الى انخفاض لزوجة المحاليل مما يعزز حركة هذه الجزيئات, لكن اللافت في هذه النتائج ان مقدار الزيادة في هذه الموصلية لم يكن مقدارا جمعيا لكلا المركبين عند كافة التراكيز تم دراستها, فعند التراكيز المنخفضة لمركب NaPSS كانت خاصية الإضافة (additivity rule) صالحة لكن حدث انحراف واضح في هذه الخاصية مع الزيادة المضطردة في تراكيز NaPSS, اما في الحالات التي تم فيها زيادة درجات الحرارة او تركيز ملح كلوريد الصوديوم فإن خاصية الإضافة كانت اكثر صلاحية وانطباقا, اما النتائج الاكثر لفتا للانتباه فهي ان اجراء عملية طرح لقيم مساهمة الملح للموصلية تبين ان موصلية ايونات NaPSS لها موصلية اعلى في حال وجودها في الماء النقي مقارنة مع وجودها في المحاليل الملحية وان هذه المساهمة تكون اعلى عند تراكيز منخفضة من الملح وعالية NaPSS, ويمكن ان يتم تفسير هذا السلوك بقيام ايونات الملح المضافة عند التركيز العالية بإعاقة حركة جزيئات NaPSS وبالتالي التقليل من الموصلية الكهربائية الناتجة عنها.

# Chapter 1

## 1.1. Introduction

### 1.1.1. Polyelectrolytes

Polyelectrolytes are polymers have repeating units that are dissociating groups. They are either polycation, polyanions and polysalts [1-2]. They dissociated in aqueous solutions, when the solvent is water just like ordinary electrolytes (acids, bases and salts), and carry one or more charges depending on the pH value. As polyelectrolytes carry dual properties that are similar to both electrolytes and polymers they are called polyelectrolytes [3]. Poly-salts are the products of a monomeric base with polyacids (polyanions) and vice versa. In solution, they are electrically conducting like regular salts and their viscosity, like polymers, depends strongly on their polymer concentration and molecular weight [4].

Carboxylate ($–COO^-$), phosphonate ($–PO_3H^-$, $–PO_3^{2-}$), and sulfonate ($–SO_3^-$) are the most common anionic groups for anionic polyelectrolytes. For cationic polyelectrolytes; primary, secondary and quaternary ammonium ($–NH_3^+$, $=NH_2^+$ & $≡N^+$) are the common groups that one encounters. The properties of a polyelectrolyte are determined by the structure of its repeating units, the counter ions it carries and its ionic group. These properties include their solubility in polar and hydrogen-bonding solvents, solution viscosity and their transport properties and their conductivity. These properties are also strongly dependent on the type of salt added and the pH of their solution. In this case, they have different properties than their counterpart neutral polymers [5].

Chemical crosslinking of polyelectrolytes molecules is achieved by incorporating a small amount of the right crosslinking agent. Cross-linked polyelectrolytes form three-dimensional structures that when dissolved in water swell rather than dissolving in it [6]. Through hydrogen bond formation with water molecules, they can retain extremely large amounts of liquid relative to their own mass. In this cross-linked form they are so to speak hydrogels or superabsorbent polyelectrolytes. These superabsorbent hydrogels can absorb water up to 500 times their weight and from 30 to 60 times their own volume. Therefore, a hydrogel may contain more than 99%

liquid. The type and amounts of crosslinks in their structure controls their total absorbency and swelling capacity of these superabsorbent materials.

Synthetic and non-synthetic polyelectrolytes are produced and manufactured on large scale. Polygalacturonic acid (pectin), alginic acid or alginates, polypeptides and carboxymethyl cellulose are examples of natural polyelectrolytes. Polystyrene sulfonate, polyallylamine, polyacrylic acid and their salts are examples of synthetic polyelectrolytes. Examples of these polyelectrolytes with their chemical structures are shown in figure 1.

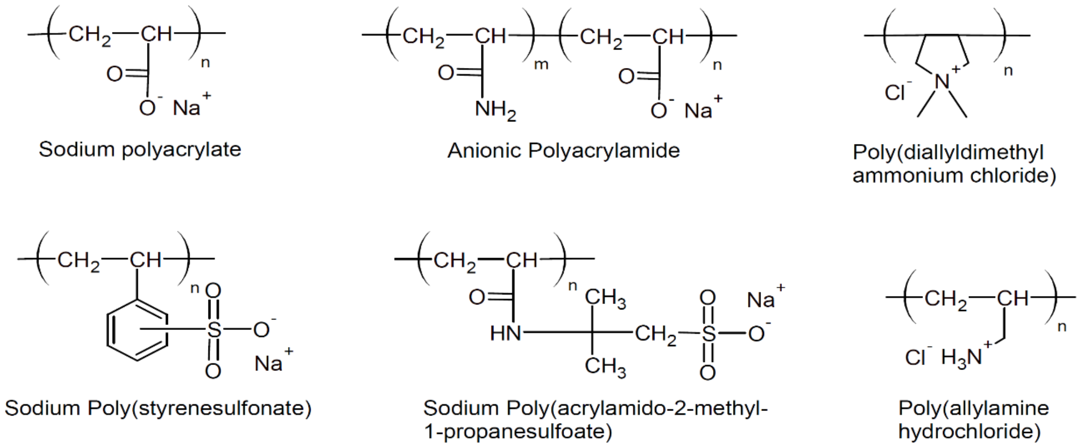
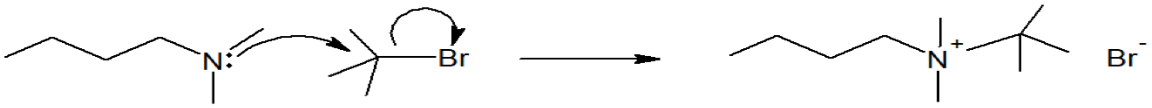
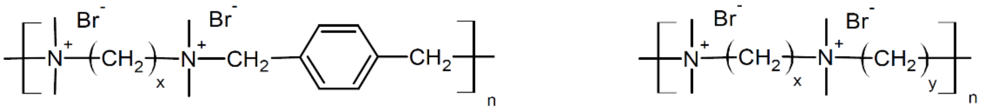


Figure 1. Names and chemical structure of some polyelectrolytes.

Some polyelectrolytes contain ionizable groups in their backbone instead of carrying them as side groups. These kinds of polyelectrolytes are called polyionenes. Quaternary ammonium group is the most common charged group in their backbone. Through Menshutkin reaction of ditertiary amines and alkyl dihalides these ionic polyamines or polyionenes are typically synthesized. This reaction mechanism is shown below:



The commercial availability of a large number of dihalides and ditertiary enables the synthesis of a large number of well-defined polyionenes. These starting materials are cheap and in combination with the simple synthesis route; these special type of polyelectrolytes can be synthesised. Polyelectrolytes with different molecular weights and different charge densities (ionic spacing on the polymer) backbone can be easily synthesis. Furthermore, different functional groups can be incorporated. This allows for tailoring the physical and mechanical properties and crosslinking. Chemical structures of some amine polyelectrolytes are shown in figure 2 below.



Semi-aromatic Ammonium Ionenes

Aliphatic Ammonium Ionenes

Heterocyclic Ammonium Ionenes
(DABCO-based Ionenes)

Alkylether Ammonium Ionenes
X = 4 --> PTMO-based Ionenes

Figure 2. Chemical structure of some amine polyelectrolytes

### 1.1.2. Physicochemical Properties

The properties of polyelectrolytes in a solution is determined by the electrostatic interaction between the charged groups in the chain and the low molecular weight ions in the solution. These charges in the polyelectrolyte generate a strong electrostatic field that has a significant effect on molecule structure. It substantially alters the macromolecular conformations. With increasing dissociation, the effective size of the chains (e.g. hydrodynamic radius, distance from end to end) increases, and the coiled molecules straighten out reaching an almost linear, rod-like shape at high degrees of polyelectrolyte dissociation[59].

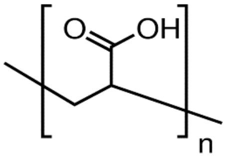
The physicochemical properties are significantly altered with a changing degree of dissociation. For example: the viscosity of the solution will increase by a factor of a hundred or even more depending on polyelectrolyte concentration, degree of dissociation, and free ion (salt) concentration (low molecular weight ions in the solution).[ 59]

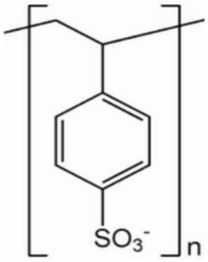
The theory established for solutions of low molecular weight electrolytes is not valid for polyelectrolyte solutions. A diffuse counter-ion cloud around the oppositely charged surface of the polymers is created, by the low molecular weight ions appearing during the dissociation of polar groups of the polyelectrolytes. The composition (solvation) and size of this diffuse counter-ion cloud affects the structure and dynamics of the polyelectrolytes in the solution and also the swelling capacity and the visco-elastic response of polyelectrolyte gels.

There is a considerable effect on the structure, stability and interactions of various (biological) molecular assemblies by the charged molecular chains that are commonly present in systems of soft matter. The theoretical approaches which goal is to describe the statistical properties of these assemblies are totally different from the approaches used to describe their electrically neutral counterparts. Many of existing biological molecules are polyelectrolytes, for example polypeptides and DNA.

### 1.1.3. Commercial Polyelectrolytes

Commercial grade polyelectrolytes (PAA's) can be obtained from Rohm & Haas (Acusol™, Acumer™), BASF (Dispex®, Magnafloc®), Dow Chemical (Duramax, Tamol™, Romax™, Dowex), and Arkema company (Rheoslove™, Terrablend).

| Polyelectrolyte | Structure of Repeat Unit | Trade Name |
|---|---|---|
| Polyacrylic acid (PAA) |  | Acusol (copolymer), Acumer, Acrysol, Alcosperse |

| Polyelectrolyte | Structure of Repeat Unit | Trade Name |
|---|---|---|
| Polystyrene sulfonate |  | Resonium, Sorbisterit, Resikali |

### 1.1.4. Applications

There are many applications of polyelectrolytes. Most are related to flow modification and the improvement of the stability of aqueous colloids and gels, or for inducing agglomeration. For example, they are used for destabilization of colloidal suspensions and for initiating flocculation and precipitation. Another use case is for imparting a surface charge to neutral particles, so that they can be dispersed in aqueous solutions. For that reason, they are often used as dispersant agents, thickeners, emulsifiers, conditioners, ion-exchanger and clarifying agents. For instance: in water treatment [6-7] they are used as flocculation agents [8], in ceramic slurries as stabilizing agents [10] and in concrete mixtures as superplasticizers. Polyelectrolytes can be found in many cosmetic products, shampoos and soaps. Some polyelectrolytes are used in food products, for instance as coatings or release agents [11]. Some examples are alginate (alginic acid), pectin (polygalacturonic acid), and carboxymethyl cellulose.

Sodium polyacrylate co-polymers of slightly corss-linked which are called hydrogels are used as superabsorbent. Baby diapers and other personal disposable hygiene products such as adult protective underwear and sanitary napkins form the largest use of these superabsorbent polyelectrolytes.

### 1.1.5. Conductivity of Polyelectrolytes

When dissolved in water polyelectrolytes dissociate into a macro ion and counter ions [12-14]. When counter-ions are released in aqueous solutions there is gain in entropy. The latter effect in combination with the presence of charged monomers along the polymer chain make polyelectrolytes systems of fundamental interest in the physical chemistry of soft condensed matter [15, 16] as well as in biological systems [17]. Due to their conducting properties, they are largely used for technological applications [18]. Of current interest is understanding the transport properties of these systems. Electrical conductivity of their solutions is the key for understanding their transport properties [19]. The transport properties of these systems is fundamentally governed by their linear charge density $\xi$ [20-22] and therefore depend on the degree of dissociation α of the polyelectrolyte.

In the last decades, these charged polymers have attracted much attention [23]. This is due to charge distribution which creates long range electrostatic interaction and this introduces a new length scale and new time scale. Thus, these systems have unusual properties. The dynamical properties and the structure of these is governs by the balance between attractive hydrophobic interactions and repulsive electrostatic interactions. When the ionisable groups along the chain are dissociated, the counter ions are partially released into the solution. This results in an effective charge of the polymer that is lower than its bare structural charge. This makes these charged polymers of important properties. The interplay between electrostatic attraction of counter ions with the polymer chain creates such phenomenon. In addition to that, this phenomenon is also caused by the loss of their conformational entropy. The thermodynamics and the transport properties of solutions of these charged polymers are largely influenced by counter ion condensation. To study and understand the coupling between counter ions condensation and chain conformation, conductivity is the key parameter. Biological functions of biological polyelectrolytes are influenced by the chain conformation, which makes the previous mentioned coupling of particular importance.  When the electrical conductivity of these systems is studied as a function of polyion concentration, in absence or presence of added salt, the outcome of these studies may provide better understanding of the chain mobility and of the coupling [23].

In order to understand how the conductivity of a polyelectrolyte solution differ from the conductivity of small electrolyte, it is inevitable to introduce the theory of polyelectrolytes conductivity. The origin of the electrical conductivity $\sigma$ of an aqueous solution of polyelectrolytes is the movement of any charged entity. This movement is made in response to an external applied electric field. This in turn depends on three contributions, the charge carriers of type $i$, the numerical concentration $n_i$, their electrical charge $(z_i e)$ and their mobility $u_i$, according to the relationship [23]:

$$\sigma = \sum_i (|z_i| e) n_i u_i \tag{1}$$

the charge mobility $u$ is defined as the ratio of the average velocity of the charged carrier to an applied electric field of unit strength. The usual definition of the conductivity σ, from an experimental point of view, is given by the linear relationship [23]:

$$\langle \overrightarrow{J} \rangle = \sigma \vec{E} \tag{2}$$

where $\langle \overrightarrow{J} \rangle$ is the volume averaged current density and $\vec{E}$ is the measured electrical field. If one expresses the numerical concentration by the molar concentration $C_i$ $(n_i = N_A C_i)$ of the polyelectrolyte, equation (1) can be written in a more usual way through the molar concentration, where $N_A$ is the Avogadro number and the mobility $u_i$ through the equivalent conductance $\lambda_i \left(u_i = \frac{\lambda_i}{F}\right)$ (where $F = eN_A$ is the Faraday constant). We obtain:

$$\sigma = \sum_i (|z_i|) C_i \lambda_i \tag{3}$$

The whole transport process is actually given by equation 3 which also forms the basis of any theoretical description of polyelectrolytes conductivity. It depends on the concentration $C_i$and the equivalent conductance $\lambda_i$ of each charge carrier. The partial dissociation of the polyelectrolyte actually drives charge and equation 3 can be written as:

$$\sigma = |z_i| C_1 \lambda_1 + |z_p| C_p \lambda_p \tag{4}$$

where the subscripts "1" and "p" refer to counter ions and polyions, respectively. Because of the counter ion condensation effect, the following relationships hold: $C_i = \nu_1 N f C_p$ and $Z_1 = z_i$, $Z_p = N f z_p$ and equation 3 can be written as:[23]:

$$\sigma = N f C_p \left(\nu_i |z_1| \lambda_1 + |z_p| \lambda_p\right) \tag{5}$$

The equivalent conductance $\lambda_1$ differs from the value $\lambda_1^o$ of the counter ion in the absence of the polyelectrolyte and this is given by:

$$\lambda_1 = \lambda_1^o \frac{D_1^u}{D_1^o} - \lambda_p \left(1 - \frac{D_1^u}{D_1^o}\right) \tag{6}$$

where $D_1^u$ and $D_1^o$ are the diffusion coefficients of counter ions in the limit of infinite dilution and in the presence of polyions, respectively. Now, substituting equation 6 in equation 5 one gets:

$$\sigma = \nu_1 |z_1| N f C_p \frac{D_1^u}{D_1^o} \left(\lambda_1^o + \lambda_p\right) \tag{7}$$

The electrical conductivity of polyelectrolytes solution is defined by the following parameters: the polyion concentration $(C_p)$, the fraction $f$ of free un-condensed counter ions, the equivalent conductance $(\lambda_p)$ of the polyion chain and the degree of polymerization $(N)$ [23].

### 1.1.6. Literature Review on Polyelectrolytes Conductivity

The conductivity of polyelectrolytes solutions in pure water and with the addition of salts had been studied by a number of authors. Vink et al [21] studied the conductivity of the polyelectrolytes poly (methacry1ic acid), carboxymethylcellulose, poly(vinylsulfonates) and poly(styrenesu1fonates). The conductivity as a function of polyelectrolyte concentration was measured to determine the limiting equivalent conductivity $(\Lambda^o)$. According to their work with dilute solutions, a rapid increase of the conductivity with increasing concentration was observed. This behaviour was explained by a decreased counterion binding. RiOS [24] investigated the electrical conductivity of dilute solutions of four prepared cationic polyelectrolytes. They calculated the distances between neighbouring charges from their experimental data and found a good agreement with those calculated according to Manning's model [25]. Highly charged strong polymers in dilute and semi-dilute solutions were studied theoretically by Wandrey [26] and the electrical conductivity was calculated. Their study was the first one to consider the influence of the charge density, polyelectrolytes concentration, the ionic strength and concentration of added salts. He found that the equivalent conductivity increases with decreasing polyelectrolyte concentration. He also found out that the effect of molar mass above the overlap concentration $(c^*)$ is weak. A strong increase of the equivalent conductivity with decreasing polyelectrolytes below this overlap concentration was also found. With an additional change of the interaction parameter and using the Manning's theory, the conductivity was explained qualitatively. He derived an empirical dependence of the interaction parameter on the ratio of the Debye length to the contour length. He also identified three concentration regimes differing in the polyelectrolyte-counter-ion interaction. Solutions of these polymers without added salt as well as solutions with any ratio of polyelectrolyte to salt concentration was considered. Zhiyong Hu et al [27] studied three different polyacrylamides with three different amination degrees by conductometric measurements. Their results show that with increasing amination degree of polyvinylamine value (a measure of electrostatic interactions of neighbouring groups on the chains) the electrostatic interaction parameter increased. They also found out that the *pK*a value of these polyelectrolytes ~~to~~ decrease with increasing amination degree. Finally, they found a gradual decrease of the equivalent conductivity with increasing concentration of the polymer and the conductivity was enhanced with increasing degree of amination.

The electrical conductivities of aqueous solutions of sodium i-carrageenan, sodium heparin, and sodium dextran sulfate in NaCl and $Na_2SO_4$ solutions at room temperature was studied by Douglas et al [28]. They found anomalous behaviour for sodium dextran sulfate. They discussed the correlation between the Manning law with their experimental results. They found theoretical justification using a modified model for the additivity of simple salt and polyelectrolyte conductivities. Their theoretical equations for the conductivity were developed for salt-containing polyelectrolyte solution and for the case where the charge density of the polyelectrolyte is less than the critical charge density. The variation of mobilities of the counter-ions in aqueous solutions of sodium polystyrenesulfonic acid over a wide concentration range was studied at room temperature by Fernandez et al [29]. They attributed the enhancement of mobilities to an increase in the degree of apparent dissociation due to purely electrostatic interactions among neighbouring chains. They found out that this interaction should be accompanied by short-range interactions which would produce entanglements among neighbouring chains. This was evident as concentration increased and chains approached each other. They found that this may be responsible for the appearance of a maximum in mobilities as the concentration increased. In addition, they found out that the counterions $Cs^+$ had a slightly larger degree of association than $Na^+$. They explained the behaviour of $Ca^{++}$ by the very strong association due to its double charge and for silver as partially due to the presence of complexes. Different salts of polystyrenesulfonic acid in salt-free aqueous solutions were studied by Szymczak et al [30]. They determined the conductivities in salt-free aqueous solutions in the concentration range from 0.003-0.02 N. The conductivity was found to increase with dilution, gradually at first, followed by a rapid increase at higher dilutions. The order of change in conductivity was found to be $Li^+ < Na^+ < K^+ = NH_4^+ < Rb^+ = Cs^+$. Good agreement was found when they compared their experimental data with that of Manning's rod like polyelectrolytes model.

Benmansour et al [31] determined the conductivities of poly[N-(3,6,9-trioxadecyl)-4-vinylpyridinium)] bromide and its chlorate and tosylate derivatives. Their method of preparation gives a grafted polyelectrolyte having a positive charge on each pyridinic moiety on the backbone. The polyelectrolyte concentration range in the aqueous solution was $10^{-4}$ to $10^{-2}$ M at 25 °C. A typical polyelectrolytes behaviour of the conductivity versus concentration was found. They also found out that the polyelectrolyte conductivity increases with the ion size. They showed in their analysis that big ions are weakly or not associated to the backbone. They suggested that counter-ion mobility is mainly influenced by steric effect. Values of the conductivity predicted from Manning rod-like polyelectrolyte model were compared with their experimental results and good agreements was found.

Rios [32] studied the interaction of alkaline ions with an anionic dicarboxylic polyelectrolyte by means of electrical conductivity measurements. His results show that lithium, sodium and potassium counter-ions interact in a very different way with this polyelectrolyte. He found out that the Kohlrausch plots bend downwards in the high-dilution zone. He determined the limiting equivalent conductivities of these polymers according to Vink's method using a polynomial adjustment of his data. He also found out that although the dissociation order follows the sequence $Li^+ > Na^+ > K^+$, the trend in equivalent conductivity follows the reverse order. This is mainly determined by the equivalent conductivity of the counter-ions. He determined the interaction parameter using the Manning theory for the limiting equivalent conductivity of the polyion species. His values of the latter parameters, the average distance between charges agreed well with that calculated from simple geometrical calculations for a mesomeric configuration. He used an alternative method to obtain the relative interaction parameter as a function of polymer concentration. He explained the results in terms of the hydration parameters and the limiting equivalent conductivities of the counter-ions.

Rios et al [33] studied the intermolecular association of amphipathic polyelectrolytes using fluorescence and conductivity methods. In their study, as the polyelectrolytes chain increases in length there is a decrease in the average distances between charges. As a consequence, the degree of dissociation and the linear charge density are modified. They calculated the average distances with the Manning counter-ion condensation theory for the conductivity of polyelectrolyte solutions. Their calculated distances were found to vary with polelectrolyte concentration. Their values of the conductivity were also found to depend on the size of the side chain of the polyelectrolyte. They explained the experimental behaviour of the solution electrical conductivity of polyelectrolytes, which increase drastically with dilution, as a continuous change in the average distances between charges which produce conformational changes.

Vuletic et al [34] studied the Manning free, uncondensed, counter-ions fraction θ for dilute aqueous solutions of rodlike polyions: 150 bp DNA fragments, in the presence of a very low concentration of monovalent salt for concentration < 0.05 mM. They measured the conductivity of these solutions for DNA base pair concentration range 0.015-8 mM. Their conductivity values were complemented by fluorescence correlation spectroscopy (FCS) measurements of the DNA polyion diffusion coefficient. They observed a crossover in the normalized conductivity that nearly halved across the c = 0.05–1 mM range. Through analysis of their data they extracted θ(c) = 0.30–0.45. By taking the Manning asymmetry field effect on polyelectrolyte conductivity into account they got θ(c) = 0.40–0.60. They related the θ(c) variation to gradual DNA denaturation occurring, in the very low salt environment, with the decrease in DNA concentration itself. They found out that the extremes of the experimental θ(c) range occur toward the highest, above 1 mM, and the lowest, below 0.05 mM, DNA concentrations and correspond to the theoretical θ values for dsDNA and ssDNA, respectively. They confirmed Manning condensation and conductivity models to be valuable in description of dilute solutions of rodlike polyions.

The electro-kinetic properties of carboxymethyldextran, a soft and anionic polysaccharide, in aqueous $NaNO_3$ solutions were analysed through measurements of the electrical conductivity of the suspensions by Jean-Pierre et al [35]. Their results actually furnish new experimental support for the structure of soft polysaccharides in electrolyte solution. They showed that the polyion concentration governs the conductance behaviour of the suspension as the ionic strength decreases. They found out that this particularly evident for large polymer concentrations, for which electrical double layer overlap is more likely. They found that the electrical conductivity of the suspension at high ionic strength reduces to the contribution of the ions in solution, as screening of the polyion charges is more efficient in such conditions. They examined applicability of Ohshima's general conductivity expression to these electrical conductivity measurements, and observed a major discrepancy against the theory. Their calculated values of the electrical conductivity deduced on the basis of this theory were found to be lower than the experimental ones. They discussed the possible reasons for this discrepancy and found out that a numerical model, based on the use of a cell approach to account for hydrodynamic and electrical interactions between particles, to be a good description of the experimental electrokinetic data.

The conductance of poly (anetholesulfonic acid) and its lithium, sodium and caesium salts in the concentration range of 0.001-0.20 mmol/L and in the temperature range of 278 – 308 K were studied by Irna et al [36]. They found that the Walden's rule to be reasonably satisfied for the alkaline salts of the polyelectrolytes but not for the polyacid itself. They determined the concentration dependence of the polyion transference number at 298 K. From their measurements they calculated the fraction of the free sodium ions in the solution. They also compared their results with the existing ones for poly (styrenesulfonic acid). They found out that the conductivities of the studied polyion and its salts are higher than that of the poly (styrenesulfonic acid). They explained this difference by a smaller fraction of free conducting counter ions. They found out that their findings are consistent with thermodynamic data for these solutions.

Nagy [37] measured the conductivity of dilute, salt free solutions of poly (vinyl alcohol) (PVA) and poly(vinyl alcohol, vinyl sulphate ester) copolymer salts in order to get information on transition from a neutral to charged macromolecules. He found out that with increasing linear charge density from a very low value to a moderate one a non-linear dependence of polyelectrolyte effect on copolymer composition. He also found out that there is a close analogy between the expansion of polyanions and swelling of polyelectrolyte networks at comparable linear charge density range. He revealed by the electric conductance measurements that the transition from a neutral to charged macromolecules could be a very complex one calling for a new and more detailed theoretical consideration of polyelectrolyte solutions.

Bratko et al [38] studied the effect of the temperature on the electrolytic conductivity of aqueous poly (styrenesu1fonate) solutions. The molar conductivities of the poly (styrenesulfonic acid) (poly [1-(4-sulfophenylethylene)]) (HPSS) and its sodium (NaPSS) and magnesium salts (MgPSS) were determined as functions of the concentration at different temperatures ranging from 0 to 40 $^{o}$C. The Walden rule was shown to apply approximately to the overall conductivity of the two polysalts as well as to the molar conductivity of the polyion. They found out that the estimated relaxation effect on the conductivity, presumably mainly determined by the equilibrium structure of the polyelectrolyte found not to depend on the temperature within the accuracy attained.

Bhattarai [39] measured the specific conductance for sodium polystyrene sulfonate in water and methanol-water mixture. The equivalent conductivity data against concentration were evaluated by scaling concept. He calculated the effects of the solvent composition and the polyelectrolyte concentration on the fractions of uncondensed counterions, the polyion conductivities, the standard state free energies of counterion association, and the polyion transference number. The charge density of sodium polystyrene sulfonate was used for the research article to see the variation of the critical aggregation concentration of cetyltrimethyl ammonium bromide in sodium polystyrene sulfonate against the charge density of sodium polystyrene sulfonate.

Recently, Ranjit De [57] studied aqueous solutions of sodium polystyrenesulfonate in the presence of NaCl by electrical conductivity. The study meant to understand the interaction between counter-ions with the polyion. By an equation developed by them and by considering the scaling description for the conformation of a polyion chain, they analysed the specific conductivity versus polyelectrolyte concentration. They investigated the influences of added salt, polelectorlyte concentration, temperature and molecular weight. Both, the concentration of the polyelctrolyte and its molecular weight were found to greatly influence counter-ion condensation.

### 1.1.7. Sodium (Polystyrene sulfonate) and its Uses

Sodium polystyrene sulfonate is an organic compound, light amber liquid, odourless. It is a water-soluble polymer with a unique effect, used in: reactive emulsifiers [40], water-soluble polymers (coagulants, dispersants, container cleaning agents and cosmetics), water treatment agents (dispersion Chemicals, flocculants), sulfur exchange resins (membrane), photographic agents (membrane), semiconductors, imaging films and heat conduction products [40]. It is well known that Sodium polystyrene sulfonate (PSS) has strong hydrophilic properties. It is used to prepare adsorption ultrafiltration membranes and is also used to treat heavy metal water pollution. It will migrate to the surface of particles when it is gelled with water. In these cases, it will be mainly fixed on the surface of the particles or the surface of the pore channels. It is used in the preparation of ultrafiltration membrane that on not only removes water, macromolecules, colloids and other substances, but is capable of can simultaneously removing various toxic and harmful cations in the water [41].

### 1.1.8. Synthesis of NaPSS

The sodium salt of the polyelectrolyte polystyrene sulfonate can be prepared using an aqueous reversible-deactivation radical polymerization (RDRP) approach to synthesize directly from functionalized monomers to give uniformly and completely sulfonated materials. This was done by Balding et al [42, 43]. Under simple one pot reaction conditions, reproducible gram scale syntheses are achieved. In addition, full monomer conversions are achieved within approximately 3 h. They found out that reaction variables such as pH, sodium chloride concentration, and methanol co-solvent have a significant effect on the molecular weights obtained by gel permeation chromatography coupled with multi angle light scattering. A parametric optimization, rather than direct variation of the monomer to initiator ratio, resulted in some of the highest molecular weight polymers. Linear progression between number average molar mass and monomer conversion occurs at a neutral reaction pH, which results in narrow polymer molecular weight distributions, along with high end-group fidelity as demonstrated with chain extension reactions. This is an up to date method of NaPSS synthesis.

### 1.1.9. Importance of the study

Despite the previously mentioned studies, the effect of different salt concentrations and wide temperature range on the conductivity of sodium (polystyrene sulfonate) aqueous solutions have never been thoroughly investigated. The scientific contribution of this work is obtaining the electrical conductivity of NaPSS solutions in wide range of concentrations of NaCl added salts at different temperatures. The effect of temperature on the conductivity of this polyion has been studied only by one author and up to 40$^o$C in pure water [38]. It has to be noted here that only few studies on the conductivity of this polyion have been carried out. However, the only study that directly measured the conductivity of this polyion was in water as a solvent and this study was indeed an old one [38]. Conductivity measurements are extremely important for the understanding of the dynamics and ion mobilities of this polyion in particular and of polyelectrolytes in general. Knowledge of the conductivity of NaPSS deepen our understanding of its behaviour and could lead to new applications of NaPSS. Through measurement of electrical conductivity, challenges for the existing theories are provided. So in this thesis work, I have studied the effect of NaCl addition in the concentration range of 0.1- 0.4 M and the effect of temperature in the range of 5 – 55 $^{o}$C on the electrical conductivity of the polyion Sodium (polystyrenesulfonate) (NaPSS). To our knowledge, such a study has never been conducted so far and will certainly contribute to the field of interest.

# Chapter 2

## 2.1. Experimental Part

### 2.1.1. Materials

NaPSS was supplied by Sigma- Aldrich, with purity of 99.8% and a weight average molar mass of $M_w$ = 70000 g/mol. It is an organic compound with the molecular formula ($C_8H_7NaO_3S$)n ). The anionic polyelectrolyte is a white to light yellow crystal. This NaPSS sample was pre-dialysed by the producer.

NaCl from Sigma-Aldrich with purity that exceeds 99% and molar mass of 58.44 gm/mol.

### 2.1.2. Conductivity Meter

Conductivity measurements were carried out by a modern Orion Star A212 Conductivity Benchtop Meter (Thermo Scientific$^{TM}$) with high precision. The uncertainty of the measurement was 0.01%.

Figure 2.1. Orion Star A212 Conductivity Benchtop Meter (Thermo Scientific$^{TM}$) with high precision. The uncertainty of the measurement was 0.01%.

Measurements were carried out in a test tube that was immersed in the water bath until the temperature in question was reached.

### 2.1.3. Furnace

A Lab furnace manufactured by CM Furnaces and has a maximum operating temperature up to 2000 K was used for drying salts. The furnace shown in the figure below has sealed designs that support atmosphere control necessary for advanced processes including heat treating, sintering, annealing, glass or ceramic firing.

Figure 2.2. A Lab furnace by CM Furnaces with heating temperature up to 2000 K.

### 2.1.4 Preparation of Solution

In this work, preparation of different concentrations of solutions was carried out either by direct weighing or by successive dilution. In both cases, solutions give us the same conductivity reading exactly. Measurement of each sample was repeated three times and the average value was tabulated. The solutions were prepared and then left them to the next day to made the conductivity measurments.

To control the temperature of the sample, it was putted in a refrigerated circulating water bath and its temperature was measured manually with a thermometer to check it.

NaCl used is a hygroscopic salt, so it was putted in the furnace for two hours to drying and then waited until it cooled to use.

All glassware (beakers, volumetric flasks, test tubes) were carefully cleaned by filling them with hot distilled water for several hours and then rinsed thoroughly with distilled. Freshly prepared distilled water that was used to prepare solutions throughout this work was tested repeatedly for the values of conductivity to ensure its purity. Distilled water conductivity was measured to be of the order of $10^{-6}$ S/cm at 298 K. This method of cleaning proved to yield good results.

Figure 2.3. Refrigerated circulating water bath with temperature controller that has an accuracy of + 0.1℃.

# Chapter 3

## 3.1. Results and Discussions

### 3.1.1. Conductivity Results of NaCl in Pure Water

Figure 3.1a. shows the conductivity of NaCl aqueous solutions, as a function of NaCl concentration at 298 K. Open circles are the experimental points while the solid line is a linear fit to the data. Figure 3.1b. shows the conductivity of NaCl aqueous solutions as a function of NaCl concentration reported by Hervas et al. [43]. The experimental data of this work is in excellent agreement with that of Hervas et al. As can be seen from figure 3.1a, the conductivity of NaCl increases.

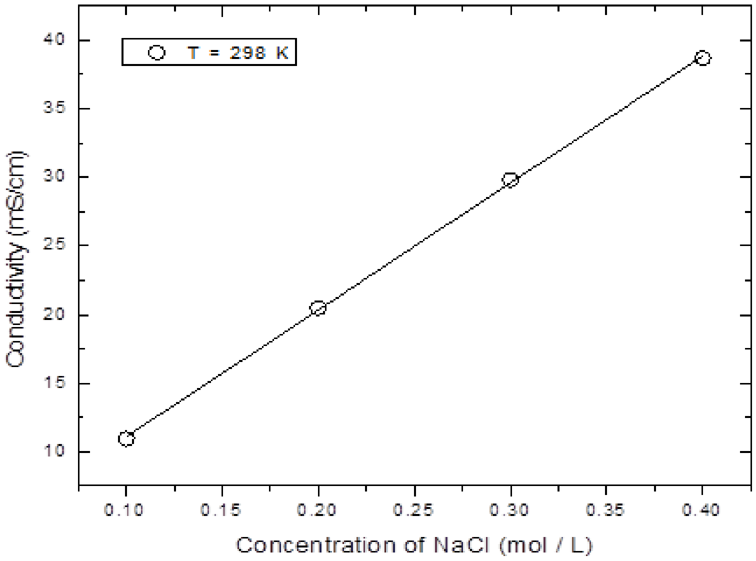


Figure 3.1a. Conductivity of NaCl aqueous solutions as a function of NaCl concentration at 298 K. Open circles are experimental data and the solid line is a linear fit to the data.

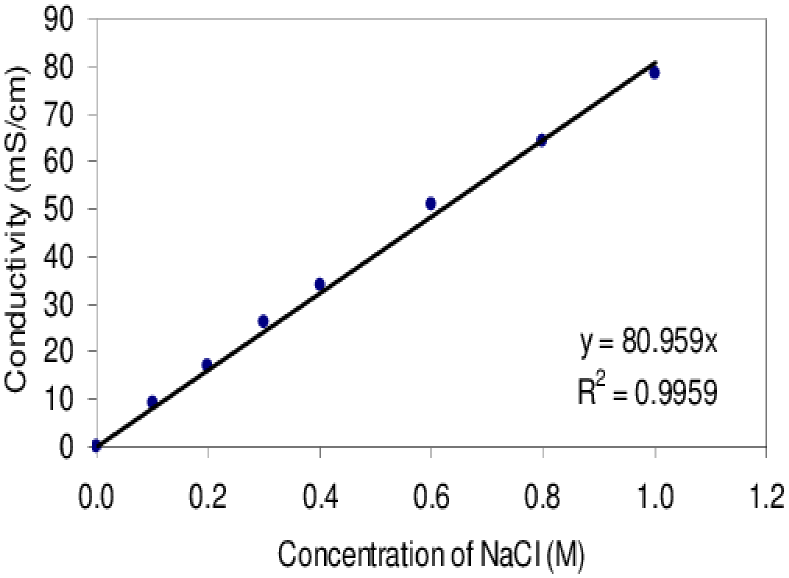


Figure 3.1b. Conductivity of NaCl aqueous solutions as a function of NaCl concentration at 298 K taken from ref [43].

with increasing NaCl concentration. The presence of ions in the solution cause the conducting properties of electrolyte solutions. The greater the concentration, the greater the number of ions in solution and the greater is the conductance. Figure 3.2 shows the molar conductivity $\Lambda_m$of NaCl aqueous solutions as a function of the square root of the concentration of NaCl. The molar conductivity decreases with increasing concentration according to the well-known Kohrausch's law for the conductivity of strong electrolytes:

$$\Lambda_m = \Lambda_m^o - k\sqrt{conc} \quad (8)$$

$$\text{Conductivity(L)= Conductance} \times \text{cell constant} \quad (9)$$

$$\Lambda_m = L/concentration \quad \mathit{(10)}$$

where $\Lambda_m$ and $\Lambda_m^o$ are the molar conductivities at a given concentration and at infinite dilution respectively and $k$ is a constant. The molar conductivities decrease as a result of increasing concentration of the electrolytes, compared to what it was at infinite dilution. Chemically, what this means is that the ion-ion interaction increases as the concentration of salt in solution increases. The decrease in the molar conductivity comes from different contributions: first the ion-solvent and second the solvent-solvent interactions of the electrolytic solution. It has to be mentioned here that there is no contradiction between figures 3.1a. and figure 3.2 because the conductivity of a solution is the conductance of one-unit volume of the solution, but molar conductivity is the conductance of that volume solution containing one mole of electrolyte. So the conductivity increases with increasing concentration while the molar conductivity decreases with increasing concentration.

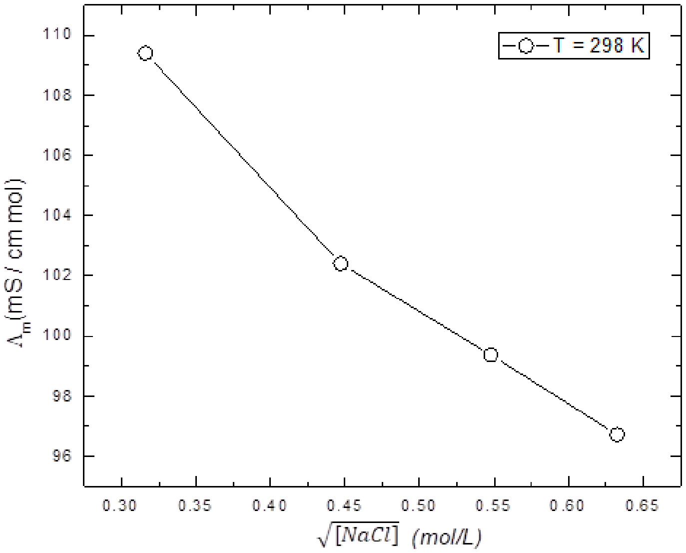


Figure 3.2. The molar conductivity of NaCl aqueous solutions as a function of the square root of the NaCl concentration. The open circles are the experimental data and the solid line is drawn just to guide the eye.

The temperature dependence of the conductivity of NaCl aqueous solution is shown in figure 3.3. As indicated in the figure, open stars, open triangle, open circles and open squares are for 0.1, 0.2 0.3 and 0.4 Molar of NaCl, respectively. As can be seen from figure 3.3, the conductivity increases with increasing the temperature. This is due to a number of factors. First of all, there is decrease in the viscosity of the solution and an increase in the mobility of the ions in solution. Secondly, there is gain in energy by the molecules of the electrolyte (ions), as temperature increases. This leads the ions to have higher energy and to be in higher state of energy. The mobility of the ions increases as the energy gained by them is converted to kinetic energy. As the ion mobility increase so the conductivity of the solution increases. The previous concentration measurements and the explanation provided is already known in the literature and presented in chemistry text books. The object here is to prove that our experimental set up has produced data that is consistent with the published and known.

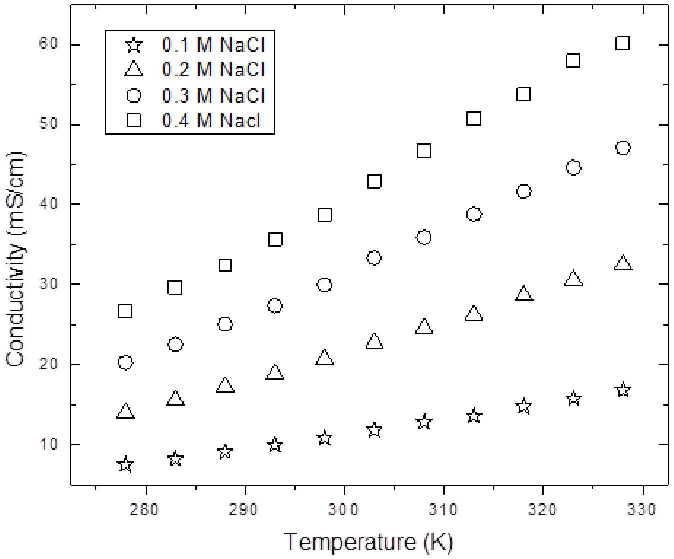


Figure 3.3. Temperature dependence of the conductivity of NaCl aqueous solutions in different concentrations.

### 3.1.2. Results for NaPSS in Pure Water

Temperature dependence of NaPSS conductivity at different concentrations of NaCl in pure water is shown in figure 3.4(a+b). The concentration range is 0.15 g NaPSS/100ml – 2.0 g NaPSS / 100 ml distilled water and the temperature range is 278 K – 328 K. As can be seen in the figure, the conductivity increases with increasing temperature. This could primarily be explained as mentioned above for Pure NaCl which is due to viscosity decrease with increasing temperature and due to increase in energy that these ions have acquired due to temperature increase. In order to compare with limited available data in the literature(Szymczak), the conductivity per gram NaPSS as a function of NaPSS concentration at 298 K was plotted in figure 3.5. It is seen in the figure that the conductivity of NaPSS in pure water increases slightly in the beginning with increasing dilution or decreasing polyelectrolyte concentration and then rapidly increases at high dilution.

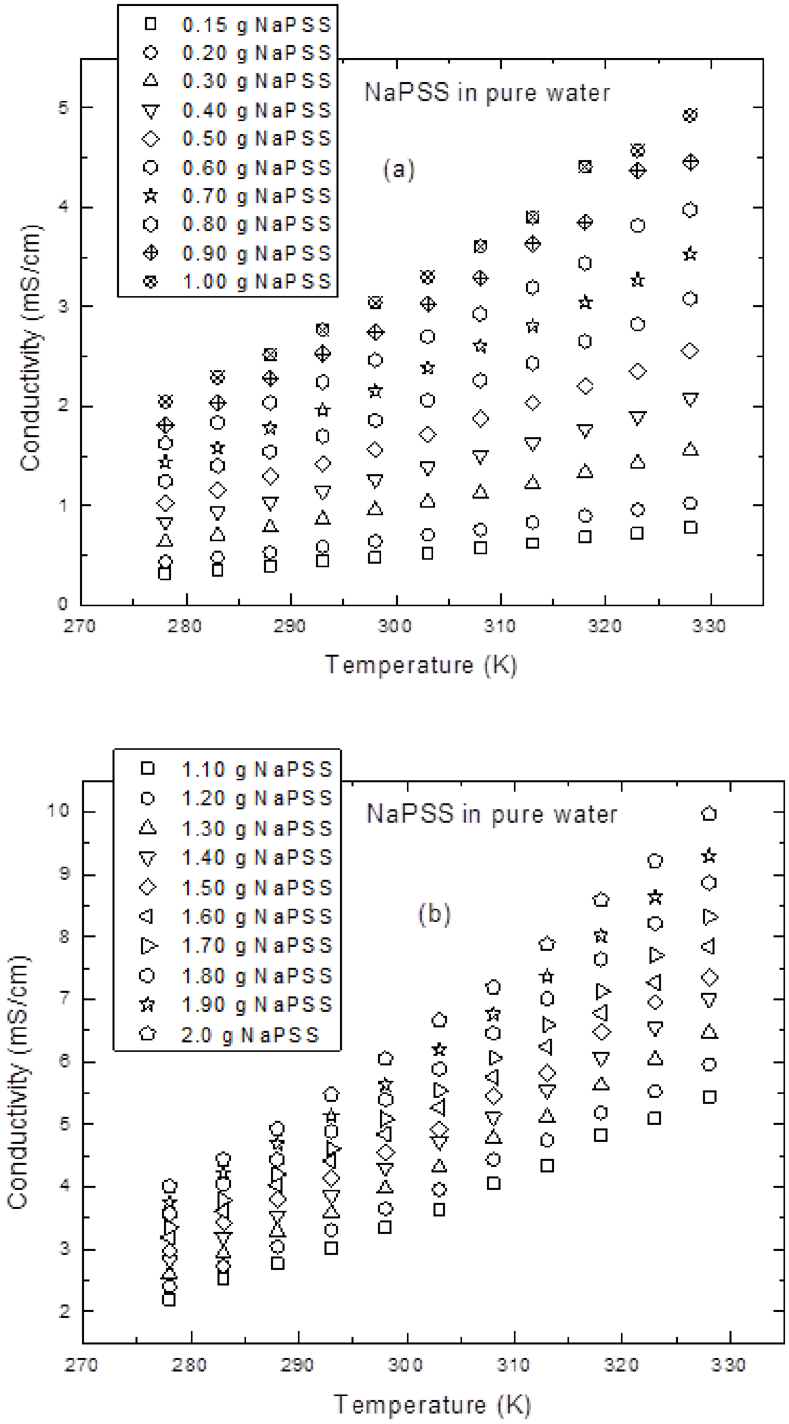


Figure 3.4(a+b). The NaPSS conductivity as a function of temperature

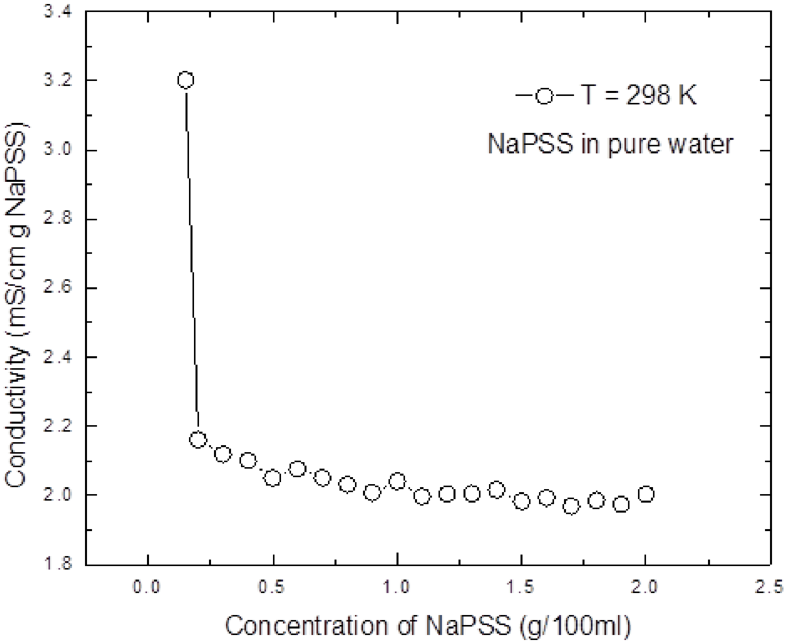


Figure 3.5. Concentration dependence of the conductivity per gram of NaPSS in pure water at 298. Open circle are experimental data and solid line is just drawn to guide the eye.

Szymczak et al [30] measured the conductivity of NaPSS in pure water at 298 K and found a similar behavior. However, their NaPSS has been prepared from polystyrene sulfonic acid. So in this case the behavior of conductivity per gram NaPSS can be compared rather than the exact conductivity values. The same order of magnitude of conductivity was found here as those found by Szymczak. The behavior of polyelectrolyte conductivity as a function of polyelectrolyte concentration cannot be explained as those of simple salt. In the absence of added salt, the electrical conductivities of dilute aqueous solutions of polyelectrolyte salts increase with decreasing polyelectrolyte concentration, slightly first followed by a rapid increase at higher dilutions. The increase in ionization of the polyelectrolytes with dilution of the solution by itself cannot explain the behaviour of the conductivity. But rather a well-defined charge fraction parameter that is independent on the concentration (the ratio of the number of counter-ions moving in the opposite direction in an electric field to the total number of counter-ions resulted from the dissociation of the polyelectrolyte) that plays a decisive role of the transport properties and thus conductivity of polyelectrolytes solutions [44]. A positive deviation from the limiting law was found by Szymczak comparing theory with experiment. This behaviour was found even at low concentration. Manning [45] mentioned that the degree of coiling of the polyelectrolytes could have a huge effect on the polyelectrolytes. This is due to the influence of the frictional constant of the polyelectrolyte. At higher polyelectrolyte concentration there is coiling of the polyion which, might be responsible for the increase in the counter-ion mobility with increasing concentration [46]. It has been mentioned here that due to the strong electrostatic interactions between counter-ions in solution and charged groups on the polyelectrolyte chain, electrical transport properties of aqueous polyelectrolyte solutions, differ from their neutral polymer solutions and those of simple electrolytes [47-55].

The increase in NaPSS conductivity with temperature is definitely not simple to interpret. The contribution of the non-Coulombic forces to the thermodynamic quantities have been revealed by temperature effects and this have been observed in calorimetric studies of the same system [56]. Due to the temperature dependence of the viscosity of water, which is usually the solvent in most studies, significant influence of the temperature is to be expected and indeed have been found in the case of the transport properties in these systems. This also determines the ionic mobilites and hydrodynamic interactions, among ions [38].

### 3.1.3. Results for NaPSS in Salt Solutions

Temperature dependence of NaPSS conductivity in 0.1 M, 0.2 M, 0.3 M and 0.4 M NaCl solutions is shown in figures 3.6(a+b) – 3.9(a+b), respectively. These figures are also at different NaPSS concentration ranging from 0.15 g – 2.0 g NaPSS in 100 ml of distilled water. Also here the conductivity is seen to increase with increasing temperature, NaPSS concentration and the concentration of NaCl. The interaction between different polyelectrolytes, polycation and polyanion and sodium chloride in aqueous solutions have been investigated using electrical conductivity. The conductivity data in these studies was coupled with a developed model using the scaling description for the conformation of a polyion chain. It has been found that high level of counter-ion condensation takes place with decreasing polyelectrolyte concentration. The same trend was found for increasing temperature and increasing addition simple salt concentration. An increase in the dielectric constant of the solvent was caused by an increase in the concentration of the polyelectrolyte accompanied by a reduction in counter-ion condensation. Higher counter-ion condensation and dehydration of the counter-ions was found with increasing the temperature.

The role of the monomer size and its effective charge explained the variations of polyion equivalent conductivity with salt concentration, polyelectrolyte concentration and temperature.

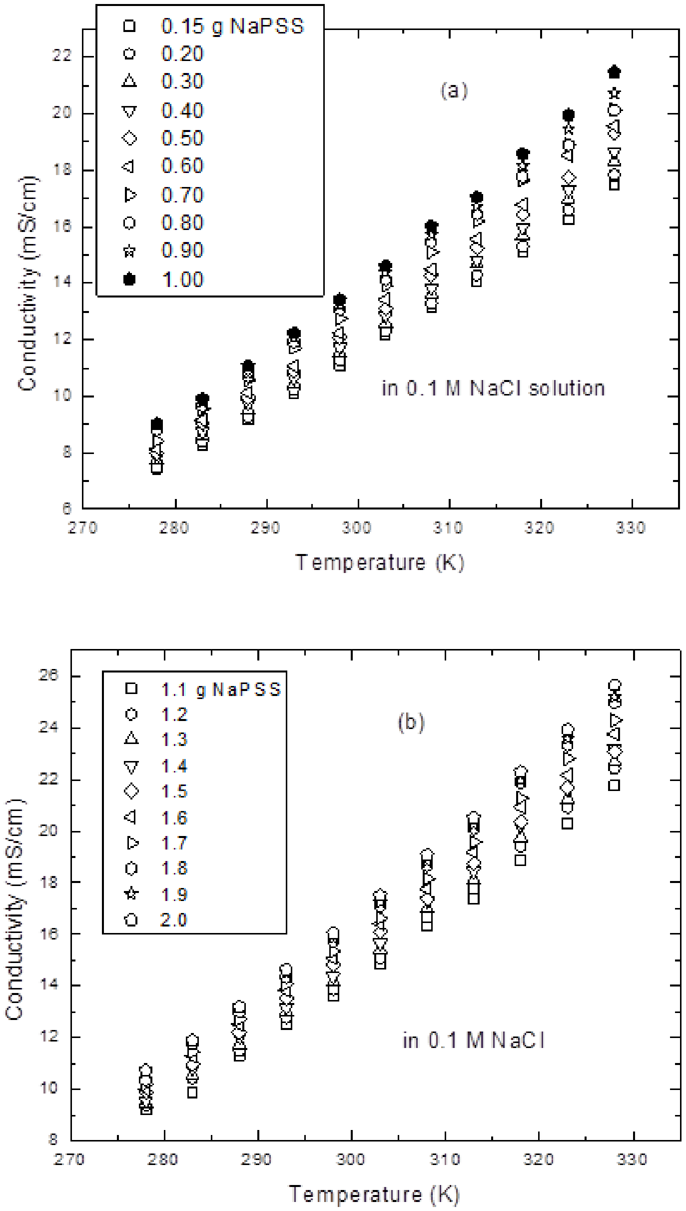


Figure 3.6. (a) Temperature dependence of NaPSS conductivity at different NaPSS concentrations (0.15g – 1.0g NaPSS) in 0,1 M NaCl solutions. (b) Temperature dependence of NaPSS conductivity at different NaPSS concentrations (1.0g – 2.0g NaPSS) in 0.1 M NaCl solutions.

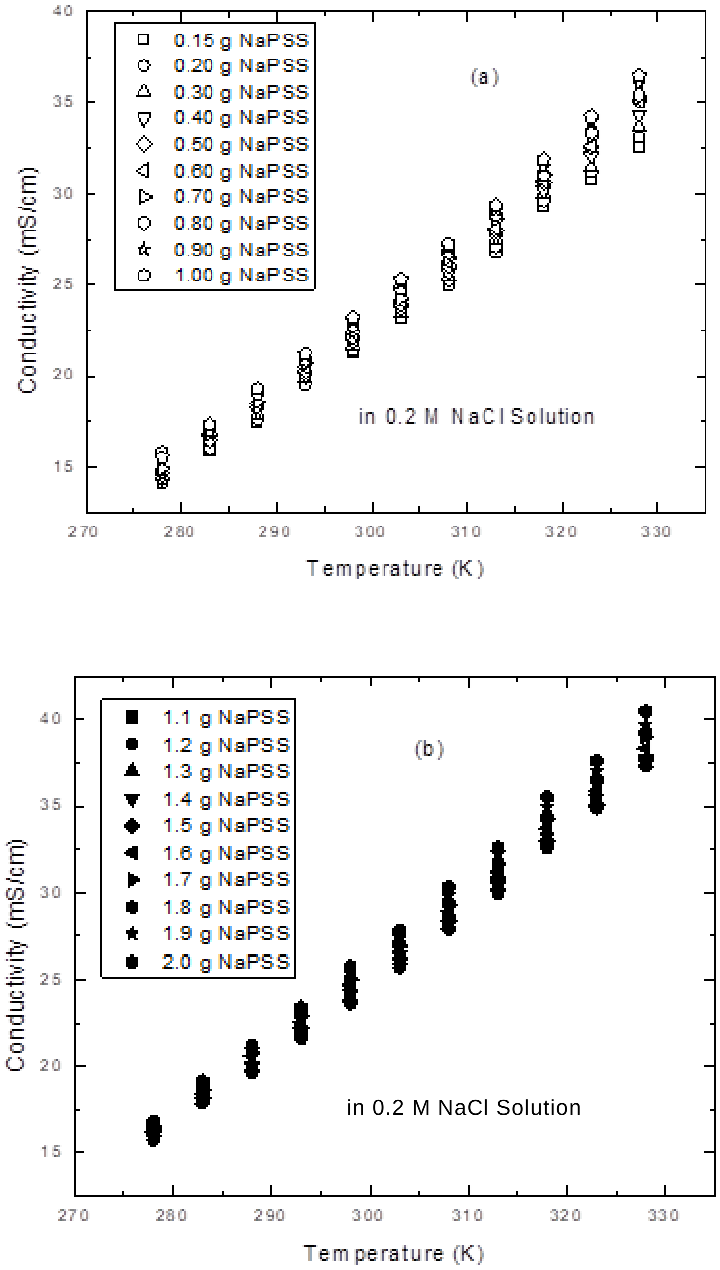


Figure 3.7. (a) Temperature dependence of NaPSS conductivity at different NaPSS concentrations (0.15 g – 1.0 g NaPSS) in 0.2 M NaCl solutions. (b) Temperature dependence of NaPSS conductivity at different NaPSS concentrations (1.0 g – 2.0 g NaPSS) in 0.2 M NaCl solutions.

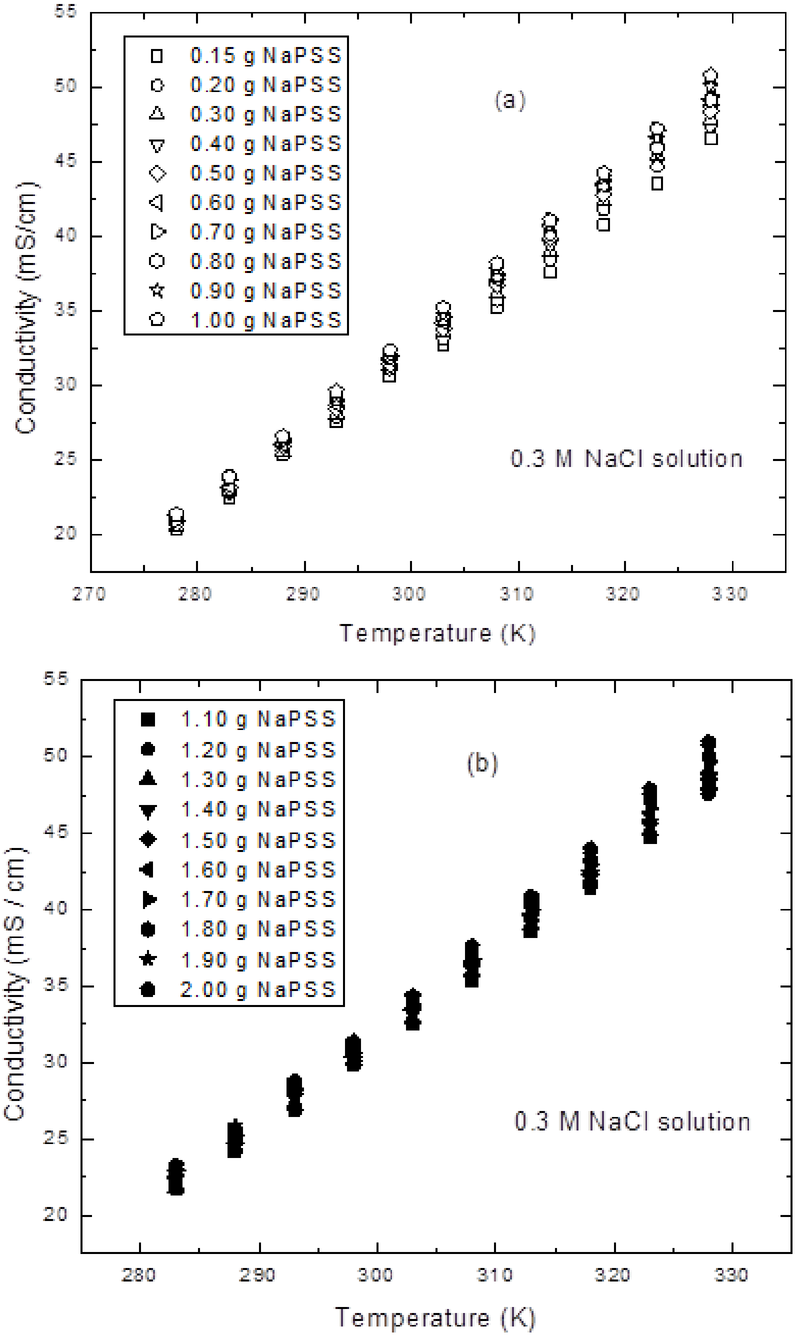


Figure 3.8. (a) Temperature dependence of NaPSS conductivity at different NaPSS concentrations (0.15 g – 1.0 g NaPSS) in 0.3 M NaCl solutions. (b) Temperature dependence of NaPSS conductivity at different NaPSS concentrations (1.0 g – 2.0 g NaPSS) in 0.3 M NaCl solutions.

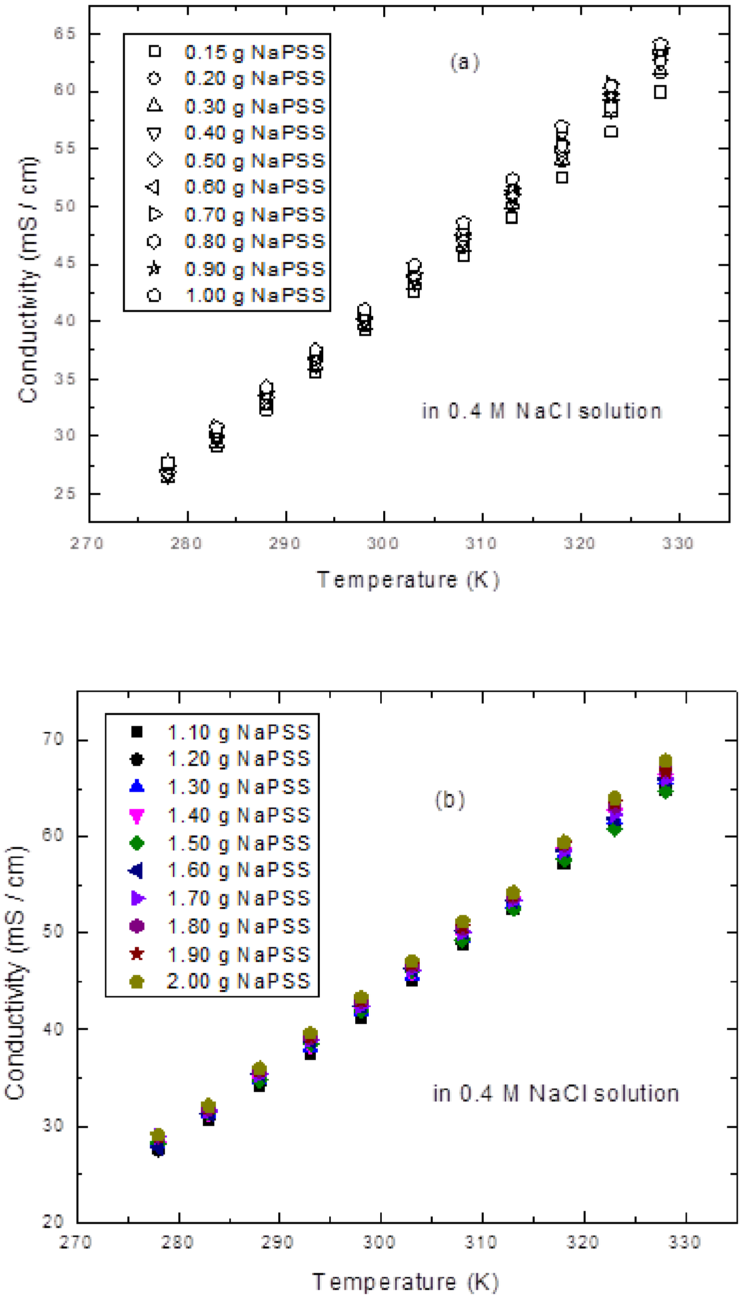


Figure 3.9. (a) Temperature dependence of NaPSS conductivity at different NaPSS concentrations (0.15 g – 1.0 g NaPSS) in 0.4 M NaCl solutions. (b) Temperature dependence of NaPSS conductivity at different NaPSS concentrations (1.0 g – 2.0 g NaPSS) in 0.4 M NaCl solutions

In these systems, the charge effects govern the variation of the polyelectrolyte conductivity with the concentration of simple added salt. On the other hand, the size effect governs the variation of the polyelectrolyte conductivity with the concentration of the polyelectrolyte. Recently, Ranjit De [57] studied aqueous solutions of sodium polystyrene sulfonate in the presence of NaCl by electrical conductivity. The study meant to understand the interaction between counter-ions with the polyion. By an equation developed by them and by considering the scaling description for the conformation of a polyion chain, they analysed the specific conductivity versus polyelectrolyte concentration. They investigated the influences of added salt, polelectorlyte concentration, temperature and molecular weight. Both, the concentration of the polyelctrolyte and its molecular weight were found to greatly influence counter-ion condensation. The molecular weight and the concentration of the polyelectrolyte was found to influence the extent of the counter-ion condensation. From Ranijt De study, information on the importance of the size and charge of the polyelectrolyte were provided by the conductivity measurements coupled with their derived friction coefficient (between the polyion monomer units and the solvent). The overall results have been elucidated taking the medium dielectric constant, the hydration behaviour of the counter-ions, and the coiling behaviour of the polyion chains into account. However, Ranjit De study has been carried out at only three different temperatures, namely at 298 K, 308 K and 318 K and at much lower NaCl concentrations namely, 0.0001 M, 0.001 M and 0.01 M NaCl. The work presented in this thesis work has extended the study to a wider NaPSS concentration, wider temperature ranges and more concentrated NaCl salt solution.

Going back to figures (3.6), (3.9), one can see that the difference in conductivity with increasing NaCl concentration becomes smaller with increasing NaPSS concentration. Figure 3.10 shows the NaPSS solutions conductivities as a function of temperature at different NaCl concentration for constant NaPSS concentration of 2.0 g NaPSS/100 ml solution. It is clearly seen that the conductivity increases with both temperature and increasing NaCl solution. Of course there is large contribution to the conductivity due to the presence of the salts. The reason for these effect can be explained by the same arguments mentioned above. This figure is presented to clarify the behaviour of conductivity with temperature and NaCl concentration.

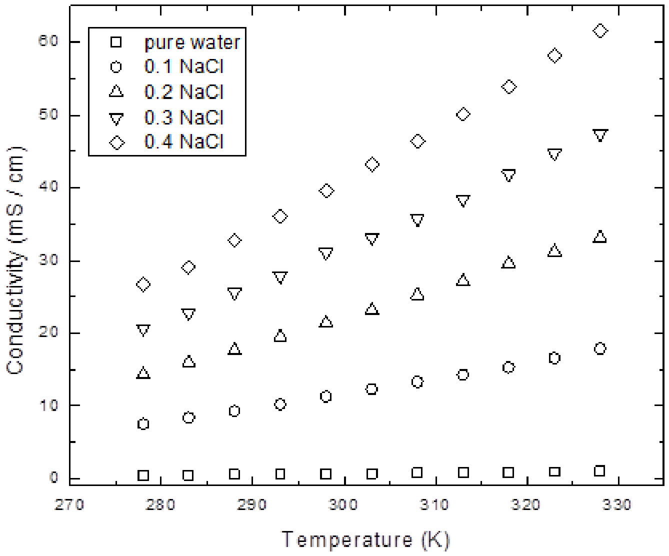


Figure 3.10. Temperature dependence of NaPSS solution conductivity at different NaCl concentration for a constant NaPSS concentration of 2.0 g NaPSS / 100 ml of distilled water.

Figure 3.11 shows the conductivity per gram of NaPSS as a function of NaPSS concentration at 298 K for NaPSS in pure water and in 0.1 M, 0.2 M, 0.3 M and 0.4 M NaCl as is indicated in the figure. The conductivity presented in this work is similar to the equivalent conductivity presented by Ranjit De [57]. The authors found the same trend of the conductivity as a function of polyion concentration, though they carried out their measurements only at three different temperatures and at lower NaCl concentrations. Nevertheless, the general behaviour is the same in both cases and our conductivity behaviour is in consistent with their data. The general behaviour which talked about here is the following: in the beginning the conductivity decreases rapidly with increasing NaPSS concentration and then settles down and almost becomes constant at large concentration of NaPSS. However, our data show a more significant decrease in conductivity per gram NaCl than those presents by Ranijt De.  Our conductivity curve is steeper than that of Ranijt. This is probably due to much higher NaCl concentration used in this work.  Figure 3.12 shows NaPSS conductivity as a function of NaPSS concentration in pure water and in different NaCl solutions as is indicated in the figure at 298K.

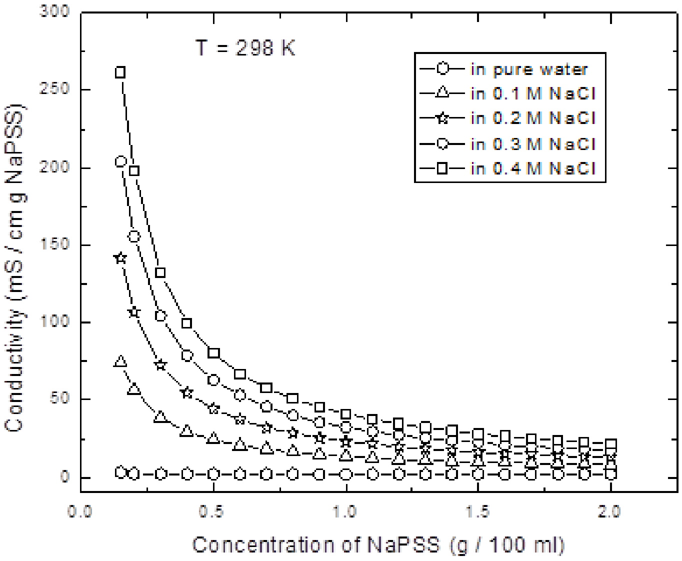


Figure 3.11. Conductivity per gram of NaPSS versus NaPSS concentration at different NaCl concentrations as indicated in the figure and at 298 K.

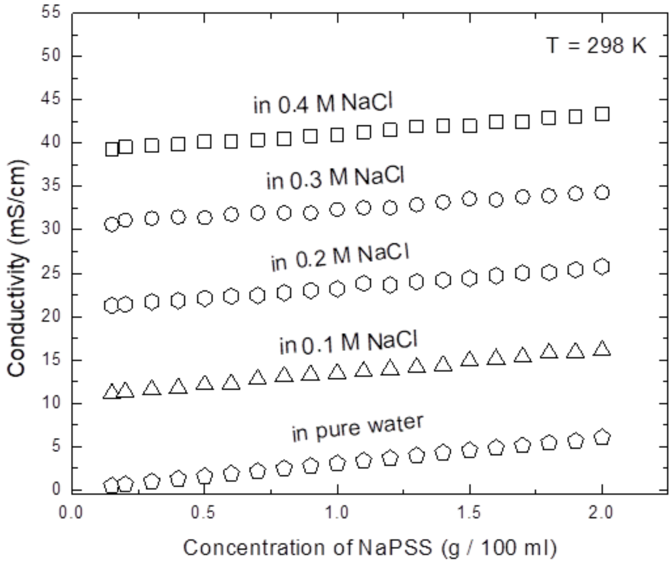


Figure 3.12. NaPSS conductivity as a function of NaPSS concentration in pure water and in different NaCl solutions as is indicated in the figure at 298 K. (zoom in view of fig 3.11).

As can be seen from the figure the presence of salt has a significant influence on the conductivity of NaPSS solutions as conductivity increases largely with increasing NaCl concentration. Polyelectrolyte conformation and polyelectrolyte-counter-ion interaction change when a salt is added. The previous effect will lead to a different degree of counter ion-condensation. In salt media, the dissociation of the counter-ions was found to be significantly reduced. Reduction of the counter-ion dissociation was found to occur at different temperatures. An observation was noticed through different studies on the polyelectrolytes solutions that the higher the temperature the higher the reduction in counter-ion dissociations. Through different studies mentioned in this thesis the polyelectrolyte-counter-ion interactions was largely influenced by the charge density along the polyelectrolyte chain. The charge density is greatly affected by the presence of added salt [58]. It has been claimed that the simple additivity given by:

$$k_{PS} = k_P + k_S \tag{6.1}$$

where $k_{PS}$ is the conductivity of the polyelectrolyte in the presence of a salt, $k_P$ is the conductivity of the polyelectrolyte in the absence of a salt and $k_S$ is the conductivity of the salt without the polyelectrolyte, does not hold and therefore modification has to be applied [58]. This modification is given by:

$$k_{PS} = k_P + k_S \left(\frac{D_S}{D_S^o}\right) \tag{6.2}$$

where $D_S$ is the diffusion coefficient of the co-ion in polyelectrolyte salt solution and $D_S^o$ is that in a salt solution as the salt concentration approaches zero. My data confirm this assumption and is represented by figure 3.13 which shows the conductivity of NaPSS solutions in pure water and that in pure water plus the conductivity of 0.1 M NaCl solution without NaPSS and the conductivity of NaPSS in 0.1 M NaCl. In fact, the additivity rule is valid at low polyelectrolyte solution and deviates at high polyelectrolyte concentration. My data result adds to the existing data in the literature that the higher the temperature and the higher the polyelectrolyte concentration the less the deviation from simple additivity rule. This is shown in figure 3.14 which shows the conductivity of NaPSS solutions in pure water and the conductivity of NaPSS in pure water plus the conductivity of 0.1 M NaCl without the NaPSS, at two temperatures of 298 K and 323 K, respectively. It is clearly seen that as the temperature increases the difference between the conductivity of NaPSS solutions and that of the conductivity of NaPSS + the conductivity of the 0.1 M NaCl becomes smaller. It is also interesting to note (in figure 3.14) that the conductivity of NaPSS solutions in pure water increases as temperature increases at higher NaPSS concentrations. This is represented in figure 3.14 by the solid and open circles.

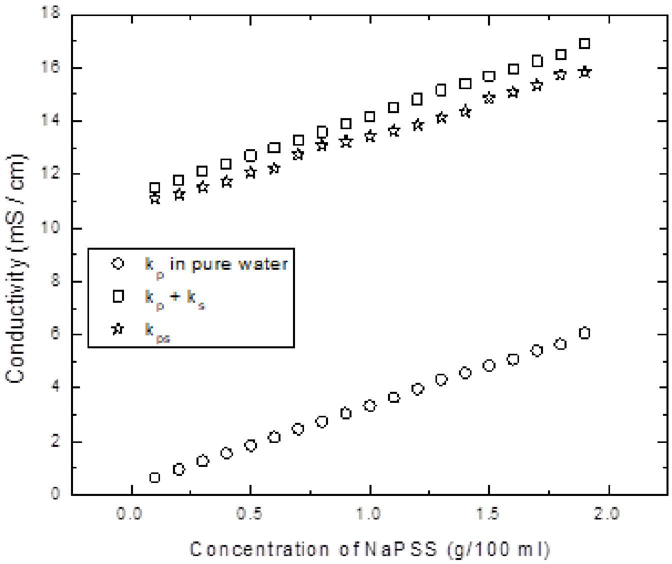


Figure 3.13. The conductivity of NaPSS solutions in pure water ($k_p$), conductivity of NaPSS + the conductivity of the 0.1 M NaCl in pure water ($k_p + k_s$) and the conductivity of NaPSS in 0.1 M NaCl at 298K.

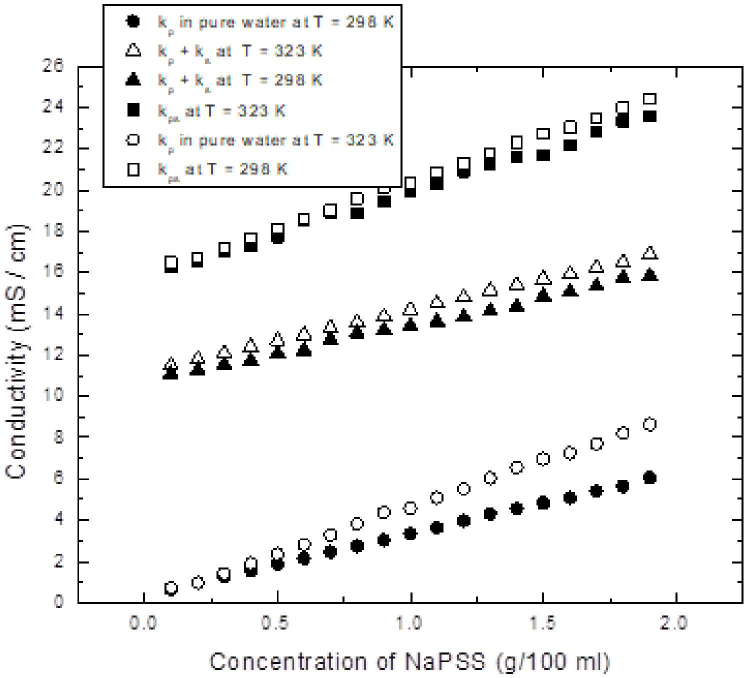


Figure 3.14. The conductivity of NaPSS solutions in pure water ($k_p$), conductivity of NaPSS + the conductivity of the 0.1 M NaCl without NaPSS ($k_p$ + $k_s$) and the conductivity of NaPSS in 0.1 M NaCl, ($k_{ps}$) at 298 K and 323 K.

One of the interesting results in this thesis work are the results shown in figure 3.15 which shows the conductivity of NaPSS in pure water and in different NaCl concentration where the conductivity of the NaCl salt was subtracted. This figure is different from figure 3.14 and in fact summarises our results in this thesis work. In this figure what is drawn is the pure contribution of the conductivity due to the presence of the polyelectrolyte only. That is, this figure gives an indication of the transport of charge by the polyelectrolyte in salt free environment in comparison to its ability in presence of salt.

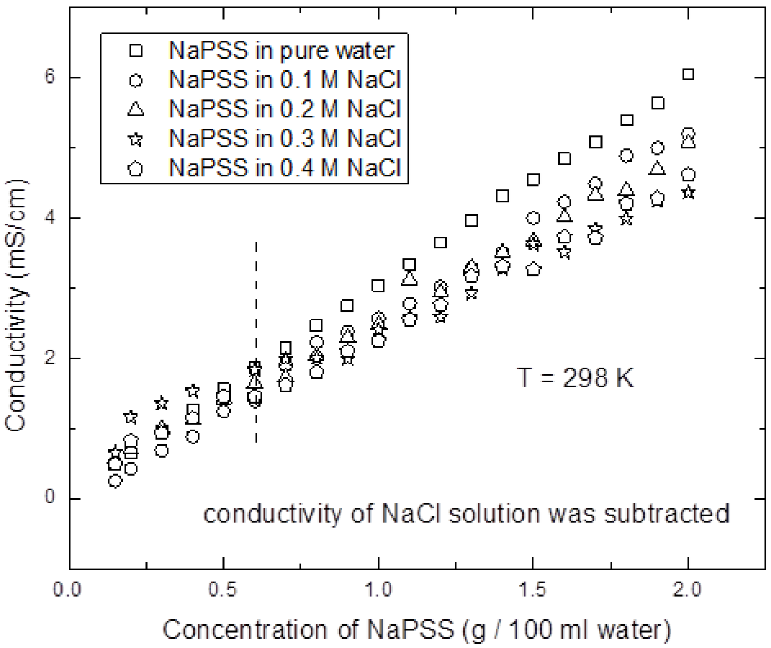


Figure 3.15. The conductivity of NaPSS in pure water and in different NaCl concentrations where the conductivity of the NaCl salt was subtracted at 298 K.

This interesting result shows that NaPSS is better able to transport charge when no salt is present. That is in pure water. The conformation of the polyion in pure water differs substantially from its conformation in salt solutions. In pure water it has an extended conformation due to charge-charge repulsion on its back bone while in the presence of salt this repulsion is screened. It seems that the salt hinders the ability of the polyion in transporting charges while this crippling effect does not exist in pure water. In addition, it seems that the polyion-salt interactions plays very important role in charge transport phenomena of polyelectrolyte solutions. What is also interesting to note in figure 3.15 is that the higher the salt concentration the lower the ability of the polyion to transport charges. This is clearly seen when comparing open stars with open circles in the figure. To add more to this interesting result, we claim that the higher the salt concentration the higher the polyion-salt interaction and the more of this crippling effect.It is also interesting to note in figure 3.15 is that when one compares the open circles and open stars below the vertical dashed line at low NaPSS concentration then an opposite effect is observed. That is at low NaPSS concentration the contribution of NaPSS to the conductivity of the solution is higher in the salt solution than in salt free solution and that this contribution increases with increasing salt concentration. To make things more clear let's compare values of the conductivity. Table 3.1 shows a comparison between conductivity values at two different NaPSS concentration of 0.3 g/100 ml and 2.0 g /100 ml and two different NaCl concentrations. This table confirms the previous discussion.

Table 3.1. Comparison of conductivity values at two different NaPSS concentrations and two NaCl Concentrations.

| NaPSS concentration (g/100 ml) | 0.3 | | 2.0 | |
|---|---|---|---|---|
| NaCl concentration (M) | 0.10 | 0.30 | 0.10 | 0.30 |
| Conductivity (mS/ cm) | 0.66 | 1.34 | 5.20 | 4.36 |

It has to be remembered that the accuracy of the conductivity meter is very high and is less than 1% so the values of conductivity in table 3.1. reflect this accuracy.

## 4. Conclusions

In this thesis work the conductivity of NaPSS solutions was studied as a function of temperature, NaPSS concentration and NaCl salt concentration. It is found that:

1. Conductivity of NaPSS increases with increasing temperature. This increase can be explained by many factors. One is the decrease in the solution viscosity with increasing temperature, which lead to increase in mobility of the conducting species. The other is the increase in energy of the conducting species with increasing temperature which enhances the mobility of the conducting species. A third factor is the decrease in the fraction of free counter-ions. At higher temperatures, there will be a gradual dehydration of the counter-ions and more dissociated sites on the polyelectrolyte chain. These combined effects result in more counter-ion condensation. In addition, and as the temperature is raised there will be higher electrostatic attraction between the surface charges on the polyion

and the dehydrated. At higher temperatures, there will be lower degree of counter-ion condensation.

2. The conductivity increases with increasing NaPSS concentration. An increase in polyelectrolyte concentration will cause an increase in the dielectric constant of the solvent and this in turn will cause a decrease in the Bjerrum length. The length scale between the dissociated sites on the polyelectrolyte is set by the value of the Bjerrum length. This increase in the dielectric constant of the solvent will lead to lower counter-ion condensation. At higher polyion concentration this effect is more important.
3. The polyion conductivity is found to increase as the concentration of the added salt increases. Counter-ion condensation is higher as the salt concentration is higher and there will be also less effective charge on the monomer.
4. The contribution of the polyion to the solution conductivity is more in pure than in salt solution only at high NaPSS concentration. At very low NaPSS concentration its contribution is less in pure water and higher at higher NaCl concentration.
5. The additivity rule: that the conductivity of the polyelectrolyte in salt solution is equal to the sum of its conductivity in pure water plus the conductivity of the salt alone is not valid at high NaPSS while it is valid only at low NaPSS concentration.
6. The conductivity of NaPSS in water is higher at higher temperatures only at high NaPSS concentration. At very low NaPSS concentrations the temperature effect is weak.

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**Table1. Conductivity of NaCl in Pure Water**

**% Error = The uncertainty of conductivity meter(0.01) × conductivity value**

| 0.1 NaCl | | | 0.2 NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 7.496 | 0.07496 | 278 | 13.92 | 0.1392 |
| 278 | 8.222 | 0.08222 | 278 | 15.51 | 0.1551 |
| 288 | 9.104 | 0.09104 | 288 | 17.23 | 0.1723 |
| 293 | 9.94 | 0.0994 | 293 | 18.84 | 0.1884 |
| 298 | 10.85 | 0.1085 | 298 | 20.7 | 0.207 |
| 303 | 11.84 | 0.1184 | 303 | 22.77 | 0.2277 |
| 308 | 12.82 | 0.1282 | 308 | 24.58 | 0.2458 |
| 313 | 13.59 | 0.1359 | 313 | 26.21 | 0.2621 |
| 318 | 14.78 | 0.1478 | 318 | 28.59 | 0.2859 |
| 323 | 15.77 | 0.1577 | 323 | 30.56 | 0.3056 |
| 328 | 16.83 | 0.1683 | 328 | 32.53 | 0.3253 |

| 0.3 NaCl | | | 0.4 NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 20.28 | 0.2028 | 278 | 26.69 | 0.2669 |
| 278 | 22.52 | 0.2252 | 278 | 29.62 | 0.2962 |
| 288 | 25.05 | 0.2505 | 288 | 32.42 | 0.3252 |
| 293 | 27.37 | 0.2737 | 293 | 35.62 | 0.3562 |
| 298 | 29.95 | 0.2995 | 298 | 38.74 | 0.3874 |
| 303 | 33.36 | 0.3336 | 303 | 42.93 | 0.4293 |
| 308 | 35.92 | 0.3592 | 308 | 46.69 | 0.4669 |
| 313 | 38.8 | 0.388 | 313 | 50.74 | 0.5074 |
| 318 | 41.64 | 0.4164 | 318 | 53.8 | 0.538 |
| 323 | 44.63 | 0.4463 | 323 | 57.95 | 0.5795 |
| 328 | 47.09 | 0.4709 | 328 | 60.15 | 0.6015 |

**Tables 2. Conductivity of NaPSS in Pure Water.**

| 0.15gm NaPSS | | | 0.2gm NaPSS | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(μs) | % Error ± | Temp(K) | Cond(μs) | % Error ± |
| 278 | 318.8 | 3.188 | 278 | 432.2 | 4.322 |
| 278 | 356 | 3.56 | 278 | 479.3 | 4.793 |
| 288 | 395.4 | 3.954 | 288 | 528 | 5.28 |
| 293 | 438.3 | 4.383 | 293 | 584.4 | 5.844 |
| 298 | 480.4 | 4.804 | 298 | 642.4 | 6.424 |
| 303 | 523.6 | 5.236 | 303 | 703.5 | 7.035 |
| 308 | 573.2 | 5.732 | 308 | 756.6 | 7.566 |
| 313 | 618.8 | 6.188 | 313 | 828.9 | 8.289 |
| 318 | 678.4 | 6.784 | 318 | 896.4 | 8.964 |
| 323 | 722.1 | 7.221 | 323 | 958.1 | 9.581 |
| 328 | 772.5 | 7.725 | 328 | 1021 | 10.21 |

| 0.3gm NaPSS | | | 0.4gm NaPSS | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(μs) | % Error ± | Temp(K) | Cond(μs) | % Error ± |
| 278 | 635.8 | 6.358 | 278 | 840.4 | 8.404 |
| 278 | 702.5 | 7.025 | 278 | 936.6 | 9.366 |
| 288 | 780 | 7.8 | 288 | 1038 | 10.38 |
| 293 | 861.8 | 8.618 | 293 | 1140 | 11.4 |
| 298 | 955.8 | 9.558 | 298 | 1261 | 12.61 |
| 303 | 1038 | 10.38 | 303 | 1387 | 13.87 |
| 308 | 1125 | 11.25 | 308 | 1508 | 15.08 |
| 313 | 1214 | 12.14 | 313 | 1629 | 16.29 |
| 318 | 1334 | 13.34 | 318 | 1768 | 17.68 |
| 323 | 1427 | 14.27 | 323 | 1896 | 18.96 |
| 328 | 1555 | 15.55 | 328 | 2081 | 20.81 |

| **0.5gm NaPSS** | | | **0.6gm NaPSS** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(μs)** | **% Error ±** | **Temp(K)** | **Cond(μs)** | **% Error ±** |
| **278** | **1025** | **10.25** | **278** | **1246** | **12.46** |
| **278** | **1154** | **11.54** | **278** | **1399** | **13.99** |
| **288** | **1292** | **12.92** | **288** | **1543** | **15.43** |
| **293** | **1418** | **14.18** | **293** | **1699** | **16.99** |
| **298** | **1558** | **15.58** | **298** | **1858** | **18.58** |
| **303** | **1714** | **17.14** | **303** | **2061** | **20.61** |
| **308** | **1873** | **18.73** | **308** | **2259** | **22.59** |
| **313** | **2032** | **20.32** | **313** | **2431** | **24.31** |
| **318** | **2200** | **22** | **318** | **2651** | **26.51** |
| **323** | **2351** | **23.51** | **323** | **2825** | **28.25** |
| **328** | **2557** | **25.57** | **328** | **3079** | **30.79** |

| **0.7gm NaPSS** | | | **0.8gm NaPSS** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(μs)** | **% Error ±** | **Temp(K)** | **Cond(μs)** | **% Error ±** |
| **278** | **1436** | **14.36** | **278** | **1626** | **16.26** |
| **278** | **1585** | **15.85** | **278** | **1833** | **18.33** |
| **288** | **1778** | **17.78** | **288** | **2036** | **20.36** |
| **293** | **1957** | **19.57** | **293** | **2246** | **22.46** |
| **298** | **2149** | **21.49** | **298** | **2463** | **24.63** |
| **303** | **2384** | **23.84** | **303** | **2701** | **27.01** |
| **308** | **2604** | **26.04** | **308** | **2926** | **29.26** |
| **313** | **2805** | **28.05** | **313** | **3195** | **31.95** |
| **318** | **3043** | **30.43** | **318** | **3436** | **34.36** |
| **323** | **3268** | **32.68** | **323** | **3817** | **38.17** |
| **328** | **3528** | **35.28** | **328** | **3976** | **39.76** |

| 0.9gm NaPSS | | | 1.0gm NaPSS | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(μs) | % Error ± | Temp(K) | Cond(μs) | % Error ± |
| 278 | 1808 | 18.08 | 278 | 2041 | 20.41 |
| 278 | 2038 | 20.38 | 278 | 2287 | 22.87 |
| 288 | 2278 | 22.78 | 288 | 2517 | 25.17 |
| 293 | 2527 | 25.27 | 293 | 2766 | 27.66 |
| 298 | 2743 | 27.43 | 298 | 3040 | 30.4 |
| 303 | 3034 | 30.34 | 303 | 3297 | 32.97 |
| 308 | 3291 | 32.91 | 308 | 3610 | 36.1 |
| 313 | 3636 | 36.36 | 313 | 3895 | 38.95 |
| 318 | 3850 | 38.5 | 318 | 4407 | 44.07 |
| 323 | 4374 | 43.74 | 323 | 4570 | 45.7 |
| 328 | 4456 | 44.56 | 328 | 4921 | 49.21 |

| 1.1gm NaPSS | | | 1.2gm NaPSS | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(μs) | % Error ± | Temp(K) | Cond(μs) | % Error ± |
| 278 | 2197 | 21.97 | 278 | 2406 | 24.06 |
| 278 | 2520 | 25.2 | 278 | 2735 | 27.35 |
| 288 | 2772 | 27.72 | 288 | 3044 | 30.44 |
| 293 | 3031 | 30.31 | 293 | 3309 | 33.09 |
| 298 | 3342 | 33.42 | 298 | 3647 | 36.47 |
| 303 | 3631 | 36.31 | 303 | 3953 | 39.53 |
| 308 | 4049 | 40.49 | 308 | 4436 | 44.36 |
| 313 | 4340 | 43.4 | 313 | 4750 | 47.5 |
| 318 | 4828 | 48.28 | 318 | 5182 | 51.82 |
| 323 | 5091 | 50.91 | 323 | 5526 | 55.26 |
| 328 | 5441 | 54.41 | 328 | 5963 | 59.63 |

| **1.3gm NaPSS** | | | **1.4gm NaPSS** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(μs)** | **% Error ±** | **Temp(K)** | **Cond(μs)** | **% Error ±** |
| **278** | **2608** | **26.08** | **278** | **2824** | **28.24** |
| **278** | **2936** | **29.36** | **278** | **3201** | **32.01** |
| **288** | **3287** | **32.87** | **288** | **3543** | **35.43** |
| **293** | **3583** | **35.83** | **293** | **3857** | **38.57** |
| **298** | **3969** | **39.69** | **298** | **4308** | **43.08** |
| **303** | **4309** | **43.09** | **303** | **4726** | **47.26** |
| **308** | **4778** | **47.78** | **308** | **5109** | **51.09** |
| **313** | **5111** | **51.11** | **313** | **5539** | **55.39** |
| **318** | **5623** | **56.23** | **318** | **6063** | **60.63** |
| **323** | **6039** | **60.39** | **323** | **6551** | **65.51** |
| **328** | **6465** | **64.65** | **328** | **7004** | **70.04** |

| **1.5gm NaPSS** | | | **1.6gm NaPSS** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(μs)** | **% Error ±** | **Temp(K)** | **Cond(μs)** | **% Error ±** |
| **278** | **2974** | **29.74** | **278** | **3191** | **31.91** |
| **278** | **3432** | **34.32** | **278** | **3610** | **36.1** |
| **288** | **3799** | **37.99** | **288** | **4030** | **40.3** |
| **293** | **4140** | **41.4** | **293** | **4414** | **44.14** |
| **298** | **4557** | **45.57** | **298** | **4845** | **48.45** |
| **303** | **4922** | **49.22** | **303** | **5272** | **52.72** |
| **308** | **5456** | **54.56** | **308** | **5756** | **57.56** |
| **313** | **5829** | **58.29** | **313** | **6244** | **62.44** |
| **318** | **6478** | **64.78** | **318** | **6780** | **67.8** |
| **323** | **6956** | **69.56** | **323** | **7266** | **72.66** |
| **328** | **7350** | **73.5** | **328** | **7841** | **78.41** |

| **1.7gm NaPSS** | | | **1.8gm NaPSS** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(μs)** | **% Error ±** | **Temp(K)** | **Cond(μs)** | **% Error ±** |
| **278** | **3348** | **33.48** | **278** | **3575** | **35.75** |
| **278** | **3789** | **37.89** | **278** | **4042** | **40.42** |
| **288** | **4202** | **42.02** | **288** | **4433** | **44.33** |
| **293** | **4608** | **46.08** | **293** | **4893** | **48.93** |
| **298** | **5084** | **50.84** | **298** | **5396** | **53.96** |
| **303** | **5541** | **55.41** | **303** | **5883** | **58.83** |
| **308** | **6063** | **60.63** | **308** | **6456** | **64.56** |
| **313** | **6591** | **65.91** | **313** | **7011** | **70.11** |
| **318** | **7128** | **71.28** | **318** | **7642** | **76.42** |
| **323** | **7706** | **77.06** | **323** | **8220** | **82.2** |
| **328** | **8316** | **83.16** | **328** | **8866** | **88.66** |

| **1.9gm NaPSS** | | | **2.0gm NaPSS** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(μs)** | **% Error ±** | **Temp(K)** | **Cond(μs)** | **% Error ±** |
| **278** | **3753** | **37.53** | **278** | **4008** | **40.08** |
| **278** | **4222** | **42.22** | **278** | **4444** | **44.44** |
| **288** | **4688** | **46.88** | **288** | **4931** | **49.31** |
| **293** | **5128** | **51.28** | **293** | **5482** | **54.82** |
| **298** | **5635** | **56.35** | **298** | **6051** | **60.51** |
| **303** | **6196** | **61.96** | **303** | **6665** | **66.65** |
| **308** | **6763** | **67.63** | **308** | **7197** | **71.97** |
| **313** | **7364** | **73.64** | **313** | **7885** | **78.85** |
| **318** | **8018** | **80.18** | **318** | **8588** | **85.88** |
| **323** | **8637** | **86.37** | **323** | **9221** | **92.21** |
| **328** | **9293** | **92.93** | **328** | **9963** | **99.63** |

## Tables 3. Conductivity of NaPSS in 0.1 NaCl

| 0.15 NaPSS\0.1NaCl | | | 0.2 PSS\0.1NaCL | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 7.441 | 0.0744 | 278 | 7.484 | 0.0748 |
| 278 | 8.271 | 0.0827 | 278 | 8.392 | 0.0839 |
| 288 | 9.152 | 0.0915 | 288 | 9.284 | 0.0928 |
| 293 | 10.12 | 0.1012 | 293 | 10.24 | 0.1024 |
| 298 | 11.1 | 0.111 | 298 | 11.27 | 0.1127 |
| 303 | 12.16 | 0.1216 | 303 | 12.31 | 0.1231 |
| 308 | 13.13 | 0.1313 | 308 | 13.3 | 0.133 |
| 313 | 14.06 | 0.1406 | 313 | 14.28 | 0.1428 |
| 318 | 15.12 | 0.1512 | 318 | 15.31 | 0.1531 |
| 323 | 16.25 | 0.1625 | 323 | 16.59 | 0.1659 |
| 328 | 17.48 | 0.1748 | 328 | 17.84 | 0.1784 |

| 0.3 PSS\0.1NaCl | | | 0.4 PSS\0.1NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 7.732 | 0.0773 | 278 | 7.859 | 0.0785 |
| 278 | 8.611 | 0.0861 | 278 | 8.752 | 0.0875 |
| 288 | 9.532 | 0.0953 | 288 | 9.744 | 0.0974 |
| 293 | 10.46 | 0.1046 | 293 | 10.63 | 0.1063 |
| 298 | 11.53 | 0.1153 | 298 | 11.73 | 0.1173 |
| 303 | 12.58 | 0.1258 | 303 | 12.84 | 0.1284 |
| 308 | 13.62 | 0.1362 | 308 | 13.82 | 0.1382 |
| 313 | 14.69 | 0.1469 | 313 | 14.83 | 0.1483 |
| 318 | 15.69 | 0.1569 | 318 | 15.98 | 0.1598 |
| 323 | 16.99 | 0.1699 | 323 | 17.3 | 0.173 |
| 328 | 18.34 | 0.1834 | 328 | 18.66 | 0.1866 |

| **0.5 PSS\0.1NaCl** | | | **0.6 PSS\0.1NaCl** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(ɱs)** | **% Error ±** | **Temp(K)** | **Cond(ɱs)** | **% Error ±** |
| **278** | **7.99** | **0.0799** | **278** | **8.142** | **0.0814** |
| **278** | **9.031** | **0.0903** | **278** | **9.164** | **0.0916** |
| **288** | **9.967** | **0.0996** | **288** | **10.13** | **0.1013** |
| **293** | **10.9** | **0.109** | **293** | **11.07** | **0.1107** |
| **298** | **12.09** | **0.1209** | **298** | **12.24** | **0.1224** |
| **303** | **13.12** | **0.1312** | **303** | **13.43** | **0.1343** |
| **308** | **14.28** | **0.1428** | **308** | **14.5** | **0.145** |
| **313** | **15.26** | **0.1526** | **313** | **15.57** | **0.1557** |
| **318** | **16.44** | **0.1644** | **318** | **16.79** | **0.1679** |
| **323** | **17.73** | **0.1773** | **323** | **18.53** | **0.1853** |
| **328** | **19.3** | **0.193** | **328** | **19.57** | **0.1957** |

| **0.7 PSS\0.1NaCl** | | | **0.8 PSS\0.1NaCl** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(ɱs)** | **% Error ±** | **Temp(K)** | **Cond(ɱs)** | **% Error ±** |
| **278** | **8.415** | **0.0841** | **278** | **8.811** | **0.0881** |
| **278** | **9.552** | **0.0955** | **278** | **9.643** | **0.0964** |
| **288** | **10.59** | **0.1059** | **288** | **10.72** | **0.1072** |
| **293** | **11.71** | **0.1171** | **293** | **11.92** | **0.1192** |
| **298** | **12.75** | **0.1275** | **298** | **13.08** | **0.1308** |
| **303** | **13.92** | **0.1392** | **303** | **14.14** | **0.1414** |
| **308** | **15.11** | **0.1511** | **308** | **15.46** | **0.1546** |
| **313** | **16.2** | **0.162** | **313** | **16.46** | **0.1646** |
| **318** | **17.66** | **0.1766** | **318** | **17.78** | **0.1778** |
| **323** | **18.92** | **0.1892** | **323** | **18.9** | **0.189** |
| **328** | **20.15** | **0.2015** | **328** | **20.14** | **0.2014** |

| 0.9 PSS\0.1NaCL | | | 1.0 PSS\0.1NaCL | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 8.991 | 0.0899 | 278 | 9.029 | 0.0902 |
| 278 | 9.795 | 0.0979 | 278 | 9.905 | 0.099 |
| 288 | 10.82 | 0.1082 | 288 | 11.08 | 0.1108 |
| 293 | 12.09 | 0.1209 | 293 | 12.24 | 0.1224 |
| 298 | 13.23 | 0.1323 | 298 | 13.42 | 0.1342 |
| 303 | 14.39 | 0.1439 | 303 | 14.61 | 0.1461 |
| 308 | 15.72 | 0.1572 | 308 | 16.02 | 0.1602 |
| 313 | 16.72 | 0.1672 | 313 | 17.05 | 0.1705 |
| 318 | 18.16 | 0.1816 | 318 | 18.6 | 0.186 |
| 323 | 19.46 | 0.1946 | 323 | 19.96 | 0.1996 |
| 328 | 20.74 | 0.2074 | 328 | 21.48 | 0.2148 |

| 1.1 PSS\0.1NaCl | | | 1.2 PSS\0.1NaCL | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 9.204 | 0.092 | 278 | 9.376 | 0.0937 |
| 278 | 9.879 | 0.0987 | 278 | 10.42 | 0.1042 |
| 288 | 11.31 | 0.1131 | 288 | 11.48 | 0.1148 |
| 293 | 12.51 | 0.1251 | 293 | 12.77 | 0.1277 |
| 298 | 13.63 | 0.1363 | 298 | 13.87 | 0.1387 |
| 303 | 14.85 | 0.1485 | 303 | 15.06 | 0.1506 |
| 308 | 16.31 | 0.1631 | 308 | 16.67 | 0.1667 |
| 313 | 17.38 | 0.1738 | 313 | 17.76 | 0.1776 |
| 318 | 18.88 | 0.1888 | 318 | 19.4 | 0.194 |
| 323 | 20.3 | 0.203 | 323 | 20.91 | 0.2091 |
| 328 | 21.77 | 0.2177 | 328 | 22.42 | 0.2242 |

| 1.3 PSS\0.1NaCL | | | 1.4 PSS\0.1NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 9.443 | 0.0944 | 278 | 9.562 | 0.0956 |
| 278 | 10.52 | 0.1052 | 278 | 10.8 | 0.108 |
| 288 | 11.72 | 0.1172 | 288 | 12.03 | 0.1203 |
| 293 | 12.98 | 0.1298 | 293 | 13.16 | 0.1316 |
| 298 | 14.14 | 0.1414 | 298 | 14.36 | 0.1436 |
| 303 | 15.41 | 0.1541 | 303 | 15.66 | 0.1566 |
| 308 | 17 | 0.17 | 308 | 17.31 | 0.1731 |
| 313 | 18.11 | 0.1811 | 313 | 18.46 | 0.1846 |
| 318 | 19.77 | 0.1977 | 318 | 20.22 | 0.2022 |
| 323 | 21.24 | 0.2124 | 323 | 21.59 | 0.2159 |
| 328 | 22.68 | 0.2268 | 328 | 23.19 | 0.2319 |

| 1.5 PSS\0.1NaCl | | | 1.6 PSS\0.1NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 9.896 | 0.0989 | 278 | 9.999 | 0.0999 |
| 278 | 10.96 | 0.1096 | 278 | 11.29 | 0.1129 |
| 288 | 12.21 | 0.1221 | 288 | 12.51 | 0.1251 |
| 293 | 13.53 | 0.1353 | 293 | 13.83 | 0.1383 |
| 298 | 14.85 | 0.1485 | 298 | 15.08 | 0.1508 |
| 303 | 16.1 | 0.161 | 303 | 16.41 | 0.1641 |
| 308 | 17.37 | 0.1737 | 308 | 17.75 | 0.1775 |
| 313 | 18.75 | 0.1875 | 313 | 19.18 | 0.1918 |
| 318 | 20.36 | 0.2036 | 318 | 20.93 | 0.2093 |
| 323 | 21.69 | 0.2169 | 323 | 22.17 | 0.2217 |
| 328 | 23.07 | 0.2307 | 328 | 23.77 | 0.2377 |

| 1.7 PSS\0.1NaCl | | | 1.8 PSS\0.1NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 10.21 | 0.1021 | 278 | 10.37 | 0.1037 |
| 278 | 11.45 | 0.1145 | 278 | 11.77 | 0.1177 |
| 288 | 12.72 | 0.1272 | 288 | 13.02 | 0.1302 |
| 293 | 14.08 | 0.1408 | 293 | 14.35 | 0.1435 |
| 298 | 15.34 | 0.1534 | 298 | 15.74 | 0.1574 |
| 303 | 16.63 | 0.1663 | 303 | 17.09 | 0.1709 |
| 308 | 18.15 | 0.1815 | 308 | 18.67 | 0.1867 |
| 313 | 19.58 | 0.1958 | 313 | 20.11 | 0.2011 |
| 318 | 21.28 | 0.2128 | 318 | 21.88 | 0.2188 |
| 323 | 22.82 | 0.2282 | 323 | 23.34 | 0.2334 |
| 328 | 24.3 | 0.243 | 328 | 24.99 | 0.2499 |

| 1.9 PSS\0.1NaCl | | | 2.0 PSS\0.1NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 10.68 | 0.1068 | 278 | 10.72 | 0.1072 |
| 278 | 11.85 | 0.1185 | 278 | 11.89 | 0.1189 |
| 288 | 13.17 | 0.1317 | 288 | 13.2 | 0.132 |
| 293 | 14.49 | 0.1449 | 293 | 14.64 | 0.1464 |
| 298 | 15.85 | 0.1585 | 298 | 16.05 | 0.1605 |
| 303 | 17.24 | 0.1724 | 303 | 17.49 | 0.1749 |
| 308 | 18.82 | 0.1882 | 308 | 19.08 | 0.1908 |
| 313 | 20.25 | 0.2025 | 313 | 20.52 | 0.2052 |
| 318 | 21.98 | 0.2198 | 318 | 22.3 | 0.223 |
| 323 | 23.58 | 0.2358 | 323 | 23.93 | 0.2393 |
| 328 | 25.21 | 0.2521 | 328 | 25.65 | 0.2565 |

**Tables 4. Conductivity of NaPSS in 0.2 NaCl**

| 0.1 PSS\0.2NaCl | | | 0.2 PSS\0.2NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 14.15 | 0.1415 | 278 | 14.29 | 0.1429 |
| 278 | 15.88 | 0.1588 | 278 | 15.98 | 0.1598 |
| 288 | 17.48 | 0.1748 | 288 | 17.61 | 0.1761 |
| 293 | 19.6 | 0.196 | 293 | 19.5 | 0.195 |
| 298 | 21.26 | 0.2126 | 298 | 21.4 | 0.214 |
| 303 | 23.13 | 0.2313 | 303 | 23.17 | 0.2317 |
| 308 | 25 | 0.25 | 308 | 25.24 | 0.2524 |
| 313 | 26.81 | 0.2681 | 313 | 27.05 | 0.2705 |
| 318 | 29.29 | 0.2929 | 318 | 29.59 | 0.2959 |
| 323 | 30.81 | 0.3018 | 323 | 31.19 | 0.3119 |
| 328 | 32.57 | 0.3257 | 328 | 33.09 | 0.3309 |

| 0.3 PSS\0.2NaCl | | | 0.4 PSS\0.2NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 14.52 | 0.1452 | 278 | 14.47 | 0.1447 |
| 278 | 16.34 | 0.1634 | 278 | 16.48 | 0.1648 |
| 288 | 17.89 | 0.1789 | 288 | 18.05 | 0.1805 |
| 293 | 19.81 | 0.1981 | 293 | 19.97 | 0.1997 |
| 298 | 21.7 | 0.217 | 298 | 21.83 | 0.2183 |
| 303 | 23.4 | 0.234 | 303 | 23.59 | 0.2359 |
| 308 | 25.46 | 0.2546 | 308 | 25.64 | 0.2564 |
| 313 | 27.49 | 0.2749 | 313 | 27.64 | 0.2764 |
| 318 | 29.99 | 0.2999 | 318 | 30.17 | 0.3017 |
| 323 | 31.43 | 0.3143 | 323 | 32.05 | 0.3205 |
| 328 | 33.64 | 0.3364 | 328 | 34.35 | 0.3435 |

| 0.5 PSS\0.2NaCl | | | 0.6 PSS\0.2NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 14.68 | 0.1468 | 278 | 14.82 | 0.1482 |
| 278 | 16.44 | 0.1644 | 278 | 16.84 | 0.1684 |
| 288 | 18.31 | 0.1813 | 288 | 18.49 | 0.1849 |
| 293 | 20.25 | 0.2025 | 293 | 20.47 | 0.2047 |
| 298 | 22.12 | 0.2212 | 298 | 22.34 | 0.2234 |
| 303 | 23.9 | 0.239 | 303 | 24.12 | 0.2412 |
| 308 | 26.01 | 0.2601 | 308 | 26.25 | 0.2625 |
| 313 | 28 | 0.28 | 313 | 28.06 | 0.2806 |
| 318 | 30.63 | 0.3063 | 318 | 30.66 | 0.3066 |
| 323 | 32.57 | 0.3257 | 323 | 32.61 | 0.3261 |
| 328 | 35.11 | 0.3511 | 328 | 35.12 | 0.3512 |

| 0.7 PSS\0.2NaCl | | | 0.8 PSS\0.2NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 14.92 | 0.1492 | 278 | 15.82 | 0.1582 |
| 278 | 16.81 | 0.1618 | 278 | 17.02 | 0.1702 |
| 288 | 18.55 | 0.1855 | 288 | 19.02 | 0.1902 |
| 293 | 20.65 | 0.2065 | 293 | 20.88 | 0.2088 |
| 298 | 22.43 | 0.2243 | 298 | 22.74 | 0.2274 |
| 303 | 24.26 | 0.2426 | 303 | 24.8 | 0.284 |
| 308 | 26.45 | 0.2645 | 308 | 26.76 | 0.2676 |
| 313 | 28.58 | 0.2858 | 313 | 28.83 | 0.2883 |
| 318 | 31.07 | 0.3107 | 318 | 31.03 | 0.3103 |
| 323 | 33.1 | 0.331 | 323 | 33.33 | 0.3333 |
| 328 | 35.29 | 0.3529 | 328 | 35.41 | 0.3541 |

| **0.9 PSS\0.2NaCl** | | | **1.0 PSS\0.2NaCl** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(ɱs)** | **% Error ±** | **Temp(K)** | **Cond(ɱs)** | **% Error ±** |
| **278** | **15.38** | **0.1538** | **278** | **15.52** | **0.1552** |
| **278** | **17.2** | **0.172** | **278** | **17.33** | **0.1733** |
| **288** | **19.24** | **0.1924** | **288** | **19.28** | **0.1928** |
| **293** | **21.06** | **0.2106** | **293** | **21.2** | **0.212** |
| **298** | **22.99** | **0.2299** | **298** | **23.18** | **0.2318** |
| **303** | **25.05** | **0.2505** | **303** | **25.3** | **0.253** |
| **308** | **27.02** | **0.2702** | **308** | **27.24** | **0.2724** |
| **313** | **29.08** | **0.2908** | **313** | **29.36** | **0.2936** |
| **318** | **31.45** | **0.3145** | **318** | **31.89** | **0.3189** |
| **323** | **33.96** | **0.3396** | **323** | **34.22** | **0.3422** |
| **328** | **36.03** | **0.3603** | **328** | **36.5** | **0.365** |

| **1.1 PSS\0.2NaCl** | | | **1.2 PSS\0.2NacL** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(ɱs)** | **% Error ±** | **Temp(K)** | **Cond(ɱs)** | **% Error ±** |
| **278** | **15.85** | **0.1585** | **278** | **15.73** | **0.1573** |
| **278** | **18.05** | **0.1805** | **278** | **17.9** | **0.179** |
| **288** | **19.91** | **0.1991** | **288** | **19.63** | **0.1963** |
| **293** | **21.77** | **0.2177** | **293** | **21.6** | **0.216** |
| **298** | **23.82** | **0.2382** | **298** | **23.64** | **0.2364** |
| **303** | **25.96** | **0.2596** | **303** | **25.72** | **0.2572** |
| **308** | **28.07** | **0.2807** | **308** | **27.87** | **0.2787** |
| **313** | **30.14** | **0.3014** | **313** | **29.92** | **0.2992** |
| **318** | **32.86** | **0.3286** | **318** | **32.6** | **0.326** |
| **323** | **35.23** | **0.3523** | **323** | **34.87** | **0.3487** |
| **328** | **37.44** | **0.3744** | **328** | **37.34** | **0.3734** |

| **1.3 PSS\0.2NaCl** | | | **1.4 PSS\0.2NaCl** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(ɱs)** | **% Error ±** | **Temp(K)** | **Cond(ɱs)** | **% Error ±** |
| **278** | **16.17** | **0.1617** | **278** | **16.33** | **0.1633** |
| **278** | **18.01** | **0.1801** | **278** | **18.13** | **0.1813** |
| **288** | **19.97** | **0.1997** | **288** | **20.06** | **0.2006** |
| **293** | **21.9** | **0.219** | **293** | **22.08** | **0.2208** |
| **298** | **24** | **0.24** | **298** | **24.21** | **0.2421** |
| **303** | **26.11** | **0.2611** | **303** | **26.34** | **0.2634** |
| **308** | **28.12** | **0.2812** | **308** | **28.42** | **0.2842** |
| **313** | **30.38** | **0.3038** | **313** | **30.63** | **0.3063** |
| **318** | **32.94** | **0.3294** | **318** | **33.27** | **0.3327** |
| **323** | **35.19** | **0.3519** | **323** | **35.47** | **0.3547** |
| **328** | **37.51** | **0.3751** | **328** | **37.7** | **0.377** |

| **1.5 PSS\0.2NaCl** | | | **1.6 PSS\0.2NaCl** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(ɱs)** | **% Error ±** | **Temp(K)** | **Cond(ɱs)** | **% Error ±** |
| **278** | **16.23** | **0.1623** | **278** | **16.23** | **0.1623** |
| **278** | **18.17** | **0.1817** | **278** | **18.17** | **0.1817** |
| **288** | **20.13** | **0.2013** | **288** | **20.61** | **0.2061** |
| **293** | **22.23** | **0.2223** | **293** | **22.55** | **0.2255** |
| **298** | **24.38** | **0.2438** | **298** | **24.71** | **0.2471** |
| **303** | **26.21** | **0.2621** | **303** | **26.58** | **0.2658** |
| **308** | **28.36** | **0.2836** | **308** | **28.91** | **0.2891** |
| **313** | **30.63** | **0.3063** | **313** | **31.18** | **0.3118** |
| **318** | **32.99** | **0.3299** | **318** | **33.7** | **0.337** |
| **323** | **35.07** | **0.3507** | **323** | **35.88** | **0.3588** |
| **328** | **37.68** | **0.3768** | **328** | **38.34** | **0.3834** |

| **1.7 PSS\0.2NaCl** | | | **1.8 PSS\0.2NaCl** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(ɱs)** | **% Error ±** | **Temp(K)** | **Cond(ɱs)** | **% Error ±** |
| **278** | **16.38** | **0.1638** | **278** | **16.44** | **0.1644** |
| **278** | **18.65** | **0.1865** | **278** | **18.52** | **0.1852** |
| **288** | **20.8** | **0.208** | **288** | **20.8** | **0.208** |
| **293** | **22.89** | **0.2289** | **293** | **22.99** | **0.2299** |
| **298** | **25.03** | **0.2503** | **298** | **25.09** | **0.2509** |
| **303** | **26.94** | **0.2694** | **303** | **27.03** | **0.2703** |
| **308** | **29.3** | **0.293** | **308** | **29.41** | **0.2941** |
| **313** | **31.62** | **0.3162** | **313** | **31.78** | **0.3178** |
| **318** | **34.3** | **0.343** | **318** | **34.36** | **0.3436** |
| **323** | **36.52** | **0.3652** | **323** | **36.53** | **0.3653** |
| **328** | **39.04** | **0.3904** | **328** | **39.28** | **0.3928** |

| **1.9 PSS\0.2NaCl** | | | **2.0 PSS\0.2NaCl** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(ɱs)** | **% Error ±** | **Temp(K)** | **Cond(ɱs)** | **% Error ±** |
| **278** | **16.64** | **0.1664** | **278** | **16.8** | **0.168** |
| **278** | **18.72** | **0.1872** | **278** | **19.15** | **0.1915** |
| **288** | **20.93** | **0.2093** | **288** | **21.2** | **0.212** |
| **293** | **23.17** | **0.2317** | **293** | **23.41** | **0.2341** |
| **298** | **25.39** | **0.2539** | **298** | **25.78** | **0.2578** |
| **303** | **27.39** | **0.2739** | **303** | **27.82** | **0.2782** |
| **308** | **29.81** | **0.2981** | **308** | **30.32** | **0.3032** |
| **313** | **32.25** | **0.3225** | **313** | **32.63** | **0.3263** |
| **318** | **34.92** | **0.3492** | **318** | **35.53** | **0.3553** |
| **323** | **37.03** | **0.3703** | **323** | **37.62** | **0.3762** |
| **328** | **39.7** | **0.397** | **328** | **40.5** | **0.405** |

### Tables 5. Conductivity of NaPSS in 0.3 NaCl

| 0.1 PSS\0.3NaCl | | | 0.2 PSS\0.3NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 20.37 | 0.2037 | 278 | 20.67 | 0.2067 |
| 278 | 22.51 | 0.2251 | 278 | 22.81 | 0.2281 |
| 288 | 25.39 | 0.2539 | 288 | 25.63 | 0.2563 |
| 293 | 27.56 | 0.2756 | 293 | 27.9 | 0.279 |
| 298 | 30.6 | 0.306 | 298 | 31.11 | 0.3111 |
| 303 | 32.75 | 0.3275 | 303 | 33.15 | 0.3315 |
| 308 | 35.25 | 0.3525 | 308 | 35.73 | 0.3573 |
| 313 | 37.59 | 0.3759 | 313 | 38.46 | 0.3846 |
| 318 | 40.79 | 0.4079 | 318 | 41.82 | 0.4182 |
| 323 | 43.59 | 0.4359 | 323 | 44.7 | 0.447 |
| 328 | 46.53 | 0.4653 | 328 | 47.42 | 0.4742 |

| 0.3 PSS\0.3NaCl | | | 0.4 PSS\0.3NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 20.53 | 0.2053 | 278 | 20.75 | 0.2075 |
| 278 | 22.89 | 0.2289 | 278 | 23.01 | 0.2301 |
| 288 | 25.56 | 0.2556 | 288 | 25.91 | 0.2591 |
| 293 | 28.09 | 0.2809 | 293 | 28.36 | 0.2836 |
| 298 | 31.31 | 0.3131 | 298 | 31.48 | 0.3148 |
| 303 | 33.53 | 0.3353 | 303 | 33.95 | 0.3395 |
| 308 | 36.18 | 0.3618 | 308 | 36.8 | 0.368 |
| 313 | 38.92 | 0.3892 | 313 | 39.44 | 0.3944 |
| 318 | 42.34 | 0.4234 | 318 | 42.94 | 0.4294 |
| 323 | 45.4 | 0.454 | 323 | 45.79 | 0.4579 |
| 328 | 47.85 | 0.4785 | 328 | 48.56 | 0.4856 |

| **0.5 PSS\0.3NaCl** | | | **0.6 PSS\0.3NaCl** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(ɱs)** | **% Error ±** | **Temp(K)** | **Cond(ɱs)** | **% Error ±** |
| **278** | **20.73** | **0.2073** | **278** | **21.26** | **0.2126** |
| **278** | **23.16** | **0.2316** | **278** | **23.19** | **0.2319** |
| **288** | **25.9** | **0.259** | **288** | **26.03** | **0.2603** |
| **293** | **28.4** | **0.284** | **293** | **28.7** | **0.287** |
| **298** | **31.41** | **0.3141** | **298** | **31.78** | **0.3178** |
| **303** | **33.81** | **0.3381** | **303** | **34.21** | **0.3421** |
| **308** | **36.75** | **0.3675** | **308** | **37.09** | **0.3709** |
| **313** | **39.84** | **0.3984** | **313** | **40.69** | **0.4069** |
| **318** | **42.8** | **0.428** | **318** | **43.49** | **0.4349** |
| **323** | **46.09** | **0.4609** | **323** | **46.68** | **0.4668** |
| **328** | **48.37** | **0.4837** | **328** | **49.19** | **0.4919** |

| **0.7 PSS\0.3NaCl** | | | **0.8 PSS\0.3NaCl** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(ɱs)** | **% Error ±** | **Temp(K)** | **Cond(ɱs)** | **% Error ±** |
| **278** | **20.94** | **0.2094** | **278** | **21.32** | **0.2132** |
| **278** | **23.74** | **0.2374** | **278** | **23.92** | **0.2392** |
| **288** | **26.41** | **0.2641** | **288** | **26.41** | **0.2641** |
| **293** | **29.05** | **0.2905** | **293** | **29.12** | **0.2912** |
| **298** | **31.94** | **0.3194** | **298** | **31.95** | **0.3195** |
| **303** | **34.57** | **0.3457** | **303** | **34.48** | **0.3448** |
| **308** | **37.45** | **0.3745** | **308** | **37.41** | **0.3741** |
| **313** | **41.09** | **0.4109** | **313** | **40.2** | **0.402** |
| **318** | **43.73** | **0.4373** | **318** | **43.52** | **0.4352** |
| **323** | **47.12** | **0.4712** | **323** | **45.95** | **0.4595** |
| **328** | **49.39** | **0.4939** | **328** | **49.15** | **0.4915** |

| **0.9 PSS\0.3NaCl** | | | **1.0 PSS\0.3NaCl** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(ɱs)** | **% Error ±** | **Temp(K)** | **Cond(ɱs)** | **% Error ±** |
| **278** | **21.28** | **0.2128** | **278** | **21.38** | **0.2138** |
| **278** | **23.74** | **0.2374** | **278** | **23.88** | **0.2388** |
| **288** | **26.35** | **0.2635** | **288** | **26.58** | **0.2658** |
| **293** | **29.27** | **0.2927** | **293** | **29.61** | **0.2961** |
| **298** | **31.94** | **0.3194** | **298** | **32.36** | **0.3236** |
| **303** | **34.72** | **0.3472** | **303** | **35.22** | **0.3522** |
| **308** | **37.74** | **0.3774** | **308** | **38.19** | **0.3819** |
| **313** | **40.64** | **0.4064** | **313** | **41.08** | **0.4108** |
| **318** | **43.93** | **0.4393** | **318** | **44.27** | **0.4427** |
| **323** | **46.59** | **0.4659** | **323** | **47.19** | **0.4719** |
| **328** | **50.08** | **0.5008** | **328** | **50.77** | **0.5077** |

| **1.1 PSS\0.3NaCl** | | | **1.2 PSS\0.3NaCl** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(ɱs)** | **% Error ±** | **Temp(K)** | **Cond(ɱs)** | **% Error ±** |
| **278** | **21.81** | **0.2181** | **278** | **21.74** | **0.2174** |
| **278** | **24.13** | **0.2413** | **278** | **24.22** | **0.2422** |
| **288** | **26.93** | **0.2693** | **288** | **27.12** | **0.2712** |
| **293** | **29.85** | **0.2985** | **293** | **29.86** | **0.2986** |
| **298** | **32.53** | **0.3253** | **298** | **32.54** | **0.3254** |
| **303** | **35.32** | **0.3532** | **303** | **35.54** | **0.3554** |
| **308** | **38.55** | **0.3855** | **308** | **38.71** | **0.3871** |
| **313** | **41.42** | **0.4142** | **313** | **41.48** | **0.4148** |
| **318** | **44.75** | **0.4475** | **318** | **44.84** | **0.4484** |
| **323** | **47.89** | **0.4789** | **323** | **47.58** | **0.4758** |
| **328** | **51.18** | **0.5118** | **328** | **51.28** | **0.5128** |

| **1.3 PSS\0.3NaCl** | | | **1.4 PSS\0.3NaCl** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(ɱs)** | **% Error ±** | **Temp(K)** | **Cond(ɱs)** | **% Error ±** |
| **278** | **21.82** | **0.2182** | **278** | **22.68** | **0.2268** |
| **278** | **24.43** | **0.2443** | **278** | **24.75** | **0.2475** |
| **288** | **27.2** | **0.272** | **288** | **27.84** | **0.2784** |
| **293** | **30.13** | **0.3013** | **293** | **30.35** | **0.3035** |
| **298** | **32.88** | **0.3288** | **298** | **33.22** | **0.3322** |
| **303** | **35.98** | **0.3598** | **303** | **36.32** | **0.3632** |
| **308** | **39.04** | **0.3904** | **308** | **39.47** | **0.3947** |
| **313** | **42.03** | **0.4203** | **313** | **42.31** | **0.4231** |
| **318** | **45.22** | **0.4522** | **318** | **45.59** | **0.4559** |
| **323** | **48.17** | **0.4817** | **323** | **48.66** | **0.4866** |
| **328** | **51.95** | **0.5195** | **328** | **51.17** | **0.5117** |

| **1.5 PSS\0.3NaCl** | | | **1.6 PSS\0.3NaCl** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(ɱs)** | **% Error ±** | **Temp(K)** | **Cond(ɱs)** | **% Error ±** |
| **278** | **22.59** | **0.2259** | **278** | **22.38** | **0.2238** |
| **278** | **24.74** | **0.2474** | **278** | **24.76** | **0.2476** |
| **288** | **27.91** | **0.2791** | **288** | **28** | **0.28** |
| **293** | **30.39** | **0.3039** | **293** | **30.4** | **0.304** |
| **298** | **33.58** | **0.3358** | **298** | **33.46** | **0.3346** |
| **303** | **36.31** | **0.3631** | **303** | **36.49** | **0.3649** |
| **308** | **39.3** | **0.393** | **308** | **39.6** | **0.396** |
| **313** | **42.3** | **0.423** | **313** | **42.54** | **0.4254** |
| **318** | **45.68** | **0.4568** | **318** | **46.33** | **0.4633** |
| **323** | **48.55** | **0.4855** | **323** | **48.97** | **0.4897** |
| **328** | **51.81** | **0.5181** | **328** | **52.24** | **0.5224** |

| 1.7 PSS\0.3NaCl | | | 1.8 PSS\0.3NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 22.95 | 0.2295 | 278 | 22.67 | 0.2267 |
| 278 | 25.27 | 0.2527 | 278 | 25.24 | 0.2524 |
| 288 | 28.28 | 0.2828 | 288 | 28.36 | 0.2836 |
| 293 | 30.09 | 0.3009 | 293 | 30.94 | 0.3094 |
| 298 | 33.79 | 0.3379 | 298 | 33.94 | 0.3394 |
| 303 | 36.78 | 0.3678 | 303 | 37.07 | 0.3707 |
| 308 | 39.99 | 0.3999 | 308 | 40.31 | 0.4031 |
| 313 | 42.98 | 0.4298 | 313 | 43.21 | 0.4321 |
| 318 | 46.66 | 0.4666 | 318 | 47.23 | 0.4723 |
| 323 | 49.69 | 0.4969 | 323 | 50.06 | 0.5006 |
| 328 | 53.01 | 0.5301 | 328 | 53.66 | 0.5366 |

| 1.9 PSS\0.3NaCl | | | 2.0 PSS\0.3NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 23.12 | 0.2312 | 278 | 23.29 | 0.2329 |
| 278 | 25.82 | 0.2582 | 278 | 25.63 | 0.2563 |
| 288 | 28.67 | 0.2867 | 288 | 28.76 | 0.2876 |
| 293 | 31.15 | 0.3115 | 293 | 31.38 | 0.3138 |
| 298 | 34.19 | 0.3419 | 298 | 34.32 | 0.3432 |
| 303 | 37.33 | 0.3733 | 303 | 37.6 | 0.376 |
| 308 | 40.56 | 0.4056 | 308 | 40.84 | 0.4084 |
| 313 | 43.59 | 0.4359 | 313 | 43.97 | 0.4397 |
| 318 | 47.41 | 0.4741 | 318 | 47.88 | 0.4788 |
| 323 | 50.59 | 0.5059 | 323 | 50.94 | 0.5094 |
| 328 | 53.94 | 0.5394 | 328 | 54.56 | 0.5456 |

## Tables 6. Conductivity of NaPSS in 0.4 NaCl

| 0.1 PSS\0.4NaCl | | | 0.2 PSS\0.4NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 26.86 | 0.2686 | 278 | 26.74 | 0.2674 |
| 278 | 29.13 | 0.2913 | 278 | 29.13 | 0.2913 |
| 288 | 32.26 | 0.3226 | 288 | 32.78 | 0.3278 |
| 293 | 35.62 | 0.3562 | 293 | 36.04 | 0.3604 |
| 298 | 39.23 | 0.3923 | 298 | 39.56 | 0.3956 |
| 303 | 42.57 | 0.4257 | 303 | 43.23 | 0.4323 |
| 308 | 45.61 | 0.4561 | 308 | 46.45 | 0.4645 |
| 313 | 49.04 | 0.4904 | 313 | 50.07 | 0.5007 |
| 318 | 52.48 | 0.5248 | 318 | 53.9 | 0.539 |
| 323 | 56.47 | 0.5647 | 323 | 58.2 | 0.582 |
| 328 | 59.91 | 0.5991 | 328 | 61.58 | 0.6158 |

| 0.3 PSS\0.4NaCl | | | 0.4 PSS\0.4NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 26.43 | 0.2643 | 278 | 26.6 | 0.266 |
| 278 | 29.41 | 0.2941 | 278 | 29.72 | 0.2972 |
| 288 | 32.8 | 0.328 | 288 | 32.94 | 0.3294 |
| 293 | 36.18 | 0.3618 | 293 | 36.32 | 0.3632 |
| 298 | 39.67 | 0.3967 | 298 | 39.88 | 0.3988 |
| 303 | 43.2 | 0.432 | 303 | 43.52 | 0.4352 |
| 308 | 46.52 | 0.4652 | 308 | 46.82 | 0.4682 |
| 313 | 50.18 | 0.5018 | 313 | 50.64 | 0.5064 |
| 318 | 54.06 | 0.5406 | 318 | 54.42 | 0.5442 |
| 323 | 58.2 | 0.582 | 323 | 58.86 | 0.5886 |
| 328 | 61.83 | 0.6183 | 328 | 62.42 | 0.6242 |

| 0.5PSS\0.4NaCl | | | 0.6 PSS\0.4NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 26.92 | 0.2692 | 278 | 27.16 | 0.2716 |
| 278 | 29.95 | 0.2995 | 278 | 30.14 | 0.3014 |
| 288 | 33.42 | 0.3342 | 288 | 33.54 | 0.3354 |
| 293 | 36.75 | 0.3675 | 293 | 36.85 | 0.3685 |
| 298 | 40.2 | 0.402 | 298 | 40.2 | 0.402 |
| 303 | 43.78 | 0.4378 | 303 | 44.1 | 0.441 |
| 308 | 47.15 | 0.4715 | 308 | 47.56 | 0.4756 |
| 313 | 51.02 | 0.5102 | 313 | 51.32 | 0.5132 |
| 318 | 54.89 | 0.5489 | 318 | 55.16 | 0.5516 |
| 323 | 59.71 | 0.5971 | 323 | 60.3 | 0.603 |
| 328 | 63.36 | 0.6336 | 328 | 63.42 | 0.6342 |

| 0.7 PSS\0.4NaCl | | | 0.8 PSS\0.4NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 27.46 | 0.2746 | 278 | 27.64 | 0.2764 |
| 278 | 30.79 | 0.3079 | 278 | 30.17 | 0.3017 |
| 288 | 33.95 | 0.3395 | 288 | 33.75 | 0.3375 |
| 293 | 37.11 | 0.3711 | 293 | 37.13 | 0.3713 |
| 298 | 40.36 | 0.4036 | 298 | 40.54 | 0.4054 |
| 303 | 44.19 | 0.4419 | 303 | 44.07 | 0.4407 |
| 308 | 47.68 | 0.4768 | 308 | 47.49 | 0.4749 |
| 313 | 51.48 | 0.5148 | 313 | 51.09 | 0.5109 |
| 318 | 55.49 | 0.5549 | 318 | 55.28 | 0.5528 |
| 323 | 60.61 | 0.6061 | 323 | 58.61 | 0.5861 |
| 328 | 63.76 | 0.6376 | 328 | 62.68 | 0.6268 |

| 0.9 PSS\0.4NaCl | | | 1.0 PSS\0.4NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 27.9 | 0.279 | 278 | 27.69 | 0.2769 |
| 278 | 30.27 | 0.3027 | 278 | 30.74 | 0.3074 |
| 288 | 34.01 | 0.3401 | 288 | 34.28 | 0.3428 |
| 293 | 37.26 | 0.3726 | 293 | 37.5 | 0.375 |
| 298 | 40.84 | 0.4084 | 298 | 40.99 | 0.4099 |
| 303 | 44.51 | 0.4451 | 303 | 44.89 | 0.4489 |
| 308 | 47.79 | 0.4779 | 308 | 48.54 | 0.4854 |
| 313 | 51.54 | 0.5154 | 313 | 52.33 | 0.5233 |
| 318 | 56.15 | 0.5615 | 318 | 56.98 | 0.5698 |
| 323 | 59.51 | 0.5951 | 323 | 60.4 | 0.604 |
| 328 | 63.39 | 0.6339 | 328 | 64.09 | 0.6409 |

| 1.1 PSS\0.4NaCl | | | 1.2 PSS\0.4NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| Temp(K) | Cond(ɱs) | % Error ± | Temp(K) | Cond(ɱs) | % Error ± |
| 278 | 27.7 | 0.277 | 278 | 27.52 | 0.2752 |
| 278 | 30.6 | 0.306 | 278 | 30.83 | 0.3083 |
| 288 | 34.12 | 0.3412 | 288 | 34.35 | 0.3435 |
| 293 | 37.59 | 0.3759 | 293 | 37.72 | 0.3772 |
| 298 | 41.29 | 0.4129 | 298 | 41.5 | 0.415 |
| 303 | 45.11 | 0.4511 | 303 | 45.17 | 0.4517 |
| 308 | 48.88 | 0.4888 | 308 | 49.06 | 0.4906 |
| 313 | 52.55 | 0.5255 | 313 | 52.69 | 0.5269 |
| 318 | 57.2 | 0.572 | 318 | 57.63 | 0.5763 |
| 323 | 61.06 | 0.6106 | 323 | 61.41 | 0.6141 |
| 328 | 64.83 | 0.6483 | 328 | 65.42 | 0.6542 |

| 1.3 PSS\0.4NaCl | | | 1.4 PSS\0.4NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(ɱs)** | **% Error ±** | **Temp(K)** | **Cond(ɱs)** | **% Error ±** |
| 278 | 28.3 | 0.283 | 278 | 27.99 | 0.2799 |
| 278 | 31.35 | 0.3135 | 278 | 31.31 | 0.3131 |
| 288 | 34.78 | 0.3478 | 288 | 34.75 | 0.3475 |
| 293 | 38.11 | 0.3811 | 293 | 38.34 | 0.3834 |
| 298 | 41.91 | 0.4191 | 298 | 42.05 | 0.4205 |
| 303 | 45.55 | 0.4555 | 303 | 45.91 | 0.4591 |
| 308 | 49.57 | 0.4957 | 308 | 49.75 | 0.4975 |
| 313 | 53.09 | 0.5309 | 313 | 53.23 | 0.5323 |
| 318 | 58.12 | 0.5812 | 318 | 58.49 | 0.5849 |
| 323 | 61.75 | 0.6175 | 323 | 62.46 | 0.6246 |
| 328 | 65.91 | 0.6591 | 328 | 66.11 | 0.6611 |

| 1.5 PSS\0.4NaCl | | | 1.6 PSS\0.4NaCl | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(ɱs)** | **% Error ±** | **Temp(K)** | **Cond(ɱs)** | **% Error ±** |
| 278 | 28.24 | 0.2824 | 278 | 27.78 | 0.2778 |
| 278 | 31.41 | 0.3141 | 278 | 31.28 | 0.3128 |
| 288 | 34.77 | 0.3477 | 288 | 35.42 | 0.3542 |
| 293 | 38.56 | 0.3856 | 293 | 38.86 | 0.3886 |
| 298 | 42 | 0.42 | 298 | 42.47 | 0.4247 |
| 303 | 46.09 | 0.4609 | 303 | 46.29 | 0.4629 |
| 308 | 49.34 | 0.4934 | 308 | 50.22 | 0.5022 |
| 313 | 52.53 | 0.5253 | 313 | 53.37 | 0.5337 |
| 318 | 57.6 | 0.576 | 318 | 58.59 | 0.5859 |
| 323 | 60.8 | 0.608 | 323 | 61.89 | 0.6189 |
| 328 | 64.77 | 0.6477 | 328 | 65.99 | 0.6599 |

| **1.7 PSS\0.4NaCl** | | | **1.8 PSS\0.4NaCl** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(ɱs)** | **% Error ±** | **Temp(K)** | **Cond(ɱs)** | **% Error ±** |
| **278** | **28.98** | **0.2898** | **278** | **28.91** | **0.2891** |
| **278** | **31.58** | **0.3158** | **278** | **31.74** | **0.3174** |
| **288** | **35.33** | **0.3533** | **288** | **35.67** | **0.3567** |
| **293** | **38.94** | **0.3894** | **293** | **39.17** | **0.3917** |
| **298** | **42.46** | **0.4246** | **298** | **42.95** | **0.4295** |
| **303** | **46.24** | **0.4624** | **303** | **46.6** | **0.466** |
| **308** | **50.08** | **0.5008** | **308** | **50.48** | **0.5048** |
| **313** | **53.4** | **0.534** | **313** | **53.76** | **0.5376** |
| **318** | **58.54** | **0.5854** | **318** | **59.19** | **0.5919** |
| **323** | **62.32** | **0.6232** | **323** | **63.18** | **0.6318** |
| **328** | **65.99** | **0.6599** | **328** | **66.84** | **0.6684** |

| **1.9 PSS\0.4NaCl** | | | **2.0 PSS\0.4 NaCl** | | |
|---|---|---|---|---|---|
| | | | | | |
| **Temp(K)** | **Cond(ɱs)** | **% Error ±** | **Temp(K)** | **Cond(ɱs)** | **% Error ±** |
| **278** | **28.9** | **0.289** | **278** | **29.07** | **0.2907** |
| **278** | **31.9** | **0.319** | **278** | **32.14** | **0.3214** |
| **288** | **35.68** | **0.3568** | **288** | **36.01** | **0.3601** |
| **293** | **39.18** | **0.3918** | **293** | **39.62** | **0.3962** |
| **298** | **43.02** | **0.4302** | **298** | **43.36** | **0.4336** |
| **303** | **46.75** | **0.4675** | **303** | **47.11** | **0.4711** |
| **308** | **50.62** | **0.5062** | **308** | **51.21** | **0.5121** |
| **313** | **53.88** | **0.5388** | **313** | **54.26** | **0.5426** |
| **318** | **59.2** | **0.592** | **318** | **59.46** | **0.5946** |
| **323** | **63.47** | **0.6347** | **323** | **64.04** | **0.6404** |
| **328** | **66.74** | **0.6674** | **328** | **67.88** | **0.6788** |