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Thermal Conductivity and Viscosity of Aqueous of $Mg(NO_3)_2$, $Sr(NO_3)_2$, $Ca(NO_3)_2$, and $Ba(NO_3)_2$ Solutions

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The experimental data of thermal conductivity and dynamic viscosity of aqueous solutions of the alkaline earth metals' nitrates in temperature range (298.15 to 598.15) K, pressure (0.1 to 40) MPa, and molality for $H_2O + Mg(NO_3)_2$ (0.7507, 1.689, 2.8950, and 4.5040) $mol \cdot kg^{-1}$, for $H_2O + Sr(NO_3)_2$ (0.525, 1.181, 2.025, and 3.150) $mol \cdot kg^{-1}$, for $H_2O + Ca(NO_3)_2$ (0.6771, 1.5235, 2.598, and 4.063) $mol \cdot kg^{-1}$, and for $H_2O + Ba(NO_3)_2$ (0.0781, 0.1594, 0.2442, and 0.3327) $mol \cdot kg^{-1}$ have been summarized. The measured values of thermal conductivity and viscosity were compared with data and correlations reported in the literature. A relationship between relative dynamic viscosity and relative thermal conductivity is established. A correlation equation relating relative dynamic viscosity and thermal conductivity of aqueous solutions was obtained as a function of temperature and composition. The equation describes values of viscosity within ± 2.2 %.

Introduction

To understand and control processes that used electrolyte solutions, it is necessary to know their thermodynamic and transport properties. The properties of electrolyte solutions are useful in many industrial and scientific applications. They are also important for environmental and regulatory-related applications. The treatment of wastewater often requires accurate electrolyte solution properties data.

The main object of this paper is to develop a relationship between thermal conductivity and dynamic viscosity of electrolytes. Interest in high-temperature thermophysical research of aqueous solutions of electrolytes continuously increases. This work is a part of a continuing program on the transport properties of electrolytes in aqueous solutions.

Aseyev[1] represented viscosity data from the literature for $H_2O + Ca(NO_3)_2$ solutions by the correlation equation:

$$\log(\eta/\eta_0)_r = 1.486w + 0.00211(t/°C)w \qquad (1)$$

where η_0 is the viscosity of pure water at temperature t, and w is the mass fraction.

Experimental Procedures

Dynamic viscosities for $H_2O + Mg(NO_3)_2$ at (0.7507, 1.689, 2.8950, and 4.5040) $mol \cdot kg^{-1}$, for $H_2O + Sr(NO_3)_2$ at (0.525, 1.181, 2.025, and 3.150) $mol \cdot kg^{-1}$, for $H_2O + Ca(NO_3)_2$ at (0.6771, 1.5235, 2.598, and 4.063) $mol \cdot kg^{-1}$, and for $H_2O + Ba(NO_3)_2$ at (0.0781, 0.1594, 0.2442, and 0.3327) $mol \cdot kg^{-1}$ have been measured with a capillary flow technique. Measurements were made at six isobars (0.1, 5, 10, 20, 30, and 40) MPa. The range of temperatures was from (298 to 573) K.

The apparatus and procedures used for the viscosity measurements of $H_2O + Mg(NO_3)_2$, $H_2O + Sr(NO_3)_2$, $H_2O + Ca(NO_3)_2$, and $H_2O + Ba(NO_3)_2$ solutions have been described in detail in previous papers[2,3] and were used without modification. Only essential information will be given here. The measurements were made using a capillary flow method, which gives an uncertainty of 1.5 % for the viscosity. The main parts of the apparatus consisted of a working capillary with extension tube, a high-temperature and high-pressure autoclave, movable and immovable cylinders, electrical heaters, and a solid red copper block. The working capillary with an inside diameter of 0.3 mm and length of 216 mm was made from stainless steel (1X18H9T). A capillary together with an extension tube was located in the high-temperature and high-pressure autoclave. The input and output sections of the capillary had conical extensions. The capillary tube was filled with mercury. When the movable cylinder was moved vertically at constant speed, the fluid flowed through the capillary. Both cylinders were supplied with two viewing windows that were made with plexiglass. The autoclave was placed in a solid red copper block. Two electrical heaters were wound around the surface of the copper block. To create and measure the pressure, the autoclave was connected with a dead-weight pressure gauge (MP-600) by means of a separating vessel, and mercury was used as a separating liquid. The mercury was in contact with the solution only at room temperature. The uncertainty in pressure measurements was 0.05 %.

The thermal conductivity of aqueous $Mg(NO_3)_2$, $Ca(NO_3)_2$, $Sr(NO_3)_2$, and $Ba(NO_3)_2$ solutions was measured by a concentric-cylinder (steady-state) technique. The experimental apparatus and procedures that were described previously[4−8] were used without modification. In this paper, only a brief discussion will be given.

The main part of the apparatus consisted of a high-pressure autoclave, thermostat, and thermal conductivity cell. The thermal conductivity cell consisted of two coaxial cylinders: an inner (emitting) cylinder and an outer (receiving) cylinder. The cylinders were located in a high-pressure autoclave. The deviation from concentricity was 0.002 cm or 2 % of the sample layer.

The autoclave was located in a thermostat, which was a solid (massive) copper block. The temperature in the thermostat was controlled with a heater. The thermostat was controlled with a three-section heating element, PRT-10. Three chromel−alumel thermocouples were located on three different levels of the

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Table 1. Data of η_r and λ_r at Various Temperatures and Molality for P = 20 MPa

T/K	m/mol·kg^{-1}	η_r	λ_r	T/K	m/mol·kg^{-1}	η_r	λ_r
$H_2O + Mg(NO_3)_2$							
298.15	0.3555	1.10	0.975	473.15	0.3555	1.17	0.990
298.15	0.7507	1.14	0.963	473.15	0.7507	1.25	0.970
298.15	1.6890	1.75	0.940	473.15	1.6890	1.75	0.950
298.15	2.8950	2.68	0.915	473.15	2.8950	2.58	0.925
298.15	4.5040	5.2	0.895	473.15	4.5040	4.25	0.910
373.15	0.3555	1.21	0.988	573.15	0.3555	1.18	0.985
373.15	0.7507	1.35	0.970	573.15	0.7507	1.23	0.970
373.15	1.6890	1.75	0.950	573.15	1.6890	1.75	0.930
373.15	2.8950	2.65	0.930	573.15	2.8950	2.70	0.908
373.15	4.5040	4.55	0.902	573.15	4.5040	4.20	0.885
$H_2O + Ca(NO_3)_2$							
298.15	0.6771	1.22	0.99	473.15	0.6771	1.32	0.98
298.15	1.5235	1.50	0.96	473.15	1.5235	1.62	0.96
298.15	2.5980	2.20	0.94	473.15	2.5980	2.20	0.94
298.15	4.0630	3.70	0.93	473.15	4.0630	3.12	0.93
373.15	0.6771	1.20	0.98	573.15	0.6771	1.32	0.98
373.15	1.5235	1.62	0.96	573.15	1.5235	1.65	0.95
373.15	2.5980	2.20	0.94	573.15	2.5980	2.23	0.92
373.15	4.0630	3.30	0.92	573.15	4.0630	3.00	0.91
$H_2O + Sr(NO_3)_2$							
298.15	0.525	1.17	0.99	473.15	0.525	1.23	0.99
298.15	1.181	1.35	0.97	473.15	1.181	1.5	0.97
298.15	2.025	1.80	0.96	473.15	2.025	1.9	0.96
298.15	3.150	2.81	0.95	473.15	3.150	2.72	0.94
373.15	0.525	1.19	0.98	573.15	0.525	1.25	0.98
373.15	1.181	1.32	0.97	573.15	1.181	1.55	0.96
373.15	2.025	1.82	0.96	573.15	2.025	1.95	0.95
373.15	3.150	2.75	0.94	573.15	3.150	2.72	0.93
$H_2O + Ba(NO_3)_2$							
298.15	0.3327	1.04	0.995	373.15	0.0781	1.15	0.880
298.15	0.2442	1.0	0.994	473.15	0.3327	1.04	0.996
298.15	0.1594	1.11	0.993	473.15	0.2442	1.15	0.993
298.15	0.0781	1.09	0.883	473.15	0.1594	1.17	0.881
373.15	0.3327	1.02	0.997	573.15	0.3327	1.05	0.996
373.15	0.2442	1.9	0.994	573.15	0.2442	1.1	0.993
373.15	0.1594	1.12	0.990	573.15	0.1594	1.2	0.883

copper block. The temperature differences between the various sections (levels) of the copper block were within 0.02 K of each other. Temperature was measured with a PRT and with three chromel−alumel thermocouples. The thermocouples were located of different levels of the thermostat to minimize temperature inhomogeneities. One of the junctions of a differential chromel−copel thermocouple was located in the inner cylinder and was tightly applied to the cylinder's wall. The second junction of the thermocouple was located in the shell capillary. Thermocouples were twice calibrated with a standard resistance thermometer. The difference between calibrations was 10 mK. The reading of the single thermocouple differs by ± 10 mK. The measurements were started when the differences in the readings of all of the thermocouples were minimal (0.02 K).

Results and Discussion

The thermal conductivity and dynamic viscosity for aqueous $Mg(NO_3)_2$, $Ca(NO_3)_2$, $Sr(NO_3)_2$, and $Ba(NO_3)_2$ solutions were performed along five isobars (0.1, 10, 20, 30, and 40) MPa from (294 to 591.06) K and were presented in previous studies[2−8] for various compositions.

The experimental and calculated values of thermal conductivity for pure water from the IAPWS formulation show excellent agreement within their experimental uncertainties (AAD within 0.51 %) in the temperature range from (290 to 575) K and at pressures up to 40 MPa. The experimental and calculated values from IAPWS formulation for the viscosity of pure water show excellent agreement within their experimental uncertainties (AAD within 0.27 %).

Table 2. Parameters a, b, and c of Equation 4 at P = 20 MPa

	$i = 0$	$i = 1$	$i = 2$	$i = 3$
$H_2O + Mg(NO_3)_2$				
a	241.9889	−3.66897	$2.17481 \cdot 10^{-2}$	$-4.02591 \cdot 10^{-5}$
b	−511.5512	7.88013	$-4.67473 \cdot 10^{-2}$	$8.64433 \cdot 10^{-5}$
c	270.6384	−4.22505	$2.50831 \cdot 10^{-2}$	$-4.63358 \cdot 10^{-5}$
$H_2O + Ca(NO_3)_2$				
a	47.12377	−0.17357	$-5.70642 \cdot 10^{-4}$	$2.44474 \cdot 10^{-6}$
b	−89.41969	0.283602	$1.52196 \cdot 10^{-3}$	$-5.6213 \cdot 10^{-6}$
c	42.4231	0.106753	$-9.65190 \cdot 10^{-4}$	$3.31994 \cdot 10^{-6}$
$H_2O + Sr(NO_3)_2$				
a	44.89065	−1.212649	$6.989745 \cdot 10^{-3}$	$-1.091899 \cdot 10^{-5}$
b	82.61765	2.460622	$-1.435702 \cdot 10^{-2}$	$2.246287 \cdot 10^{-5}$
c	37.79605	−1.24701	$7.371169 \cdot 10^{-3}$	$-1.155296 \cdot 10^{-5}$
$H_2O + Ba(NO_3)_2$				
a	−5.243099	0.288265	$-3.889558 \cdot 10^{-3}$	$1.011354 \cdot 10^{-5}$
b	9.206068	−0.5649582	$6.97443 \cdot 10^{-3}$	$-1.765573 \cdot 10^{-5}$
c	−3.719697	0.2781761	$-3.081231 \cdot 10^{-3}$	$7.527425 \cdot 10^{-5}$

In this work, the experimental data of thermal conductivity and dynamic viscosity of aqueous solutions have been summarized. A relationship between the relative dynamic viscosity of aqueous solutions on its molality for $H_2O + Mg(NO_3)_2$, $H_2O + Sr(NO_3)_2$, $H_2O + Ca(NO_3)_2$, and $H_2O + Ba(NO_3)_2$ solutions was established as

$$\eta_r = 1 + Am + Bm^2 + Cm^3 \tag{2}$$

where A, B, and C are the coefficient depending on temperature; m is the molality; and η_r is the relative viscosity of aqueous solution, $\eta_r = \eta_s/\eta_w$, where η_s is dynamic viscosity of aqueous solution and η_w is dynamic viscosity of pure water.

The relative thermal conductivity of aqueous solutions depends on concentration:

$$\lambda_r = 1 + Dm \tag{3}$$

where D is empirical coefficient; m is molality; and λ_r is relative thermal conductivity, $\lambda_r = \lambda_s/\lambda_w$, where λ_s is thermal conductivity of aqueous solutions and λ_w is thermal conductivity of pure water.

In this paper are given data ofη_r and λ_r in the investigated temperatures range and compositions at P = 20 MPa. The numerical data of η_r and λ_r are given in Table 1.

We found an analytical relationship between relative thermal conductivity λ_r and relative viscosity η_r of aqueous solutions in the form of

$$\eta_r = 1 + \alpha m + \beta m \lambda_r + \gamma m \lambda_r^2 \tag{4}$$

where m is the molality; λ_r is relative thermal conductivity; and α, β, and γ are the coefficients depending of temperature:

$$\alpha = \sum_{i=0}^{3} a_i t^i; \quad \beta = \sum_{i=0}^{3} b_i t^i; \quad \gamma = \sum_{i=0}^{3} c_i t^i$$

where t is the temperature (in °C).

Equation 4 describes data on viscosity within ± 2.2 %. The values of the coefficients a, b, and c in eq 4 at P = 20 MPa for each studied solutions are given in Table 2. Equation 4 is valid in the temperature range from (293 to 580) K, at pressure up to 40 MPa and for various compositions. The correlation equation was obtained as a function of temperature and composition by a least-squares method. Figure 1 shows the dependence of the

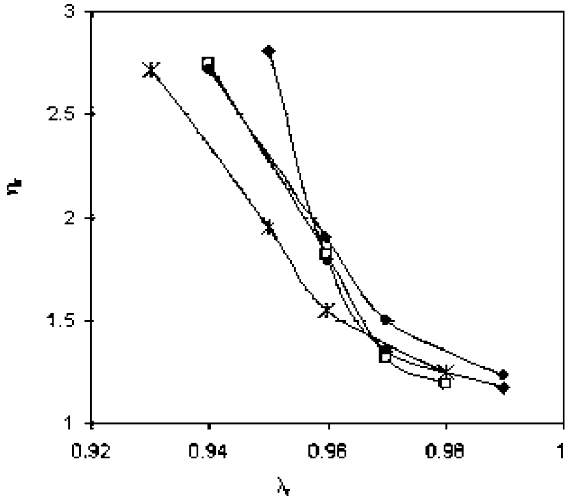

Figure 1. Dependence relative viscosity from relative thermal conductivity of $H_2O + Sr(NO_3)_2$ at deference temperatures: ◆, 298.15 K; □, 373.15 K; ●, 473.15 K; ∗, 573,15 K.

relative viscosity on the thermal conductivity for aqueous of $H_2O + Sr(NO_3)_2$ solutions.

Conclusion

A correlation of the dependence of relative dynamic viscosity of aqueous solutions on its molality was established. The correlation equation between relative dynamic viscosity and thermal conductivity of aqueous solutions of the alkaline earth metals' nitrates was also established as a function of temperature and composition by a least-squares method from the experimental data. The offered equation describes values on viscosity within ± 2.2 %.

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