(6) Briggs, D. K. H., *Ind. Eng. Chem.* **49**, 418 (1957).
(7) Bromley, L. A., University of California Radiation Lab., Berkeley, Calif., Rept. **UCRC-1852** (June 12, 1952).
(8) Bromley, L. A., Wilke, C. R., *Ind. Eng. Chem.* **43**, 1641 (1951).
(9) Burns, W. G., Morris, B., Wilkinson, R. W., *J. Sci. Instr.* **35**, 291 (1958).
(10) Cecil, O. B., Koerner, W. E., Munch, R. H., J. CHEM. ENG. DATA **2**, 54 (1957).
(11) Ellard, J. A., King, C. D., Hedley, W. H., Moodie, W. J., Woo, C., Yanko, W. H., "Organic Coolant Essential Data," Sixth Quarterly Report, 1 July to 30 September 1962, Monsanto Research Corp., Rept. **IDO-11,003** (1962).
(12) Ellard, J. A., King, C. D., Milnes, M. V., Hedley, W. H., Moodie, W. J., Yanko, W. H., "Organic Coolant Essential Data," Annual Report, Monsanto Research Corp., Rept. **IDO-11,004** (1962).
(13) Ellard, J. A., King, C. D., Milnes, M. V., Moodie, W. J., Yanko, W. H., "Organic Coolant Essential Data," Annual Report, Monsanto Research Corp., Rept. **IDO-11,000** (Jan. 23, 1962).
(14) Gercke, R. H. J., Keen, R. T., Atomics International, Quarterly Progress Report **NAA-SR-6777** (September 1961).
(15) Grunberg, L., Nissan, A. H., *Ind. Eng. Chem.* **42**, 885 (1950).
(16) Hedley, W. H., Milnes, M. V., Yanko, W. H., "Viscosity and Thermal Conductivity of Polyphenyls in the Liquid and Vapor States," Monsanto Research Corp., Rept. **IDO-11,007** (1963).
(17) Horrocks, J. K., McLaughlin, E., *Proc. Roy. Soc. London* **A273**, 259 (1963).
(18) Mandel, H., Ewbank, N., "Critical Constants of Diphenyl and the Terphenyls," Atomics International, Rept. **NAA-SR-5129** (December 1960).
(19) McCready, D. W., "Thermal Conductivity of Lubricating Oils and Hydraulic Fluids," **WADC TH58-405** (December 1958).
(20) McEwen, M., "Organic Coolant Databook," Monsanto Co., Tech. Pub. **AT-1** (July 1958).
(21) McLaughlin, E., Ubbelohde, A. R., *Trans. Faraday Soc.* **54**, 1804 (1958).
(22) Mason, H. L., *Trans. ASME* **76**, 817 (1954).
(23) Riedel, L., *Chem. Ing. Tech.* **23**, 321 (1951).
(24) Stone, J. P., Ewing, C. T., Blachly, C. H., Walker, B. E., Miller, R. R., *Ind. Eng. Chem.* **50**, 895 (1958).
(25) Stone, J. P., Ewing, C. T., Miller, R. R., J. CHEM. ENG. DATA **7**, 519 (1962).
(26) Zieband, H., Burton, J. T. A., *Ibid.*, **6**, 579 (1961).

RECEIVED for review February 3, 1967. Resubmitted May 29, 1969. Accepted September 2, 1969. Work sponsored by the U. S. Atomic Energy Commission, Idaho Operations Office, under contracts AT(11-1)-705 and AT(10-1)1088.

Viscosity of Solutions of Some Electrolytes in Heavy Water

ANATOL SELECKI, BOGDAN TYMINSKI, and ANDRZEJ G. CHMIELEWSKI
Department of Nuclear Chemical Engineering, Warsaw Technical University, Warsaw, Poland

The viscosities of solutions of nine electrolytes—KCl, KI, KBr, $KMnO_4$, LiCl, Li_2SO_4, Na_2CO_3, NaF, and $MnSO_4$—in heavy water have been determined at 25°, 35°, 45°, 60°, 75°, and 90° C. at various concentrations up to near saturation.

INVESTIGATIONS of viscosity of electrolyte solutions can give some information about their structure (*1, 4*). There are also relationships between viscosity and heat of evaporation (*2*) or activity coefficients of solution components (*3*). This paper investigates the differences that may be caused in viscosity and solution structure by replacing ordinary water with heavy water.

EXPERIMENTAL

The viscosities of solutions were measured with an Ostwald viscosimeter (Figure 1). The time of flow was four minutes for ordinary water at 25° C. Because of the viscosimeter design, the solutions did not come into contact with the atmosphere, thus protecting the heavy water from dilution by air moisture.

Viscosity was calculated according to the formula

$$\eta = \eta_0 \frac{\rho t}{\rho_0 t_0} \tag{1}$$

where η = viscosity, ρ = density, t = time of flow, and 0 refers to pure heavy water, which was used as a reference standard.

The ratio ρ/ρ_0 was measured in two manometers (Figure 2). One of the manometers was filled with the solution under investigation and the second one with pure heavy water, which was also used for preparing the solution. The ratio $\rho/\rho_0 = \Delta h_0/\Delta h$, where Δh is the difference of liquid levels in the arms of the manometer. The level of liquid was measured with a cathetometer.

Measurements were made in each case, and the ratio ρ/ρ_0 was determined for each solution. The viscosimeter and manometers were thermostated with an accuracy of ±0.05° C.

MATERIALS

The heavy water used in these experiments was produced in the USSR. Its concentration was determined by the picnometric method. For measurements 1 to 27, the concentration of heavy water was 99.8 mole % D_2O; for 28 to 35, 98.8 mole % D_2O; and for 36 to 43, 98.5 mole % D_2O. Before preparation of the solutions, the heavy water was distilled twice.

The salts used were of analytical purity and were dried but not purified before use.

RESULTS

Measurements were made for the solutions of nine salts—KCl, KI, KBr, $KMnO_4$, LiCl, Li_2SO_4, Na_2CO_3, NaF, and $MnSO_4$—at 25°, 35°, 45°, 60°, 75°, and 90° C.

Table I. Viscosity of Solutions of Some Electrolytes in Heavy Water (Centipoises)

No.	Concn., Mole %	Temp., °C. 25	35	45	60	75	90
1	0.0	1.103	0.864	0.713	0.551	0.445	0.366
				KCl			
2	0.5	1.095	0.868	0.714	0.552	0.448	0.368
3	1.0	1.080	0.859	0.709	0.554	0.451	0.373
4	2.2	1.076	0.871	0.732	0.582	0.477	0.398
5	4.0	1.089	0.889	0.755	0.603	0.501	0.423
6	6.4	1.101	0.912	0.784	0.632	0.529	0.451
				KI			
7	1.1	1.036	0.829	0.692	0.542	0.442	0.369
8	2.1	0.970	0.794	0.667	0.541	0.453	0.374
9	3.6	0.942	0.776	0.662	0.536	0.457	0.381
10	5.3	0.936	0.783	0.680	0.556	...	...
11	7.6	0.972	0.823	0.715	0.597	0.508	0.440
12	12.1	1.098	0.942	0.827	0.695	0.601	0.521
				KBr			
13	1.2	1.086	0.854	0.715	0.557	0.462	0.380
14	3.75	1.046	0.856	0.725	0.581	0.483	0.414
15	5.6	1.024	0.853	0.732	0.600	...	...
16	6.7	1.018	0.850	0.739	0.607	0.512	0.437
17	7.3	1.030	0.868	0.754	0.617	0.525	0.450
18	8.1	1.047	0.884	0.767	0.635	0.541	0.463
				$KMnO_4$			
19	0.21	1.101	0.873	0.717	0.553	0.452	0.371
20	0.34	1.092	0.861	0.709	0.551	0.450	0.368
21	0.52	1.079	0.853	0.703	0.546	0.446	0.370
22	0.62	1.082	0.850	0.704	0.547	0.443	0.366
				LiCl			
23	2.4	1.335	1.039	0.854	0.653	0.526	0.431
24	.7.6	1.712	1.351	1.112	0.853	0.685	0.559
25	14.1	3.692	3.018	2.397	1.818	1.453	1.178
26	19.7	6.900	5.334	4.216	3.123	2.410	1.851
27	21.5	8.914	6.744	5.422	3.879	2.924	2.270
				Li_2SO_4			
28	0.5	1.243	0.975	0.802	0.613	0.494	0.403
29	1.6	1.740	1.355	1.102	0.833	0.650	0.533
30	3.2	2.887	2.216	1.770	1.315	1.021	0.808
31	5.2	5.343	3.964	3.084	2.232	1.694	1.307
				Na_2CO_3			
32	0.9	1.400	1.094	0.895	0.691	0.550	0.444
33	1.8	1.847	1.443	1.167	0.884	0.701	0.564
34	3.1	2.881	2.174	1.725	1.262	0.969	0.764
35	4.1	4.233	3.115	2.435	1.713	1.280	0.990
				NaF			
36	0.54	1.159	0.913	0.747	0.576	0.463	0.380
37	1.22	1.246	0.980	0.800	0.615	0.493	0.404
38	1.63	1.326	1.043	0.857	0.650	0.520	0.425
				$MnSO_4$			
39	0.5	1.297	1.00	0.827	0.620	0.503	0.411
40	1.2	1.590	1.247	1.008	0.765	0.609	0.489
41	2.0	2.183	1.696	1.371	1.045	0.802	0.645
42	2.9	3.140	2.404	1.912	1.413	1.087	0.847
43	3.7	4.452	3.327	2.575	1.878	1.432	1.167

Table II. Ratio of Density of Some Electrolyte Solutions to the Density of Pure Heavy Water

No.	Concn., Mole %	Temp., ° C.					
		25	35	45	60	75	90
1	0.0	1.000	1.000	1.000	1.000	1.000	1.000
				KCl			
2	0.5	1.012	1.012	1.012	1.012	1.012	1.012
3	1.0	1.028	1.029	1.027	1.031	1.026	1.022
4	2.2	1.040	1.046	1.041	1.042	1.039	1.041
5	4.0	1.094	1.087	1.082	1.087	1.087	1.087
6	6.4	1.119	1.117	1.122	1.120	1.120	1.120
				KI			
7	1.1	1.067	1.068	1.069	1.059	1.062	1.055
8	2.1	1.095	1.094	1.097	1.097	1.096	1.096
9	3.6	1.170	1.170	1.170	1.170	1.170	1.170
10	5.3	1.267	1.269	1.267	1.264	...	...
11	7.6	1.370	1.366	1.369	1.373	1.370	1.363
12	12.1	1.560	1.558	1.555	1.548	1.547	1.557
				KBr			
13	1.2	1.075	1.075	1.076	1.065	1.057	1.073
14	3.7	1.171	1.171	1.167	1.163	1.169	1.169
15	5.6	1.219	1.219	1.215	1.215	...	...
16	6.7	1.248	1.247	1.249	1.252	1.249	1.253
17	7.3	1.276	1.269	1.273	1.269	1.265	1.261
18	8.1	1.285	1.289	1.287	1.287	1.287	1.287
				$KMnO_4$			
19	0.21	1.009	1.024	1.010	1.030	1.008	1.012
20	0.34	1.016	1.017	1.015	1.016	1.010	1.014
21	0.52	1.037	1.034	1.035	1.030	1.025	1.027
22	0.62	1.024	1.024	1.019	1.020	1.020	1.020
				LiCl			
23	2.4	1.042	1.040	1.040	1.039	1.037	1.039
24	7.6	1.088	1.087	1.085	1.085	1.085	1.079
25	14.1	1.176	1.173	1.174	1.175	1.178	1.181
26	19.7	1.219	1.220	1.220	1.221	1.220	1.219
27	21.5	1.232	1.233	1.233	1.232	1.229	1.239
				Li_2SO_4			
28	0.5	1.028	1.028	1.024	1.026	1.027	1.025
29	1.6	1.073	1.077	1.079	1.083	1.084	1.080
30	3.2	1.146	1.140	1.147	1.156	1.157	1.165
31	5.2	1.212	1.209	1.210	1.208	1.213	1.213
				Na_2CO_3			
32	0.9	1.055	1.055	1.055	1.053	1.052	1.057
33	1.8	1.109	1.106	1.102	1.103	1.109	1.103
34	3.1	1.166	1.173	1.177	1.176	1.166	1.169
35	4.1	1.210	1.220	1.215	1.223	1.225	1.211
				NaF			
36	0.54	1.017	1.018	1.021	1.018	1.019	1.019
37	1.22	1.028	1.020	1.018	1.018	1.028	1.024
38	1.63	1.038	1.038	1.040	1.040	1.043	1.042
				$MnSO_4$			
39	0.5	1.038	1.039	1.038	1.038	1.045	1.042
40	1.2	1.071	1.087	1.082	1.076	1.074	1.060
41	2.0	1.168	1.165	1.160	1.164	1.161	1.156
42	2.9	1.211	1.210	1.205	1.200	1.196	1.198
43	3.7	1.284	1.286	1.280	1.275	1.281	1.281

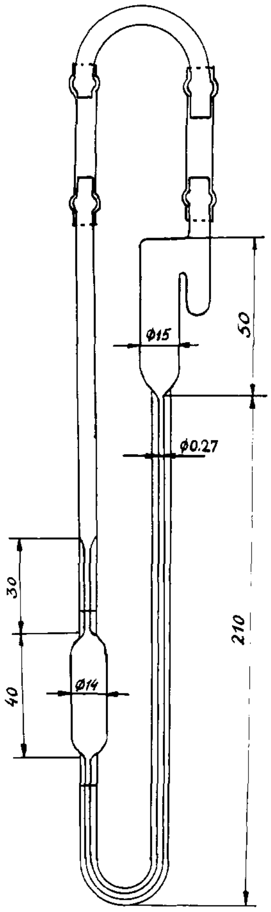

Figure 1. An Ostwald viscosimeter

The viscosity values and the values of ρ/ρ_0 are listed (Tables I and II). The estimated precision is $\pm 0.8\%$. The greater part of the error comes from values of ρ/ρ_0, which were determined with an estimated accuracy of $\pm 0.5\%$.

DISCUSSION

The viscosities of heavy water solutions are greater than the viscosities of ordinary water solutions at the same temperature and salt concentration. However, the character of the curves is similar. For instance, both heavy water

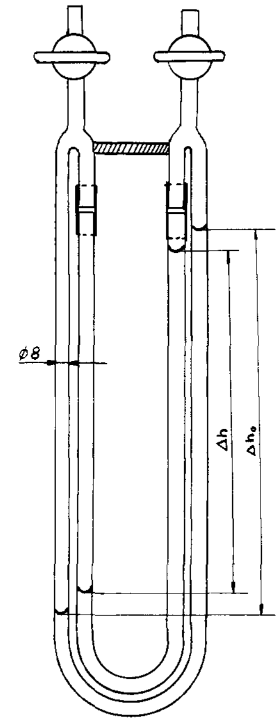

Figure 2. U-tubes for determination of density of solutions

and ordinary water solutions of KCl, KI, KBr, and $KMnO_4$ exhibit a minimum of viscosity, which disappears with temperature increase. For the other salts, viscosities increase with concentrations for both ordinary and heavy water.

A discussion of structure of electrolyte solutions on the basis of above data would be premature. Such an analysis will be made separately, after more relevant data are available.

LITERATURE CITED

(1) Good, W., *Electrochim. Acta* **9**, 203 (1964); *Ibid.*, **10**, 1 (1965).
(2) Panchenkov, G.M., *Zh. Fiz. Khim.* **20**, 811 (1946); *Ibid.*, **20**, 1011 (1946); *Ibid.*, **21**, 187 (1947); *Ibid.*, **24**, 1390 (1950).
(3) Reik, H.G., *Z. Electrochem.* **59**, 35 (1955); *Ibid.*, **59**, 126 (1955).
(4) Stokes, R.H., Mills, R., "Viscosity of Electrolyte Solutions and Related Properties," Pergamon, London, 1960.

RECEIVED for review June 20, 1968. Accepted April 15, 1969.

Solubilities and Refractive Indices of Some Inorganic Salts in Heavy Water

ANATOL SELECKI, BOGDAN TYMINSKI, and BARBARA MARIANKOWSKA
Department of Nuclear Chemical Engineering, Warsaw Technical University, Warsaw, Poland

Solubilities and refractive indices were measured for concentrated solutions in heavy water of 14 salts—LiCl, NaF, NaCl, NaBr, NaI, Na_2CO_3, $NaClO_4$, KCl, KSCN, $KMnO_4$, $K_2Cr_2O_7$, $K_4Fe(CN)_6$, CsCl, and Li_2SO_4—at 25°, 35°, 45°, 60°, 75.5°, and 91° C.

DURING an investigation, it was necessary to determine the differences of solubilities of some salts in heavy and light water. Some of the relevant data were available in the literature (*2, 4, 5, 6, 7, 9, 10*), but they were not sufficient. In this work, measurements of solubility were made for 14 salts—LiCl, NaF, NaCl, NaBr, NaI, $NaClO_4$, Na_2CO_3, KCl, KSCN, $KMnO_4$, $K_2Cr_2O_7$, $K_4Fe(CN)_6$, CsCl, and Li_2SO_4—at 25°, 35°, 45°, 60°, 75.5° and 91° C.

SOLUBILITY DETERMINATION METHOD

A curve of refractive indices of salt solutions against concentration at a constant temperature was plotted. At