Viscosity and Density of Aqueous Solutions of LiBr, LiCl, $ZnBr_2$, $CaCl_2$, and $LiNO_3$. 1. Single Salt Solutions

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New experimental data for the viscosity and density of the binary systems lithium chloride + water, lithium bromide + water, calcium chloride + water, lithium nitrate + water, and zinc bromide + water are presented. Densities are presented in tabular form and as 10-parameter correlations, while kinematic and dynamic viscosities are presented in tabular form. Data are presented in the concentration range from intermediate dilution to close to room temperature crystallization concentration. The temperature ranges are 20–70 °C for density and 25–90 °C for viscosity. When available, literature data are compared with the new data, and some disagreement is found. New thermogravimetric curves are presented for the dehydration of $CaCl_2$, $ZnBr_2$, and LiBr in order to enable evaluation of drying as a composition determination technique.

Introduction

The scope of this study was to determine the viscosity and density of the systems lithium chloride + water, calcium chloride + water, lithium nitrate + water, lithum bromide + water, and zinc bromide + water at conditions that prevail in absorption heat pumps, heat transformers, and refrigeration plants. Literature data are available for the systems LiBr + H_2O, LiCl + H_2O, and $CaCl_2$ + H_2O (*1–6*) and for $LiNO_3$ + H_2O at 25 °C (*7*). Since the literature data are not consistent, this study has resolved some conflicts. In the following paper in this issue, data for mixed electrolyte solutions will be presented, and the single solute data presented here will be a useful base for modeling the viscosity of the multisolute solutions.

Experimental Section

Materials. Double-distilled water was used as the solvent in all solutions. LiCl, $CaCl_2$, and $LiNO_3$ were of reagent grade, with certified purities of 99, 99, and 97% by mass, respectively. $ZnBr_2$ and LiBr were of technical quality with type analyses of 98 and 99.4%. Both the $ZnBr_2$ and the LiBr were analyzed with AAS and HPLC to check the purity. The LiBr and $ZnBr_2$ contents were 97 and 98% by mass. The chloride content was 0.4 and 0.05% by mass in LiBr and $ZnBr_2$, respectively. For each system a stock solution was prepared. All stock solutions were filtered through a 40-μm glass filter before composition determination. The samples were prepared by dilution of the stock solution with known amounts of water.

Density Determination. Densities were determined with an Anton Paar DMA 602 vibrating tube densitometer. The tube was filled at 20 °C, and the temperature was increased in 10 °C steps to 70 °C. The error in the temperature reading was estimated to ±0.05 °C. Calibration was performed with double-distilled water and air. The average calibration error was 0.03 kg/m³, but due to the fact that all measured densities are well above the density of water, we estimated the uncertainty to be ±0.1 kg/m³.

Composition Determination. Approximately 10 g of each stock solution was poured into flasks which were heated in a thermostated furnace at 150 °C. When the samples were solidified, the water loss was determined with a balance and the samples were put into the furnace. The temperature was

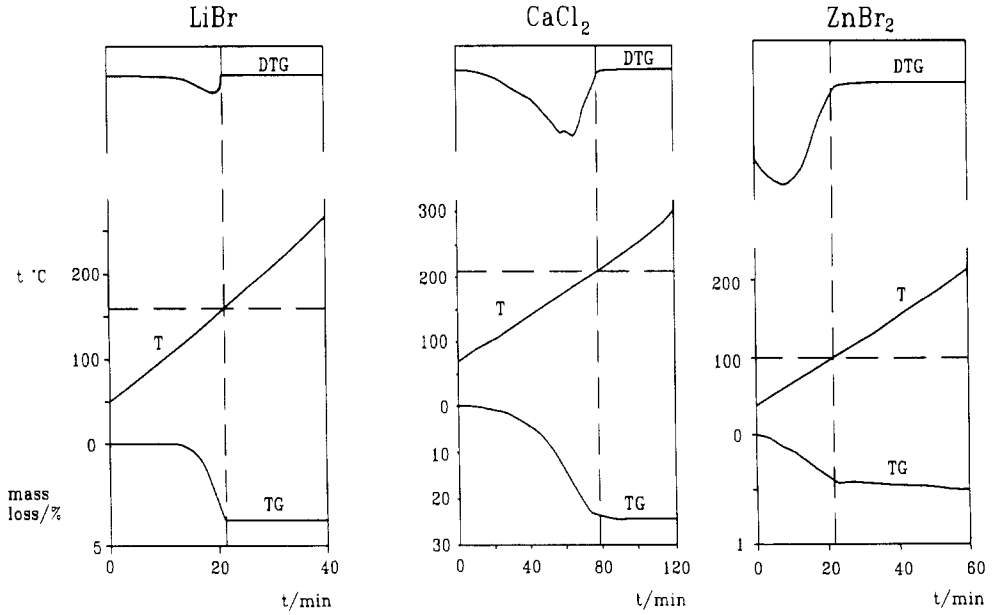

Figure 1. TG and DTG curves for LiBr, $CaCl_2$, and $ZnBr_2$.

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Table 1. Parameters of Equation 2, Number of Experimental Points, NPTS, and Standard Deviation, SD

	LiCl	LiBr	$CaCl_2$	$LiNO_3$	$ZnBr_2$
NPTS	174	162	198	151	231
d_1	1002.8	1002.0	1002.0	1003.9	1000.4
d_2	−0.15582	-8.7932×10^{-2}	−0.13105	−0.16818	6.3124×10^{-2}
d_3	-2.88385×10^{-3}	-3.79848×10^{-3}	-3.10677×10^{-3}	-6.04868×10^{-3}	-3.07465×10^{-3}
d_4	6.1379	8.5425	8.6803	5.5354	8.9448
d_5	-5.8452×10^{-2}	-2.9368×10^{-2}	-5.2079×10^{-3}	6.0786×10^{-2}	9.0820×10^{-2}
d_6	6.0650×10^{-4}	-5.7606×10^{-3}	-1.1526×10^{-2}	-1.2607×10^{-2}	-1.6852×10^{-2}
d_7	-1.2546×10^{-4}	-8.2838×10^{-5}	-1.7701×10^{-5}	3.5172×10^{-5}	-3.5556×10^{-5}
d_8	5.8029×10^{-5}	7.3685×10^{-5}	7.5160×10^{-5}	5.9957×10^{-5}	7.2958×10^{-5}
d_9	2.6623×10^{-3}	1.4834×10^{-3}	1.9404×10^{-3}	-8.0913×10^{-4}	-9.5113×10^{-4}
d_{10}	-2.5941×10^{-5}	4.2006×10^{-7}	-2.3542×10^{-5}	8.6480×10^{-6}	1.8973×10^{-5}
SD/(kg m^{-3})	0.40	0.76	0.60	0.53	0.82

Table 2. Density, ρ, and Dynamic Viscosity, η, of the System LiCl + H_2O as a Function of Mass Fraction, w, and Temperature, t

100w	t/°C	$10^3\eta$/(Pa·s)	ρ/(kg/m^3)	100w	t/°C	$10^3\eta$/(Pa·s)	ρ/(kg/m^3)
41.50	24.99	9.89	1261.2	31.22	24.95	3.82	1186.7
41.50	29.98	8.68	1259.4	31.22	29.95	3.41	1185.1
41.50	40.00	6.81	1255.6	31.22	39.94	2.77	1181.8
41.50	50.00	5.36	1251.7	31.22	50.14	2.30	1178.1
41.50	60.00	4.41	1246.9	31.22	60.15	1.94	1174.4
41.50	70.03	3.68	1243.6	31.22	70.14	1.67	1170.4
41.50	80.13	3.09	1239.4	31.22	80.20	1.46	1166.1
41.50	90.15	2.66	1235.1	31.22	90.25	1.29	1161.7
41.50	25.04	9.86	1261.2	37.97	30.03	6.06	1233.4
39.88	30.03	7.28	1247.4	37.97	40.04	4.81	1229.8
39.88	40.04	5.69	1243.7	37.97	50.04	3.90	1226.0
39.88	50.04	4.58	1239.9	37.97	60.08	3.24	1222.1
39.88	60.08	3.80	1235.9	37.97	70.10	2.74	1218.1
39.88	70.10	3.18	1231.8	37.97	80.12	2.34	1213.9
39.88	80.12	2.71	1227.7	37.97	90.16	2.05	1209.6
39.88	90.16	2.33	1223.4	37.97	30.02	6.08	1233.4
39.88	30.02	7.27	1247.4	34.53	25.01	5.00	1210.1
37.97	30.03	6.06	1233.4	34.53	29.99	4.44	1208.5
37.97	40.04	4.81	1229.8	34.53	39.98	3.58	1205.0
37.97	50.04	3.90	1226.0	34.53	50.00	2.95	1201.4
37.97	60.08	3.24	1222.1	34.53	59.94	2.47	1197.6
37.97	70.10	2.74	1218.1	34.53	69.95	2.12	1193.6
37.97	80.12	2.34	1213.9	34.53	79.98	1.84	1189.4
37.97	90.16	2.05	1209.6	34.53	90.00	1.62	1185.0
37.97	30.02	6.08	1233.4	34.53	24.91	4.97	1210.2
34.53	25.01	5.00	1210.1	31.22	24.95	3.82	1186.7
34.53	29.99	4.44	1208.5	31.22	29.95	3.41	1185.1
34.53	39.98	3.58	1205.0	31.22	39.94	2.77	1181.8
34.53	50.00	2.95	1201.4	31.22	50.14	2.30	1178.1
34.53	59.94	2.47	1197.6	31.22	60.15	1.94	1174.4
34.53	69.95	2.12	1193.6	31.22	70.14	1.67	1170.4
34.53	79.98	1.84	1189.4	31.22	80.20	1.46	1166.1
34.53	90.00	1.62	1185.0	31.22	90.25	1.29	1161.7
34.53	24.91	4.97	1210.2				

Table 3. Density, ρ, and Dynamic Viscosity, η, of the System LiBr + H_2O as a Function of Mass Fraction, w, and Temperature, t

100w	t/°C	$10^3\eta$/(Pa·s)	ρ/(kg/m^3)	100w	t/°C	$10^3\eta$/(Pa·s)	ρ/(kg/m^3)
58.50	60.02	3.41	1662.5	45.50	24.91	2.59	1458.1
58.50	70.01	2.93	1656.0	45.50	29.92	2.35	1455.4
58.50	80.02	2.53	1649.7	45.50	39.94	1.97	1449.9
58.50	90.08	2.22	1643.5	45.50	49.94	1.69	1444.2
58.50	100.11	1.97	1637.3	45.50	59.96	1.46	1438.5
58.50	59.93	3.42	1662.5	45.50	69.98	1.29	1432.7
58.50	24.94	6.81	1685.8	45.50	80.01	1.14	1426.8
58.50	29.93	6.30	1682.4	45.50	90.03	1.05	1420.8
58.50	39.92	4.88	1675.7	45.50	24.98	2.62	1458.1
58.50	49.93	4.02	1669.0	15.31	24.97	1.14	1124.7
58.50	59.95	3.48	1662.5	15.31	29.95	1.01	1123.0
58.50	69.96	2.90	1656.1	15.31	39.92	0.83	1119.2
58.50	79.98	2.52	1655.7	15.31	49.92	0.70	1114.8
58.50	90.01	2.21	1643.5	15.31	24.94	1.12	1124.7
58.50	24.94	6.79	1685.8				

then increased to 160 °C. After 24 h, the sample was weighed again, and if the determinations differed by more than 0.02% by mass, the procedure was repeated at 170 °C. On the basis

Table 4. Density, ρ, and Dynamic Viscosity, η, of the System $ZnBr_2$ + H_2O as a Function of Mass Fraction, w, and Temperature, t

100w	t/°C	$10^3\eta$/(Pa·s)	ρ/(kg/m^3)	100w	t/°C	$10^3\eta$/(Pa·s)	ρ/(kg/m^3)
80.24	24.81	42.91	2561.5	59.64	24.90	3.83	1867.5
80.24	29.85	33.94	2551.0	58.87	19.91	4.01	1853.9
80.24	39.84	22.41	2537.2	58.87	29.91	3.08	1842.5
80.24	49.86	15.57	2521.8	58.87	39.89	2.44	1830.8
80.24	59.88	11.37	2506.4	58.87	49.92	1.98	1818.7
80.24	69.90	8.66	2490.9	58.87	59.93	1.64	1806.2
80.24	79.93	6.82	2475.4	58.87	69.91	1.38	1793.4
80.24	89.96	5.52	2459.9	58.87	79.91	1.18	1780.3
80.24	24.87	43.23	2560.1	58.87	19.90	4.05	1853.9
76.09	24.90	17.97	2388.0	54.20	19.96	3.27	1744.4
76.09	29.90	14.94	2380.8	54.20	29.94	2.53	1733.8
76.09	39.86	10.64	2366.2	54.20	39.94	2.04	1722.8
76.09	49.87	7.95	2351.5	54.20	19.94	3.28	1744.4
76.09	59.87	6.11	2336.7	54.20	19.96	3.23	1744.4
76.09	69.91	4.87	2321.8	54.20	29.97	2.51	1733.8
76.09	79.94	3.99	2306.7	54.20	39.97	2.00	1722.8
76.09	89.96	3.34	2291.6	54.20	49.94	1.63	1711.4
76.09	24.90	18.25	2388.0	54.20	59.94	1.36	1699.6
72.36	24.81	10.60	2249.2	54.20	69.94	1.15	1687.3
72.36	29.85	9.04	2242.2	54.20	19.93	3.27	1744.4
72.36	39.84	6.72	2228.3	52.79	24.90	2.78	1708.7
72.36	49.86	5.18	2214.1	52.79	29.90	2.42	1703.5
72.36	59.88	4.14	2219.8	52.79	39.86	1.90	1692.7
72.36	69.90	3.39	2185.4	52.79	49.87	1.56	1681.5
72.36	79.93	2.82	2170.8	52.79	59.87	1.30	1669.8
72.36	24.87	10.65	2249.1	52.79	69.91	1.10	1657.7
65.07	19.91	5.95	2021.0	52.79	24.90	2.75	1708.7
65.07	29.91	4.48	2008.5	44.91	19.96	2.36	1559.9
65.07	39.89	3.49	1995.8	44.91	29.94	1.85	1550.9
65.07	49.92	2.81	1982.7	44.91	39.94	1.49	1541.3
65.07	59.93	2.31	1969.4	44.91	49.94	1.23	1531.2
65.07	19.90	5.98	2021.0	44.91	59.94	1.03	1520.5
59.64	24.90	3.77	1867.5	44.91	19.94	2.36	1560.0
59.64	29.90	3.31	1861.7	29.56	19.96	1.64	1323.2
59.64	39.86	2.61	1849.9	29.56	29.94	1.30	1316.6
59.64	49.87	2.14	1837.7	29.56	39.94	1.06	1309.3
59.64	59.87	1.81	1825.1	29.56	49.94	0.87	1301.1
59.64	69.91	1.50	1812.2	29.56	19.94	1.63	1323.2
59.64	79.94	1.32	1798.9				

Table 5. Density, ρ, and Dynamic Viscosity, η, of the System $LiNO_3$ + H_2O as a Function of Mass Fraction, w, and Temperature, t

100w	t/°C	$10^3\eta$/(Pa·s)	ρ/(kg/m^3)	100w	t/°C	$10^3\eta$/(Pa·s)	ρ/(kg/m^3)
42.01	24.90	2.86	1294.5	35.15	49.79	1.28	1220.7
42.01	29.88	2.56	1291.2	35.15	59.81	1.10	1214.2
42.01	39.89	2.11	1284.4	35.15	24.79	2.07	1237.0
42.01	49.88	1.74	1277.6	27.93	24.79	1.68	1180.5
42.01	59.90	1.49	1270.6	27.93	29.79	1.50	1177.6
42.01	69.93	1.28	1263.5	27.93	39.78	1.25	1171.7
42.01	24.89	2.88	1294.5	27.93	49.79	1.07	1165.5
35.15	24.79	2.08	1237.0	27.93	59.81	0.93	1159.1
35.15	29.79	1.88	1233.7	27.93	69.82	0.82	1152.3
35.15	39.78	1.54	1227.5	27.93	24.79	1.70	1180.5

of repeated determinations, we estimated the uncertainty to be ±0.05% by mass for all systems except $ZnBr_2$ + H_2O and $CaCl_2$ + H_2O, for which we estimated the error to be ±0.1%

Table 6. Density, ρ, and Dynamic Viscosity, η, of the System $CaCl_2 + H_2O$ as a Function of Mass Fraction, w, and Temperature, t

100w	t/°C	$10^3\eta$/(Pa·s)	ρ/(kg/m^3)	100w	t/°C	$10^3\eta$/(Pa·s)	ρ/(kg/m^3)
51.32	25.04	33.78	1514.1	46.50	25.03	17.68	1462.2
51.32	30.01	28.25	1510.5	39.58	24.90	7.43	1384.8
51.32	39.99	20.27	1503.4	39.58	29.90	6.58	1381.6
51.32	49.93	15.40	1496.4	39.58	39.94	5.19	1375.4
51.32	59.96	11.91	1489.5	39.58	49.96	4.20	1369.1
51.32	69.99	9.45	1482.4	39.58	60.01	3.48	1362.8
51.32	80.02	7.68	1476.2	39.58	70.03	2.95	1356.4
51.32	90.09	6.35	1469.7	39.58	80.07	2.54	1350.0
51.32	24.99	34.07	1514.2	39.58	90.11	2.20	1343.7
49.54	24.94	27.44	1495.3	39.58	24.98	7.44	1384.7
49.54	29.92	23.01	1491.8	29.78	25.04	3.07	1276.0
49.54	39.94	16.80	1484.8	29.78	30.01	2.82	1273.3
49.54	49.96	12.75	1477.8	29.78	39.99	2.28	1267.8
49.54	60.00	9.95	1471.0	29.78	49.96	1.92	1262.2
49.54	70.06	7.93	1464.4	29.78	60.00	1.64	1256.3
49.54	80.11	6.48	1457.8	29.78	70.06	1.42	1250.2
49.54	90.12	5.43	1451.4	29.78	80.11	1.24	1244.0
49.54	24.95	27.55	1495.3	29.78	90.12	1.08	1237.6
46.50	25.00	17.45	1462.2	29.78	24.99	3.01	1276.0
46.50	29.99	14.89	1458.8	9.87	24.94	1.22	1081.4
46.50	39.99	11.21	1452.0	9.87	29.92	1.09	1079.5
46.50	49.91	8.80	1445.4	9.87	39.94	0.91	1074.4
46.50	59.93	7.05	1438.7	9.87	49.93	0.77	1070.8
46.50	69.95	5.76	1432.2	9.87	59.96	0.68	1065.7
46.50	80.00	4.78	1425.7	9.87	24.95	1.21	1081.4
46.50	90.00	4.04	1419.3				

Table 7. Measured Densities, ρ, as a Function of Temperature, t, and mass fraction, w, for the system LiCl + H_2O

100w	ρ/(kg m^{-3})	t/°C	100w	ρ/(kg m^{-3})	t/°C
45.39	1292.58	17.00	39.32	1232.34	59.67
45.39	1288.73	27.10	39.32	1228.34	69.64
45.39	1284.77	37.14	24.86	1145.59	20.19
45.39	1280.71	47.28	24.86	1142.54	30.09
45.39	1276.50	57.43	24.86	1139.14	40.03
45.39	1272.27	67.49	24.86	1135.53	50.00
30.01	1179.84	19.21	24.86	1131.72	59.96
30.01	1176.60	29.64	24.86	1127.78	69.91
30.01	1173.23	39.71	20.22	1116.57	19.33
30.01	1169.69	49.71	20.22	1113.54	29.65
30.01	1165.89	59.93	20.22	1111.02	39.83
30.01	1161.97	69.89	20.22	1107.29	49.92
10.03	1056.76	19.29	20.22	1116.57	19.33
10.03	1053.86	29.50	20.22	1099.53	69.96
10.03	1050.38	39.63	41.56	1264.07	19.55
10.03	1046.41	49.63	41.56	1260.32	29.54
43.03	1274.80	20.17	41.56	1256.73	39.36
43.03	1271.20	30.16	41.56	1252.64	49.32
43.03	1267.16	39.97	41.56	1248.53	59.30
43.03	1263.16	49.94	41.56	1244.63	69.24
43.03	1259.07	59.90	35.91	1221.72	18.84
43.03	1255.00	69.89	35.91	1218.43	28.63
39.32	1247.59	18.99	35.91	1214.89	38.63
39.32	1243.82	29.67	35.91	1211.19	48.58
39.32	1240.10	39.70	35.91	1207.43	58.41
39.32	1236.28	49.65	35.91	1203.53	68.35

by mass. The TG curves of Rassonskaya and Semendyaeva (8) show that anhydrous $LiNO_3$ forms at 130–140 °C and that anhydrous LiCl forms at 150–170 °C, which confirms that no water remained in our samples after drying.

LiBr, $CaCl_2$, and LiCl samples were precipitated with reagent grade $AgNO_3$. The precipitate was washed, dried, and weighed. The calculated salt content was 0.03, 0.10, and 0.10% by mass lower than the drying determination for the samples, respectively. We believe that the difference stems from filtration losses in the silver precipitation analysis.

For dehydration of LiBr, $ZnBr_2$, and $CaCl_2$, thermogravimetric tests were made in a Mettler thermobalance at a heating rate of 6 K/min. The TG curves are shown in Figure 1. Anhydrous samples of $ZnBr_2$ and LiBr were exposed to room

Table 8. Measured Densities, ρ, as a Function of Temperature, t, and Mass Fraction, w, for the system LiBr + H_2O

100w	ρ/(kg m^{-3})	t/°C	100w	ρ/(kg m^{-3})	t/°C
61.34	1750.09	20.08	44.55	1447.41	19.70
61.34	1742.68	30.26	44.55	1442.29	29.66
61.34	1735.35	40.40	44.55	1436.98	39.62
61.34	1728.06	50.50	44.55	1431.46	49.60
61.34	1722.34	58.49	44.55	1425.81	59.58
61.34	1722.11	58.82	44.55	1420.05	69.60
14.16	1117.41	20.00	50.33	1537.20	19.85
14.16	1114.08	30.06	50.33	1531.69	29.67
14.16	1110.06	40.07	50.33	1525.97	39.63
14.16	1105.43	50.18	50.33	1520.14	49.58
14.16	1100.26	60.32	50.33	1514.19	59.55
14.16	1094.64	70.59	50.33	1508.21	69.53
29.97	1263.56	19.75	52.81	1579.93	19.82
29.97	1259.46	29.66	52.81	1574.13	29.73
29.97	1254.94	39.60	52.81	1568.19	39.67
29.97	1250.06	49.56	52.81	1562.11	49.63
29.97	1244.83	59.51	52.81	1555.96	59.59
29.97	1239.32	69.53	52.81	1549.77	69.60
39.56	1378.87	18.68	56.22	1642.75	20.16
39.56	1374.11	28.88	56.22	1636.25	30.32
39.56	1369.00	39.21	56.22	1629.73	40.46
39.56	1363.70	49.43	56.22	1623.13	50.63
39.56	1358.18	59.60	56.22	1619.92	55.55
39.56	1352.41	69.79	56.22	1619.62	56.03

Table 9. Measured Densities, ρ, as a Function of Temperature, t, and Mass Fraction, w, for the system $ZnBr_2 + H_2O$

100w	ρ/(kg m^{-3})	t/°C	100w	ρ/(kg m^{-3})	t/°C
14.69	1144.88	16.74	58.87	1857.07	16.76
14.69	1140.80	27.42	58.87	1845.12	27.52
14.69	1136.05	37.52	58.87	1833.57	37.54
14.69	1130.45	47.50	58.87	1821.74	47.52
14.69	1121.67	57.48	58.87	1809.61	57.49
14.69	1109.34	67.47	58.87	1797.20	67.48
29.56	1324.71	17.33	65.07	2023.56	17.15
29.56	1318.17	27.32	65.07	2011.16	27.22
29.56	1310.92	37.38	65.07	1998.36	37.38
29.56	1303.15	47.32	65.07	1985.29	47.55
29.56	1294.75	57.34	65.07	1972.17	57.51
29.56	1285.86	67.31	65.07	1958.86	67.49
44.91	1561.09	17.78	70.21	2187.15	16.07
44.91	1552.15	27.80	70.21	2173.45	26.26
44.91	1543.01	37.65	70.21	2159.75	36.32
44.91	1533.24	47.56	70.21	2145.68	46.51
44.91	1522.95	57.54	70.21	2131.49	56.66
44.91	1512.48	67.49	70.21	2117.21	66.81
54.20	1746.70	17.93	76.02	2392.95	20.05
54.20	1736.37	27.83	76.02	2378.61	29.75
54.20	1725.84	37.65	76.02	2363.72	39.76
54.20	1714.68	47.59	76.02	2348.75	49.78
54.20	1703.16	57.56	76.02	2333.74	59.80
54.20	1691.43	67.51	76.02	2318.72	69.86

atmosphere (approximately 20 °C and 60% relative humidity) for 3 h before they were inserted into the thermobalance, while the dihydrate form of $CaCl_2$ was inserted without conditioning.

The TG curve for LiBr shows weight loss in the range 100–150 °C, which we interpret as complete dehydration. The major part of the weight loss for $ZnBr_2$ occurs below 110 °C, but there appear to be small losses above that temperature, which can explain the greater uncertainty in the composition determination. For $CaCl_2$, the TG curve breaks at 210 °C. There are, however, reasons to believe that the anhydrous salt is obtained at lower temperatures: Since the charged sample is known to be in the dihydrate form and if we assume that the salt only exists in anhydrous, monohydrate or dihydrate forms, the mass balance tells us, that the anhydrous form appears when more than half of the weight loss is recorded, which is at 160 °C. This is confirmed by the DTG curve, which has a double dip around 165 °C, thus indicating that there are two transitions, the second one of which has

Table 10. Measured Densities, ρ, as a Function of Temperature, t, and Mass Fraction, w, for the system $LiNO_3 + H_2O$

$100w$	ρ/(kg m^{-3})	t/°C	$100w$	ρ/(kg m^{-3})	t/°C
10.84	1064.57	18.88	32.32	1217.61	18.88
10.84	1060.42	29.02	32.32	1211.57	29.12
10.84	1055.35	39.46	32.32	1205.27	39.44
10.84	1049.58	49.83	32.32	1198.87	49.68
10.84	1042.41	60.25	32.32	1192.08	60.05
10.84	1040.18	61.39	32.32	1187.54	66.97
24.74	1158.71	19.73	37.78	1261.53	19.92
24.74	1153.38	29.72	37.78	1255.19	29.90
24.74	1147.75	39.75	37.78	1248.67	39.92
24.74	1141.84	49.74	37.78	1241.97	49.97
24.74	1135.67	59.79	37.78	1235.19	59.98
24.74	1129.30	69.87	37.78	1228.38	69.99
27.03	1176.65	19.85	48.33	1349.59	28.40
27.03	1171.13	29.87	48.33	1342.15	38.97
27.03	1165.27	39.95	48.33	1334.56	49.39
27.03	1159.17	50.00	48.33	1326.99	59.65
27.03	1152.82	60.13	48.33	1319.51	69.89
27.03	1146.25	70.37			

Table 11. Measured Densities, ρ, as a Function of Temperature, t, and Mass Fraction, w, for the System $CaCl_2 + H_2O$

$100w$	ρ/(kg m^{-3})	t/°C	$100w$	ρ/(kg m^{-3})	t/°C
51.32	1516.43	19.74	34.71	1333.25	18.40
51.32	1509.46	29.68	34.71	1327.35	28.47
51.32	1502.58	39.66	34.71	1321.38	38.56
51.32	1495.78	49.62	34.71	1315.31	48.65
51.32	1489.06	59.59	34.71	1309.24	58.63
51.32	1482.46	69.59	34.71	1303.03	68.83
9.87	1082.68	20.11	39.58	1388.21	19.76
9.87	1079.10	30.22	39.58	1381.79	29.75
9.87	1074.90	40.39	39.58	1375.32	39.77
9.87	1070.17	50.51	39.58	1368.79	49.81
9.87	1066.13	58.48	39.58	1362.26	59.80
9.87	1065.99	58.76	39.58	1355.75	69.91
19.45	1172.50	18.73	42.70	1423.84	19.82
19.45	1168.13	28.92	42.70	1417.08	29.87
19.45	1163.44	39.06	42.70	1410.39	39.89
19.45	1158.43	49.10	42.70	1403.69	49.85
19.45	1153.15	59.12	42.70	1396.95	59.94
19.45	1147.62	69.21	42.70	1390.31	69.99
24.61	1224.17	19.67	46.51	1466.46	19.26
24.61	1219.33	29.65	46.51	1459.53	29.31
24.61	1214.26	39.67	46.51	1452.66	39.37
24.61	1208.97	49.68	46.51	1445.81	49.51
24.61	1203.50	59.67	46.51	1439.05	59.51
24.61	1197.84	69.73	46.51	1432.32	69.69
29.78	1278.92	19.78	49.54	1500.08	19.76
29.78	1273.59	29.78	49.54	1493.08	29.78
29.78	1268.11	39.81	49.54	1486.16	39.79
29.78	1262.48	49.77	49.54	1479.29	49.82
29.78	1256.66	59.84	49.54	1472.51	59.86
29.78	1250.77	69.92	49.54	1465.84	69.92

its rate maximum around 165 °C. The TG curve for $CaCl_2$ thus indicates that dehydration is a slow transition which explains why the uncertainty in composition is greater than the lithium salts.

Viscosity Determination. The viscosities were determined with Ubbelohde capillaries immersed in a thermostat bath with a temperature stability of ±0.02 °C. The temperature was read with a Pt100 instrument, calibrated to a maximum deviation of 0.02 °C from the IPTS68 temperature scale. The capillaries were calibrated with water and calibration oils, supplied by Cannon Instrument Co. The viscosity of water was calculated with eqs 4.94 and 4.95 in Kestin and Wakeham's book (9). The viscosities of the calibration oils were given with four significant digits. All measurements were performed within the calibration range. The flow time was measured with a standard photocell arrangement with a digital stopwatch.

As a working equation we used eq 4.75 of Kestin and Wakeham (9). The parameters in the working equation was

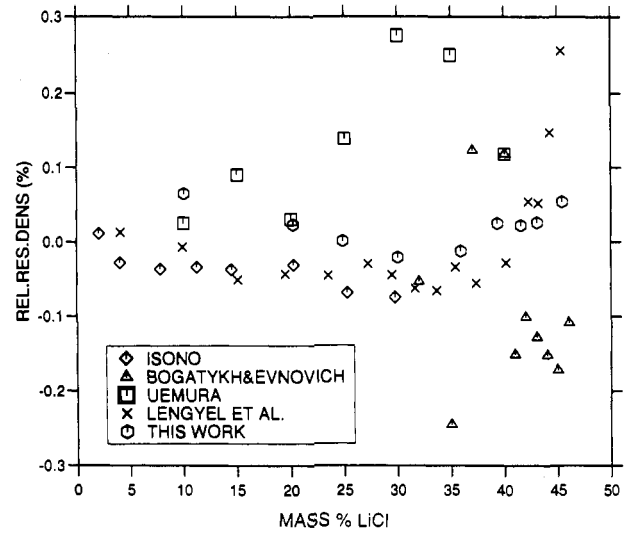

Figure 2. Relative residuals from the fit of a fifth-order polynomial to available data for the density of LiCl + H_2O at 30 °C.

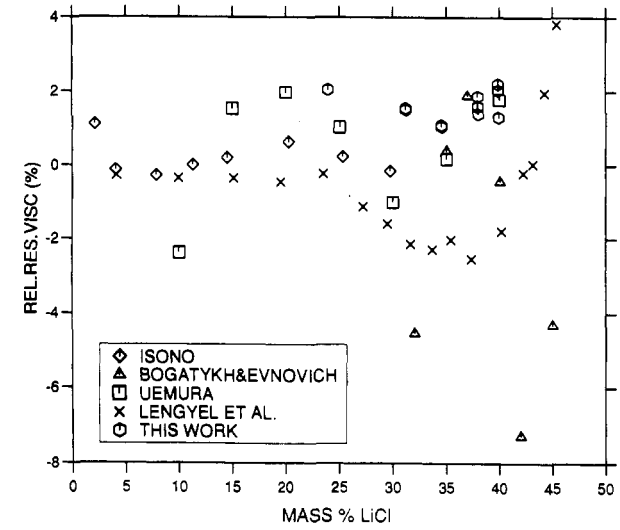

Figure 3. Relative residuals from the fit of a fifth-order polynomial to available data for the viscosity of LiCl + H_2O at 30 °C.

determined by a least-squares minimization of the deviation from the viscosity of the calibration fluids. The working equation then reads

$$\mu = a(f + (f^2 - b)^{1/2}) \quad (1)$$

where μ is the kinematic viscosity, a and b are the viscometer constants, and f is the flow time. The absolute deviation was less than 0.01×10^{-6} m^2/s for all calibration points. The capillaries were filled at 25, 20, or 60 °C, the temperature was increased by 10 °C steps, and the viscosity was determined twice before each step. If the standard deviation exceeded 1% of the average, the first determination was remade. The procedure was repeated until the standard deviation was less than 1%. After the maximum temperature was reached, the first point was determined again. For solutions, with a larger difference between the initial and final determination than 2%, the results were rejected. We have followed Kestin and Wakeham (9), who suggest the Re number range 0.5–100 with $Re = \bar{u}a/\mu$, where $\bar{u}$ is the average velocity and a is the diameter of the capillary. The dynamic viscosity was calculated with the density–temperature relationship (eq 2) obtained from the density measurements.

Results and Discussion

The measured values of the density are presented in Tables 7–11 and in Table 1 as parameters of the density–temperature–composition relationship

$$\rho/(\text{kg m}^{-3}) = d_1 + d_2 t + d_3 t^2 + d_4 \zeta + d_5 \zeta^2 + d_6 \zeta t + d_7 \zeta^2 t + d_8 t^2 \zeta + d_9 \zeta^3 + d_{10} \zeta^4 \quad (2)$$

where t is the temperature (°C) and ζ is $100w$, where w is the mass fraction. The parameters d_1 to d_{10} are listed in Table 1.

In Figure 2 the lithium chloride density has been regressed to fifth-order polynominal, using the 30 °C data for this study and of Lengyel et al. (*4*), Uemura (*3*), and Bogatykh and Evnovich (*2*). Up to 43 mass % the data of this study follow the ones of Lengyel et al. within ±1 kg/m^3, but above that the difference becomes as high as 3 kg/m^3.

The experimental values of the dynamic viscosity are given in Tables 2–6. For comparison of data from this study with the ones of Lengyel et al. (*4*), Isono (*1*), Bogatykh and Evnovich (*2*), and Uemura (*3*), we have regressed the viscosity of lithium chloride solutions at 30 °C to a fifth-order polynomial in composition. The error plot of the regression, shown in Figure 3, illustrates the discrepancies between the sources. It is seen that data of Bogatykh and Evnovich show great deviations, while the data of this study and of the other two sources are contained within a ±1.5% span.

Literature Cited

(1) Isono, T. *Rikagaku Konkyusho Hokoku* **1980**, *56*, 103.
(2) Bogatykh, S. A.; Evnovich, I. D. *Zh. Prikl. Khim.* **1963**, *36*, 1867.
(3) Uemura, T. *Kansai Univ. Technol. Rep.* **1967**, *9*, 71.
(4) Lengyel, S.; Tamas, J.; Giber, J.; Holderith, J. *Acta Chim. Acad. Sci. Hung.* **1964**, *40*, 125.
(5) Lee, R. J.; DiGuilio, R. M.; Jeter, S. M.; Teja, A. S. *ASHRAE Trans.* **1990**, *96*, Part 1.
(6) Uemura, T.; Hasaba, S. *Kansai Univ. Technol. Rep.* **1964**, *6*, 31.
(7) Campbell, A. N.; Debus, G. H.; Kartzmark, E. M. *Can. J. Chem.* **1955**, *33*, 1508.
(8) Rassonskaya, I. S.; Semendyaeva, N. K. *Zh. Neorg. Khim.* **1963**, *8*, 1419.
(9) Kestin, J.; Wakeham, W. A. In *Transport Properties of Fluids: Thermal Conductivity, Viscosity and Diffusion Coefficient*; Ho, C. Y., Ed.; Hemisphere: Bristol, PA, 1988.

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