

Determination of the diffusion coefficient in sodium chloride solution at different concentrations

Determinação do coeficiente de difusão em uma solução de cloreto de sódio em diferentes concentrações

Determinación del coeficiente de difusión de una solución de cloruro de sodio en diferentes concentraciones

Article Info:

Article history: Received 2019-04-15 / Accepted 2022-03-25/ Available online 2022-03-26

doi: 10.18540/jcecvl8iss3pp14053-01e

Antonio Marcos de Oliveira Siqueira

ORCID: <https://orcid.org/0000-0001-9334-0394>

Universidade Federal de Viçosa, Viçosa, MG, Brazil

E-mail: antonio.siqueira@ufv.br

Gabriel Luz Chaves

Universidade Federal de Viçosa, Viçosa, MG, Brazil

E-mail: gabriel.luz@ufv.br

Joyce de Souza Tanure

Universidade Federal de Viçosa, Viçosa, MG, Brazil

E-mail: joyce.tanure@ufv.br

Luana Ventura Dutra

Universidade Federal de Viçosa, Viçosa, MG, Brazil

E-mail: luana.ventura@ufv.br

Nathan Barros de Souza

Universidade Federal de Viçosa, Viçosa, MG, Brazil

E-mail: nathan.souza@ufv.br

Paula Geovana Gomes

Universidade Federal de Viçosa, Viçosa, MG, Brazil

E-mail: paula.gomes@ufv.br

Thomás Corrêa Vianna

Universidade Federal de Viçosa, Viçosa, MG, Brazil

E-mail: thomas.vianna@ufv.br

Abstract

Phenomena of diffusion are present in several industrial phenomena and therefore need to be properly studied and understood. The study of liquid-liquid diffusion allows to perfect and model several industrial systems. The development of instruments capable of doing this study allows to create methodologies for the development of students of the most diverse engineering. This work employed the study of the diffusion phenomena in a diffusion cell constructed by the authors themselves based on materials found in laboratories, trying to calculate the diffusion coefficient of a solution of sodium chloride in water through the variation of conductivity. The diffusion coefficients obtained presented values in the same order of magnitude in relation to the experimental values reported by other authors and with low experimental error.

Keywords: Diffusion coefficient, Diffusion cell, Sodium chloride.

Resumo

Os fenômenos de difusão estão presentes em vários fenômenos industriais e por isso precisam ser devidamente estudados e compreendidos. O estudo da difusão líquido-líquido permite aperfeiçoar e modelar muitos sistemas industriais. O desenvolvimento de instrumentos capazes de fazer-se este estudo permite criar metodologias para desenvolvimento dos alunos das mais diversas engenharias. Este trabalho empregou o estudo do fenômeno de difusão, em uma célula de difusão construída pelos próprios autores com base em materiais encontrados em laboratórios, querendo-se calcular o coeficiente de difusão de uma solução de cloreto de sódio em água através da variação da condutividade. Os coeficientes de difusão obtidos apresentaram valores na mesma ordem de grandezas em relação aos valores experimentais reportados por outros autores e com erro experimental baixo.

Palavras-Chave: Coeficiente de difusão, célula de difusão, cloreto de sódio.

Resumen

Los fenómenos de difusión están presentes en varios fenómenos industriales y, por lo tanto, deben estudiarse y comprenderse adecuadamente. El estudio de la difusión líquido-líquido permite perfeccionar y modelar varios sistemas industriales. El desenvolvimiento de instrumentos capaces de realizar este estudio posibilita crear metodologías para el desarrollo de estudiantes de diversas ingenierías. Este trabajo empleó el estudio de los fenómenos de difusión en una celda de difusión construida por los propios autores con base en materiales encontrados en laboratorios, tratando de calcular el coeficiente de difusión de una solución de cloruro de sodio en agua a través de la variación de la conductividad. Los coeficientes de difusión obtenidos presentaron valores en el mismo orden de magnitud en relación con los valores experimentales informados por otros autores y con un bajo error experimental.

Palabras clave: Coeficiente de difusión, Celda de difusión, cloruro de sodio.

Introduction

Diffusion is defined as the spontaneous mixing of atoms or molecules by random thermal motion, causing the movement of chemical species relative to the movement of the mixture. In the absence of gradients such as temperature, electrical or gravitational potential, the molecules of a given species within a single phase diffuse from regions of high concentrations to regions of low concentrations, which generates a molar flux of determined in the direction of a concentration gradient (Fogler, 2009; Welty et al., 2017).

One can observe the phenomenon in the diffusion in everyday situations like a drop of paint that falls in a glass with water and the liquid changes of color gradually until everything that is contained in the container becomes colored. Thus, the chemical species that promotes color dilutes and is distributed evenly by the liquid. In this work the process of diffusion of saline solutions in water will be studied, through the variation of the conductivity of the electrolytic solution. Since the electrolytes are formed by a solvent, in this case water, in which a certain substance decomposes into ions. For example, when sodium chloride (NaCl) is dissolved in water, dissolution occurs in Na^+ and Cl^- ions.

A liquid-liquid diffusion cell consists of a system in which the liquid to be diffused comes in contact with the solvent gradually, either through pores, membranes or capillaries, as will occur in the experiments of this work. Thus, the objective was to determine the net diffusion coefficient of saline solutions in distilled water and to compare them with the reference values in the literature.

Bibliographical Review

Mass transfer comprises many chemical processes and underlying separation processes in which one or more components migrate within one phase or from one phase to another through the interface towards a decreasing chemical potential. The transfer mechanism depends on the dynamics of the systems involved. Thus, the transfer can be done by two different transport modes, being they the one of molecular mass and the one by convection (Hamborg et al., 2010; Griskey, 2002). Where a mixture contains two or more molecular compounds in the different relative compositions from point to point, a natural process occurs in the sense of decreasing the inequalities of the compositions until the equilibrium, which is the molecular mass transfer, is achieved, wherein the macroscopic transport, does not depend on any convection within the system (Hamborg et al., 2010; Benítez, 2009).

Convective transfer is divided into two types: if the motion is caused by a pump or any other device, the process is called forced convection transfer; if, on the other hand, the transfer is due to density differences, the process is called natural convection (Hamborg et al., 2010; Wankat, 2012). The movement of molecules in the liquid phase is more complicated to be analyzed and applied to laws than in the gas phase due to intermolecular forces, since they are more intense in liquids than gases. Only in cases of solutions diluted enough that a molecule can only be influenced by the solvent, the movement of molecules can be studied by laws developed for gases (Lino, 1997).

By Fick's law, the diffusion coefficient is a function of the flow of flow and directed to a concentration gradient, and when the concentration gradient is different from zero the process is called interdiffusion. Fick's law can be written in the form of equation 1 (Welty et al., 2017):

$$J_{j,z} = -D_j \frac{\partial C_j}{\partial z} i \quad (1)$$

In what, is the mass flux of component j , in the z -direction; C_j is the concentration; D_j is the diffusion coefficient and i is the unit vector. As the diffusion coefficient is proportional to the particle's motion, the larger the diffusion coefficient the faster the movement between two points (Lino, 1997; Welty et al., 2017). According to Cussler (2009), Zou et al. (2012), and Sun et al. (2015), the diffusion coefficient is a important and basic physical property data in chemical engineering. The knowledge about diffusion coefficient is needed for mass transfer studies and in many other fields such as crystal growth, biological systems, pollution control and separation of isotopes and so on (Cussler, 2009; Zou et al., 2012); Sun et al., 2015).

The size of the molecules interferes in the movement of the particle so that, in a same gradient of concentration, the smaller the molecules the more they move, and the lower their affinity with other molecules present in the solution. In addition, from studies of the entropy of the systems under different conditions, Einsten demonstrated the influence of temperature on the movement of particles, and the increase in temperature implies an increase of total energy of the system and part of that energy converts to kinetic energy, which causes the particle to move faster points (Welty et al., 2017; Cussler, 2009; Lino, 1997). Thus, the higher the temperature, the higher the diffusion coefficient.

In a work carried out Chan and Chan, the solute-solvent interaction was studied, in which pseudo-planar solutes were used with groups forming hydrogen bonds. From the comparison of the diffusion coefficient measure of these species in water and other different solvents, they compared the effects of the solvents on the hydrogen iterations. Thus, they concluded that the diffusion coefficient is sensitive to hydrogen bonds and that, for these compounds, the -OH group forms stronger iterations than the -NH₂, besides that the effects of the bonds are greater in polar solvents than in apolar.

Leaist and Hao (1994) conducted an experiment to measure the diffusion coefficient in a sample of water, solute and HDO injected in a flow of water and solute. The detector measured the difference between water and HDO, and the double adjustment obtained allowed the simultaneous determination of the water-solute diffusion coefficient and the deuterated water was used as a probe. Subsequently, aqueous solutions of sucrose, urea and polyethylene glycol were used to analyze the possibility of being in an infinite dilution, where, the concentration bands where a solute molecule does not suffer any effect of molecules equal to it. In most cases, the difference between the diffusion coefficients at different concentrations is in the order of magnitude of the experimental error.

Gaffney and Chau (2001) and Ribeiro et al. (2002) has been measured the interdiffusion between two liquids by using laser beam deflection method and conductometric technique, respectively. They found the diffusion coefficient of NaCl-aqueous solution in good agreement with coefficient values specified in the literature.

Methodology

The experimental diffusion cell was constructed based on the model shown in Figure 1. Four capillaries were united with Durepoxi ® mass and glued to the bottom of the whole U - shaped, being allowed to dry for a day before use. A known concentration of NaCl solution is placed in a diffusion cell immersed in distilled water.



Figure 1. Diffusion cell.

A magnetic stirrer and a conductivity meter are provided to monitor the progress of diffusion over time. A plot of conductivity against time will allow for the determination of the liquid diffusivity. The experimental module adapted with the diffusion vessel is shown in Figure 2.

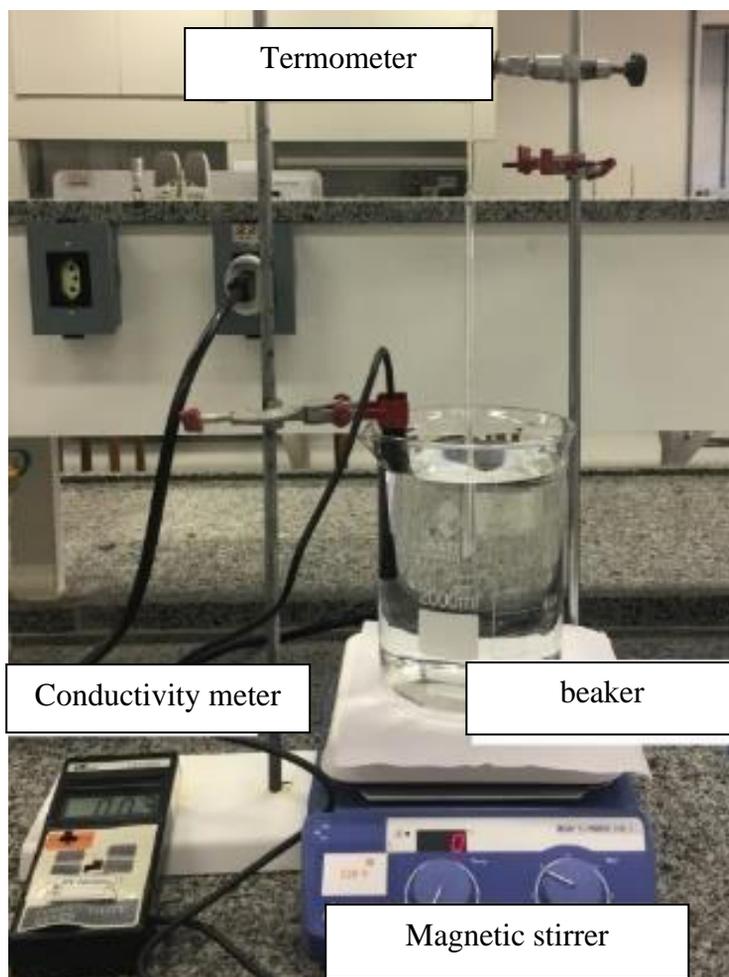


Figure 2. Adapted experimental module.

Material

For the accomplishment of this experiment the following materials were used: salt sodium chloride (Impex®), beakers (1000 ± 10 mL and 2000 ± 2 mL), volumetric flasks (100 ± 1 mL), a conductivity meter (Lutren CD-4301, $e = 10^{-4}$ μS), distilled water, U-tubes with internal diameter of 1 cm, analytical balance (± 0.001 g), stopwatch ($e = \pm 0.005$ s), thermometer ($e = \pm 0.5$ °C), ruler, magnetic stirrer, Pasteur pipette, claws, capillaries with 1.1 mm internal diameter and 3.5 cm height and Durepoxi® mass.

Preparation of the NaCl solutions NaCl

Solutions at five different concentrations (2 mol L^{-1} , 1 mol L^{-1} , 0.5 mol L^{-1} , 0.25 mol L^{-1} and 0.125 mol L^{-1}) were prepared in serial dilutions. 11.688 g of salt was weighed and diluted in 100 ml of distilled water in a volumetric flask. 50 ml of this solution was withdrawn into another 100 ml flask and distilled water was added until the volume was complete. The described procedure was repeated until all five solutions were obtained.

Assembling the Diffusion Cell

Thereafter, the diffusion vessel was assembled: a beaker was filled with 1,200 ml of distilled water. This beaker was then placed under gentle stirring with a magnetic stirrer. To this beaker, with the aid of a claw, the conductivity meter was immersed in the beaker and the initial conductivity of the system was read. A thermometer was also immersed in the beaker in order to measure the temperature

of the system. Using a Pasteur pipette, the diffusion cell was filled with the NaCl solution and this was carefully immersed into the diffusion system, being supported with a claw. The conductivity was read in the first minute and then every 5 min at concentrations of 2 and 1 mol L⁻¹. For the more dilute concentrations of 0.5 mol L⁻¹, 0.25 mol L⁻¹, and 0.125 mol L⁻¹, the time was read at larger intervals (10 min) due to the reading sensitivity of the conduit meter. The same procedure was used for the five concentrations of the salt, in triplicate for each concentration. Through the slope of the regression line of the conductivity data versus time it was possible to calculate the molar diffusion coefficient for each of the concentrations.

Calculation of the diffusion coefficient

The molar diffusion coefficient, D (m² s⁻¹), can be calculated by Equation 01 obtained from the first Fick Law.

$$D = \frac{4 V x}{\pi d^2 N M C_M} \frac{dk}{dt} \quad (2)$$

where V is the volume of the diffusion vessel (L), x is the length of the capillaries (m), d is the internal diameter of the capillaries (m), N is the number of capillaries, M is the concentration of the solution (mol L⁻¹), dk/dt is the slope of the conductivity versus time curve (μS s⁻¹) and C_M is a constant (μS (mol L⁻¹)⁻¹).

For the calculation of the C_M constant, the conductivity of each salt solution was measured and the concentration versus conductivity curve was plotted. The constant is given by the slope of the obtained line.

Results And Discussions

Figures 3 to 7 show the mean values of conductivity as a function of time in relation to the measurements made in triplicate for NaCl solutions of concentrations equal to 2 mol L⁻¹, 1 mol L⁻¹, 0.5 mol L⁻¹, 0.25 mol L⁻¹, 0.125 mol L⁻¹. The coefficients of determination (R^2), which show the correlation between the measured variables, were displayed in the captions.

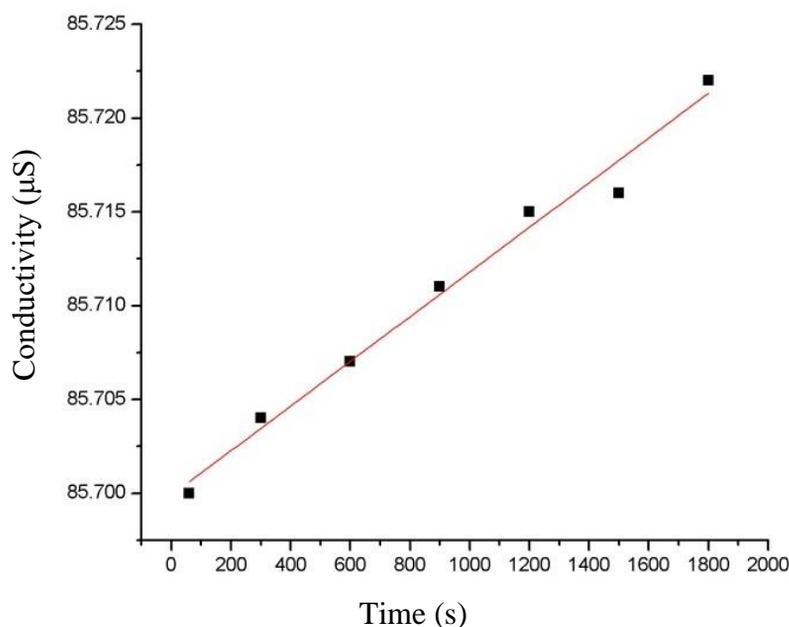


Figure 3. Experimental graph for concentration of 2.0 mol.L⁻¹ ($R^2 = 0.9856$).

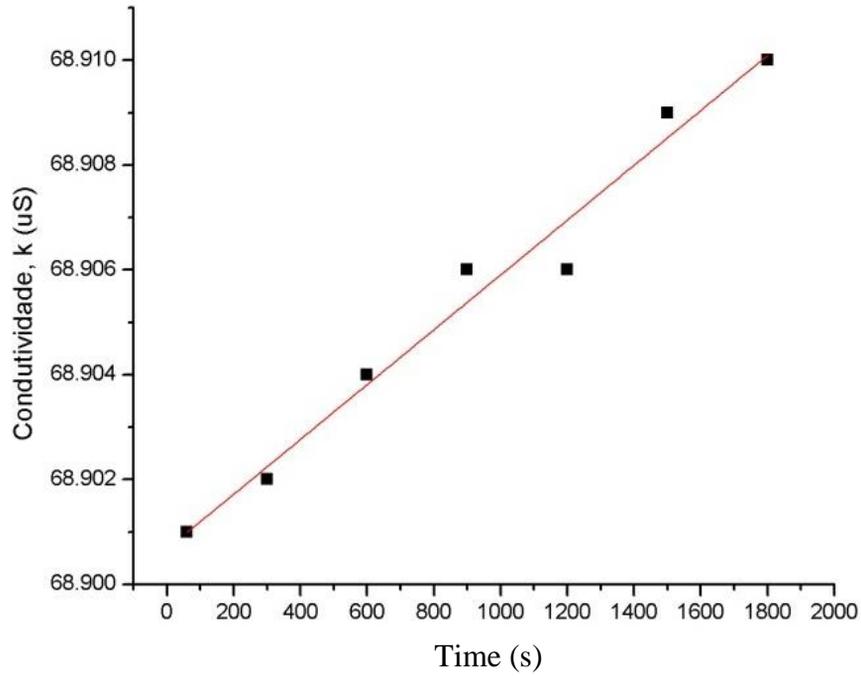


Figure 4. Experimental chart for concentration of 1.0 mol.L^{-1} ($R^2 = 0.9761$).

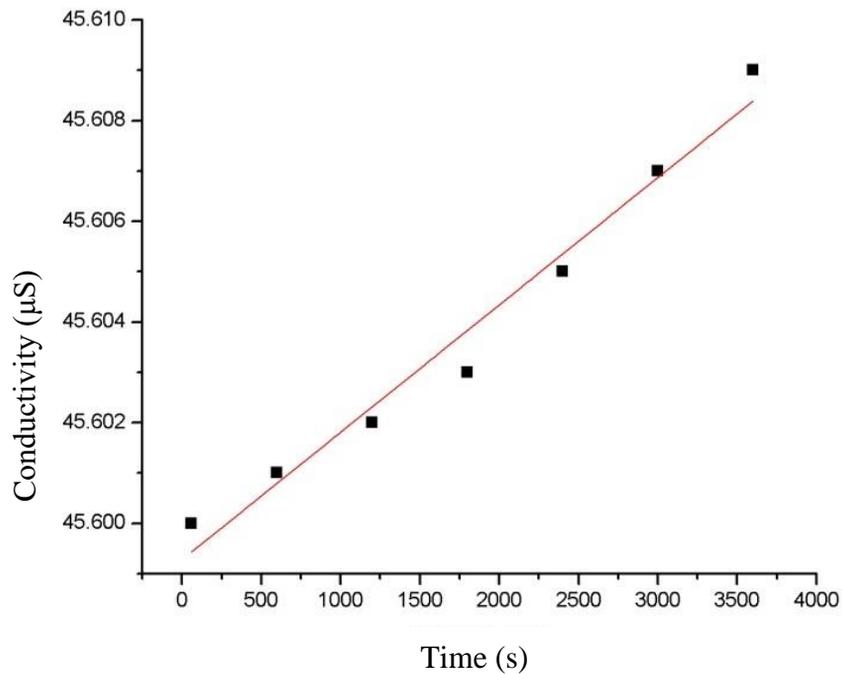


Figure 5. Experimental plot for concentration of 0.5 mol.L^{-1} ($R^2 = 0.9742$).

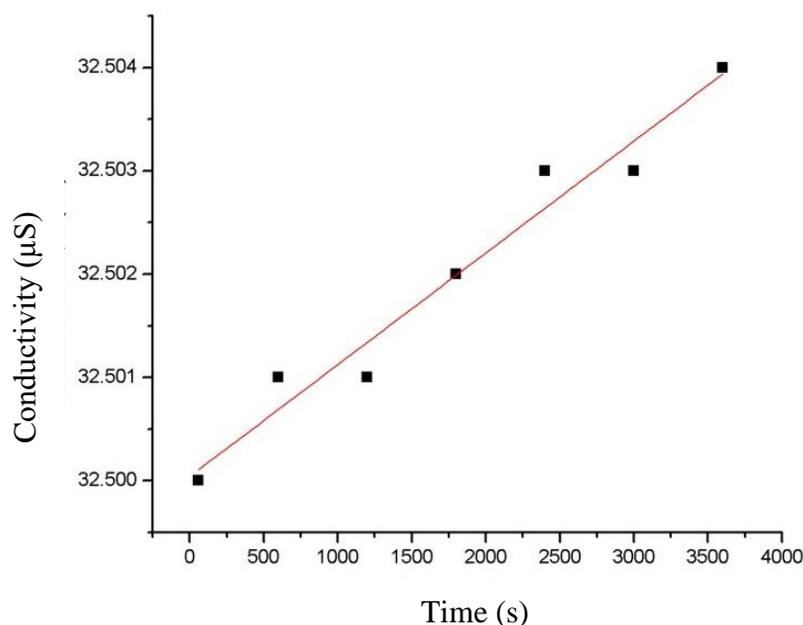


Figure 6. Experimental chart for concentration of 0.25 mol.L^{-1} ($R^2 = 0.9633$).

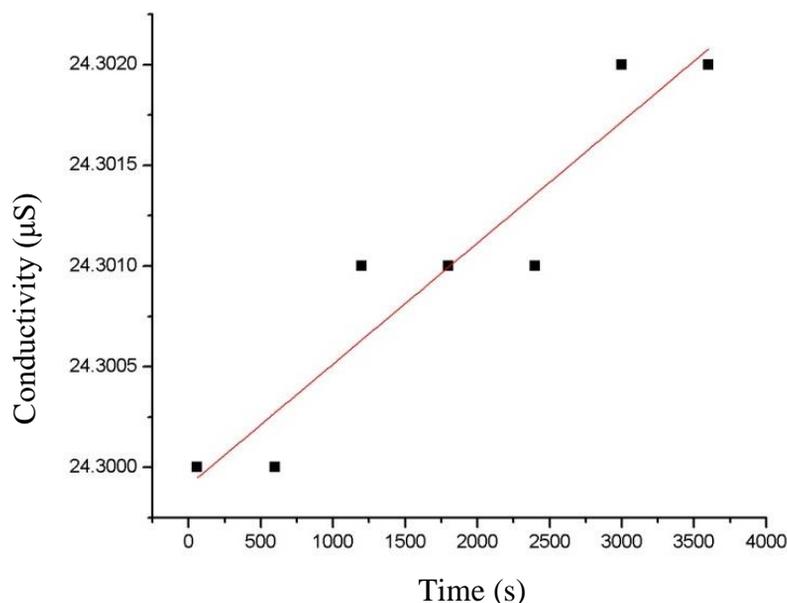


Figure 7. Experimental plot for concentration of 0.125 mol.L^{-1} ($R^2 = 0.8940$).

From the graphs, it is noted that R^2 has a tendency to decrease with the drop in NaCl concentration. In fact, there is a greater dispersion in the experimental data in relation to the linear trend line as shown in Figures 3 and 4. This is explained by the fact that there is little precision of the device used - conductivity meter - in cases of low concentration, where reading by the equipment varies very little and becomes inaccurate. This is evident when analyzing the conductivity data of Figure 5, where a change occurred in the estimate of the fourth decimal place.

It is also noted that experiments conducted at molar concentrations of 0.5 mol L^{-1} , 0.25 mol L^{-1} and 0.125 mol L^{-1} are in function of longer time intervals than those carried out at the concentrations of 2 mol L^{-1} and 1 mol L^{-1} . This was done in order to allow a better reading by the equipment and to minimize the experimental errors, since in larger time intervals a larger amount of NaCl would be diffused from the capillaries to the diffusion vessel.

For each NaCl concentration, the slopes - associated angular coefficients, dk/dt , expressed in Table 1, were obtained from the curves of Figures 3 to 7. The uncertainties (Mills et al., 2004; Andrade et al., 2017; Silva et al., 2017) were calculated using the EES: Engineering Equation Solver® software and are presented in Figure 8.

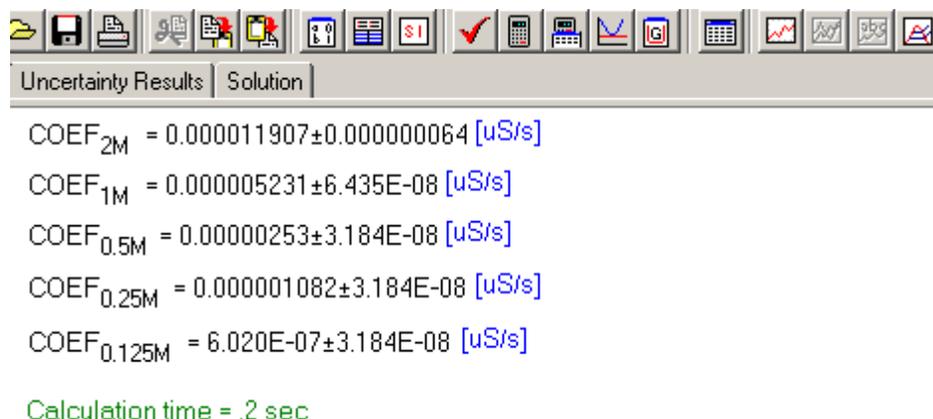


Figure 8. Uncertainties associated to the angular coefficients of each linear regression of data and evaluated by the EES program.

Table 1. Experimental results of the angular coefficients for each molar concentration of NaCl.

Temp., (K)	Conc., (mol L ⁻¹)	Angular coefficient, ($\mu\text{S}\cdot\text{s}^{-1}$)
297.0 ± 0.5	2.000 ± 0.020	$1.191 \times 10^{-5} \pm 6.400 \times 10^{-8}$
297.0 ± 0.5	1.000 ± 0.010	$5.231 \times 10^{-6} \pm 6.435 \times 10^{-8}$
295.0 ± 0.5	0.500 ± 0.005	$2.530 \times 10^{-6} \pm 3.184 \times 10^{-8}$
292.0 ± 0.5	0.2500 ± 0.0025	$1.082 \times 10^{-6} \pm 3.184 \times 10^{-8}$
294.0 ± 0.5	0.1250 ± 0.0013	$6.020 \times 10^{-7} \pm 3.184 \times 10^{-8}$

It can be seen from Table 1 that the uncertainties measured for the slopes referring to the concentrations of 2 mol L⁻¹ and 1 mol L⁻¹ were practically the same. The same holds for the uncertainties regarding the concentrations of 0.5 mol L⁻¹, 0.25 mol L⁻¹ and 0.125 mol L⁻¹, whose values were identical. This indicates that most of the uncertainty in this case is associated with time measurements by the timer.

For the calculation of the CM constant used in Equation 2, we used the conductivity data measured as a function of the NaCl concentration for each of the previously standardized solutions shown in the experimental chart of Figure 9.

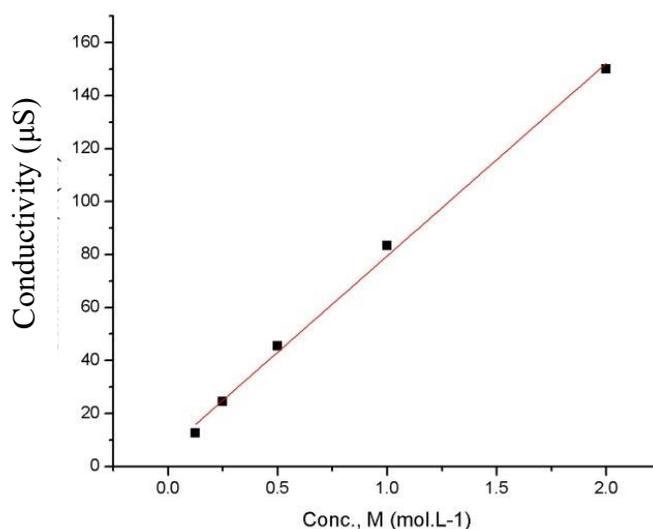


Figure 9. Experimental graph for the calculation of the constant CM ($R^2 = 0.9971$).

The good correlation between the variables is noteworthy, indicating a correct reading by the conductivity meter. The value obtained for the constant CM (regression line angular of the graph of Figure 10) was $(72.678.0 \pm 787.1) \mu\text{S} (\text{mol L}^{-1})^{-1}$, according to data reported by the EES (Figure 10). From the data of Table 1 and the CM constant, the molar diffusivity coefficients of each solution shown in Table 2 were then calculated by Equation 2.

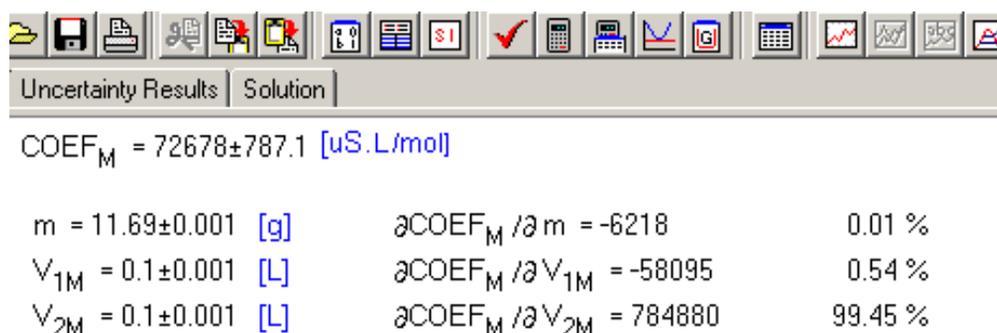


Figure 10. Uncertainty associated with the calculation of the linear regression coefficient by the program EES.

Table 2. Results of the experimental diffusion coefficient at a given temperature for each molar concentration of NaCl.

Temp., (K)	Conc., (mol L ⁻¹)	Diffusion coefficient (m ² s ⁻¹) x10 ⁹
297.0 ± 0.5	2.000 ± 0.020	1.659 ± 0.027
297.0 ± 0.5	1.000 ± 0.010	1.458 ± 0.036
295.0 ± 0.5	0.500 ± 0.005	1.410 ± 0.035
292.0 ± 0.5	0.2500 ± 0.0025	1.206 ± 0.044
294.0 ± 0.5	0.1250 ± 0.0013	1.342 ± 0.077

The propagation of uncertainties associated with these diffusion coefficients and made by the EES is shown in Figure 11.

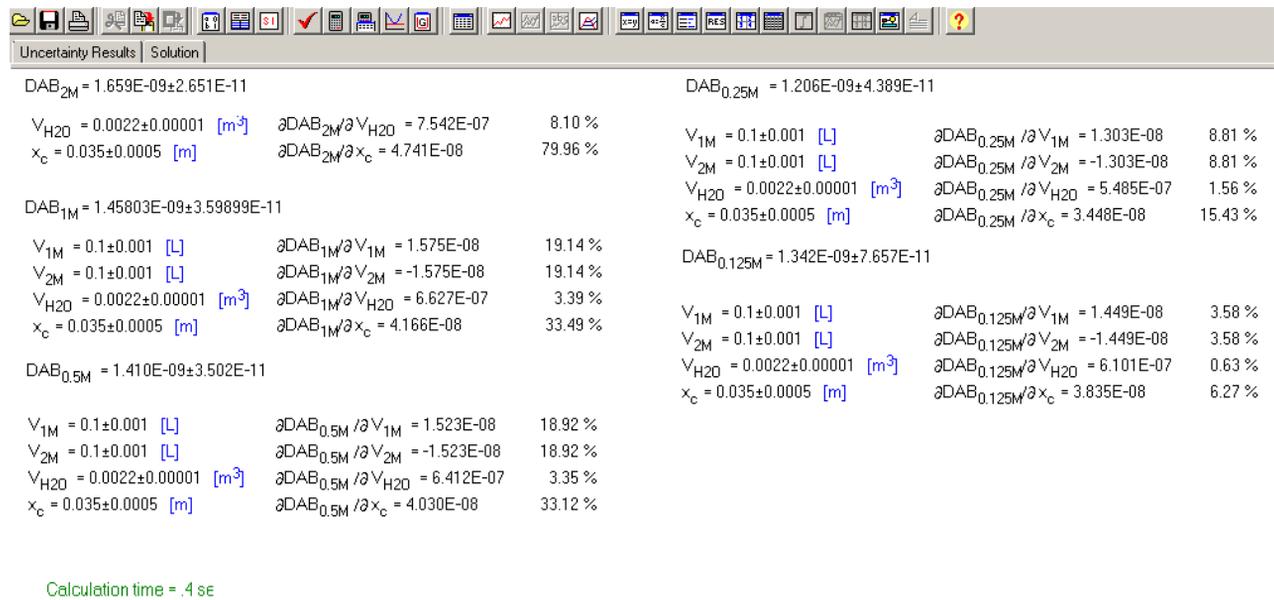


Figure 11. Uncertainty propagation for the values of molar diffusivity coefficient, D_{AB} (m^2 / s).

Figure 11 shows that the uncertainties are basically related to four parameters: the length of the capillary (x_c) measured by the ruler, the volume of the diffusion vessel (V_{H2O}) measured by the 1 L beaker, and the dilution volumes of the solutions (V_{1M} and V_{2M}) measured by the pipette. In other words, the instruments associated with these measures should be used with greater attention. Furthermore, from Table 2, it was found that the uncertainties correlated to D_{AB} were relatively low (less than 2%).

For purposes of comparison with the experimental data, Table 3 was assembled with theoretical diffusion coefficient data (found in the literature) for solutions of different concentrations of NaCl in water. The diffusion coefficients for aqueous solutions of sodium chloride were obtained at $(25 \pm 0.01)^\circ C$, using the Gouy interferometric technique by Vitagliano and Lyons (1956). They supplement existing data, in each case confirm the electrometric results for dilute solutions and assist in the selection of consistent self-diffusion measurements in concentrated sodium chloride solutions

Table 3. Theoretical diffusion coefficients of NaCl solutions

Conc., (mol L ⁻¹)	Diffusion coefficient, (m ² s ⁻¹) x10 ⁹
2.000c	1.5125 ^a , 1.519 ^d
1.000	1.2400 ^b , 1.485 ^d
0.500c	1.4730 ^a , 1.473 ^d
0.2500c	1.4745 ^a
0.1250c	1.4850 ^a

^aValues obtained at 298 K and reported by Chang and Myerson (1985)

^bValue obtained at 291 K and reported by Treybal (1981)

^cconcentration and approximate D_{AB} values.

^dValue obtained at 298 K and reported by Vitagliano and Lyons (1956).

The data in Table 3 are at a different temperature from the experimental data. For this it was necessary to convert them according to Equation 3.

$$D_{AB(T_2)} = D_{AB(T_1)} \left(\frac{T_2}{T_1} \right)^{1,75} \quad (3)$$

Where T_1 and T_2 are the temperatures (in Kelvin). Theoretical and experimental values of D_{AB} were tabulated in Table 4.

Table 4. NaCl Experimental and Theoretical diffusion coefficients.

Temp., (K)	Conc., (mol L ⁻¹)	D _{AB} Experimental, (m ² s ⁻¹) x10 ⁹	D _{AB} , (m ² s ⁻¹) x10 ⁹
297 ± 0.5	2.000 ± 0.020	1.659 ± 0.027	1.504
297 ± 0.5	1.000 ± 0.010	1.458 ± 0.036	1.285
295 ± 0.5	0.500 ± 0.005	1.410 ± 0.035	1.447
292 ± 0.5	0.2500 ± 0.0025	1.206 ± 0.044	1.423
294 ± 0.5	0.1250 ± 0.0013	1.342 ± 0.077	1.450

Each relative error will eventually have an associated uncertainty value due to the experimental value. Therefore, the relative error values were obtained by the EES, according to Figure 12.

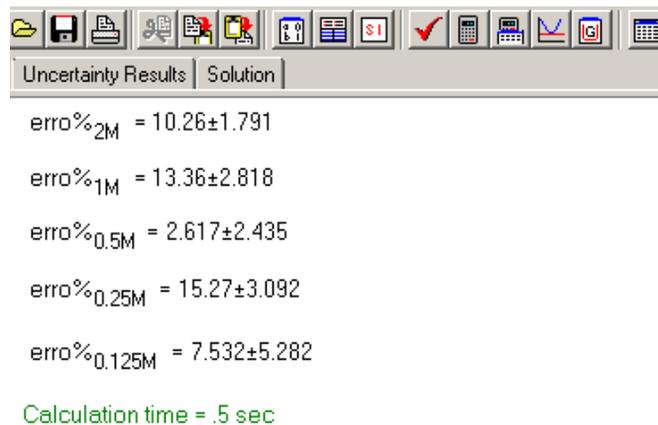


Figure 12. Relative errors and associated uncertainty propagation.

Table 5 summarizes the relative errors obtained and associated uncertainty propagation.

Table 5. Relative errors and associated uncertainties related to the diffusion coefficient calculated for each concentration of NaCl.

Concentration, (mol L ⁻¹)	Relative error, (%)
2.000 ± 0.020	10.260 ± 1.791
1.000 ± 0.010	13.360 ± 2.818
0.500 ± 0.005	2.617 ± 2.435
0.2500 ± 0.0025	15.270 ± 3.092
0.1250 ± 0.0013	7.532 ± 5.282

Note from Table 5 that the uncertainties associated with the errors are high, with some reaching about 90% of the relative error value. In general, it has been that the error values were less than 20%, which represents, in this case, a low value, when dealing with the rusticity of the experiment. Still, it is possible to correlate it to some probable sources. Firstly, it may have been the formation of air within the diffusion cell blisters (U-tube), blocking the capillaries and hindering the diffusion of sodium chloride solution to the diffusion vessel, which reduces the rate of diffusivity. These bubbles may have formed due to the incorrect filling of the diffusion cell with the NaCl solution. To minimize the formation of bubbles at the end or inside the capillaries it is necessary to fill the diffusion cell slowly. In addition, there was inaccuracy at the time of starting and stopping the time measurement in the stopwatch due to the human reaction time. In addition, the solution might not be sufficiently agitated, which would result in a higher concentration of NaCl in the contact surface of the capillaries with the diffusion vessel, since the solution would be poorly homogenized. In the case of the experiment performed, the speed of rotation of the agitator was maintained to minimize the formation of vortices that could arise and cause some destabilization in the diffusion cell structure that was submerged in the vessel. In order to obtain more accurate conductivity readings in this situation, the reader of the conductivity meter could be positioned in a position of greater agitation, that is, next to the magnetic stirrer in the zone of greater depth of the diffusion vessel. In addition, it is possible that the equipment, especially the diffusion vessel, was not sufficiently clean. Cleaning equipment and materials in experiments based on conductivity measurements is of crucial importance, since residues or impurities present may cause erroneous measurements by the apparatus. In the case of this experiment, distilled water was used.

However, in order to obtain better results and to ensure greater removal of impurities, deionized water should be used to clean materials and equipment two or three times. Also, as seen earlier, some conductivity measurements suffered variations so small that they could not be measured with high accuracy. In this case, a high-performance digital conductivity meter is used to guarantee more accurate readings, or even computational systems coupled to the diffusion cell and the conductivity meter. Finally, it was assumed that the temperature of the solution remained constant throughout the experiment. However, this may not be true, since the experimental setup was exposed to the surroundings, making it difficult to guarantee a constant temperature inside the system. However, the temperature affects the diffusion coefficient and, therefore, for this experiment, it would be necessary to isolate the system thermally by minimizing the contact with the surroundings, in order to reduce the errors associated with temperature. Although the temperature was constantly being measured, and no significant variation was observed in the values, the duration of the experiment was extended for 30 or 60 minutes. In this range, it is possible that a slight change in temperature occurred.

Conclusion

It is possible to conclude from the above results that the experiment performed and the methodology used were satisfactory. It was possible to determine the diffusion coefficient of the NaCl solution with relatively small errors due to the approximations and considerations made. Based on the discussions of the errors, it is possible to make the experiment even more precise, using modifications in both the equipment and the experimental apparatus and, consequently, minimizing the experimental errors. However, it is worth noting that this experiment is not only limited to NaCl solutions, it is possible to use it for any electrolytic solutions, that is, solutions of compounds that undergo ionic dissociation in aqueous medium, since its principle is based on the measurement of conductivity solution. The video of the experimental procedures adopted in this article is available online and can be accessed through the link <https://www.youtube.com/watch?v=CCIQT3sWpxM&feature=youtu.be>.

Acknowledgment

The authors thank the support of Federal University of Viçosa (UFV), especially to the Department of Chemistry (DEQ). This paper was carried out with the support of the Higher Education Personnel Improvement Coordination - Brazil (CAPES) - Financing Code 001 and the Minas Gerais State Research Support Foundation (FAPEMIG).

References

- Andrade, A. C. A., Reis, H. F. A. F., Siqueira, A. M. de O., Madureira, M. F., Gouvea, N. A., Gonzaga, L. F., Menezes, T. L. de, & Freire, B. H. de F. (2017). Propagação de incertezas: um experimento acadêmico simples. *The Journal of Engineering and Exact Sciences*, 3(3), 358–368. <https://doi.org/10.18540/jcecvl3iss3pp358-368>
- Benítez, J. (2009). *Principles and Modern Applications of Mass Transfer Operations*, 2nd edition. John Wiley & Sons, Inc.
- Chan, T. C., Ma, N. L., & Chen, N. (1997). The effects of molecular association on mutual diffusion in acetone. *The Journal of chemical physics*, 107(6), 1890-1895.
- Chang, Y. C.; Myerson, A. S. (1985). *The Diffusivity of Potassium Chloride and Sodium Chloride in Concentrated, Saturated and Supersaturated Aqueous Solutions*. School of Chemical Engineering. AIChE Journal. Vol. 31, no. 6. Atlanta.
- Cussler, E. L. (2009). *Diffusion: mass transfer in fluid systems*. 3. ed. New York: Cambridge University Press.
- Fogler, H. S. (2009). *Elementos de Engenharia da Reações Químicas*. Editora LTC – 4ª Ed.
- Gaffney, C., & Chau, C.K. (2001). Using refractive index gradients to measure diffusivity between liquids. *American Journal of Physics*, 69, 821-825.
- Griskey, R. G. (2002). *Transport Phenomena and Unit Operations*, Wiley-Interscience, Editor.
- Hamborg, E. S., Kersten, S. R. A., & Versteeg, G. F. (2010). Absorption and desorption mass transfer rates in non-reactive systems. *Chemical Engineering Journal*, 161(1-2), 191-195. <https://doi.org/10.1016/j.cej.2010.03.079>
- Leaist D G, Hao L. (1994). Simultaneous measurement of mutual diffusion and intradiffusion by Taylor dispersion. *J. Phys. Chem.*, 98(17): 4702-4706.
- Lino, A. C. S. (1997). *Implementação da técnica de Taylor-Aris para medidas de coeficiente de difusão em fase líquida e suas aplicações*. Tese-mestrado, Universidade Estadual de Campinas, SP. 1997.
- Mills, A. F., Chang, B. H. (2004). *Error Analysis of Experiments: A Manual for Engineering Students*. Los Angeles, California.
- Ribeiro, A.C., Lobo, V.M., & Natividade, J.J. (2002). Diffusion coefficients in aqueous solutions of cobalt chloride at 298.15 K. *Journal of Chemical & Engineering Data*, 47, 539-541.
- Silva, F. M. de C., Apolinario, M. da F., Siqueira, A. M. de O., Candian, A. L. M., Moreira, L. A. F., & Sarti, M. R. (2017). Experimento didático de Reynolds e conceitos básicos em Mecânica dos Fluidos. *The Journal of Engineering and Exact Sciences*, 3(3), 346–357. <https://doi.org/10.18540/jcecvl3iss3pp346-357> .
- Sun, L., Meng, W., and Xiaoyun Pu (2015). New method to measure liquid diffusivity by analyzing an instantaneous diffusion image. *Opt. Express* 23, 23155-23166.
- Treybal, E. R. (1981). *Mass-Transfer Operations*. McGraw-Hill Chemical Engineering Series. 3rd Edition. New York.
- Vitagliano, V, & Lyons, P A. (1956). Diffusion coefficients for aqueous solutions of sodium chloride and barium chloride. *J. Am. Chem. Soc.* 1956, 78, 8, 1549–1552. Publication Date: April 1, 1956. <https://doi.org/10.1021/ja01589a011>
- Wankat, P. C. (2012). *Separation Process Engineering*. Prentice Hall, Editor.
- Welty, J. R.; Wicks, C. E.; Wilson, R. E.; Rorrer, G. L. (2017). *Fundamentals of momentum, heat, and mass transfer*. 4. ed. Hoboken (NJ): John Wiley & Sons.

Zou, Y., Shen, Z., Chen, X., Di, Z., & Chen, X. (2012). An integrated tunable interferometer controlled by liquid diffusion in polydimethylsiloxane. *Optics express*, 20(17), 18931–18936. <https://doi.org/10.1364/OE.20.018931>