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Investigation of Heat Transfer Characteristics and Electrical Conductivities in NaCl, KCl, and $NaNO_3$ Solutions

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Abstract

This study aims to optimize heat exchanger systems by investigating the effects of water-soluble salts (NaCl, KCl, and $NaNO_3$) on heat transfer rates and electrical conductivity. Experiments are conducted using plate-type (PHE) and double-pipe (DPHE) heat exchangers. The heat transfer coefficient ranged from 1.5–6.5 kW/m²K in PHE and 3.5–20 kW/m²K in DPHE. NaCl achieves the highest heat transfer rates, followed by KCl and $NaNO_3$, all outperforming pure water. Electrical conductivity peaks at 1 MHz, decreasing afterward, with NaCl and KCl showing higher conductivity than $NaNO_3$. Conductivity increases with temperature, peaking at 70°C, and is more sensitive to temperature for KCl and NaCl. This dual-focus study correlates thermal and electrical properties, illustrating how variations in salt type, concentration, and temperature influence ion behavior, which plays a critical role in optimizing industrial heat transfer and electrical conductivity processes.

Keywords: heat transfer coefficient, conductivity, sodium chloride (NaCl), potassium chloride (KCl), sodium nitrate ($NaNO_3$)

1. Introduction

Heat transfer between flowing fluids is a fundamental physical phenomenon that has long attracted researchers' interest. Several types of heat exchangers are used in different combinations, whereas, fundamentally, they all facilitate the transfer of thermal energy between two distinct fluids at different temperatures. They are integral to the operation of many applications across a wide range of fields, such as the glass and metal melting industries; all power-involved processes and operations, such as refineries, chemical, food, and pharmaceutical industries, waste heat recovery, and environmental engineering. Several types of heat exchangers, including plates, double-pipes, shells, tubes, and compact designs, are used in a variety of applications [1-2]. The fundamental concept in designing a heat exchanger is to use pipes or similar containers to transfer heat between fluids, whether hot or cold. Typically, a heat exchanger consists of coil-shaped pipes circulating the fluid within a closed chamber, allowing another fluid to flow around them.

Heat exchangers can be classified based on several factors: the contact area between hot and cold fluids, the direction of fluid flow, the mechanism of heat transfer, and their mechanical structure. Structurally, heat exchangers are categorized into two main types: plate heat exchangers (PHEs) and coil heat exchangers (CHEs) [3-4].

A plate heat exchanger (PHE) uses metal plates with various folds to transfer heat between two fluids. PHEs are compact and offer numerous advantages and unique application features, including flexible thermal sizing, easy cleaning to maintain hygienic conditions, close approach temperatures due to their pure counterflow operation, and enhanced heat transfer performance [4]. PHE includes multiple alternating channels for hot and cold fluids, each confined between two corrugated

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plates. Compared to shell-and-tube and double-pipe heat exchangers, the use of corrugated plates enhances the heat transfer coefficient and reduces the required heat transfer surface area. PHEs are widely used in various applications, such as cooling systems, food processing, chemical industries, and power generation. They are preferred for their compactness and high heat recovery efficiency [5].

Coil heat exchangers (CHEs) feature one or more pipes or tubes within a pipe shell, with two straight pipe segments joined at one end to create a U or "hairpin" configuration. The outer surface of the inner tube may have longitudinal fins. In this study, a double-pipe heat exchanger (DPHE) system is employed. The flow in a DPHE follows a counter-current configuration, which is advantageous for achieving close temperature approaches and handling a wide range of temperatures [6]. The primary advantage of using double-pipe heat exchangers (DPHEs) is the flexibility of adjusting the number of hairpins to achieve different heat transfer rates. As fins increase the heat transfer surface area, it is essential to allow for optimized arrangements of hairpins. Additionally, DPHEs can accommodate a variety of working fluids supporting higher operating pressures and temperatures. However, DPHEs are typically used in low-capacity heat transfer applications. In high-capacity applications, the pressure drops increase significantly, leading to a notable rise in operating costs [7-8].

The basic tool for heat exchanger design and analysis can be obtained by

$$q = U \cdot A \cdot \Delta T_{LM} \tag{1}$$

where q is the heat transfer rate (W); A is the heat transfer area (m^2); U is the overall heat transfer coefficient (W/m^{2}K); and ΔT_{LM} is the logarithmic mean temperature difference (Kelvin). The mean temperature difference depends on the device's design characteristics of the fluid flow direction [9-10]. The logarithmic mean temperature ΔT_{LM} difference can be calculated by

$$\Delta T_{LM} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \tag{2}$$

The temperature differences ΔT_1 and ΔT_2 between the two fluids are calculated based on the inlet and outlet process temperatures at the four terminals of the equipment. The logarithmic mean temperature difference for two fluid streams exchanging energy in counter-current flow is greater than the value calculated for the same streams in parallel flow. As indicated by Eq. (1), counter-current flow is the preferred design choice because it requires a smaller heat transfer area, and results in lower costs for achieving the same level of heat recovery compared to concurrent flow [10].

This study aims to investigate the effects of salt type, concentration, and temperature on the heat transfer performance and electrical conductivity of water-soluble electrolytes (NaCl, KCl, and $NaNO_3$). By comparing results obtained from plate heat exchangers (PHEs) and double-pipe heat exchangers (DPHEs), the study seeks to identify how these parameters influence the thermal and electrical properties of the solutions, with potential implications for optimizing industrial heat exchange systems.

2. Literature Review

Studying the heat transfer characteristics of aqueous solutions is essential for optimizing the design and operation of heat exchanger systems, improving energy efficiency, reducing operational costs, and enhancing performance. Moreover, understanding the heat transfer behavior of aqueous solutions ensures the safety and reliability of heat exchanger systems. This allows engineers to identify potential issues such as fouling, corrosion, and thermal stress, and implement measures to mitigate these risks. Efficient heat transfer in aqueous solutions reduces energy consumption and greenhouse gas emissions associated with heating and cooling processes. It also facilitates the use of renewable energy sources and waste heat recovery systems. Heat transfer research in aqueous solutions has applications across various industries, including chemical processing, food and beverage production, pharmaceuticals, wastewater treatment, and renewable energy systems [11].

Several recent studies based on heat transfer measurements in nanofluidic systems, exploring experimental, theoretical, and numerical analyses, have been conducted. Kakac & Pramuanjaroenkij (2009) presented a detailed review of experimental and theoretical heat transfer enhancements using nanofluids [12]. Minea (2017) conducted a numerical analysis of hybrid nanofluids and their impacts on heat transfer performance [13]. Another recent study by Rehman et al. (2024) investigates the impacts of radiation and magnetohydrodynamics (MHD) on the water-based nanofluid flow through a shrinking/stretching wedge, with numerical solutions obtained through MATLAB [14].

The study of electrolyte solution conductivity is a crucial field in physical chemistry, with significant scientific inquiry focused on overcoming its fundamental obstacles. Moreover, examining the concentration and temperature dependence of the conductivity of an electrolyte solution is incredibly important for evaluating and improving the performance of electrochemical systems [15]. Chandra and Bagchi (2000) utilized molecular dynamics simulations to investigate the frequency-dependent variation in solution conductivities [16]. Their research revealed that ionic friction distributions occur at high frequencies and are influenced by frequency-dependent friction and electrolyte concentration.

Relative permittivity changes are used to measure material properties employing advanced measurement technologies Yamaguchi et al. (2009) provided a detailed explanation of frequency-dependent conductivity variations, attributing these to the dynamics of ion pairs and fluid flow interactions. Conductivity measurements are significant because they provide essential insights into ion behavior in solutions, facilitating prompt and precise evaluation of solution parameters. This capability is crucial for ensuring quality, safety, and integrity across various industries [17].

Adding solid particles to heat transfer media has long been recognized as an effective technique for enhancing heat transfer. However, using suspended millimeter- or micrometer-sized particles can cause significant issues, such as abrasion, clogging, high-pressure drops, and particle sedimentation [18]. To circumvent these problems, recent studies have focused on using nanoparticles and nanofluids to improve heat transfer characteristics [19-20]. Several recent studies based on electrical conductivity specifically in nanofluids, through experimental, theoretical, and numerical analyses, have been investigated. Choi et al. (1995) conducted one of the foundational studies introducing the concept of nanofluids and discussed their enhanced thermal properties [21].

In the present study, the heat transfer characteristics, and electrical conductivities of common water-soluble salts, including NaCl, KCl, and $NaNO_3$, were investigated. Heat transfer was studied via two different media: plate heat exchangers (PHEs) and double-pipe heat exchangers (DPHEs). The analysis focused on how the type of salt affects the overall heat transfer coefficient and how the inlet temperature of the salt solution influences the heat transfer rate. Additionally, the effects of the salt type, concentration, and temperature on the electrical conductivity of these solutions were examined. By evaluating the heat transfer rates and conductivity values while analyzing the factors influencing them, this study offers insights into the physical properties of ions in solution, the nature and strength of ion interactions, and their effects on heat transfer and electrical conductivity, which are crucial in many industrial operations. This work explores the interplay between electrical conductivity and thermal properties by evaluating the impact of salt type, concentration, and temperature on conductivity. This dual-focus approach, which correlates heat transfer characteristics with the electrical behavior of ion solutions, highlights the underlying physical properties of ions, their interactions, and their influence on both thermal and electrical processes.

The insights gained are particularly significant for industrial applications, where understanding these properties is critical for optimizing heat exchanger performance, designing efficient cooling systems, and improving process efficiencies. The integration of two heat exchanger systems and the detailed analysis of ionic interactions marks a novel contribution to the field, offering practical relevance and advancing the knowledge of heat and mass transfer in electrolyte solutions.

The basic results of the study were that DPHE demonstrated more efficient heat transfer than the PHE. In PHE, the highest heat transfer rate was observed for NaCl, followed by KCl and NaNO3, all of which outperform pure water. The conductivity follows a linear trend with increasing signal frequency up to a threshold of 1 MHz. At low salt concentrations (up to 4% w/w), the conductivity typically increases linearly with increasing salt concentration. Above a concentration of 4%, a further increase in concentration does not result in a significant increase in conductivity.

3. Experimental Studies to Investigate Heat Transfer Rate

The calculation of the heat load and overall heat transfer coefficient in a counter-current flow plate-type heat exchanger (PHE) and a double-pipe heat exchanger (DPHE) is conducted using the same procedure. A schematic of the compact heat exchanger, obtained from Argemsan model HT320 (https://www.argemsan.com/assets/pdf/encatalog.pdf), is presented in Fig. 1. Plate heat exchangers (PHEs) and double pipe heat exchangers (DPHEs) are studied to measure and compare the heat transfer rates of pure water, NaCl, KCl, and $NaNO_3$ salt solutions. PHE and DPHE circuit diagrams on the right-hand side of Fig. 1 display the flows of hot (red) and cold (blue) streams. The hot streams are the tested aqueous solutions, which are cooled by tap water. The experiments are performed for pure water, 2% w/w NaCl, KCl, and $NaNO_3$ solutions in both exchangers, keeping the flow rates of the hot and cold streams constant at 500 L/h and 100 L/h, respectively. Additionally, to observe the effect of temperature on heat transfer, the inlet temperatures of the entering solutions are altered to 25, 30, 40, and 50°C.

In each case, three data sets are recorded for the entering and exiting temperatures of the hot aqueous solutions and cooling water. The average value is calculated for the three datasets in calculating the heat transfer coefficient, specific heat transfer coefficient for water (C_p), and density. The heat load that is drawn from hot water ($\dot{Q}_{hot}$) and the heat load transferred to the cold water ($\dot{Q}_{cold}$) are both calculated by

$$\dot{Q} = \dot{m} \cdot C_p \cdot \Delta T \tag{3}$$

where $\dot{Q}$ is the rate of heat transfer (kJ/s), $\dot{m}$ is the mass flow rate (kg/s), Cp is the specific heat capacity of the water (or saltwater) in kJ/kg K, and ΔT is the temperature difference (K) between inlet and outlet water (or saltwater). The volumetric flow rates of the hot aqueous salt solution and cooling water are kept constant in this study at 500 and 100 liters/h, respectively. The density value is converted to the mass flow rate as follows

$$\dot{m} = \rho \cdot \dot{V} \tag{4}$$

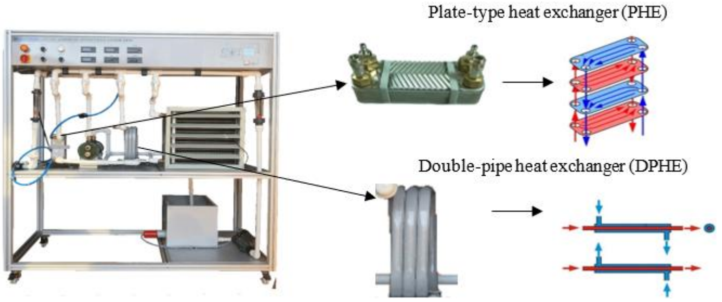


Fig. 1 Setup of the compact heat exchanger system used in this study

Since both density and specific heat capacity values depend on temperature, average values are calculated for both the density and specific heat capacity values evaluated at the inlet and outlet stream temperatures. For the salt solutions, a total of 11 kg of salt solution is prepared by dissolving 0.22 kg of (NaCl, KCl, or $NaNO_3$) to achieve a 2% w/w concentration. For the density and specific heat capacity values of salt solutions, the weighted average value for 2% w/w is evaluated as follows [22]

$$C_{p,mix} = C_{p,water} \cdot 0.98 + C_{p,salt} \cdot 0.02 \tag{5}$$

The Cp values for NaCl, KCl, and $NaNO_3$ are estimated utilizing the NIST Chemistry WebBook (webbook.nist.gov), where the solid phase heat capacity is calculated using the Shomate equation as follows

$$C_{p,salt} = A + B \cdot T + C \cdot T^2 + D \cdot T^3 + \frac{E}{T^2} \tag{6}$$

where A to E are salt-specific constants, and T represents the temperature in Kelvin, divided by 1000 [23]. The overall heat transfer coefficient U is then obtained by

$$U = \frac{\dot{Q}}{A \cdot \Delta T_{LM}} \tag{7}$$

where U is the overall heat transfer coefficient (kW/m^{2}K), $\dot{Q}$ is the rate of heat transfer from the hot stream (kW), and A is the cross-sectional area of the exchanger, which is 0.0299 and 0.168 m^2 for the DPHE and PHE systems, respectively. ΔT_{LM} is the logarithmic temperature difference (Kelvin) given by Eq. (2). For the counter-current flow regime, ΔT_1 represents the temperature difference between the hot stream outflow and cold stream inflow, whereas ΔT_2 represents the temperature difference between the hot stream inflow and the cold stream outflow. For heat transfer experiments, the salt mixtures are assumed to enter the heat exchangers as perfectly mixed and homogenous streams, temperature and flow rates are kept constant throughout the system, while density and specific heat values are averaged over the temperature range. The flow regimes in the heat exchanger systems are entirely laminar, with the Reynolds number ranging from 110 to 185 for pure water and 2% w/w water-salt systems.

4. Experimental Studies to Investigate Conductivity

The electrical conductivity of a material is related to its ability to conduct an electric current. The electrical conductivity, σ, measured in Siemens per meter (S/m), is a characteristic of all materials. For highly conductive materials such as metals, this value is approximately 10^7 S/m, whereas for poorly conductive or insulating materials such as quartz, it is approximately 10^{-18} S/m. The conductivity values of aqueous solutions fall between these values. To measure the conductance of an electrolyte, two electrodes are immersed into the solution, and a voltage is applied. This setup generates a current in the external circuit connecting the electrodes. However, using DC voltages can lead to electrolysis and polarization of the electrodes, which eventually reduces the current passing through the circuit to zero. This issue can be avoided by using an alternating current (AC). When AC voltage is applied to the sample, both the in-phase current (related to the conductance) and the out-of-phase current (related to the capacitance, C) are monitored over a range of frequencies using an impedance analyzer. This method is known as admittance (or impedance) spectroscopy [24].

In the present study, the electrical conductivity of the samples is tested with an SFG-1003-Gw Instek function generator, i.e., direct digital synthesis (DDS) with 1 channel, 3 MHz, and an AATech ADS-3072B digital oscilloscope. Electrical measurements involved placing probes into the prepared salt solutions in a beaker. The electrical conductivity and resistance of the salt solutions were measured using an AC circuit. The frequency is optimized by scanning a range from 1 Hz to 3 MHz. Fig. 2 shows an image of the experimental setup, which consists of a frequency generator and digital oscilloscope for conductivity measurements in Fig. 2(a) along with the AC circuit of the setup in Fig. 2(b). The variable resistance icon represents the resistance values obtained for the salt solutions. To determine the circuit's current, I (A), a 50 Ohm resistor (R_1) is added to the system. The voltage (V_{R1}) across the 50 Ohm resistor is divided by this resistance value to find the current, which is constant for all circuits, as presented in Eq. (8). The voltage across the aqueous salt solution (V_{R2}) is then calculated using Eq. (9), subtracting the voltage across the 50 Ohm resistor (V_{R1}) from the source voltage (V_{source}) [25]:

$$I(A) = \frac{V_{R_1}}{R_1} \tag{8}$$

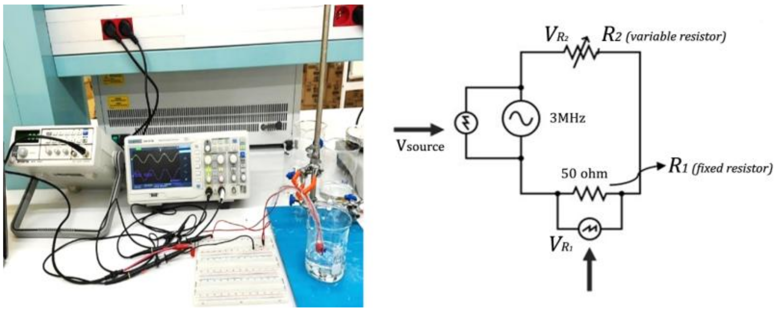
$$V_{R_2} = V_{Source} - V_{R_1} \tag{9}$$

To determine the resistance of the salt solution (R_2), V_{R2} is divided by the following equation

$$R_2 = \frac{V_{R_2}}{I} \tag{10}$$

$$\sigma = \frac{1}{R_2} \tag{11}$$

where R_2, assumed to represent impedance, is used to derive the conductivity value σ in Siemens per centimeter (S/cm) by taking the reciprocal of R_2 ($1/R_2$), as given by Eq. (11). For the conductivity measurements it is assumed that the voltage readings are uniform throughout the solutions, the frequency generator supplies a constant frequency, then the voltage difference between the source and the sample is used to calculate the resistance of solutions.



(a) Frequency generator and digital oscilloscope (b) Diagram of the AC circuit setup

Fig. 2 Experimental setup for conductivity measurements

5. Results and Discussion

The results are divided into two sections: heat transfer and conductivity measurements. Heat transfer results, obtained from experiments on plate-type and coiled heat exchanger systems, represent the average of three runs per measurement. Conductivity measurements are recorded, after stabilizing the oscilloscope voltage readings for both the sample and the source.

5.1. *Heat transfer measurements*

The salt solutions serve as the hot fluid in the heat exchanger system while cooling is maintained with cold water. The overall heat transfer coefficient is determined for the PHE and DPHE systems using pure water and 2% w/w NaCl, KCl, and $NaNO_3$ salt solutions. Additionally, keeping the concentration of salt solutions constant at 2%, the effect of increasing the inlet temperatures of the salt solutions on the heat transfer characteristics of both the PHE and the DPHE systems is investigated. For each measurement, three data sets are recorded, and the average U value, along with the standard error, is reported. The raw data for the average U values obtained from the studied systems are presented in Tables 1 and 2 for DPHE and PHE systems.

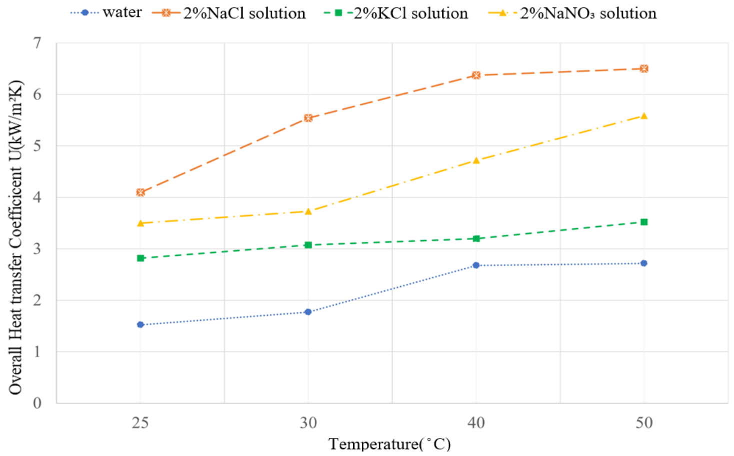
Table 1 Overall heat transfer coefficient (*U*) values with standard errors obtained for the systems studied in the DPHE

Overall Heat Transfer Coefficient Values (kW/m^{2}K)				
Temperature	Double pipe heat exchanger (DPHE)			
	Pure Water	2% NaCl	2% KCl	2% $NaNO_3$
25°C	8,62±0,16	8,63±0,85	3,60±0,79	4,09±0,23
30°C	13,08±0,18	20,26±0,60	16,73±0,35	18,36±0,46
40°C	14,11±0,13	15,29±0,55	15,05±0,68	13,02±0,12
50°C	13,42±0,12	12,31±0,70	11,63±0,15	13,35±0,09

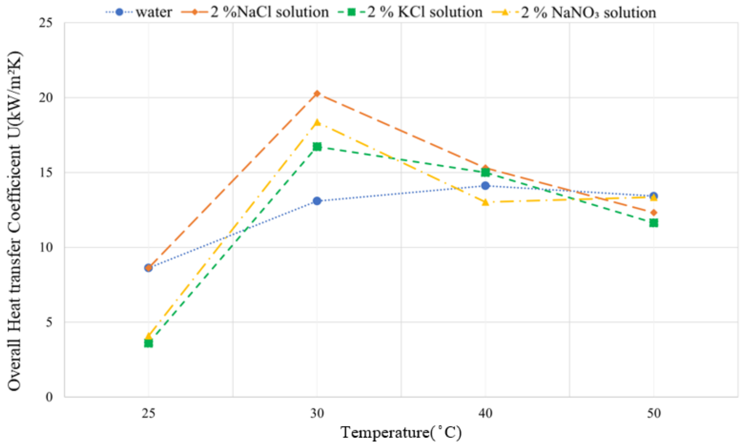
Table 2 Overall heat transfer coefficient (*U*) values with standard errors obtained for the systems studied in the PHE

Overall Heat Transfer Coefficient Values (kW/m^{2}K)				
Temperature	Plate type heat exchanger system (PHE)			
	Pure Water	2% NaCl	2% KCl	2% $NaNO_3$
25°C	1,52±0,07	4,09±0,24	2,82±0,17	3,50±0,22
30°C	1,77±0,09	5,54±0,46	3,07±0,12	3,73±0,17
40°C	2,68±0,02	6,37±0,42	3,20±0,13	4,72±0,21
50°C	2,72 ± 0,04	6,50±0,50	3,52±0,13	5,59±0,18

In the PHE system, the overall heat transfer coefficient ranges from 1.52 to 6.50 kW/m^{2}K, whereas in the DPHE system, it varies more widely between 3.60 and 20.26 kW/m^{2}K. The corresponding profiles for all salts and pure water in both heat exchanger types are presented in Fig. 3, with PHE in Fig. 3(a) and DPHE in Fig. 3(b).



(a) PHE



(b) DPHE

Fig. 3 Variation of the overall heat transfer coefficient (*U*) with temperature measured in a PHE (a) and DPHE (b)

Consequently, this study demonstrates the DPHE achieves more efficient heat transfer than the PHE. This may also explain why similar heat transfer profiles are obtained for water and saltwater systems in the DPHE in Fig. 3(a). In contrast, the differences between the studied systems are particularly noticeable in the case of PHE in Fig. 3(b). In PHE, the highest heat transfer rate is obtained for NaCl, followed by KCl and $NaNO_3$, all of which surpass pure water. This finding aligns with previous research, which indicates that the heat transfer coefficient of salt solutions is greater than that of pure water and increases with increasing salt concentration [26].

The inlet fluid temperature (water or saltwater) strongly influences heat transfer. As the temperature of the inlet water or salt solutions increases from the ambient temperature of 25°C to 50°C, the overall heat transfer coefficient (*U*) also increases. The contrast is particularly noticeable in PHE compared with DPHE. In the DPHE, once the temperature reaches 40°C, U values for water and salt solutions become nearly identical and stabilize, indicating that there is no significant difference in heat transfer characteristics between water and saltwater solutions. Additionally, the influence of the type of salt also becomes less distinguishable.

The thermophysical properties of sodium chloride (NaCl) solutions are more extensively studied than those of potassium chloride (KCl) and sodium nitrate ($NaNO_3$) solutions [27]. NaCl-rich water is prevalent in subsurface environments, including geothermal reservoirs, deep aquifers, and regions affected by saltwater intrusion. Therefore, previous research on the thermophysical behavior of NaCl solutions can provide a basis for understanding the properties of KCl and $NaNO_3$ solutions [28]. In this study, the heat transfer characteristics of these salts are found to be similar, especially in the DPHE system. However, there is a more significant difference among the salt solutions in the PHE system, and the highest U value is obtained in the NaCl solution.

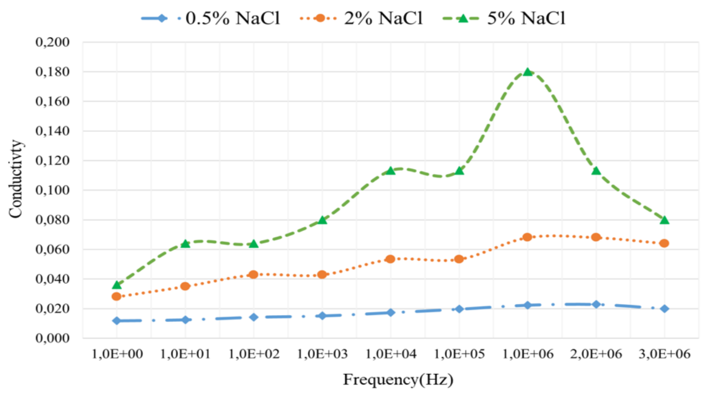
5.2. Conductivity measurements

To determine the optimal signal frequency, frequency scans from 1 Hz to 3 MHz on NaCl, KCl, and $NaNO_3$ solutions are conducted at three different concentrations, 0.5%, 2.0%, and 5%, while maintaining a constant temperature at 23°C. The raw conductivity data (σ) values for different frequencies obtained from the studied systems are presented in Table 3.

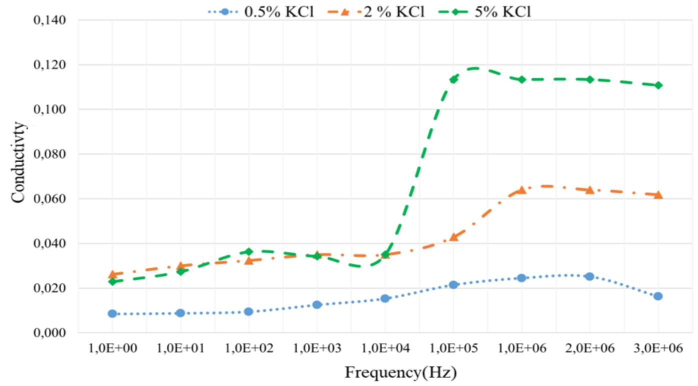
Table 3 Conductivity values for salt solutions measured at different frequencies

Signal frequency	Conductivity (σ)					
	NaCl 0.5%	NaCl 5%	KCl 0.5%	KCl 5.0%	$NaNO_3$ 0.5%	$NaNO_3$ 5%
1 Hz	0.012	0.036	0.008	0.023	0.007	0.018
10 Hz	0.013	0.064	0.009	0.027	0.007	0.020
100 Hz	0.014	0.064	0.009	0.036	0.006	0.026
1KHz	0.015	0.080	0.012	0.034	0.007	0.031
10 KHz	0.017	0.113	0.015	0.035	0.008	0.038
100 KHz	0.020	0.113	0.021	0.113	0.009	0.043
1 MHz	0.022	0.180	0.024	0.113	0.011	0.053
2 MHz	0.023	0.113	0.025	0.113	0.011	0.053
3 MHz	0.020	0.080	0.016	0.111	0.012	0.050

An illustration of the variation in conductivity values of these salt solutions with increasing signal frequency is depicted in Fig. 4. Panels (a), (b), and (c) represent NaCl, KCl, and $NaNO_3$ solutions, respectively. Upon examination of the profiles, it can be inferred that the conductivity follows a linear trend for all investigated systems up to a certain frequency threshold, which is determined as 1 MHz in this study. The conductivity values increase with frequency, peaking at approximately 1 MHz and then either decreasing or remaining constant with further increases in frequency. Consequently, the optimal frequency for all the salt solutions is determined to be 1 MHz. Beyond this frequency, all three salt solutions exhibit resistive behavior, and the conductivity becomes independent of the signal frequency. By determining the optimum frequency value, the effect of concentration on conductivity is explored for the three aqueous salt solutions while keeping the temperature and frequency constant at 1 MHz.

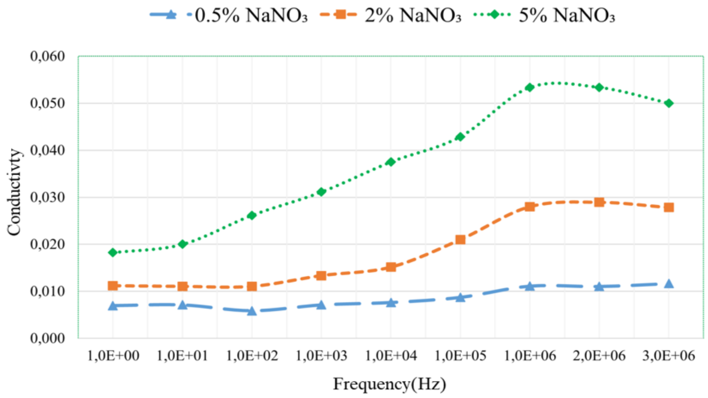


(a) Conductivities of NaCl-water solution at 20°C at different frequencies



(b) Conductivities of KCl solutions at different frequencies

Fig. 4 Conductivity profiles of NaCl (a), KCl (b), and $NaNO_3$ (c) solutions at different frequencies



(c) Conductivities of $NaNO_3$ solutions at different frequencies

Fig. 4 Conductivity profiles of NaCl (a), KCl (b), and $NaNO_3$ (c) solutions at different frequencies (continued)

The viscosity of a solution is defined as its resistance to flow and is a function of the solute concentration and mass of its particles. When more ions are introduced into a solution, the resistance to flow is enhanced. Additionally, as the concentration of ions in the solution increases, they are positioned closer together, reducing the distance between them. Consequently, the resistance of the solution decreases because more ions are available to carry the electrical charge, and there is less free space in between. Therefore, a more concentrated solution can conduct more current. Additionally, when ions are dissolved in different solutions, the conductivity depends on the specific electrolyte used. Several types of ions and their mobility affect the conductivity of a solution [29]. At low salt concentrations, the conductivity typically increases with increasing salt concentration. However, in certain viscous solutions, reduced ion mobility can lead to a decline in conductivity despite the higher concentration [28]. Fig. 4 demonstrates that the conductivities of all aqueous salt solutions (NaCl, KCl, and $NaNO_3$) increase with increasing salt concentration, which aligns with the findings in literature review.

To better illustrate the effect of salt concentration on conductivity, with the frequency fixed at 1 MHz, a wide concentration range of 0.5-20% w/w is investigated next, and the results are depicted in Fig. 5. As the salt concentration increased, the conductivity rose until reaching 4–5% w/w. Above 5%, further increases in concentration had no significant effect on conductivity, which remained constant. Consequently, the lower concentration range is prioritized for conductivity measurements to evaluate the effects of salts more efficiently. This approach is also adopted in heat transfer studies.

Additionally, using lower salt concentrations minimized the risk of altering the instrument's internal structure, which could otherwise be compromised by salt-induced aggregation within the circulating system, thereby preventing potential disruption. This finding aligns with the study by Bera and colleagues, who investigated the conductivity of a KCl solution conductivity and reported that it follows a linear function of concentration up to 1%. Beyond this threshold, they found that the rate of increase in conductivity decreases due to the greater ion concentration effects [29].

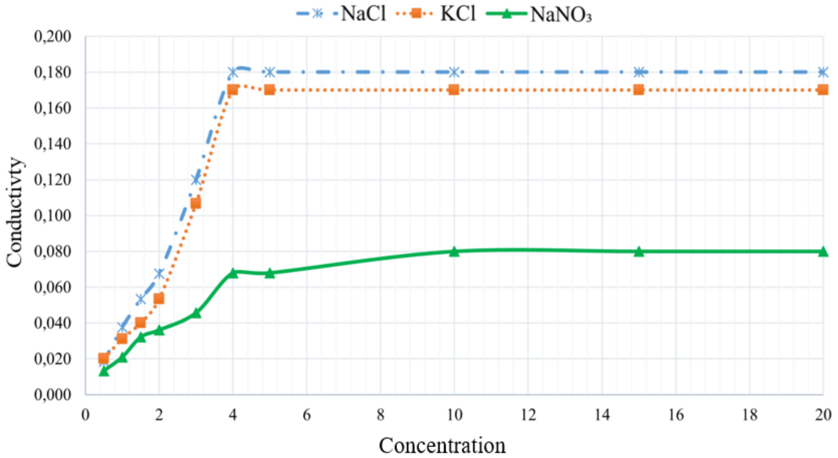


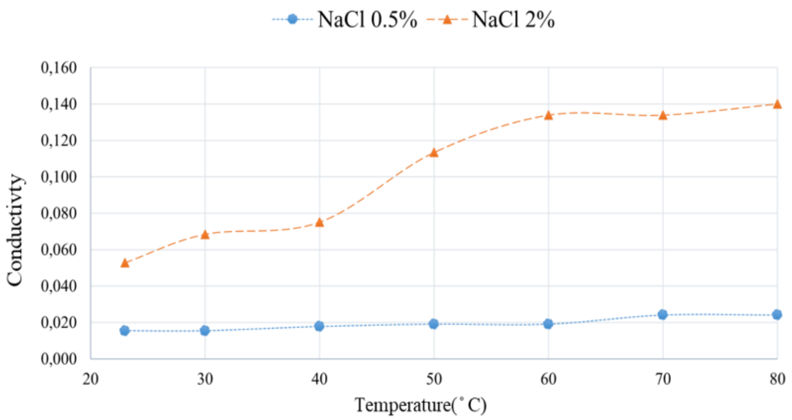
Fig. 5 Conductivity profiles for NaCl, KCl, and $NaNO_3$ salt solutions at 1 MHz and at different concentrations

In the present study, this critical concentration is determined to be approximately 4% w/w. Interestingly, the same trend and critical concentration value were observed for all salt solutions independently. It can also be concluded that conductivity is not a colligative property, meaning that it depends on both the type and amount of solute. NaCl and KCl yielded similar values and trends, with NaCl exhibiting slightly higher conductivity than KCl at the same concentration. However, $NaNO_3$ demonstrated significantly lower conductivity than NaCl and KCl. Previous heat transfer experiments have consistently shown that NaCl results in a higher heat transfer rate at the same temperature and concentration than KCl and $NaNO_3$. Therefore, NaCl also demonstrated the highest conductivity among the tested salt solutions.

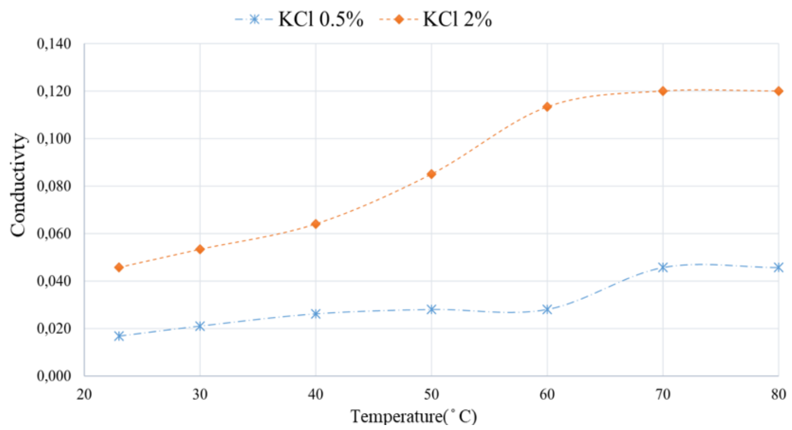
To examine the impact of temperature on the conductivity of the salt solutions, two different concentrations (0.5% and 2% w/w) are tested for each salt solution, with temperatures ranging from 23°C to 80°C. Lower concentrations are selected to minimize the influence of high salt concentrations, allowing for a clearer assessment of the effect of increasing temperature. The raw data for the conductivity (σ) values obtained from the experiments at different temperatures are presented in Table 4.

Table 4 Conductivity values for salt solutions measured at different temperatures

Conductivity(σ)						
Temperature	NaCl 0.5%	NaCl 2%	KCl 0.5%	KCl 2%	$NaNO_3$ 0.5%	$NaNO_3$ 2%
23 °C	0.015	0.053	0.017	0.046	0.012	0.026
30 °C	0.015	0.068	0.021	0.053	0.010	0.028
40 °C	0.018	0.075	0.026	0.064	0.009	0.028
50 °C	0.019	0.113	0.028	0.085	0.013	0.032
60 °C	0.019	0.134	0.028	0.113	0.015	0.040
70 °C	0.024	0.134	0.046	0.120	0.019	0.044
80 °C	0.024	0.140	0.046	0.120	0.019	0.040

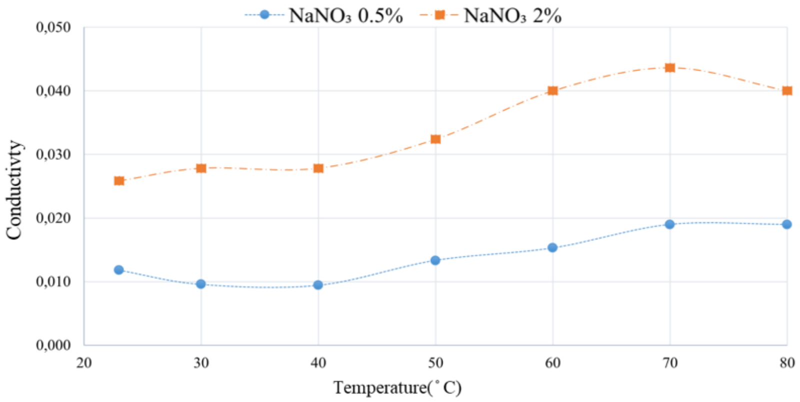


(a) Effect of temperature on NaCl-water solution conductivity at 1 MHz



(b) Effect of temperature on KCl-water solution conductivity at 1 MHz

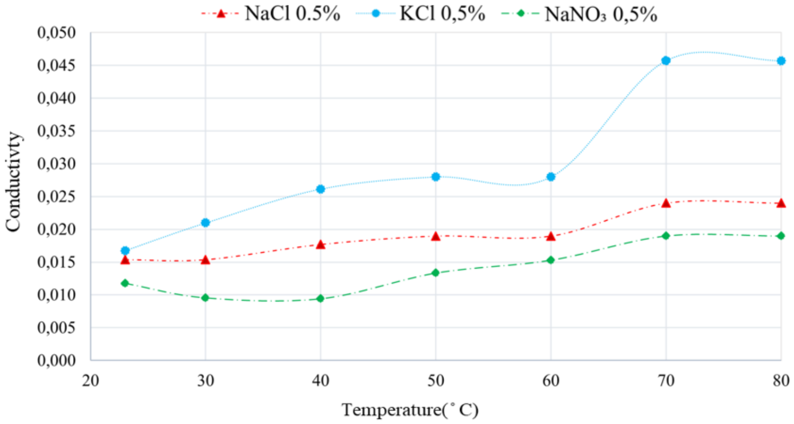
Fig. 6 Conductivity profiles for NaCl (a), KCl (b), and $NaNO_3$ (c) salt solutions with increasing temperature at a 1 MHz frequency



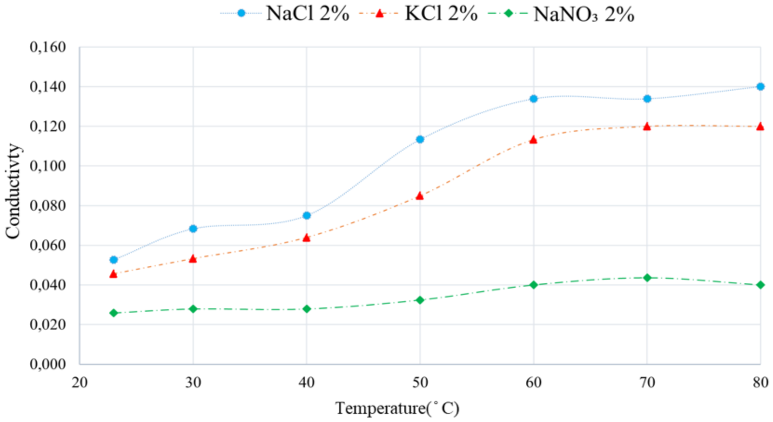
(c) Effect of temperature on $NaNO_3$-water solution conductivity at 1 MHz

Fig. 6 Conductivity profiles for NaCl (a), KCl (b), and $NaNO_3$ (c) salt solutions with increasing temperature at a 1 MHz frequency (continued)

The variation in conductivity with increasing temperature is illustrated in Fig. 6, with panels (a), (b), and (c) representing NaCl, KCl, and NaNO3, respectively. As the temperature rises, conductivity also increases due to enhanced molecular motion. Additionally, temperature influences energy transfer in all materials. Higher temperatures increase kinetic energy for the particles in the solution, facilitating ion movement. This enhanced motion allows charged ions to overcome attraction to each other and migrate toward their respective electrodes. This trend is observed across all the salt systems at both the 0.5% and 2% w/w concentrations. However, at approximately 70°C, the conductivity values reach a peak and remain constant thereafter.



(a) %0,5 concentration solution



(b) %2 concentration solution

Fig. 7 Conductivity profiles with increasing temperatures for comparing NaCl, KCl, and $NaNO_3$ at the same concentration

As seen in Fig. 7, the comparison of conductivity values at various temperatures for salt solutions at concentrations of 0.5% and 2% w/w have been shown. For all the salts and concentrations investigated, the conductivity increased with increasing temperature. At 0.5% NaCl, KCl has higher conductivity than NaCl does (although at 23°C, NaCl has a slightly greater conductivity). However, temperature significantly impacts KCl conductivity more than it does for NaCl, as shown in Fig. 7(a). The conductivity increases to approximately 70°C, where it peaks and then remains constant. When the concentration increases to 2%, the conductivity values for NaCl and KCl converge more, indicating that higher ion concentrations hinder the identifiability between the two salts, as shown in Fig. 7(b).

Higher salt concentrations produce effects similar to those of high signal frequencies. As temperature increases, the conductivity rises and stabilizes at approximately 60°C, becoming remarkably close for 2% KCl and NaCl. Beyond this point, temperature increases do not significantly affect conductivity, facilitating conductivity nearly independent of temperature. $NaNO_3$ consistently exhibits the lowest conductivity values. At a 2% concentration, NaNO3 maintains an almost flat profile, with increasing temperature having a minimal effect on its conductivity, unlike NaCl and KCl. These findings suggest that $NaNO_3$ is more resistant to temperature changes than NaCl and KCl. More specifically, at a concentration of 0.5%, increasing the temperature from 25°C to 70°C resulted in conductivity increases of 172%, 56%, and 61% for KCl, NaCl, and $NaNO_3$, respectively. Moreover, at a concentration of 2%, the conductivity increased by 162%, 165%, and 55% for KCl, NaCl, and $NaNO_3$, respectively. These findings suggest that KCl and NaCl are more sensitive to temperature changes than $NaNO_3$, which exhibits a less pronounced response.

6. Conclusions and Recommendations

In this study, heat transfer and conductivity experiments were conducted to investigate the influence of electrolytic solute particles in water. These investigations aimed to provide insights into the physical properties of ions in solution, the strength and nature of ion interactions, and their effects on both heat transfer and electrical conductivity. The following section points out the important findings of this study:

(1) The introduction of solute particles as water-soluble electrolytes significantly altered the heat transfer and conductivity properties compared with those of pure water.

(2) Two different heat exchanger systems, PHE and DPHE, were compared, and it was observed that the DPHE demonstrated more efficient heat transfer than the PHE. Therefore, similar profiles were obtained for the heat transfer characteristics of the water and water salt systems in the DPHE. In PHE, the highest heat transfer rate was obtained for NaCl, followed by KCl and $NaNO_3$, all of which surpass pure water.

(3) For the conductivity measurements, it was observed that the conductivity follows a linear trend with increasing signal frequency up to a threshold of 1 MHz, as determined in this study. At low salt concentrations (up to 4% w/w), the conductivity typically increases linearly with increasing salt concentration. Above a concentration of 4%, a further increase in concentration does not result in a significant increase in conductivity, and conductivity stays constant or, in some cases, begins to decrease.

(4) It can also be concluded that conductivity is not a colligative property, meaning that it depends on both the type and amount of matter. NaCl and KCl yielded similar values and trends, with NaCl having slightly higher conductivity at the same concentration. However, $NaNO_3$ has a significantly lower conductivity than NaCl and KCl. As the temperature increases, the conductivity also increases due to enhanced molecular motion. However, at approximately 70°C, the conductivity values peak and remain constant thereafter. KCl and NaCl are more sensitive to temperature changes than $NaNO_3$, which demonstrates a weaker response.

As a recommendation for future work, greater focus should be placed on expanding the scope of electrolytes studied, including organic salts, multivalent ions, and mixed systems, to better understand their effects on heat transfer and conductivity. Investigating higher temperature ranges and more concentrated solutions could offer further insights into their behavior under extreme conditions. Analyzing flow dynamics, such as laminar and turbulent regimes, could help optimize heat exchanger performance, while computational modeling, such as CFD, could provide more detailed simulations. Exploring advanced materials or coatings for heat exchangers may enhance durability and efficiency, particularly in corrosive environments. Long-term stability studies addressing issues like fouling or scaling would help ensure the practical applicability of these solutions. Additionally, testing in real-world industrial systems and comparing electrolytic solutions with alternatives, such as nanofluids, could highlight potential advantages. Environmental and economic assessments should also be conducted to evaluate the sustainability and cost-effectiveness of employing electrolytic solutions in industrial applications.

Conflicts of Interest

The authors declare no conflict of interest.

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