(4) Tanner, J. E.; Lamb, F. W. J. Solution Chem. 1978, 7, 303.
(5) Liphard, K. G.; Jost, A.; Schneider, G. M. J. Phys. Chem. 1977, 81, 547.
(6) Chen, C. T. A. Ph.D. Dissertation, University of Miami, Coral Gables, FL, 1977.
(7) Chen, C. T. A.; Millero, F. J. J. Chem. Eng. Data 1981, 26, 270.
(8) Fofonoff, N. P. "The Sea"; Hill, M. N., Ed.; Interscience: New York, 1962; Vol. 1, pp 3-30.
(9) Millero, F. J.; Perron, G.; Desnoyers, J. E. J. Geophys. Res. 1973, 78, 4499.
(10) Chen, C. T. A.; Fine, R. A.; Millero, F. J. J. Chem. Phys. 1977, 66, 2142.
(11) Sirota, A. M.; Beljakov, P. E. Teploenergetika (Moscow) 1959, 6, 67.
(12) Sirota, A. M.; Shrago, Z. Kh. Teploenergetika (Moscow) 1968, 15, 86.
(13) Schneider, G. M., Ruhr-Univensitat, private communication, 1981.

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Viscosity of Some Binary and Ternary Liquid Mixtures

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Kinematic viscosities and densities of eight binary and four ternary liquid mixtures of polar components are reported for various temperatures. Experimental viscosities were correlated with McAllister's equation of viscosity and with a modified form of the McAllister equation.

Introduction

The solution to many engineering problems requires quantitative information on the viscosity of liquid mixtures. Examples of such problems include heat transfer, mass transfer, and fluid flow in many technical situations.

In the present work, kinematic viscosities and densities of eight binary and four ternary systems of strongly polar components are presented. For comparison the viscosity data were correlated by means of the methods of McAllister (*1*) and that of Dizechi (*2*).

Experimental Section

Kinematic viscosities were measured with a Schott automated viscosity measuring system. This system consists of a basic control unit including a printer, a measuring stand, a constant-temperature-bath circulator, and a calibrated capillary viscometer depending on measuring range. For measurements at and below ambient temperature, this system was used in conjunction with a Model RTE-4 Neslab cooling system. Bath temperatures can be set and held constant to about ±0.01 °C. Time measurements were made automatically with the help of a quartz timer with a resolution of 0.01 s and two light barriers across the viscometer. The light barriers detect the passing meniscus of the studied fluid and provide the start-stop signals for the time measurement.

Liquid mixtures were prepared with a Mettler precision digital balance Model PT 1200 with an accuracy of $\pm 10^{-2}$ g. The buoyancy effect was neglected, since errors in measured mass fractions introduced by this effect were much smaller than 0.1%.

Densities were determined with a Paar Model DMA 46 calculating density meter with built-in thermostat with an accuracy of $\pm 1 \times 10^{-4}$ g/cm^3. This system simplifies the accurate determination of the density of the liquids by reducing the measuring procedure to the electronic measurement of a time period from which the density is automatically calculated with a built-in arithmetic processor. The instrument can measure densities between 15 and 40 °C. Extrapolation is used for lower or higher temperatures.

Table I. Physical Properties of Pure Components

component	M, g/mol	t_b, °C	Z
water	18.01	100.00	−1.10
methanol	32.04	64.70	+5.30
ethanol	46.07	78.30	+4.40
acetone	58.08	56.30	+10.90
1-propanol	60.10	97.20	+8.60
ethylene glycol	62.07	197.30	+1.60

Fluids used in this work were all purified, Spectar AR, with physical properties as listed in Table I. Evaporation rates were negligible in transferring the mixtures into capillary viscometers.

Results and Discussion

Viscosities and densities of the 12 following mixtures were measured at different temperatures, and the results of these measurements are listed in Table II; densities at 10 and 50 °C were found from extrapolation: acetone–water mixtures at 20, 25, 30, 37.8, and 50 °C; methanol–water mixtures at 10, 20, 30, 40, and 50 °C; ethanol–water mixtures at 10, 20, 30, 40, and 50 °C; methanol–ethanol mixtures at 10, 20, 30, 40, and 50 °C; methanol–ethanol–water mixtures at 10, 20, 30, 40, and 50 °C; 1-propanol–water mixtures at 30 °C; ethylene glycol–water mixtures at 30 °C; methanol–1-propanol mixtures at 30 °C; ethanol–1-propanol mixtures at 30 °C; methanol–1-propanol–water mixtures at 30 °C; ethanol–1-propanol–water mixtures at 30 °C; methanol–ethanol–1-propanol mixtures at 30 °C.

The binary and ternary data were correlated by means of the McAllister equation of viscosity (*1*), which for n-component mixtures reads

$$\ln \nu_m = \sum_{i=1}^{n} x_i^3 \ln \nu_i M_i - \ln M_{av} + \sum_{i=1}^{n} \sum_{\substack{j=1 \\ i \neq j}}^{n} x_i^2 x_j \ln \nu_{ij} M_{ij} + \sum_{i=1}^{n} \sum_{\substack{j=1 \\ i \neq j}}^{n} \sum_{\substack{k=1 \\ i \neq j \neq k}}^{n} x_i x_j x_k \ln \nu_{ijk} M_{ijk} \quad (1)$$

where

$$M_{av} = \sum_{i=1}^{n} x_i M_i$$

$$M_{ij} = (2M_i + M_j)/3$$

$$M_{ijk} = (M_i + M_j + M_k)/3$$

In eq 1, ν_m and x_i are the kinematic viscosity of the mixture and

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Table II. Densities and Viscosities of Binary and Ternary Mixtures

x_1[a]	ρ, g/cm³	$10^6\nu$, m²/s	x_1[a]	ρ, g/cm³	$10^6\nu$, m²/s
Acetone–Water, Temperature = 20.0 °C					
0.0000	0.9982	1.005	0.4989	0.8588	0.888
0.0315	0.9857	1.271	0.5997	0.8409	0.720
0.0577	0.9764	1.439	0.6886	0.8275	0.606
0.0946	0.9643	1.600	0.7192	0.8219	0.566
0.1485	0.9472	1.678	0.7810	0.8148	0.520
0.2024	0.9300	1.634	0.8438	0.8072	0.476
0.2716	0.9103	1.468	0.9102	0.7994	0.441
0.3665	0.8863	1.194	0.9840	0.7914	0.409
Acetone–Water, Temperature = 25.0 °C					
0.0000	0.9970	0.895	0.6079	0.8344	0.657
0.0598	0.9733	1.268	0.6890	0.8218	0.568
0.1052	0.9576	1.427	0.7384	0.8151	0.526
0.1555	0.9413	1.457	0.7920	0.8081	0.485
0.2140	0.9228	1.417	0.8502	0.8006	0.448
0.2789	0.9039	1.275	0.9164	0.7931	0.416
0.3758	0.8796	1.056	0.9840	0.7856	0.392
0.5044	0.8528	0.806			
Acetone–Water, Temperature = 30.0 °C					
0.0000	0.9957	0.804	0.6079	0.8290	0.612
0.0598	0.9710	1.121	0.6890	0.8163	0.534
0.1052	0.9545	1.249	0.7384	0.8096	0.498
0.1555	0.9375	1.281	0.7920	0.8024	0.460
0.2140	0.9186	1.248	0.8502	0.7950	0.428
0.2789	0.8992	1.141	0.9164	0.7873	0.400
0.3758	0.8746	0.954	0.9840	0.7798	0.378
0.5044	0.8477	0.744			
Acetone–Water, Temperature = 37.8 °C					
0.0000	0.9930	0.690	0.6079	0.8202	0.553
0.0598	0.9666	0.935	0.6890	0.8073	0.488
0.1052	0.9490	1.038	0.7384	0.8005	0.456
0.1555	0.9311	1.068	0.7920	0.7931	0.426
0.2140	0.9123	1.045	0.8502	0.7857	0.399
0.2789	0.8914	0.961	0.9164	0.7779	0.374
0.3758	0.8665	0.825	0.9840	0.7703	0.355
0.5044	0.8389	0.658			
Acetone–Water, Temperature = 50.0 °C					
0.0000	0.9881	0.558	0.6079	0.8058	0.478
0.0598	0.9586	0.736	0.6890	0.7927	0.429
0.1052	0.9393	0.806	0.7384	0.7856	0.404
0.1555	0.9206	0.831	0.7920	0.779	0.382
0.2140	0.9028	0.826	0.8502	0.7704	0.360
0.2789	0.8785	0.765	0.9164	0.7627	0.341
0.3758	0.8533	0.679	0.9840	0.7549	0.326
0.5044	0.8239	0.559			
Methanol–Water, Temperature = 10.0 °C					
0.0000	0.9997	1.290	0.4112	0.9109	2.420
0.0228	0.9926	1.480	0.5187	0.8891	2.125
0.0460	0.9866	1.685	0.6496	0.8637	1.741
0.0985	0.9749	2.112	0.8015	0.8345	1.332
0.1578	0.9631	2.445	0.8739	0.8222	1.134
0.2197	0.9513	2.635	0.9310	0.8126	0.996
0.3153	0.9312	2.616	1.0000	0.8008	0.854
Methanol–Water, Temperature = 20.0 °C					
0.0000	0.9982	1.005	0.4112	0.9039	1.864
0.0228	0.9910	1.135	0.5187	0.8812	1.673
0.0460	0.9846	1.273	0.6496	0.8551	1.414
0.0985	0.9718	1.560	0.8015	0.8258	1.105
0.1578	0.9592	1.794	0.8739	0.8130	1.969
0.2197	0.9458	1.940	0.9310	0.8031	0.862
0.3153	0.9246	1.970	1.0000	0.7912	0.750
Methanol–Water, Temperature = 30.0 °C					
0.0000	0.9957	0.804	0.4112	0.8965	1.451
0.0228	0.9885	0.894	0.5187	0.8732	1.330
0.0460	0.9818	0.992	0.6496	0.8465	1.152
0.0985	0.9681	1.189	0.8015	0.8169	0.932
0.1578	0.9546	1.353	0.8739	0.8038	0.831
0.2197	0.9401	1.465	0.9310	0.7936	0.747
0.3153	0.9178	1.503	1.0000	0.7816	0.659
Methanol–Water, Temperature = 40.0 °C					
0.0000	0.9922	0.662	0.4076	0.8892	1.158
0.0228	0.9850	0.729	0.5164	0.8653	1.080
0.0468	0.9779	0.799	0.6468	0.8387	0.961
0.0976	0.9639	0.937	0.8012	0.8079	0.796
0.1578	0.9494	1.057	0.8755	0.7942	0.715
0.2204	0.9338	1.142	0.9327	0.7838	0.652
0.3194	0.9104	1.185	1.0000	0.7720	0.581
Methanol–Water, Temperature = 50.0 °C					
0.0000	0.9881	0.558	0.4076	0.8812	0.941
0.0228	0.9809	0.603	0.5164	0.8569	0.892
0.0468	0.9736	0.654	0.6568	0.8304	0.823
0.0976	0.9589	0.754	0.8012	0.7986	0.683
0.1578	0.9435	0.842	0.8755	0.7850	0.622
0.2204	0.9273	0.917	0.9327	0.7744	0.573
0.3194	0.9028	0.945	1.0000	0.7623	0.516
Ethanol–Water, Temperature = 10.0 °C					
0.0000	0.9997	1.290	0.2431	0.9311	4.502
0.0069	0.9966	1.401	0.3236	0.9094	4.262
0.0131	0.9939	1.520	0.4260	0.8856	3.830
0.0185	0.9914	1.647	0.5600	0.8604	3.274
0.0265	0.9889	1.772	0.7387	0.8318	2.634
0.0329	0.9867	1.916	0.8278	0.8198	2.339
0.0704	0.9766	2.775	0.9037	0.8094	2.113
0.115	0.9669	3.689	1.0000	0.7983	1.819
0.1633	0.9537	4.318			
Ethanol–Water, Temperature = 20.0 °C					
0.0000	0.9982	1.005	0.1887	0.9399	2.994
0.0069	0.9952	1.080	0.2364	0.9260	3.068
0.0140	0.9920	1.171	0.3273	0.9011	3.066
0.0185	0.9898	1.242	0.4386	0.8756	2.807
0.0265	0.9871	1.331	0.5600	0.8523	2.481
0.0335	0.9843	1.434	0.7324	0.8245	2.101
0.0712	0.9731	1.975	0.8282	0.8114	1.901
0.1164	0.9610	2.523	0.9083	0.8010	1.718
0.1683	0.9462	2.899	1.0000	0.7895	1.527
Ethanol–Water, Temperature = 30.0 °C					
0.0000	0.9957	0.804	0.2431	0.9162	2.192
0.0069	0.9926	0.864	0.3236	0.8937	2.202
0.0131	0.9899	0.914	0.4260	0.8685	2.085
0.0185	0.9870	0.969	0.5600	0.8435	1.905
0.0265	0.9845	1.023	0.7387	0.8148	1.671
0.0329	0.9819	1.086	0.8278	0.8026	1.524
0.0704	0.9696	1.428	0.9037	0.7926	1.425
0.1115	0.9567	1.765	1.0000	0.7807	1.280
0.1633	0.9409	2.036			
Ethanol–Water, Temperature = 40.0 °C					
0.0000	0.9922	0.662	0.3255	0.8845	1.663
0.0160	0.9851	0.755	0.4266	0.8592	1.616
0.0331	0.9782	0.863	0.5608	0.8338	1.503
0.0704	0.9647	1.099	0.7414	0.8054	1.329
0.1131	0.9503	1.324	0.8282	0.7934	1.247
0.1645	0.9331	1.505	0.9083	0.7831	1.173
0.2461	0.9072	1.638	1.0000	0.7717	1.079
Ethanol–Water, Temperature = 50.0 °C					
0.0000	0.9881	0.558	0.3255	0.8753	1.296
0.0160	0.9811	0.627	0.4266	0.8478	1.278
0.0331	0.9739	0.706	0.5608	0.8241	1.212
0.0704	0.9591	0.871	0.7414	0.7958	1.093
0.1131	0.9437	1.030	0.8282	0.7843	1.037
0.1645	0.9251	1.162	0.9083	0.7740	0.985
0.2461	0.8987	1.268	1.0000	0.7625	0.920
Methanol–Ethanol, Temperature = 10.0 °C					
0.0000	0.7983	1.819	0.6420	0.7996	1.121
0.0702	0.7983	1.740	0.6870	0.7997	1.089
0.1372	0.7983	1.649	0.7309	0.7999	1.047
0.2019	0.7984	1.566	0.7737	0.8000	1.017
0.2636	0.7986	1.491	0.8139	0.8001	0.980
0.3227	0.7986	1.435	0.8534	0.8003	0.958
0.3797	0.7988	1.371	0.8918	0.8004	0.925
0.4344	0.7989	1.319	0.9292	0.8006	0.898
0.4871	0.7991	1.262	0.9647	0.8007	0.874
0.5382	0.7992	1.221	1.0000	0.8008	0.854
0.5880	0.7994	1.174			

Table II (*Continued*)

x_1[a]	ρ, g/cm³	$10^6\nu$, m²/s	x_1[a]	ρ, g/cm³	$10^6\nu$, m²/s
Methanol–Ethanol, Temperature = 20.0 °C					
0.0000	0.7895	1.527	0.6420	0.7903	0.977
0.0702	0.7895	1.468	0.6870	0.7904	0.940
0.1372	0.7895	1.390	0.7309	0.7905	0.936
0.2019	0.7896	1.328	0.7737	0.7006	0.890
0.2636	0.7897	1.272	0.8139	0.7907	0.858
0.3227	0.7897	1.233	0.8534	0.7908	0.830
0.3797	0.7898	1.174	0.8918	0.7909	0.809
0.4344	0.7899	1.131	0.9292	0.7910	0.786
0.4871	0.7900	1.088	0.9647	0.7911	0.768
0.5382	0.7901	1.053	1.0000	0.7912	0.750
0.5880	0.7902	1.012			
Methanol–Ethanol, Temperature = 30.0 °C					
0.0000	0.7807	1.280	0.6420	0.7810	0.847
0.0702	0.7807	1.223	0.6870	0.7811	0.817
0.1372	0.7807	1.175	0.7309	0.7811	0.797
0.2019	0.7808	1.128	0.7733	0.7812	0.769
0.2636	0.7808	1.080	0.8139	0.7813	0.750
0.3227	0.7808	1.045	0.8534	0.7813	0.726
0.3797	0.7808	1.003	0.8918	0.7814	0.712
0.4344	0.7809	0.972	0.9292	0.7814	0.712
0.4871	0.7809	0.935	0.9647	0.7815	0.672
0.5382	0.7810	0.912	1.0000	0.7816	0.659
0.5880	0.7810	0.881			
Methanol–Ethanol, Temperature = 40.0 °C					
0.0000	0.7717	1.079	0.5920	0.7718	0.760
0.0704	0.7717	1.038	0.6414	0.7718	0.744
0.1372	0.7717	1.038	0.6870	0.7718	0.716
0.2019	0.7717	0.997	0.7304	0.7718	0.700
0.2019	0.7717	0.964	0.7732	0.7718	0.676
0.2636	0.7717	0.927	0.8142	0.7718	0.662
0.3230	0.7718	0.900	0.8535	0.7719	0.640
0.3798	0.7718	0.866	0.8915	0.7719	0.627
0.4344	0.7718	0.843	0.9290	0.7719	0.607
0.4867	0.7718	0.821	0.9650	0.7720	0.595
0.5379	0.7718	0.790	1.0000	0.7720	0.581
Methanol–Ethanol, Temperature = 50.0 °C					
0.0000	0.7625	0.920	0.6414	0.7624	0.648
0.0704	0.7625	0.889	0.6870	0.7624	0.634
0.1372	0.7624	0.864	0.7304	0.7624	0.614
0.2019	0.7624	0.827	0.7732	0.7624	0.602
0.2636	0.7624	0.805	0.8142	0.7623	0.583
0.3230	0.7624	0.775	0.8535	0.7623	0.571
0.3798	0.7624	0.756	0.8925	0.7623	0.554
0.4344	0.7624	0.730	0.9290	0.7623	0.544
0.4867	0.7624	0.713	0.9650	0.7623	0.528
0.5379	0.7624	0.689	1.0000	0.7623	0.516
0.5920	0.7624	0.671			
1-Propanol–Water, Temperature = 30.0 °C					
0.0000	0.9957	0.804	0.3372	0.8747	2.610
0.0553	0.9705	1.477	0.4762	0.8496	2.547
0.895	0.9546	1.803	0.5641	0.8373	2.490
0.1323	0.9358	2.112	0.6686	0.8248	2.384
0.1845	0.9162	2.376	0.8077	0.8112	2.295
0.2618	0.8929	2.544	1.0000	0.7960	2.183
Ethylene Glycol–Water, Temperature = 30.0 °C					
0.0000	0.9957	0.804	0.4397	1.0845	4.919
0.0334	1.0088	1.026	0.5020	1.0889	5.703
0.0725	1.0223	1.298	0.5678	1.0927	6.546
0.1158	1.0352	1.646	0.6499	1.0964	7.638
0.1676	1.0478	2.059	0.7449	1.1000	8.941
0.2298	1.0599	2.651	0.8634	1.1033	10.587
0.3379	1.0749	3.751	1.0000	1.1063	12.437
0.3851	1.0796	4.288			
Methanol–1-Propanol, Temperature = 30.0 °C					
0.0000	0.7960	2.183	0.5505	0.7900	1.194
0.0878	0.7956	2.004	0.6484	0.7882	1.072
0.1691	0.7947	1.834	0.7353	0.7868	0.946
0.2456	0.7939	1.687	0.8129	0.7855	0.859
0.3183	0.7928	1.562	0.8001	0.7844	0.779
0.3800	0.7920	1.450	0.9437	0.7830	0.714
0.4399	0.7912	1.357	1.0000	0.7816	0.659
Ethanol–1-Propanol, Temperature = 30.0 °C					
0.0000	0.7960	2.183	0.5814	0.7885	1.608
0.1123	0.7955	2.067	0.6518	0.7873	1.550
0.2186	0.7955	1.964	0.7343	0.7857	1.477
0.3083	0.7928	1.868	0.8296	0.7839	1.402
0.3836	0.7917	1.789	0.9134	0.7824	1.335
0.4951	0.7900	1.689	1.0000	0.7807	1.280

x_1[a]	x_2[b]	ρ, g/cm³	$10^6\nu$, m²/s
Methanol–Ethanol–Water, Temperature = 10.0 °C			
0.0903	0.4376	0.9704	3.214
0.0698	0.2412	0.9190	4.011
0.0578	0.1199	0.9547	3.836
0.2086	0.5100	0.8397	2.352
0.1774	0.3748	0.8682	2.940
0.1526	0.2634	0.8974	3.421
0.1362	0.1879	0.9197	3.687
0.1234	0.1278	0.9387	3.674
0.1135	0.0782	0.9537	3.385
0.1049	0.0363	0.9656	2.783
0.2579	0.2974	0.8710	2.758
0.2015	0.1395	0.9191	3.335
0.3320	0.2290	0.8725	2.554
0.2926	0.1511	0.8778	2.907
0.2621	0.0905	0.9185	3.037
0.2382	0.0411	0.9376	2.976
0.3597	0.1001	0.8970	2.644
0.5523	0.1901	0.8420	1.773
0.4764	0.1092	0.8724	2.176
0.4204	0.0482	0.8977	2.460
0.5536	0.0543	0.8698	1.987
0.7103	0.0608	0.8390	1.483
0.8499	0.0331	0.8203	1.140
Methanol–Ethanol–Water, Temperature = 20 °C			
0.0903	0.4376	0.8615	2.421
0.0698	0.2412	0.9108	2.858
0.578	0.1199	0.9480	2.617
0.2086	0.5100	0.8306	1.903
0.1774	0.3748	0.8596	2.249
0.1526	0.2634	0.8889	2.528
0.1362	0.1879	0.9117	2.649
0.1234	0.1278	0.9314	2.588
0.1135	0.0782	0.9475	2.383
0.1049	0.0363	0.9606	1.990
0.2579	0.2974	0.8623	2.121
0.2015	0.1395	0.9113	2.430
0.3883	0.3354	0.8332	1.667
0.3320	0.2290	0.8638	1.992
0.2926	0.1511	0.8895	2.190
0.2621	0.0905	0.9118	2.245
0.2382	0.0411	0.9307	2.173
0.5523	0.1901	0.8330	1.461
0.4764	0.1092	0.8637	1.728
0.4204	0.0482	0.8896	1.876
0.5536	0.0543	0.8612	1.580
0.7103	0.0608	0.8304	1.227
0.8499	0.0331	0.8110	0.979
Methanol–Ethanol–Water, Temperature = 30.0 °C			
0.0908	0.4453	0.8508	1.841
0.0698	0.2420	0.9022	2.067
0.0575	0.1198	0.9414	1.878
0.2098	0.5121	0.8210	1.497
0.1778	0.3738	0.8511	1.733
0.1548	0.2725	0.8776	1.882
0.1364	0.1894	0.9032	1.945
0.1232	0.1280	0.9240	1.883
0.1130	0.0784	0.9413	1.727
0.1047	0.0363	0.9556	1.474

Table II (*Continued*)

x_1[a]	x_2[b]	ρ, g/cm³	$10^6\nu$, m²/s
0.2592	0.3023	0.8521	1.640
0.2010	0.1391	0.9036	1.814
0.3959	0.3465	0.8210	1.318
0.3339	0.2305	0.8543	1.550
0.2926	0.1521	0.8810	1.691
0.2627	0.0909	0.9039	1.626
0.3575	0.0991	0.8813	1.567
0.5681	0.1942	0.8204	1.153
0.4889	0.1113	0.8522	1.349
0.4306	0.0488	0.8793	1.457
0.5542	0.0545	0.8526	1.267
0.7146	0.0622	0.8204	1.019
0.8528	0.0331	0.8013	0.830
Methanol-Ethanol-Water, Temperature = 40.0 °C			
0.0908	0.4453	0.8421	1.456
0.0698	0.2420	0.8941	1.570
0.0575	0.1198	0.9345	1.405
0.2098	0.5121	0.8119	1.219
0.1778	0.3738	0.8422	1.380
0.1548	0.2725	0.8691	1.466
0.1364	0.1894	0.8950	1.489
0.1232	0.1280	0.9165	1.430
0.1130	0.0784	0.9348	1.314
0.1047	0.0363	0.9501	1.137
0.2592	0.3023	0.8434	1.310
0.2010	0.1391	0.8956	1.401
0.3959	0.3465	0.8119	1.089
0.3339	0.2305	0.8457	1.246
0.2926	0.1521	0.8724	1.320
0.2627	0.0909	0.8959	1.320
0.2384	0.0414	0.9167	1.263
0.3575	0.0991	0.8731	1.245
0.5681	0.1942	0.8115	0.966
0.4889	0.1113	0.8435	1.100
0.4306	0.0488	0.8711	1.169
0.5542	0.0545	0.8439	1.042
0.7146	0.0622	0.8114	0.863
0.8528	0.0331	0.7919	0.718
Methanol-Ethanol-Water, Temperature = 50.0 °C			
0.0908	0.4453	0.8333	1.174
0.0698	0.2420	0.8860	1.232
0.0575	0.1198	0.9277	1.092
0.2098	0.5121	0.8028	1.012
0.1778	0.3738	0.8334	1.115
0.1548	0.2725	0.8606	1.172
0.1364	0.1894	0.8867	1.170
0.1232	0.1280	0.9090	1.125
0.1130	0.0784	0.9283	1.032
0.1047	0.0363	0.9446	0.909
0.2582	0.3023	0.8346	1.064
0.2010	0.1391	0.8876	1.116
0.3959	0.3465	0.8028	1.913
0.3339	0.2305	0.8371	1.018
0.2926	0.1521	0.8638	1.062
0.2627	0.0909	0.8879	1.059
0.2384	0.0414	0.9097	1.006
0.3575	0.0991	0.8648	1.013
0.5681	0.1942	0.8027	0.815
0.4306	0.0488	0.8628	1.954
0.5542	0.0545	0.8351	0.868
0.7146	0.0622	0.8024	0.738
0.8528	0.0331	0.7826	0.627
Methanol-1-Propanol-Water, Temperaure = 30.0 °C			
0.0562	0.0295	0.9673	1.392
0.0677	0.1065	0.9323	2.006
0.0880	0.2306	0.8872	2.327
0.1111	0.3764	0.8525	2.296
0.1318	0.0690	0.9334	1.827
0.1657	0.1767	0.8894	2.128
0.1964	0.2561	0.8646	2.090
0.2127	0.3028	0.8526	2.057
0.1937	0.0337	0.9337	1.656
0.2402	0.1217	0.8926	1.914
0.2743	0.1917	0.8675	1.901
0.3097	0.2442	0.8505	1.839
0.3143	0.0822	0.8904	1.734
0.3365	0.1393	0.8701	1.748
0.4320	0.2256	0.8360	1.575
0.3095	0.0369	0.9065	1.635
0.4005	0.0880	0.8720	1.596
0.4753	0.1559	0.8427	1.490
0.4172	0.0408	0.8824	1.525
0.6367	0.1562	0.8167	1.187
0.5225	0.0448	0.8601	1.367
0.6132	0.0992	0.8310	1.235
0.6924	0.0500	0.8270	1.099
0.8218	0.0277	0.8080	0.901
Ethanol-1-Propanol-Water, Temperature = 30.0 °C			
0.0428	0.0648	0.9518	1.864
0.0532	0.1606	0.9106	2.364
0.0692	0.2951	0.8712	2.521
0.1024	0.5852	0.8227	2.259
0.0945	0.0716	0.9324	2.141
0.1223	0.1851	0.8870	2.417
0.1608	0.3442	0.8470	2.353
0.2023	0.5056	0.8207	2.144
0.1821	0.1380	0.8870	2.363
0.2494	0.3018	0.8411	2.209
0.3004	0.4310	0.8177	2.044
0.2777	0.1583	0.8619	2.242
0.3251	0.2376	0.8400	2.134
0.3897	0.3412	0.8174	1.949
0.2841	0.0950	0.8760	2.258
0.3563	0.1557	0.8490	2.122
0.4541	0.2584	0.8193	1.909
0.3396	0.0479	0.8759	2.183
0.3991	0.1115	0.8501	2.089
0.4708	0.1852	0.8269	1.922
0.4566	0.0549	0.8511	2.032
0.5542	0.1300	0.8227	1.831
0.6227	0.0634	0.8220	1.768
0.8042	0.0350	0.8014	1.528
Methanol-Ethanol-1-Propanol, Temperature = 30.0 °C			
0.1789	0.1212	0.7935	1.705
0.1750	0.2370	0.7918	1.611
0.1712	0.3475	0.7900	1.516
0.1628	0.5408	0.7868	1.382
0.1570	0.6854	0.7841	1.269
0.3320	0.1126	0.7917	1.447
0.3248	0.2211	0.7897	1.366
0.3096	0.4112	0.7862	1.242
0.2977	0.5700	0.7836	1.146
0.4654	0.1049	0.7891	1.236
0.4501	0.0238	0.7877	1.187
0.4418	0.2993	0.7861	1.133
0.4335	0.3889	0.7846	1.083
0.5752	0.0971	0.7876	1.089
0.5503	0.2923	0.7845	1.000
0.5368	0.3965	0.7827	0.947
0.6278	0.0948	0.7868	1.020
0.6305	0.1834	0.7851	0.961
0.6991	0.0906	0.7857	0.934
0.6910	0.1692	0.7842	0.896
0.7909	0.0846	0.7841	0.829
0.7727	0.1634	0.7829	0.806
0.8579	0.0795	0.7827	0.757
0.9294	0.0373	0.7822	0.704

[a] Mole fraction of first-named component. [b] Mole fraction of second-named component.

Table III. Coefficients[a] of Eq 1 and 2

system	t, °C	eq 1			eq 2		
		$10^6\nu_{12}$	$10^6\nu_{21}$	$10^6\nu_{123}$	$10^6\nu_{12}$	$10^6\nu_{21}$	$10^6\nu_{123}$
acetone-water	20.0	0.1426	9.3436		0.5452	2.6523	
	25.0	0.1612	7.0835		0.5024	2.2847	
	30.0	0.1670	5.7191		0.4784	1.9395	
	37.8	0.1700	4.2909		0.4396	1.5527	
	50.0	0.1730	2.9264		0.3893	1.2528	
methanol-water	10.0	1.0090	9.9665		2.2648	3.8943	
	20.0	0.9277	6.1969		1.8129	2.6996	
	30.0	0.8338	4.0369		1.4564	1.9367	
	40.0	0.7453	2.7897		1.1964	1.4485	
	50.0	0.6896	1.9372		1.0071	1.0933	
ethanol-water	10.0	0.2286	100.0937		3.3490	9.5153	
	20.0	0.2244	47.1243		2.3152	6.1325	
	30.0	0.2805	22.0020		1.8217	3.9085	
	40.0	0.2675	12.7656		1.2989	2.8604	
	50.0	0.2688	7.7686		1.0359	2.0889	
methanol-ethanol	10.0	1.0662	1.4913		1.0648	1.4908	
	20.0	0.9385	1.2740		0.9381	1.2736	
	30.0	0.8483	1.0369		0.8490	1.0366	
	40.0	0.7495	0.9040		0.7456	0.9038	
	50.0	0.6447	0.7881		0.6445	0.7879	
methanol-ethanol-water	10.0			48.5410			3.3445
	20.0			15.3075			2.4283
	30.0			4.1884			1.7908
	40.0			2.1874			1.3745
	50.0			1.1795			1.1601
1-propanol-water	30.0	0.0270	72.4616		2.1339	3.1280	
ethylene glycol-water	30.0	5.2571	10.5817		7.4933	2.6284	
methanol-1-propanol	30.0	1.0828	1.6053		0.9211	1.4788	
ethanol-1-propanol	30.0	1.5316	1.8737		1.4404	1.7964	
methanol-1-propanol-water	30.0			7.2857			2.0587
ethanol-1-propanol-water	30.0			15.3454			1.6353
methanol-1-ethanol-1-propanol	30.0			1.2697			1.1585

[a] Units: m^3/s.

Table IV. Comparison of McAllister's Equation of Viscosity (Eq 1) and Eq 2 at $t = 30.00$ °C

no.	system	D, % S, % McAllister's equation	eq 2
1	acetone-water	10.314	0.168
		12.813	0.246
2	methanol-water	4.473	0.457
		5.599	0.650
3	ethanol-water	16.854	3.148
		22.290	4.587
4	methanol-ethanol	0.255	0.256
		0.346	0.346
5	1-propanol-water	27.850	0.776
		39.271	1.000
6	ethylene glycol-water	4.849	0.148
		6.497	0.218
7	methanol-1-propanol	0.489	0.530
		0.670	0.736
8	ethanol-1-propanol	0.111	0.099
		0.159	0.140
9	methanol-ethanol-water	23.644	2.037
		27.425	2.636
10	methanol-1-propanol-water	27.234	1.810
		31.843	2.054
11	ethanol-1-propanol-water	617.397	1.992
		787.304	2.626
12	methanol-ethanol-1-propanol	0.432	0.374
		0.510	0.442

the mole fraction of component i in the mixture, respectively. For comparison, the data were also correlated with the modified form of the McAllister equation of viscosity which was presented by Dizechi (*2*). This equation for an n-component mixture may be expressed in the following form:

$$\ln \nu_m = \frac{1}{t + C_{av}} \sum_{i=1}^{n} (t + C_i)x_i^3 \ln \nu_i M_i - \ln M_{av} + \frac{3}{t + C_{av}} \sum_{i=1}^{n} \sum_{\substack{j=1 \\ i \neq j}}^{n} (t + C_{ij})x_i^2 x_j \ln \nu_{ij} M_{ij} + \frac{1}{t + C_{av}} \sum_{i=1}^{n} \sum_{\substack{j=1 \\ i \neq j \neq k}}^{n} \sum_{k=1}^{n} (t + C_{ijk})x_i x_j x_k \ln \nu_{ijk} M_{ijk} \quad (2)$$

where

$$M_{av} = \sum_{i=1}^{n} x_i M_i$$

$$M_{ij} = (2M_i + M_j)/3$$

$$M_{ijk} = (M_i + M_j + M_k)/3$$

$$C_i = 239 + Zt_{b,i}$$

$$C_{av} = \sum_{i=1}^{n} x_i C_i$$

$$C_{ij} = (2C_i + C_j)/3$$

$$C_{ijk} = (C_i + C_j + C_k)/3$$

The constants ν_{ij}, ν_{ji}, and ν_{ijk} are found from experimental data of viscosities of mixtures with the help of the least-squares technique. Their values change with temperature; however, not with concentration. For binary and ternary values used in this study, the values of ν_{12}, ν_{21}, and ν_{123} calculated with eq 1 and 2 are given in Table III. For water, Goletz and Tassios (*3*)

Table V. Comparison of Measured Viscosity Data with Data Reported in the Literature

system	D, %	S, %	temp, °C	ref
acetone-water	0.65	0.88	25	4
	0.91	1.20	25	5
ethanol-water	0.38	0.51	40	6
	0.70	0.81	40	4
methanol-water	0.80	0.87	40	7

recommended $Z = -1.10$, while Dizechi (2), using an optimization technique, determined Z values for various polar liquids, some of which are listed in Table I. Even though Z is actually dependent upon temperature, this dependency is so weak that selection of only one value of Z for each polar liquid is sufficient.

For $C_1 = C_2 = C_2 = ... = 273.15$ K, eq 2 reduces to the equation proposed by McAllister (1).

Results of both correlations are compiled in Table IV. In Table IV the first column provides a count; the second column identifies the mixture whereby the sequence of components corresponds to 1, 2, 3. The mean percentage deviation and the standard percentage error for McAllister's equation (eq 1) and eq 2 are listed in columns three and four, respectively. Mean deviation and standard error on a percentage basis are calculated from the following definitions:

mean percentage deviation

$$D = \frac{1}{m}\sum_{i=1}^{m}\frac{100|\text{viscosity}_{i,\text{exptl}} - \text{viscosity}_{i,\text{calcd}}|}{\text{viscosity}_{i,\text{exptl}}} \quad (3)$$

standard percentage error

$$S = \left\{\frac{1}{m}\sum_{i=1}^{m}\left[\frac{100(\text{viscosity}_{i,\text{exptl}} - \text{viscosity}_{i,\text{calcd}})}{\text{viscosity}_{i,\text{exptl}}}\right]^2\right\}^{1/2} \quad (4)$$

where m is the number of data points.

Inspection of Table IV shows that eq 2 is superior to eq 1 when applied to mixtures of polar liquids, one of them being water. Thus, eq 2 provides for a much better correlation technique.

A comparison of experimental viscosity data obtained in this study with some data reported in the literature is provided in Table V. This comparison is based on mean percentage deviation and standard percentage error as defined in eq 3 and 4 except that reported viscosity values are used in place of the calculated viscosity values. Mean percentage deviations and standard percentage errors were found generally to be smaller than 1%. Sufficient data for comparison of viscosities of ternary mixtures could not be found.

Glossary

C	constant in eq 2
D	mean percentage deviation
m	number of experimental data points at a fixed temperature
M	molar mass
S	standard percentage error
t	temperature, °C
t_b	boiling temperature at atmospheric pressure, °C
x_i	mole fraction of component i
Z	constant in eq 2
ρ	density
ν	kinematic viscosity, m^2/s
ν_m	kinematic viscosity of the mixture

Subscripts

1, 2, 3	components 1, 2, and 3, respectively
ij	refer to interaction of type $i-i-j$, etc.
123	refer to interaction between three molecules; one of component 1, one of component 2, and one of component 3
av	average
calcd	calculated
exptl	experimental

Literature Cited

(1) McAllister, R. A. *AIChE J.* **1960**, *6*, 427.
(2) Dizechi, M. Doctoral Dissertation, University of California at Santa Barbara, Santa Barbara, CA, 1980.
(3) Goletz, E.; Tassios, D. *Ind. Eng. Chem. Process Des. Dev.* **1977**, *16*, 75.
(4) Barry, Guy; Bircumshaw, L. L. *International Critical Tables* **1929**, *5*, 22.
(5) Howard, K. S.; McAllister, R. A. *AIChE J.* **1958**, *4*, 362.
(6) Bingham, E. C.; Hatfield, J. E.; Jackson, R. F. *Bur. Stand. J. Res. Sci.* **1917**, 298.
(7) Mikhail, S. A.; Kimel, W. R. *J. Chem. Eng. Data* **1961**, *6*, 533.

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Vapor Pressures of Some Isotopic Hydrogen Cyanides

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Vapor pressures are reported for solid and liquid phases (approximately 230–300 K) of HCN, DCN, and $HC^{15}N$ with a precision of about 0.8% for the solid and 0.2% for the liquids. The data are discussed in the context of the theory of isotope effects in condensed phases.

Introduction

The vapor pressure of hydrogen cyanide has been measured only a few times in the past 50 years. A review of the literature prior to 1934 has been compiled by Kelley (1). Agreement between early workers is poor. In 1934 Lewis and Schutz (2) made measurements of the vapor pressures of HCN and DCN between 235 and 294 K by mercury manometry. Giauque and Ruehrwein (3) made more careful measurements from the triple point, 259.91 K, to 298.8 K, and also published results on the heat capacity and the heats of fusion and vaporization for HCN. Since their 1939 report, no further studies on the vapor pressure or related thermodynamic properties of HCN or its isotopic isomers have been indexed in *Chemical Abstracts*.

HCN is a simple molecule, and we concluded that new data on the vapor pressure isotope effects for isotopic cyanides would be of interest in determining details of the motions of the

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