Solubility, Density, Viscosity, Refractive Index, and Electrical Conductivity for Potassium Nitrate−Water−2-Propanol at (298.15 and 313.15) K

Yi-Chen Kao and Chein-Hsiun Tu*

Department of Applied Chemistry, Providence University, Shalu, Taichung, Taiwan 43301

The solubility of potassium nitrate in aqueous 2-propanol solution has been determined at the temperatures of (298.15 and 313.15) K and atmospheric pressure. The densities, viscosities, refractive indices, and electrical conductivities of potassium nitrate in water and in the saturated solutions of aqueous 2-propanol were measured at these two temperatures. Solubilities were determined using the analytical gravimetric method. Densities were determined using a vibrating-tube densimeter. Viscosities were measured with an automatic microviscometer based on the rolling ball principle. Refractive indices were measured using a digital Abbe-type refractometer. Electrical conductivities were determined by measuring the electrical resistance between two electrodes facing each other in the solution. The experimental values of solubility, density, and electrical conductivity were found to decrease with an increase of the concentration of 2-propanol for the saturated solutions of potassium nitrate + water + 2-propanol, while different trends with a maximum and a minimum were observed for viscosity and refractive index, respectively. Equations are given for these properties as a function of concentration.

Introduction

Addition of an organic solvent to an aqueous salt solution normally reduces the solubility of the salt. This process has a number of potential advantages over alternative crystallization techniques because it creates the possibility of carrying out the operation at room temperature, producing crystals of high purity. More particularly, knowledge of the solubility, density, viscosity, and electrical conductivity of the salt solutions is fundamentally important for the design of the crystallization process. Previously, viscosities of water−acetamide−potassium nitrate (KNO_3) were measured within the temperature range (25 to 85) °C by Woldan.[1] He concluded that the viscosity of the KNO_3 solution is larger than the viscosity of solvent, and it increases with the growth of concentration of KNO_3 in solution and content of acetamide in the mixed solvent. Mydlarz and co-workers[2,3] studied the solubilities and densities of saturated solutions for potassium sulfate (K_2SO_4) in water + methanol, ethanol, 2-propanol, or acetone over several temperatures. Okorafor[4] determined the solubility and density isotherms for the sodium sulfate−water−methanol system over the temperature range of (10 to 50) °C. Taboada et al.[5] reported solubilities, densities, viscosities, electrical conductivities, and refractive indices of saturated solutions of K_2SO_4 in water + 1-propanol at (298.15, 308.15, and 318.15) K. Farelo et al.[6] obtained solubilities of sodium chloride and potassium chloride in water + ethanol mixtures from (298 to 323) K. In all cases, the presence of either alcohol or acetone significantly reduces the solubility of the salt in aqueous solution.

Potassium nitrate is a source of potassium and soluble nitrogen, both of which are essential plant nutrients. This material is also used in the manufacture of glass, steel, and dynamite and is found as a potential oxidant for foods and the propulsion of rockets. Therefore, in the present paper we undertake to obtain the solubility of potassium nitrate in an aqueous 2-propanol mixture at T = (298.15 and 313.15) K and atmospheric pressure. The densities, viscosities, refractive indices, and electrical conductivities of potassium nitrate both in water and in the saturated solutions of water + 2-propanol were also measured. These properties are useful in the study of the salting-out precipitation of potassium nitrate from aqueous solution, using 2-propanol as the selected solvent. A literature survey showed that only the density, viscosity, and electrical conductivity data of KNO_3 in water at T = 298.15 K have been reported by Isono.[7] No other data in the literature are available for the solutions investigated in this study.

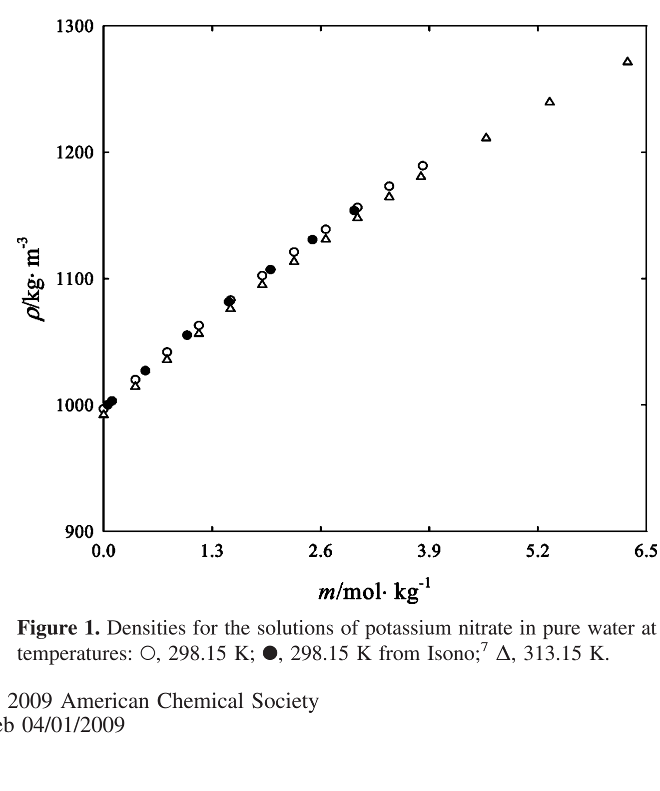

Figure 1. Densities for the solutions of potassium nitrate in pure water at temperatures: ○, 298.15 K; ●, 298.15 K from Isono;[7] Δ, 313.15 K.

* Corresponding author. E-mail: chtu@pu.edu.tw.

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Table 1. Experimental Densities ρ, Viscosities η, Refractive Indices n_D, and Conductivities κ for Potassium Nitrate in Water at (298.15 and 313.15) K

m / mol·kg^{-1}	ρ / kg·m^{-3}	η / mPa·s	n_D	κ / S·m^{-1}
		T = 298.15 K		
0.0000	997.00 ± 0.02	0.891 ± 0.003	1.33277 ± 0.00006	$1.25 \cdot 10^{-4} \pm 0.02 \cdot 10^{-4}$
0.3799	1020.03 ± 0.04	0.879 ± 0.002	1.33593 ± 0.00004	3.81 ± 0.02
0.7600	1041.91 ± 0.02	0.870 ± 0.004	1.33907 ± 0.00003	7.05 ± 0.03
1.1400	1062.91 ± 0.03	0.869 ± 0.002	1.34205 ± 0.00001	9.85 ± 0.01
1.5200	1083.04 ± 0.05	0.872 ± 0.005	1.34488 ± 0.00002	12.2 ± 0.1
1.9000	1102.40 ± 0.05	0.881 ± 0.002	1.34751 ± 0.00004	14.4 ± 0.1
2.2800	1121.03 ± 0.01	0.889 ± 0.001	1.35009 ± 0.00007	16.2 ± 0.1
2.6600	1139.02 ± 0.02	0.901 ± 0.004	1.35253 ± 0.00002	17.9 ± 0.1
3.0399	1156.32 ± 0.04	0.914 ± 0.006	1.35479 ± 0.00008	19.4 ± 0.1
3.4200	1173.06 ± 0.03	0.931 ± 0.001	1.35704 ± 0.00006	21.1 ± 0.1
3.8210	1189.24 ± 0.02	0.950 ± 0.002	1.35915 ± 0.00004	22.3 ± 0.1
		T = 313.15 K		
0.0000	992.15 ± 0.02	0.653 ± 0.002	1.33060 ± 0.00004	$1.64 \cdot 10^{-4} \pm 0.01 \cdot 10^{-4}$
0.3799	1014.52 ± 0.03	0.652 ± 0.004	1.33384 ± 0.00003	5.28 ± 0.02
0.7600	1035.85 ± 0.01	0.654 ± 0.001	1.33687 ± 0.00005	9.54 ± 0.01
1.1400	1056.36 ± 0.04	0.657 ± 0.002	1.33975 ± 0.00002	12.9 ± 0.1
1.5200	1076.08 ± 0.02	0.665 ± 0.005	1.34248 ± 0.00004	15.9 ± 0.2
1.9000	1095.07 ± 0.03	0.673 ± 0.002	1.34500 ± 0.00003	18.4 ± 0.1
2.2800	1113.37 ± 0.05	0.682 ± 0.003	1.34761 ± 0.00006	20.8 ± 0.2
2.6600	1131.04 ± 0.01	0.693 ± 0.004	1.34991 ± 0.00006	22.7 ± 0.1
3.0399	1148.05 ± 0.04	0.703 ± 0.002	1.35227 ± 0.00002	24.8 ± 0.1
3.4200	1164.53 ± 0.05	0.716 ± 0.004	1.35443 ± 0.00004	26.3 ± 0.2
3.7999	1180.49 ± 0.01	0.733 ± 0.006	1.35643 ± 0.00003	27.8 ± 0.1
4.5809	1211.11 ± 0.02	0.760 ± 0.001	1.36051 ± 0.00002	30.8 ± 0.1
5.3410	1239.46 ± 0.02	0.803 ± 0.003	1.36426 ± 0.00006	33.0 ± 0.1
6.2730	1271.30 ± 0.03	0.844 ± 0.004	1.36812 ± 0.00005	35.7 ± 0.1

Experimental Section

Reagents included anhydrous potassium nitrate (+99 %; Merck), analytical grade absolute 2-propanol (+99.5 %, Tedia), and ultrapure water (conductivity ≤ 1.5 μS·cm^{-1} at 25 °C) obtained by passing distilled water through a Millipore ultrapure cartridge kit. To avoid water contamination, potassium nitrate was dried at 393.15 K in an oven for more than three days before use.

The solubility (s) of potassium nitrate in an aqueous 2-propanol mixture was obtained at T = (298.15 and 313.15) K and atmospheric pressure. The densities (ρ), viscosities (η), refractive indices (n_D), and electrical conductivities (κ) of potassium nitrate in water and in the saturated solutions of water + 2-propanol were also measured at these two temperatures. All samples were prepared by mass using a Precisa 262SMA balance with a precision of 0.1 mg. The uncertainty in the concentration is estimated to within ± $1 \cdot 10^{-4}$ units. All measurements were performed at least three times under atmospheric pressure (100.8 ± 0.5) kPa, and the results were averaged to give the final values.

Solubility measurements were carried out by adding an excess amount of electrolytes to the solution. The contents of the solubility cell were agitated for at least 10 h at working temperatures in a thermostatic water bath controlled to ± 0.01

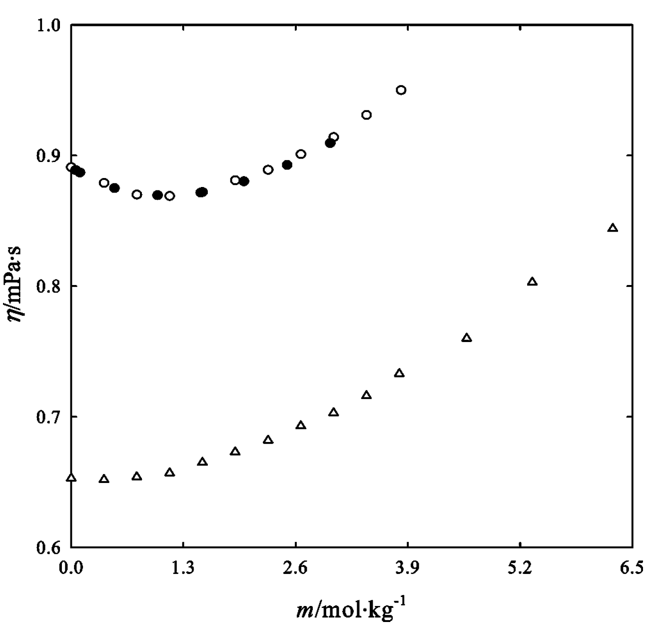

Figure 2. Viscosities for the solutions of potassium nitrate in pure water at temperatures: ○, 298.15 K; ●, 298.15 K from Isono;[7] Δ, 313.15 K.

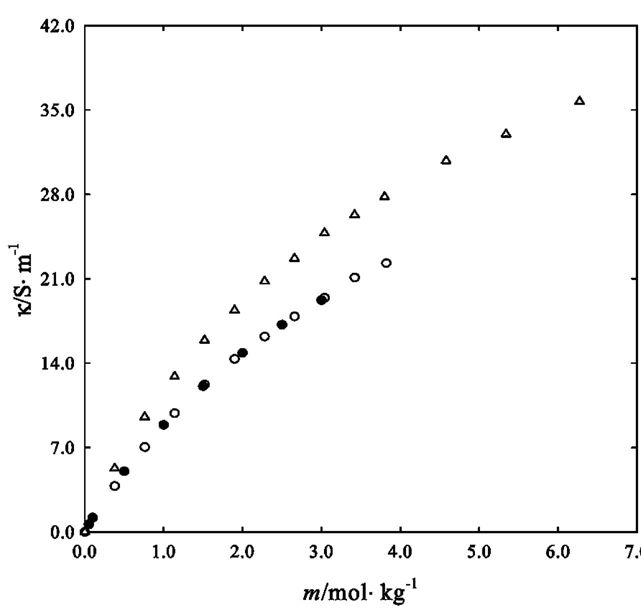

Figure 3. Electrical conductivities for the solutions of potassium nitrate in pure water at temperatures: ○, 298.15 K; ●, 298.15 K from Isono;[7] Δ, 313.15 K.

Table 2. Solubilities *s*, Densities *ρ*, Viscosities *η*, Refractive Indices n_D, and Electrical Conductivities *κ* for the Saturated Solutions of Potassium Nitrate in Various Mass Fractions *w* of (1 − *w*) Water + *w* 2-Propanol at (298.15 and 313.15) K

w	*s* (kg salt/100 kg solution)	*ρ* (kg·m^{-3})	*η* (mPa·s)	n_D	*κ* (S·m^{-1})
			T = 298.15 K		
0.0000	39.050 ± 0.009	1190.82 ± 0.04	0.966 ± 0.004	1.35952 ± 0.00002	22.4 ± 0.1
0.1000	24.498 ± 0.008	1108.97 ± 0.06	1.276 ± 0.002	1.35818 ± 0.00003	12.8 ± 0.1
0.2000	16.544 ± 0.006	1053.26 ± 0.04	1.783 ± 0.005	1.36044 ± 0.00003	7.10 ± 0.10
0.3000	11.685 ± 0.006	1008.46 ± 0.02	2.267 ± 0.004	1.36352 ± 0.00004	4.00 ± 0.02
0.4000	8.113 ± 0.004	967.01 ± 0.03	2.664 ± 0.003	1.36664 ± 0.00002	2.12 ± 0.01
0.4999	5.303 ± 0.005	929.76 ± 0.01	2.883 ± 0.004	1.36927 ± 0.00006	1.16 ± 0.01
0.6000	3.232 ± 0.004	895.75 ± 0.05	2.951 ± 0.006	1.37157 ± 0.00005	0.662 ± 0.006
0.7000	1.433 ± 0.003	862.63 ± 0.04	2.856 ± 0.002	1.37336 ± 0.00003	0.367 ± 0.005
0.8002	0.464 ± 0.002	834.12 ± 0.02	2.581 ± 0.003	1.37480 ± 0.00002	0.102 ± 0.004
0.9000	0.159 ± 0.005	807.58 ± 0.03	2.186 ± 0.002	1.37554 ± 0.00005	0.0442 ± 0.0008
1.0000	0.062 ± 0.006	781.64 ± 0.02	1.667 ± 0.004	1.37569 ± 0.00002	0.0044 ± 0.0003
			T = 313.15 K		
0.0000	64.638 ± 0.008	1274.23 ± 0.04	0.807 ± 0.002	1.36851 ± 0.00006	32.5 ± 0.2
0.1001	42.960 ± 0.006	1178.02 ± 0.02	0.998 ± 0.004	1.36427 ± 0.00003	23.1 ± 0.1
0.2000	29.543 ± 0.005	1101.89 ± 0.02	1.220 ± 0.003	1.36324 ± 0.00004	15.4 ± 0.1
0.3000	21.170 ± 0.006	1041.16 ± 0.06	1.492 ± 0.002	1.36365 ± 0.00005	9.68 ± 0.01
0.4000	14.314 ± 0.005	984.87 ± 0.02	1.708 ± 0.005	1.36447 ± 0.00002	5.57 ± 0.03
0.5000	9.543 ± 0.003	938.24 ± 0.03	1.840 ± 0.006	1.36561 ± 0.00002	2.80 ± 0.06
0.6000	5.453 ± 0.004	893.33 ± 0.05	1.858 ± 0.003	1.36684 ± 0.00004	1.34 ± 0.05
0.7002	2.832 ± 0.008	856.10 ± 0.02	1.778 ± 0.005	1.36791 ± 0.00003	0.638 ± 0.003
0.8000	0.936 ± 0.002	821.16 ± 0.01	1.625 ± 0.007	1.36860 ± 0.00001	0.195 ± 0.002
0.9002	0.295 ± 0.003	793.63 ± 0.03	1.435 ± 0.002	1.36880 ± 0.00005	0.0601 ± 0.0005
1.0000	0.098 ± 0.002	768.05 ± 0.02	1.235 ± 0.004	1.36909 ± 0.00002	0.00653 ± 0.00008

K. The solution was then allowed to settle at least 30 min, and sample solutions were collected from flasks using heated Nylon filters (47 mm, 0.45 μm, SUPELCO) under aspiration. Solution concentration measurements were made by evaporating a sample to dryness according to the procedure described by Pinho and Macedo.[8] The uncertainty of solubility measurement was estimated to be less than ± 0.009 kg of salt/100 kg of solution.

Densities *ρ* were measured with an Anton Paar DMA-5000 vibrating-tube densimeter (Anton-Paar, Graz, Austria). Viscosities *η* were determined with an automatic microviscometer (Anton Paar type AMVn), which uses the rolling-ball principle. Refractive indices, n_D, were measured with an automatic Anton Paar RXA-156 refractometer, which operates at a wavelength of 589 nm corresponding to the D-ray of sodium. The detailed measuring procedures for *ρ*, *η*, and n_D have been described in our previous studies.[9,10] All liquids were thermostatically controlled to within ± 0.01 K, ± 0.01 K, and ± 0.05 K for the *ρ*, *η*, and n_D measurements, respectively. The uncertainties of *ρ*, *η*, and n_D were estimated to be ± 0.05 kg·m^{-3}, ± 0.006 mPa·s, and ± 0.00008, respectively.

Electrical conductivities, *κ*, were carried out using a Kyoto model CM-117 conductivity meter (Tokyo, Japan) by measuring the electrical resistance between two electrodes facing each other in the sample solution. Pyrex glass detector cells K-121 (cell constant = 0.975 cm^{-1}) and K-123 (cell constant = 10.16 cm^{-1}) were used according to the conductivity of solution. The cell constants were determined at 298.15 K using the standard KCl solutions whose compositions were (7.41913 and 71.1352) g

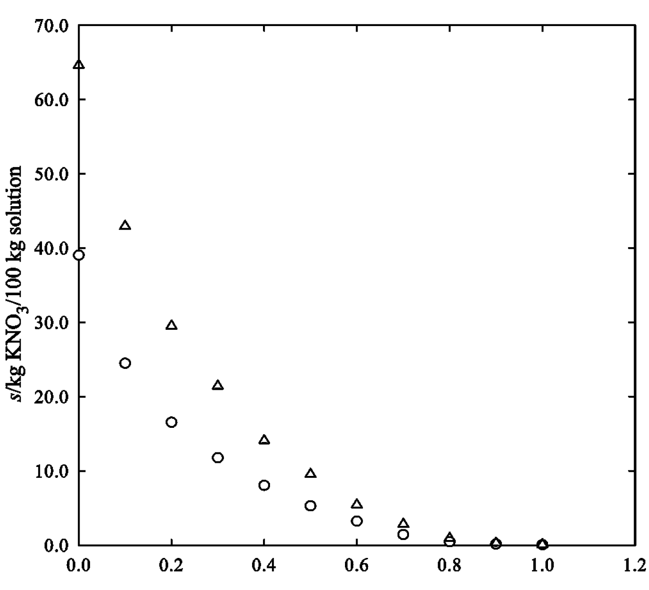

Figure 4. Solubilities of potassium nitrate in various mass fractions *w* of (1 − *w*) water + *w* 2-propanol at temperatures: ○, 298.15 K; Δ, 313.15 K.

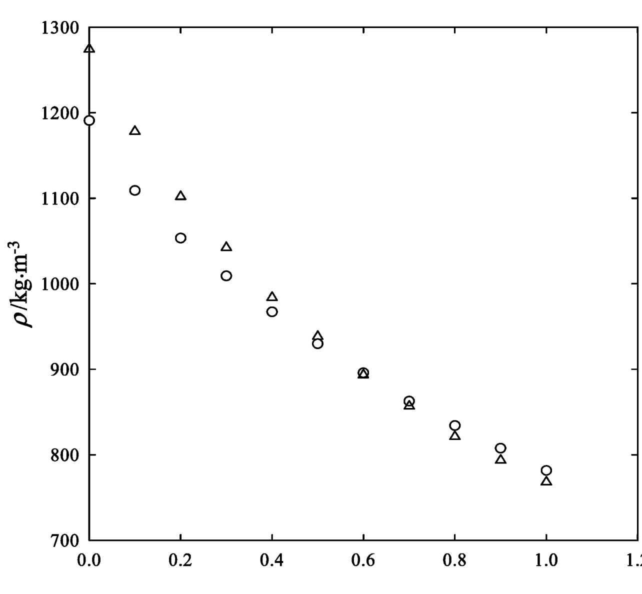

Figure 5. Densities for the saturated solutions of potassium nitrate in various mass fractions *w* of (1 − *w*) water + *w* 2-propanol at temperatures: ○, 298.15 K; Δ, 313.15 K.

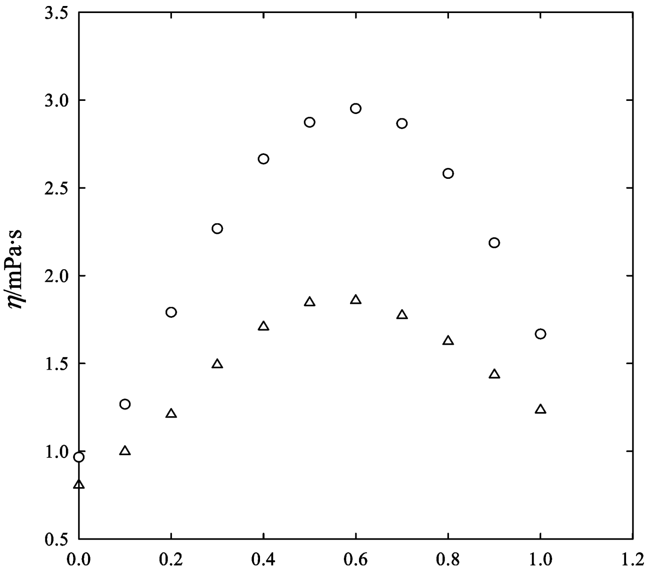

Figure 6. Viscosities for the saturated solutions of potassium nitrate in various mass fractions w of $(1 - w)$ water + w 2-propanol at temperatures: ○, 298.15 K; Δ, 313.15 K.

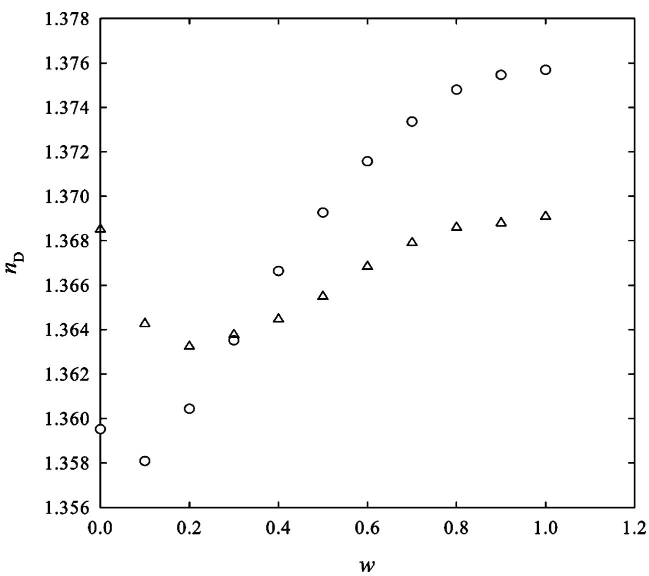

Figure 7. Refractive indices for the saturated solutions of potassium nitrate in various mass fractions w of $(1 - w)$ water + w 2-propanol at temperatures: ○, 298.15 K; Δ, 313.15 K.

of KCl in 1000 g of solution.[11] Liquid samples were thermostatically controlled to within ± 0.05 K with circulating thermostat water to a jacketed sample vessel. The uncertainty of conductivity was within ± 0.6 % $S \cdot m^{-1}$ of the measured value.

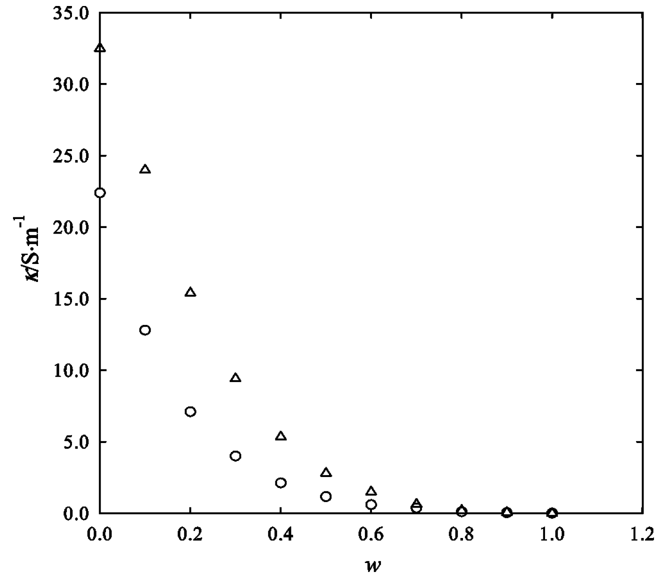

Figure 8. Electrical conductivities for the saturated solutions of potassium nitrate in various mass fractions w of $(1 - w)$ water + w 2-propanol at temperatures: ○, 298.15 K; Δ, 313.15 K.

Results and Discussion

The experimental values of density ρ, viscosity η, refractive index n_D, and electrical conductivity κ of aqueous solutions of potassium nitrate up to near saturation at T = (298.15 and 313.15) K are given in Table 1. The values of the first column show the molality ($m/mol \cdot kg^{-1}$) of potassium nitrate in water, and they were unsaturated. It can be seen that increasing the temperature from T = 298.15 K to T = 313.15 K decreases the values of density, viscosity, and refractive index but increases the values of electrical conductivity for various salt concentrations. Increasing the concentrations of the salt in water increases the values of density, viscosity, refractive index, and electrical conductivity except for the viscosities in the region of low salt concentration. Figures 1 to 3 illustrate our experimental density, viscosity, and electrical conductivity data of potassium nitrate + water together with the data at 298.15 K from Isono[7] for comparison. A good agreement was found between our data and the literature results.

The solubilities, densities, viscosities, refractive indices, and electrical conductivities for the saturated solutions of potassium nitrate in various mass fractions w of $(1 - w)$ water + w 2-propanol at T = (298.15 and 313.15) K are summarized in Table 2. A graphical presentation is given in Figures 4 to 8. It can be observed that the values of solubility and electrical conductivity increase from (298.15 to 313.15) K, while those of viscosity decrease with the increase of temperature. For density and refractive index, their values increase with the increase of temperature until mass fraction $w \approx 0.60$ of 2-propanol for density and mass fraction $w \approx 0.30$ of 2-propanol

Table 3. Coefficients and Standard Deviations σ of ρ ($kg \cdot m^{-3}$), η ($mPa \cdot s$), n_D, and κ ($S \cdot m^{-1}$) for Potassium Nitrate in Water at (298.15 and 313.15) K

y	a_0	a_1	a_2	a_3	a_4	a_5	$\sigma \cdot 10^2$
				T = 298.15 K			
ρ	996.98 ± 0.08	62.47 ± 0.34	−4.89 ± 0.38	0.81 ± 0.16	$-9.6 \cdot 10^{-2} \pm 2.0 \cdot 10^{-2}$		8.7
η	0.892 ± 0.001	−0.048 ± 0.004	0.031 ± 0.005	$-5.6 \cdot 10^{-3} \pm 1.9 \cdot 10^{-3}$	$5.0 \cdot 10^{-4} \pm 2.4 \cdot 10^{-4}$		0.10
n_D	1.33276 ± 0.00002	$8.64 \cdot 10^{-3} \pm 0.03 \cdot 10^{-3}$	$-4.53 \cdot 10^{-4} \pm 0.08 \cdot 10^{-4}$				0.0033
κ	−0.016 ± 0.070	11.06 ± 0.28	−2.62 ± 0.32	0.48 ± 0.13	−0.040 ± 0.017		7.3
				T = 313.15 K			
ρ	992.20 ± 0.08	59.80 ± 0.19	−3.27 ± 0.13	0.17 ± 0.03	$-6.7 \cdot 10^{-3} \pm 2.6 \cdot 10^{-3}$		8.8
η	0.653 ± 0.001	$-8.51 \cdot 10^{-3} \pm 0.04 \cdot 10^{-3}$	0.015 ± 0.004	$-4.1 \cdot 10^{-4} \pm 1.7 \cdot 10^{-4}$	$-7.5 \cdot 10^{-4} \pm 3.2 \cdot 10^{-4}$	$-5.3 \cdot 10^{-5} \pm 2.1 \cdot 10^{-5}$	0.066
n_D	1.33060 ± 0.00004	$8.79 \cdot 10^{-3} \pm 0.10 \cdot 10^{-3}$	$-7.34 \cdot 10^{-4} \pm 0.70 \cdot 10^{-4}$	$7.34 \cdot 10^{-5} \pm 1.75 \cdot 10^{-5}$	$-4.39 \cdot 10^{-6} \pm 1.40 \cdot 10^{-6}$		0.0047
κ	0.024 ± 0.091	15.33 ± 0.34	−4.53 ± 0.38	1.07 ± 0.17	−0.14 ± 0.03	0.0075 ± 0.0019	9.6

Table 4. Coefficients and Standard Deviations σ of s (kg salt/100 kg of solution), ρ (kg·m^{-3}), η (mPa·s), n_D, and κ (S·m^{-1}) for Potassium Nitrate at Saturation in Aqueous 2-Propanol at (298.15 and 313.15) K

Y	a_0	a_1	a_2	a_3	a_4	a_5	σ
				T = 298.15 K			
s	39.016 ± 0.114	−188.983 ± 0.028	531.525 ± 0.002	−893.304 ± 51.939	758.306 ± 58.710	−246.516 ± 23.951	0.12
ρ	1190.58 ± 0.82	−981.33 ± 20.03	2066.59 ± 140.55	−3633.21 ± 374.89	3236.21 ± 420.59	−1097.35 ± 167.42	0.84
η	0.964 ± 0.009	1.632 ± 0.227	20.125 ± 1.598	−46.836 ± 4.263	36.221 ± 4.783	−10.440 ± 1.904	0.012
n_D	1.35948 ± 0.00013	−0.03614 ± 0.00315	0.30154 ± 0.02213	−0.59673 ± 0.05903	0.52264 ± 0.06622	−0.17513 ± 0.02636	0.00013
κ	22.39 ± 0.05	−121.35 ± 1.29	289.69 ± 9.05	−368.50 ± 24.13	242.15 ± 27.08	−64.38 ± 10.78	0.054
				T = 313.15 K			
s	64.615 ± 0.197	−273.253 ± 4.769	670.344 ± 33.514	−1056.862 ± 89.398	878.946 ± 100.301	−283.717 ± 39.931	0.20
ρ	1274.26 ± 0.98	−1103.45 ± 23.76	1610.96 ± 167.00	−2290.18 ± 445.45	1875.88 ± 499.80	−599.35 ± 198.97	0.99
η	0.811 ± 0.001	1.036 ± 0.152	8.448 ± 0.668	−16.682 ± 1.028	7.624 ± 0.510		0.010
n_D	1.36846 ± 0.00015	−0.05997 ± 0.00367	0.22595 ± 0.02578	0.33640 ± 0.06877	0.23940 ± 0.07716	−0.06841 ± 0.03072	0.00015
κ	32.63 ± 0.11	−108.91 ± 1.03	121.91 ± 2.48	−45.62 ± 1.63			0.13

for refractive index. A similar tendency in temperature was found from the density result of Taboada et al., who studied potassium sulfate in water + 1-propanol.[5] On the other hand, the values of solubility, density, and electrical conductivity decrease with the increase of the concentration of 2-propanol in water, while those of viscosity and refractive index reveal a different trend. For viscosity, its values increase with the increase of the concentration of 2-propanol until $w \approx 0.6$. For refractive index, its values decrease with the increase of the concentration of 2-propanol until $w \approx 0.1$ (298.15 K) and $w \approx 0.2$ (313.15 K).

The experimental densities, viscosities, refractive indices, and electrical conductivities of potassium nitrate in water and in the saturated solutions of aqueous 2-propanol were correlated, respectively, according to the equation

$$y = a_0 + a_1x + a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5 \qquad (1)$$

where y refers to s/kg of salt/100 kg of solution, ρ/kg·m^{-3}, η/mPa·s, n_D, or κ/S·m^{-1} and x is molality m/mol·kg^{-1} in water or mass fraction w in $(1 - w)$ water + w 2-propanol. The values of coefficients a_k were determined by a nonlinear regression analysis based on the least-squares method and are summarized along with the standard deviations in Tables 3 and 4. The standard deviation (σ) is defined by

$$\sigma = \left[\sum_{k=1}^{n} \frac{(y_k^{\text{exptl}} - y_k^{\text{calcd}})^2}{n - p}\right]^{1/2} \qquad (2)$$

where n is the number of experimental points and p is the number of adjustable parameters. These results confirmed that the concentration dependence of s, ρ, η, n_D, and κ at T = (298.15 and 313.15) K could be represented with a reasonable accuracy by the variable-degree polynomials as eq 1.

Conclusion

This paper reports the experimental data of solubility, density, viscosity, refractive index, and electrical conductivity of potassium nitrate in water and in the saturated solutions of aqueous 2-propanol at T = (298.15 and 313.15) K. A reasonable agreement is found between our data and the literature results at 298.15 K for the densities, viscosities, and electrical conductivities of potassium nitrate + water solution. The values of solubility, density, and electrical conductivity were found to decrease with the increase of the concentration of 2-propanol for the saturated solutions of potassium nitrate + water + 2-propanol, while different trends with a maximum and a minimum were observed for viscosity and refractive index, respectively. These experimental data were well represented by the variable-degree polynomials in terms of concentrations for each temperature.

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