Table IV. Densities and Refractive Indices of *p*-Cymene at Several Temperatures

	d, g cm^{-3}				n_D			
t, °C	expt	ref 3	a	$10^4(-b)$, °C	expt	ref 3	c	$10^4(-f)$, °C
20	0.8561	0.8573	0.8716	7.86	1.4891	1.4909	1.4969	4.21
25	0.8521				1.4865			
30	0.8486				1.4846			
35	0.8445				1.4824			
40	0.8406				1.4802			
45	0.8374				1.4782			
50	0.8326				1.4762			

of the distillate was checked by gas chromatography with use of a Perkin-Elmer chromatograph equipped with a flame ionization detector and a Shimadzu integrator. The impurities of the compounds were the other components. The impurity contents were less than 0.1% in α-pinene and 0.15% in limonene and *p*-cymene. The purity of β-pinene was about 97%.

The water used for calibrating the pycnometer was redistilled and run through an ion-exchange column until it showed an electrical conductivity of $<1 \times 10^{-6}$ mho cm^{-1}.

Analysis of Results

Densities were correlated with temperature as

$$d = a + bt \quad (1)$$

The average of the deviations between the calculated values obtained by using eq 1 and the experimental ones is 3.4×10^{-4} g cm^{-3}, the maximum deviation being 7.0×10^{-4} g cm^{-3}.

In Figure 1, densities of pure components are plotted against temperature.

The refractive indices were correlated in the same way:

$$n_D = c + ft \quad (2)$$

dn_D/dt has a mean value of -4.23×10^{-4} °C, which is in agreement with those predicted by some authors (*3*). The average of the deviations between the calculated values obtained by using the eq 2 and the experimental ones is 2.4×10^{-4}, the maximum deviation being 7.1×10^{-4}.

Refractive indices of pure components are plotted against temperature in Figure 2.

In Tables I–IV are presented the values of densities and refractive indices for α-pinene, β-pinene, limonene, and *p*-cymene, respectively.

List of Symbols

a,b	parameters of eq 1
c,f	parameters of eq 2
d	density, g cm^{-3}
n_D	refractive index
t	temperature, °C

Registry No. α-Pinene, 80-56-8; β-pinene, 127-91-3; (-)-limonene, 5989-54-8; *p*-cymene, 99-87-6.

Literature Cited

(1) Bernardo-Gil, M. G.; Ribeiro, M. A. *Fluid Phase Equil.*, in press.
(2) Bernardo-Gil, M. G.; Ribeiro, M. A. Submitted for publication.
(3) *Handbook of Chemistry and Physics*, 57th ed.; Weast, R., Ed.; CRC Press: Cleveland, OH, 1977.

Received for review March 6, 1989. Revised October 18, 1989. Accepted November 20, 1989. We express our gratitude to the Instituto Nacional de Investigação Cientifica, which through the CPQ (Universidade Técnica de Lisboa) supported this work.

Viscosity and Density of Some Aliphatic, Cyclic, and Aromatic Hydrocarbons Binary Liquid Mixtures

J. L. E. Chevalier,* P. J. Petrino, and Y. H. Gaston-Bonhomme

Laboratoire de Génie Chimique, Ecole Supérieure de Chimie de Marseille, Avenue Escadrille Normandie Nieman F, 13397 Marseille Cédex 13, France

Kinematic viscosities and densities of 68 linear, branched, cyclic and aromatic hydrocarbons binary liquid systems have been determined at 298.15 K over the entire composition range. The McAllister model has been used to fit experimental values of kinematic viscosities.

Introduction

Many chemical engineering designs require knowledge of liquid viscosities. The number of viscosity data published is relatively low. In the present work, viscosities and densities of 68 linear, branched, cyclic and aromatic hydrocarbon binary liquid mixtures have been measured at 298.15 K.

Experimental Section

The pure hydrocarbons used are Fluka, "puriss" or "purum" quality, products (Table I). All the mixtures are prepared with a Model H-10W Mettler balance to $\pm 0.5 \times 10^{-6}$ kg.

Pure components and liquid mixtures kinematic viscosities are determined with use of an automatic viscometer Lauda S thermostat bath equipped with two KPG Ubbelohde capillary viscometers of 0.46×10^{-3} and 0.53×10^{-3} m diameter, and two Ubbelohde microviscometers of 0.40×10^{-3} and 0.53×10^{-3} m diameter, all of them being calibrated with twice-distilled water. As many authors did (*1–4*), water has been used for calibration since it is the only product whose properties are known with good accuracy and is easily available with a high level of purity.

0021-9568/90/1735-0206$02.50/0

Table I. Properties of Pure Components

components	$10^6\ \nu$, $m^2 \cdot s^{-1}$ TRC values	$10^6\ \nu$, $m^2 \cdot s^{-1}$ exptl values	$10^6\ \nu$, $m^2 \cdot s^{-1}$ lit. values	ref	$10^{-3}\ \rho$ $kg \cdot m^{-3}$ exptl values	$10^{-3}\ \rho$ $kg \cdot m^{-3}$ lit. values	ref
n-hexane	0.4545	0.4458	0.4468–0.4529	9, 10, 14, 15, 16, 17	0.655 08	0.6542–0.6562	1, 2, 9, 10, 13–16
n-heptane	0.5821	0.5702	0.573–0.583	18, 19	0.679 49	0.679 71	22, 6
n-octane	0.7352	0.7251	0.7255–0.728	13, 18	0.698 56	0.6989	13
n-nonane	0.9353	0.9206	0.9381	6	0.713 99	0.713 81	6
n-decane	1.182	1.161	1.158–1.165	18	0.726 28	0.726 25	6
n-dodecane	1.843	1.804	1.824	13	0.745 45	0.7451–0.7455	8, 13
n-tetradecane	2.771	2.716	2.7418	9	0.759 20	0.760 32	9
n-hexadecane	4.008	3.958	3.937–4.020	9, 13, 20	0.770 00	0.7702–0.770 90	9, 13, 20
2-methylpentane		0.4161			0.648 67	0.648 52	6
3-methylpentane		0.4297			0.659 77	0.659 76	6
2-methylhexane		0.5298			0.674 58	0.674 39	6
2,3-dimethylpentane		0.5513			0.690 26	0.690 91	6
2,2-dimethylpentane		0.5424			0.669 57		
2,5-dimethylpentane		0.6563			0.690 12		
2,2-dimenthypentane		0.7066			0.691 18		
isooctane		0.6832			0.687 71	0.687 81	6
cyclohexane	1.152	1.148	1.1445–1.1644	13, 16, 23	0.773 76	0.7736–0.7742	2, 13, 16
methylcyclohexane	0.893	0.8807			0.764 82	0.765 05	6
1,2-dimethylcyclohexane, cis		1.278			0.792 86		
1,2-dimethylcyclohexane, cis–trans		1.154			0.786 14		
1,2,4-trimethylcyclohexane, cis–trans		0.9976			0.781 65		
benzene	0.688	0.6844	0.6863–0.7017	9, 10, 13, 21, 17, 19, 23	0.873 44	0.873 55–0.8736	9, 10, 13
toluene	0.638	0.6345	0.6413–0.6507	10, 17, 19, 23	0.861 60	0.8619–0.8623	1, 8, 10
o-xylene	0.861	0.8542	0.8658	23	0.875 16	0.875 96	6
p-xylene	0.704	0.6975	0.7085	23	0.856 54	0.856 69	6

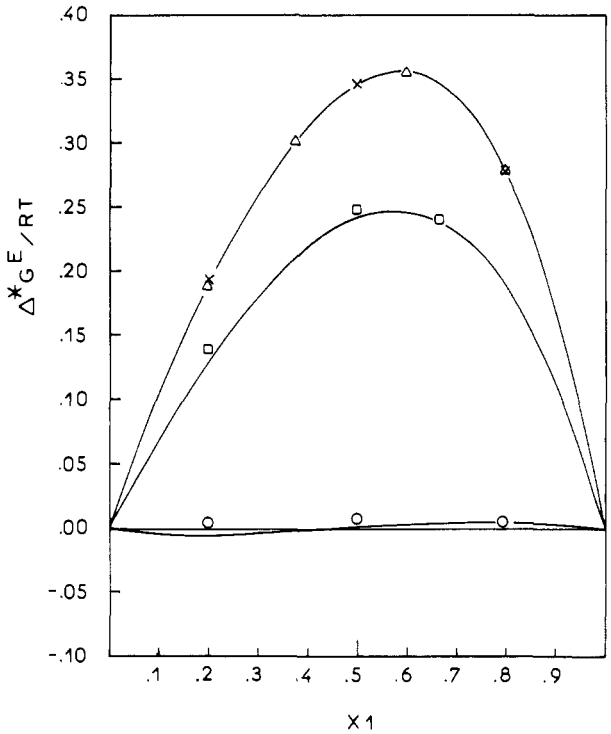

Figure 1. Comparison of present values of excess molar energy of activation of flow with literature values: hexane–hexadecane system, (Δ) values of Dymond and Young (*13*), (×) present work; hexane–tetradecane system, (□) present work; tetradecane–hexadecane system, (○) present work; (—) polynomial regression from values of Heric and Brewer (*9*) for these three systems. x_1 is the mole fraction of component 1.

The kinematic viscosity is determined from the following relationship:

$$\nu = k(t - v) \tag{1}$$

where t, k, and v are respectively the flow time, the viscometer constant, and the Hagenbach correction (*5*).

The capillary is maintained at 298.15 ± 0.01 K in a D20 Lauda ultrathermostat equipped with a R25 PID regulator. Two platinum resistance thermometers are used, the first in the regulation of the water bath temperature to ±0.01 K and the second for the measurement with a standard error estimated to ±0.02 K considering the error of a mercury thermometer calibrated at the freezing and boiling points of water. The accuracy of the flow-time measurements being ±0.01 s and the selected value results from four measurements leading to the same value. The evaporation losses are negligible and can be controlled by the steps of the flow times, which in the less favorable case do not exceed 0.04 s. In this case, the first value is kept.

Densites are measured with a DMA 02D Anton-Paar density meter thermostated with the same water bath as the one used for viscosity measurements. The constant Co of eq 2 used for

$$\rho_1 - \rho_2 = \mathrm{Co}(T_1^2 - T_2^2) \tag{2}$$

the calculation of the densities is determined from two reference liquids, octane and decane, the densities of which are known with an absolute accuracy, better than ±0.05 $kg \cdot m^{-3}$. The densities of these components have been themselves measured with isooctane and toluene obtained from preparative chromatography. These two standards have a purity higher than 99.95% but are available in so little quantity that they cannot be directly used for all calibrations. The value of their density is obtained from the literature (*6*). The calibration with octane and decane is carried out twice at the beginning and at the end of the measurements, the average value being used for density calculations. The kinematic viscosities and densities of binary mixtures are respectively determined with accuracies better than ±0.1% and ±0.5 $kg \cdot m^{-3}$.

Results

The experimental viscosities and densities of the binary liquid mixtures are shown in Table II. The McAllister equation of the three-body interaction (*7*) has been used to calculate the viscosities of binary mixtures from the mole fraction.

$$\ln \nu = x_1^3 \ln \nu_1 + 3x_1^2 x_2 \ln \nu_{12} + 3x_1 x_2^2 \ln \nu_{21} + x_2^3 \ln \nu_2 - \ln (x_1 + x_2 M_2/M_1) + 3x_1^2 x_2 \ln [(2 + M_2/M_1)/3] + 3x_1 x_2^2 \ln [(1 + 2M_2/M_1)/3] + x_2^3 \ln (M_2/M_1) \tag{3}$$

Table II. Kinematic Viscosities and Densities of Binary Mixtures at 298.15 K

x_1	$10^6\nu$, $m^2 \cdot s^{-1}$	$10^{-3}\rho$, $kg \cdot m^{-3}$	x_1	$10^6\nu$, $m^2 \cdot s^{-1}$	$10^{-3}\rho$, $kg \cdot m^{-3}$	x_1	$10^6\nu$, $m^2 \cdot s^{-1}$	$10^{-3}\rho$, $kg \cdot m^{-3}$
				n-hexane + *n*-heptane				
0.1330	0.5534	0.6766	0.4004	0.5202	0.6706	0.6995	0.4845	0.6632
0.2015	0.5448	0.6752	0.4990	0.5082	0.6682	0.8002	0.4725	0.6606
0.3004	0.5325	0.6729	0.5965	0.4963	0.6658	0.9001	0.4611	0.6579
				n-hexane + *n*-octane				
0.1008	0.6944	0.6951	0.3997	0.6072	0.6839	0.7005	0.5252	0.6707
0.2033	0.6640	0.6915	0.5002	0.5785	0.6795	0.7984	0.4997	0.6659
0.3001	0.6355	0.6878	0.5991	0.5518	0.6753	0.8954	0.4752	0.6608
				n-hexane + *n*-nonane				
0.1103	0.8592	0.7094	0.4079	0.7065	0.6951	0.6967	0.5733	0.6779
0.2240	0.7986	0.7042	0.4912	0.6666	0.6906	0.7860	0.5356	0.6719
0.3030	0.7582	0.7005	0.6267	0.6045	0.6825	0.9007	0.4898	0.6635
				n-hexane + *n*-decane				
0.1384	1.040	0.7198	0.4123	0.8220	0.7046	0.7203	0.6126	0.6826
0.1927	0.9945	0.7171	0.5131	0.7522	0.6984	0.8048	0.5594	0.6749
0.3321	0.8901	0.7100	0.6042	0.6870	0.6916	0.8935	0.5078	0.6665
				n-hexane + *n*-dodecane				
0.2004	1.443	0.7352	0.4986	0.9936	0.7124	0.8013	0.6356	0.6837
				n-hexane + *n*-tetradecane				
0.1998	2.066	0.7484	0.5001	1.295	0.7260	0.6649	0.9613	0.7095
				n-hexane + *n*-hexadecane				
0.2012	2.897	0.7572	0.4987	1.680	0.7364	0.7998	0.8361	0.6989
				n-heptane + *n*-octane				
0.0992	0.7088	0.6969	0.4001	0.6594	0.6913	0.6973	0.6148	0.6858
0.2287	0.6878	0.6946	0.5052	0.6442	0.6895	0.7898	0.6009	0.6839
0.2924	0.6778	0.6935	0.6082	0.6283	0.6875	0.8954	0.5852	0.6818
				n-heptane + *n*-nonane				
0.1048	0.8790	0.7111	0.4000	0.7683	0.7021	0.7011	0.6645	0.6915
0.2014	0.8414	0.7082	0.5008	0.7322	0.6987	0.7984	0.6330	0.6878
0.3013	0.8039	0.7052	0.5535	0.7147	0.6969	0.8990	0.6012	0.6838
				n-heptane + *n*-decane				
0.1178	1.080	0.7222	0.4135	0.8862	0.7105	0.6863	0.7289	0.6977
0.1784	1.036	0.7199	0.4703	0.8517	0.7080	0.7595	0.6898	0.6938
0.3091	0.9513	0.7149	0.6041	0.7745	0.7818	0.8884	0.6242	0.6865
				n-heptane + *n*-dodecane				
0.2001	1.485	0.7365	0.4997	1.079	0.7203	0.7999	0.7507	0.6986
				n-heptane + *n*-tetradecane				
0.1998	2.117	0.7391	0.4999	1.395	0.7315	0.7995	0.8491	0.7050
				n-heptane + *n*-hexadecane				
0.2006	2.976	0.7603	0.5002	1.796	0.7409	0.7997	0.9642	0.7109
				n-octane + *n*-nonane				
0.1101	0.8976	0.7125	0.3960	0.8396	0.7083	0.6742	0.7803	0.7035
0.2235	0.8744	0.7109	0.5085	0.8176	0.7066	0.7926	0.7633	0.7021
0.3015	0.8585	0.7097	0.5891	0.8020	0.7053	0.8879	0.7456	0.7005
				n-octane + *n*-decane				
0.1384	1.094	0.7231	0.3894	0.9766	0.7168	0.6988	0.8430	0.7082
0.2144	1.058	0.7213	0.4520	0.9487	0.7152	0.8208	0.7942	0.7044
0.3015	1.017	0.7191	0.6010	0.8842	0.7110	0.8858	0.7686	0.7024
				n-octane + *n*-dodecane				
0.2008	1.539	0.7385	0.4997	1.188	0.7262	0.7993	0.8942	0.7110
				n-octane + *n*-tetradecane				
0.2004	2.180	0.7513	0.4997	1.521	0.7359	0.8216	0.9695	0.7148
				n-octane + *n*-hexadecane				
0.2002	3.031	0.7615	0.5001	1.940	0.7449	0.7997	1.128	0.7214
				n-nonane + *n*-decane				
0.1203	1.131	0.7249	0.4037	1.060	0.7216	0.7017	0.9889	0.7179
0.2074	1.109	0.7239	0.4866	1.040	0.7206	0.7953	0.9679	0.7168
0.2916	1.088	0.7230	0.5975	1.014	0.7192	0.9017	0.9428	0.7140
				n-nonane + *n*-dodecane				
0.2008	1.597	0.7402	0.5000	1.315	0.7318	0.7994	1.071	0.7217
				n-nonane + *n*-tetradecane				
0.2005	2.246	0.7529	0.5000	1.668	0.7407	0.7977	1.191	0.7265

Table II (Continued)

x_1	$10^6\nu$, $m^2 \cdot s^{-1}$	$10^{-3}\rho$, $kg \cdot m^{-3}$	x_1	$10^6\nu$, $m^2 \cdot s^{-1}$	$10^{-3}\rho$, $kg \cdot m^{-3}$	x_1	$10^6\nu$, $m^2 \cdot s^{-1}$	$10^{-3}\rho$, $kg \cdot m^{-3}$
			n-nonane + *n*-hexadecane					
0.2022	3.110	0.7626	0.4999	2.111	0.7491	0.7993	1.328	0.7307
			n-decane + *n*-dodecane					
0.2000	1.658	0.7420	0.5001	1.461	0.7366	0.8003	1.276	0.7303
			n-decane + *n*-tetradecane					
0.2001	2.308	0.7541	0.5000	1.836	0.7452	0.7973	1.410	0.7347
			n-decane + *n*-hexadecane					
0.2028	3.206	0.7637	0.5000	2.308	0.7527	0.7998	1.562	0.7384
			n-dodecane + *n*-tetradecane					
0.2006	2.500	0.7567	0.4999	2.230	0.7527	0.7994	1.962	0.7485
			n-dodecane + *n*-hexadecane					
0.2005	3.426	0.7659	0.5001	2.729	0.7592	0.7993	2.144	0.7514
			n-tetradecane + *n*-hexadecane					
0.1998	3.660	0.7679	0.5002	3.280	0.7648	0.7932	2.929	0.7616
			3-methylpentane + *n*-decane					
0.1811	1.004	0.7183	0.4976	0.7539	0.7011	0.8024	0.5483	0.6787
0.3964	0.8308	0.7072	0.5978	0.6825	0.6945			
			3-methylpentane + *n*-hexadecane					
0.2182	2.866	0.7589	0.4735	1.817	0.7410	0.8049	0.8248	0.7014
0.3888	2.136	0.7476	0.5980	1.396	0.7288			
			2-methylpentane + *n*-hexadecane					
0.1527	3.143	0.7618	0.5684	1.451	0.7290	0.8904	0.6118	0.6774
0.3960	2.057	0.7448	0.7887	0.8313	0.6975			
			2-methylhexane + *n*-tetradecane					
0.1699	2.195	0.7509	0.4244	1.533	0.7355	0.7925	0.8206	0.7027
0.2450	1.988	0.7468	0.6102	1.140	0.7209	0.8776	0.6926	0.6923
			2,3-dimethylpentane + *n*-tetradecane					
0.2023	2.158	0.7512	0.5131	1.413	0.7348	0.8009	0.8549	0.7126
0.4104	1.650	0.7410	0.6140	1.197	0.7280	0.8108	0.8372	0.7117
			2,5-dimethylhexane + *n*-hexadecane					
0.1027	3.452	0.7653	0.4277	2.139	0.7473	0.6053	1.563	0.7340
0.2090	2.979	0.7601	0.4872	1.934	0.7432	0.7827	1.099	0.7176
			2,2-dimethylpentane + *n*-decane					
0.1808	1.037	0.7186	0.4611	0.8536	0.7049	0.7755	0.6647	0.6861
0.3562	0.9201	0.7103	0.5648	0.7890	0.6992			
			2,2-dimethylpentane + *n*-hexadecane					
0.1783	3.142	0.7607	0.4792	1.949	0.7400	0.7998	0.9790	0.7050
0.3812	2.312	0.7477	0.5691	1.640	0.7323			
			2,2-dimethylhexane + *n*-decane					
0.1989	1.063	0.7204	0.5093	0.9165	0.7102	0.7988	0.7896	0.6995
0.4072	0.9634	0.7137	0.6093	0.8714	0.7066			
			2,2-dimethylhexane + *n*-hexadecane					
0.1954	3.123	0.7609	0.5047	1.987	0.7423	0.8070	1.127	0.7157
0.3986	2.351	0.7495	0.6183	1.632	0.7335			
			isooctane + *n*-hexane					
0.1501	0.4761	0.6612	0.5114	0.5501	0.6739	0.8489	0.6359	0.6839
0.3497	0.5137	0.6686	0.6548	0.5843	0.6784			
			isooctane + *n*-decane					
0.2019	1.054	0.7199	0.5084	0.9015	0.7091	0.7994	0.7685	0.6971
0.4140	0.9503	0.7128	0.6109	0.8538	0.7051			
			isooctane + *n*-tetradecane					
0.1958	2.218	0.7503	0.5184	1.496	0.7317	0.7989	0.9852	0.7095
0.4007	1.743	0.7392	0.6092	1.319	0.7253			
			cyclohexane + *n*-hexadecane					
0.1604	2.550	0.7693	0.5044	2.599	0.7685	0.8469	1.580	0.7697
0.3525	3.032	0.7688	0.6444	2.186	0.7684			
			methylcyclohexane + *n*-hexane					
0.1432	0.4807	0.6710	0.5040	0.6007	0.7108	0.8488	0.7721	0.7484
0.3353	0.5372	0.6922	0.6394	0.6570	0.7256			
			methylcyclohexane + *n*-decane					
0.1481	1.120	0.7300	0.4719	1.029	0.7399	0.8401	0.9235	0.7557
0.3317	1.068	0.7353	0.6377	0.9805	0.7463			

Table II (Continued)

x_1	$10^6\nu$, $m^2 \cdot s^{-1}$	$10^{-3}\rho$, $kg \cdot m^{-3}$	x_1	$10^6\nu$, $m^2 \cdot s^{-1}$	$10^{-3}\rho$, $kg \cdot m^{-3}$	x_1	$10^6\nu$, $m^2 \cdot s^{-1}$	$10^{-3}\rho$, $kg \cdot m^{-3}$
			methylcyclohexane + *n*-hexadecane					
0.1260	3.525	0.7694	0.4985	2.290	0.7677	0.8494	1.269	0.7657
0.3520	2.776	0.7684	0.6375	1.875	0.7670			
			cis-1,2-dimethylcyclohexane + *n*-hexane					
0.1534	0.5044	0.6790	0.5115	0.7030	0.7307	0.8475	1.034	0.7744
0.3524	0.6015	0.7083	0.6447	0.8086	0.7486			
			cis-1,2-dimethylcyclohexane + *n*-hexadecane					
0.1434	3.597	0.7714	0.6221	2.315	0.7796	0.9360	1.450	0.7899
0.3301	3.112	0.7739						
			1,2-dimethylcyclohexane + *n*-hexane (mixture of cis and trans)					
0.3555	0.5918	0.7063	0.5228	0.6880	0.7285	0.6523	0.7801	0.7450
			1,2,4-trimethylcyclohexane + *n*-hexane (mixture of cis and trans)					
0.1445	0.4962	0.6768	0.4818	0.6440	0.7248	0.8498	0.8752	0.7667
0.3457	0.5792	0.7069	0.6493	0.7398	0.7434			
			benzene + *n*-decane					
0.0956	1.093	0.7321	0.3963	0.9029	0.7562	0.6844	0.7582	0.7923
0.2047	1.021	0.7396	0.4955	0.8481	0.7670	0.7964	0.7158	0.8154
0.3047	0.9575	0.7477	0.5940	0.7987	0.7799	0.8995	0.6884	0.8408
			toluene + *n*-decane					
0.1596	1.049	0.7381	0.5161	0.8331	0.7739	0.8451	0.6829	0.8258
0.3625	0.9200	0.7566	0.6500	0.7660	0.7920			
			toluene + *n*-tetradecane					
0.1671	2.243	0.7661	0.5104	1.439	0.7875	0.8468	0.8416	0.8278
0.3678	1.749	0.7771	0.6521	1.164	0.8009			
			o-xylene + *n*-hexane					
0.1672	0.4745	0.6907	0.4879	0.5618	0.7606	0.8402	0.7318	0.8396
0.3486	0.5180	0.7304	0.6607	0.6321	0.7990			
			o-xylene + *n*-decane					
0.1369	1.103	0.7393	0.5055	0.9676	0.7833	0.8099	0.8845	0.8337
0.3715	1.013	0.7655	0.6262	0.9312	0.8014			
			o-xylene + *n*-tetradecane					
0.1605	2.363	0.7682	0.5041	1.676	0.7952	0.8327	1.106	0.8390
0.4252	1.826	0.7878	0.6743	1.368	0.8147			
			p-xylene + *n*-hexane					
0.1549	0.4612	0.6856	0.4883	0.5182	0.7525	0.8415	0.6253	0.8243
0.3524	0.4909	0.7252	0.6608	0.5630	0.7874			
			p-xylene + *n*-decane					
0.1529	1.062	0.7393	0.5078	0.8651	0.7769	0.8435	0.7345	0.8264
0.3430	0.9494	0.7580	0.6406	0.8076	0.7944			
			p-xylene + *n*-tetradecane					
0.1663	2.252	0.7672	0.5057	1.467	0.7899	0.8494	0.8883	0.8289
0.3495	1.800	0.7781	0.6536	1.191	0.8038			
			benzene + *o*-xylene					
0.0948	0.8311	0.8744	0.5133	0.7449	0.8722	0.8369	0.6998	0.8723
0.3681	0.7712	0.8727	0.6245	0.7240	0.8720			
			benzene + *p*-xylene					
0.1804	0.6926	0.8580	0.5082	0.6847	0.8620	0.8068	0.6810	0.8678
0.3680	0.6878	0.8601	0.6195	0.6825	0.8639			
			toluene + *o*-xylene					
0.1476	0.8131	0.8732	0.5054	0.7274	0.8684	0.8513	0.6597	0.8636
0.3604	0.7600	0.8703	0.6638	0.6948	0.8662			
			toluene + *p*-xylene					
0.1698	0.6876	0.8573	0.5067	0.6675	0.8588	0.8273	0.6462	0.8605
0.3609	0.6765	0.8581	0.6258	0.6598	0.8594			
			o-xylene + *p*-xylene					
0.1708	0.7181	0.8598	0.4902	0.7632	0.8657	0.7827	0.8121	0.8711
0.3516	0.7427	0.8631	0.6200	0.7838	0.8681			
			benzene + cyclohexane					
0.1591	0.9597	0.7846	0.5201	0.7440	0.8152	0.8559	0.6797	0.8537
0.3447	0.8230	0.7992	0.6432	0.7081	0.8283			
			benzene + 1,2-dimethylcyclohexane (mixture of cis and trans)					
0.1936	0.9757	0.7956	0.4919	0.7957	0.8150	0.8352	0.6921	0.8494
0.3928	0.8452	0.8077	0.6481	0.7358	0.8286			

Table II (Continued)

x_1	$10^6\nu$, $m^2 \cdot s^{-1}$	$10^{-3}\rho$, $kg \cdot m^{-3}$	x_1	$10^6\nu$, $m^2 \cdot s^{-1}$	$10^{-3}\rho$, $kg \cdot m^{-3}$	x_1	$10^6\nu$, $m^2 \cdot s^{-1}$	$10^{-3}\rho$, $kg \cdot m^{-3}$
toluene + methylcyclohexane								
0.1563	0.7962	0.7763	0.5198	0.6794	0.8081	0.8435	0.6367	0.8426
0.3664	0.7175	0.7938	0.6594	0.6549	0.8222			
o-xylene + cyclohexane								
0.1769	0.9898	0.7905	0.5067	0.8651	0.8238	0.8202	0.8422	0.8565
0.3600	0.9026	0.8087	0.6357	0.8479	0.8372			
o-xylene + 1,2-dimethylcyclohexane (mixture of cis and trans)								
0.1499	1.050	0.7970	0.5033	0.9079	0.8257	0.8477	0.8552	0.8589
0.3427	0.9603	0.8120	0.6361	0.8775	0.8379			

Table III. Numerical Values of the Constants of Equation 3

system 1 + 2	$10^6\nu_{12}$, $m^2 \cdot s^{-1}$	$10^6\nu_{21}$, $m^2 \cdot s^{-1}$	Δ%	system 1 + 2	$10^6\nu_{12}$, $m^2 \cdot s^{-1}$	$10^6\nu_{21}$, $m^2 \cdot s^{-1}$	Δ%
n-hexane + *n*-heptane	0.4946	0.5274	0.12	2,2-dimethylhexane + *n*-hexadecane	1.750	2.730	0.23
n-hexane + *n*-octane	0.5403	0.6318	0.03	isooctane + *n*-hexane	0.5816	0.5170	0.12
n-hexane + *n*-nonane	0.6047	0.7533	0.05	isooctane + *n*-decane	0.8381	0.9972	0.10
n-hexane + *n*-decane	0.6800	0.9008	0.10	isooctane + *n*-tetradecane	1.339	1.971	0.14
n-hexane + *n*-dodecane	0.8666	1.275	0.10	cyclohexane + *n*-hexadecane	2.691	3.236	0.30
h-hexane + *n*-tetradecane	1.133	1.787	0.20	methylcyclohexane + *n*-hexane	0.6512	0.5313	0.16
n-hexane + *n*-hexadecane	1.486	2.465	0.80	methylcyclohexane + *n*-decane	0.9829	1.081	0.03
n-heptane + *n*-octane	0.6207	0.6730	0.01	methylcyclohexane + *n*-hexadecane	2.207	2.969	0.51
n-heptane + *n*-nonane	0.6834	0.7971	0.03	*cis*-1,2-dimethylcyclohexane + *n*-hexane	0.7842	0.5846	0.09
n-heptane + *n*-decane	0.7570	0.9472	0.03	*cis*-1,2-dimethylcyclohexane + *n*-hexadecane	2.574	3.233	0.19
n-heptane + *n*-dodecane	0.9424	1.329	0.06	1,2-dimethylcyclohexane (cis, trans) + *n*-hexane	0.7623	0.5747	0.02
n-heptane + *n*-tetradecane	1.198	1.855	0.18	1,2,4-trimethylcyclohexane (cis, trans) + *n*-hexane	0.7480	0.5743	0.06
n-heptane + *n*-hexadecane	1.530	2.585	0.50	benzene + *n*-decane	0.7276	0.9758	0.40
n-octane + *n*-nonane	0.7847	0.8556	0.13	toluene + *n*-decane	0.7470	0.9536	0.11
n-octane + *n*-decane	0.8636	1.008	0.01	toluene + *n*-tetradecane	1.278	1.909	0.02
n-octane + *n*-dodecane	1.050	1.405	0.07	*o*-xylene + *n*-hexane	0.6062	0.5005	0.06
n-octane + *n*-tetradecane	1.308	1.939	0.13	*o*-xylene + *n*-decane	0.9016	1.032	0.08
n-octane + *n*-hexadecane	1.662	2.623	0.14	*o*-xylene + *n*-tetradecane	1.523	2.078	0.07
n-nonane + *n*-decane	0.9987	1.079	0.01	*p*-xylene + *n*-hexane	0.5468	0.4760	0.04
n-nonane + *n*-dodecane	1.197	1.481	0.10	*p*-xylene + *n*-decane	0.7716	0.9641	0.08
n-nonane + *n*-tetradecane	1.460	2.020	0.03	*p*-xylene + *n*-tetradecane	1.247	1.916	0.04
n-nonane + *n*-hexadecane	1.810	2.734	0.05	benzene + *o*-xylene	0.7115	0.7784	0.12
n-decane + *n*-dodecane	1.370	1.570	0.09	benzene + *p*-xylene	0.6791	0.6930	0.03
n-decane + *n*-tetradecane	1.651	2.089	0.27	toluene + *o*-xylene	0.6921	0.7633	0.00
n-decane + *n*-hexadecane	1.997	2.866	0.13	toluene + *p*-xylene	0.6591	0.6798	0.02
n-dodecane + *n*-tetradecane	2.078	2.386	0.01	*o*-xylene + *p*-xylene	0.7883	0.7370	0.01
n-dodecane + *n*-hexadecane	2.421	3.164	0.09	benzene + cyclohexane	0.6623	0.7587	0.18
n-tetradecane + *n*-hexadecane	3.094	3.496	0.04	benzene + 1,2-dimethylcyclohexane (cis, trans)	0.6848	0.8573	0.15
3-methylpentane + *n*-decane	0.6743	0.9020	0.11	toluene + methylcyclohexane	0.6305	0.6968	0.07
3-methylpentane + *n*-hexadecane	1.582	2.506	0.52	*o*-xylene + cyclohexane	0.8319	0.8264	0.15
2-methylpentane + *n*-hexadecane	1.520	2.458	0.69	*o*-xylene + 1,2-dimethylcyclohexane (cis, trans)	0.8445	0.9199	0.12
2-methylhexane + *n*-tetradecane	1.167	1.839	0.23				
2,3-dimethylpentane + *n*-tetradecane	1.271	1.925	0.22				
2,5-dimethylhexane + *n*-hexadecane	1.614	2.597	0.11				
2,2-dimethylpentane + *n*-decane	0.7525	0.9532	0.02				
2,2-dimethylpentane + *n*-hexadecane	1.680	2.662	0.37				
2,2-dimethylhexane + *n*-decane	0.8557	1.007	0.02				

In most cases, the McAllister model, namely, eq 3, has been used to describe experimental data reported in the literature. This model is known as giving better results than those given by Heric, Grunberg, and Nissan (*8*), Katti and Chaudri (*9*), and Tamura and Kurata (*10*).

The ν_{12} and ν_{21} parameters of eq 3 calculated by regression from experimental data are listed in Table III together with an average percentage deviation for each system:

$$\Delta\% = \frac{1}{n}\sum^{n}\frac{|\nu_{exp} - \nu_{calc}|}{\nu_{exp}} \times 100$$

Discussion

The experimental values of pure-component viscosities here reported are in most cases lower than the lowest value recorded in the literature and in a few cases slightly above it. Nevertheless our values are lower than the TRC Thermodynamic Tables (*11*), which rather constitute the upper limit of the recorded values of the literature.

In consequence, gas chromatography analyses using a 0V17 column have been achieved on heptane, which presents the highest deviation (2.09%) with respect to the value of the TRC Tables. The chromatograms reveal the presence of impurities, the concentrations of which do not justify an error higher than $\pm 0.0003 \times 10^{-6}$ $m^2 \cdot s^{-1}$.

Thus, the addition of 0.14% of hexane involves a decrease of the viscosity value from 0.5702×10^{-6} to 0.5699×10^{-6} $m^2 \cdot s^{-1}$ and at the same time distinctly reveals the presence of a component before heptane in the chromatogram. Besides, the two following additional measurements confirm the purity of heptane: (1) The difference between the flow times of heptane Elf issued from preparative chromatography (purity > 99.95%) and heptane Fluka is lower than 0.02%. (2) The measured density of heptane is in good agreement with the TRC value (Table I).

The difference between our viscosity value and the TRC values is not due to an error of the pure water viscosity as a

standard since there is only a deviation of 0.04% between our value and the value used, 0.8925×10^{-6} $m^2 \cdot s^{-1}$ (*11*).

Moreover, although chromatograms of others' "pure" hydrocarbons have shown impurities in greater concentration, the viscosity value of these compounds remains closer to the TRC Tables than the heptane value.

In the future, it is recommended that measurements on the viscosity of heptane be improved in order to use it as a standard.

Beyond the interest of knowing the kinematic viscosities and densities of new binary systems, the purpose of this work is to get numerous data in order to extend the table of interaction parameter values of the UNIFAC-VISCO model presented in a previous paper (*12*). Therefore, we have chosen to study numerous systems with a small number of mole fractions for each one. The experimental variable used in the UNIFAC-VISCO model is the excess molar free energy of activation of flow. Therefore, the validity of our measurements has been checked comparing experimental values of this variable to the literature values for hexane-hexadecane, hexane-tetradecane, and hexadecane-tetradecane systems. Figure 1 shows good agreement between our values and those of the literature. As regards the values of Dymond and Young (*13*), the mean deviation of the present values is of 0.17%, whereas the values of Heric and Brewer (*9*) show a mean deviation of 1.12%.

The validity of the UNIFAC-VISCO model for the present systems has been checked by the authors in a previous paper (*12*). The McAllister model imposes the experimental determination of two adjustable parameters and necessarily leads to a better estimation of the viscosity than the UNIFAC-VISCO model, which is completely predictive.

Glossary

Co	density-meter constant
k	viscometer constant
M	molecular weight
T	period
t	flow time
x	mole fraction
V^E	excess volume
ν	Hagenbach correction
ρ	density
ν	kinematic viscosity
ν_{12}, ν_{21}	parameters of eq 3

Subscripts

1,2	components 1 and 2

Literature Cited

(1) Singh, R. P.; Sinha, C. P. *J. Chem. Eng. Data* **1985**, *30*, 38.
(2) Bamelis, P.; Huyskens, P.; Meenssen, E. *J. Chem. Phys.* **1985**, *62*(2), 158.
(3) Cronauer, D. C.; Rothfus, R. R.; Kermode, R. I. *J. Chem. Eng. Data* **1985**, *10*, 131.
(4) Noda, K.; Ohashi, M.; Ishida, K. *J. Chem. Eng. Data* **1982**, *27*, 326.
(5) Hardy, R. C. *NBS Monogr. (U.S.)* **1962**, *No. 55*.
(6) Riddick, J. A.; Bungar, W. B. *Organic Solvents, Physical Properties and Methods of Purification*, 3rd ed.; Techniques of Chemistry, Vol. II; Wiley-Interscience: New York, 1970.
(7) McAllister, R. A. *AIChE J.* **1960**, *6*, 427.
(8) Aucejo, A.; Part, E.; Medina, P.; Sancho-Tello, M. *J. Chem. Eng. Data* **1986**, *31*, 143.
(9) Heric, E. L.; Brewer, J. G. *J. Chem. Eng. Data* **1967**, *12*, 574.
(10) Abdul-Fattah, A. A.; Dullien, F. A. L. *J. Chem. Eng. Data* **1981**, *26*, 312.
(11) *API Project 44*, Thermodynamic Research Center, Carnegie Institute of Technology: Pittsburgh, PA, 1968.
(12) Chevalier, J. L.; Petrino, P.; Gaston-Bonhomme, Y. *Chem. Eng. Sci.* **1988**, *43* (6), 1303.
(13) Dymond, J. H.; Young, K. J. *Int. J. Thermophys.* **1980**, *1* (4), 331.
(14) Heric, E. L.; Coursey, B. M. *J. Chem. Eng. Data* **1972**, *17*, 41.
(15) Reed, T. M., III; Taylor, T. E. *J. Phys. Chem.* **1959**, *63*, 58.
(16) Wei, I. C.; Rowley, R. L. *J. Chem. Eng. Data* **1984**, *29*, 332.
(17) Teja, A. S.; Rice, P. *Chem. Eng. Sci.* **1981**, *36* (1), 7.
(18) Dusart, O.; Piekarski, C.; Piekarski, S. *J. Chim. Phys. Phys.-Chim. Biol.* **1978**, *75* (10), 919.
(19) Rao, K. P. C.; Reedy, K. S. *Can. J. Chem. Eng.* **1988**, *66* (3), 474.
(20) Coursey, B. M.; Heric, E. L. *J. Chem. Eng. Data* **1969**, *14*, 426.
(21) Grunberg, L. *Trans. Faraday Soc.* **1954**, *50*, 1293.
(22) Dusart, O.; Pierkarski, C.; Piekarski, S.; Viallard, A. *J. Chim. Phys. Phys.-Chim. Biol.* **1976**, *3* (9-10), 837.
(23) Dhillon, M. S.; Chugh, H. S. *Thermochim. Acta* **1976**, *16*, 345.

Received for review January 17, 1989. Accepted October 30, 1989.

Excess Molar Enthalpies of Seven Benzene + *n*-Alkylamine Binary Liquid Mixtures

Javier Fernández, Inmaculada Velasco, and Santos Otín*

Departamento de Química Orgánica-Química Física, Facultad de Ciencias, Universidad de Zaragoza, Zaragoza, Spain

An isobaric and quasi-isothermic calorimeter has been used to determine excess molar enthalpies, H^E, as a function of concentration at atmospheric pressure for seven binary mixtures containing an *n*-alkylamine (propyl-, butyl-, hexyl-, octyl-, decyl-, or dodecylamine, at 303.15 K, or pentadecylamine, at 313.15 K) with benzene. H^E of propylamine + benzene is positive, then, it decreases, and after reaching a minimum for butylamine, it increases with the chain length of the higher *n*-alkylamines.

Introduction

Following our study of thermodynamic properties on binary mixtures containing *n*-alkylamines (*1-4*), we report here the excess molar enthalpy, H^E, at 303.15 K, for benzene (C_6H_6) + propylamine ($PrNH_2$), + butylamine ($BuNH_2$), + hexylamine ($HeNH_2$), + octylamine ($OcNH_2$), + decylamine ($DeNH_2$), and + dodecylamine ($DoNH_2$) and for C_6H_6 + pentadecylamine ($PeNH_2$) at 313.15 K. As far as we know, the only previous measurements on these mixtures are those of Velasco et al. (*5*) of H^E for C_6H_6 + $PrNH_2$ and + $HeNH_2$ and Letcher and Bayles (*6*) for C_6H_6 + $BuNH_2$; their results of H^E of C_6H_6 + $PrNH_2$ are in very good agreement with ours, but they are higher than ours for C_6H_6 + $BuNH_2$ and + $HeNH_2$.

Experimental Section

All the *n*-alkylamines were the same as those used previously (*1*) as were their purification methods and physical properties. Benzene was from Fluka AG Buchs, better than 99.8 mol %.

Excess molar enthalpies were determined by using an isobaric and quasi-isothermic calorimeter similar to that described in ref 7. Electrical energy was measured to better than 0.5%, and temperature in the water bath was controlled to within

0021-9568/90/1735-0212$02.50/0