Measurement of Density and Viscosity of Binary 1-Alkanol Systems (C_8−C_{11}) at 101 kPa and Temperatures from (283.15 to 313.15) K

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In this paper, we present the experimental values of the density and dynamic viscosity, obtained at 101 kPa, for binary systems containing 1-octanol, 1-nonanol, 1-decanol, and 1-undecanol over the entire range of mole fractions and at the following temperatures: (283.15, 288.15, 293.15, 298.15, 303.15, 308.15, and 313.15) K. The experimental viscosity data have been correlated by means of a model previously developed in our group. The binary interaction parameters of this model are also presented. The agreement between experimental and calculated values is quite good. The overall mean relative standard deviations are 0.2 % for the system 1-octanol + 1-nonanol, 0.5 % for the system 1-octanol + 1-decanol, 0.7 % for the system 1-octanol + 1-undecanol, 0.2 % for the system 1-nonanol+1-decanol, 0.6 % for the system 1-nonanol + 1-undecanol, and 0.2 % for the system 1-decanol + 1-undecanol.

Introduction

Knowledge of the viscosity of pure liquids and mixtures is important for practical and theoretical purposes. The viscosity of liquid mixtures is an invaluable data for the chemical engineer in the design and optimization of industrial processes.

Over the last years, numerous equations for the viscosity of liquid mixtures, for implementation in computer prediction routines, have been proposed in the literature. Excellent reviews concerning viscosity modeling are available elsewhere.[1,2]

The simultaneous investigation of viscosity and volume effects on mixing may give an insight to the intermolecular interactions present in liquid mixtures. In addition, such investigations are a preliminary step to the development of equations for estimation of liquid mixture properties, which often contain parameters fitted by means of experimental viscosity data of the binary subsystems.

In this work, we present the experimental results of densities and viscosities of binary mixtures of intermediate chain length 1-alkanols (C_8−C_{11}). The following systems have been studied: 1-octanol + 1-nonanol, 1-octanol + 1-decanol, 1-octanol + 1-undecanol, 1-nonanol + 1-decanol, 1-nonanol + 1-undecanol, and 1-decanol + 1-undecanol.

Two of the systems investigated in this work have been studied by other authors.[3,4] Nevertheless, none of the previous investigations have been conducted over such a large temperature interval as presented in this work. Shan and Asfour[3] presented experimental viscosity data for the system 1-decanol + 1-undecanol at (308.15 and 313.15) K. In a subsequent work, Shan and Asfour[4] presented viscosity data for the systems 1-nonanol + 1-decanol and 1-decanol + 1-undecanol at (293.15 and 298.15) K. To our knowledge there are no viscosity data available in the literature for the other systems investigated in the present work.

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Experimental Section

1-octanol (Merck, purity >99 %), 1-nonanol (Merck, purity >98 %), 1-decanol (Merck, purity >99 %), 1-undecanol (Merck, purity >98 %) were used without further purification. Gas chromatographic analyses confirmed the purities stated by the manufacturer. The chromatograph was a HP 6890 with a HP-Innowax column (poly(ethylene glycol), 30 m × 320 μm × 0.5 μm film thickness).

The solutions were prepared by mass, using a digital balance (Chyo, model JK-180) with a precision of 0.1 mg, and stored in airtight stopped bottles. Since 1-alkanols are hygroscopic, all the solvents and respective mixtures were dried and kept over 0.4 nm molecular sieves (ACROS Organics). The amount of water was determined by Karl Fisher after the experimental measurements and did not exceeded 500 ppm. The uncertainty in mole fractions is less than 1×10^{-4}.

The efflux time of the liquids were measured with Cannon-Fenske viscometers (Schott-Gerätte), with i.d. of 0.77 mm and 1.01 mm calibrated and certified by the company that supplies us. The viscometers were coupled to an automatic module (Schott-Gerätte, model AVS 350) and then immersed in a thermostatic bath (Schott-Gerätte, model CT 1450/2), controlled to within ± 0.01 K. For each sample and temperature investigated, at least 10 repetitions of the efflux time were performed, and the results were averaged. The uncertainty in the efflux time was 0.01 s. To convert the efflux time to dynamic viscosity, the following equation was used:

$$\eta = k(t - \omega)\rho \quad (1)$$

where k is the viscometer constant, t is the efflux time, ω is the Hagenbach correction (its value was taken from the

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Table 1. Comparison of Experimental Results of Densities of Pure Solvents with Literature Values at 101 kPa

283.15 K		288.15 K		293.15 K		298.15 K		303.15 K		308.15 K		313.15 K	
exp ρ/g·cm^{-3}	lit ρ/g·cm^{-3}	exp ρ/g·cm^{-3}	lit ρ/g·cm^{-3}	exp ρ/g·cm^{-3}	lit ρ/g·cm^{-3}	exp ρ/g·cm^{-3}	lit ρ/g·cm^{-3}	exp ρ/g·cm^{-3}	lit ρ/g·cm^{-3}	exp ρ/g·cm^{-3}	lit ρ/g·cm^{-3}	exp ρ/g·cm^{-3}	lit ρ/g·cm^{-3}
						1-Octanol							
0.8321	0.8319[a]	0.8286	0.8276[b]	0.8252	0.82505[a] 0.8253[c] 0.8249[d] 0.82584[e]	0.8219	0.82157[a] 0.8211[b] 0.8218[c] 0.8216[d] 0.82182[e] 0.8215[k]	0.8184	0.81809[a] 0.8182[d] 0.8181[g,h,i] 0.8175[k]	0.8150	0.8142[b] 0.8145[f] 0.81463[e] 0.8149[i] 0.8134[k]	0.8114	0.81108[a] 0.8112[d] 0.8111[g] 0.8115[j]
						1-Nonanol							
0.8350		0.8315	0.8310[b]	0.8281	0.8279[c] 0.8277[d] 0.82797[e]	0.8247	0.8244[b,c] 0.8246[a] 0.82457[e]	0.8213	0.8216[d]	0.8178	0.8177[b] 0.8181[d] 0.81832[e] 0.8176[i]	0.8143	0.8147[d] 0.8143[j]
						1-Decanol							
0.8366		0.8333	0.8327[b]	0.8299	0.8302[c] 0.8295[d] 0.83028[e]	0.8265	0.8254[b] 0.8268[c] 0.8263[d] 0.82698[e] 0.8265[f] 0.8261[k]	0.8230	0.8230[d,k]	0.8196	0.8197[b] 0.8194[d,k] 0.8200[i]	0.8163	0.8167[d]
						1-Undecanol							
				0.8322	0.8325[c]	0.8288	0.8291[c]	0.8254		0.8217	0.8223[j]	0.8186	0.8191[j]

[a] Ref 10. [b] Ref 11. [c] Ref 4. [d] Ref 12. [e] Ref 13. [f] Ref 14. [g] Ref 15. [h] Ref 16. [i] Ref 17. [j] Ref 3. [k] Ref 18.

Table 2. Comparison of Experimental Results of Viscosities of Pure Solvents with Literature Values at 101 kPa

283.15 K		288.15 K		293.15 K		298.15 K		303.15 K		308.15 K		313.15 K	
exp η/mPa·s	lit η/mPa·s	exp η/mPa·s	lit η/mPa·s	exp η/mPa·s	lit η/mPa·s	exp η/mPa·s	lit η/mPa·s	exp η/mPa·s	lit η/mPa·s	exp η/mPa·s	lit η/mPa·s	exp η/mPa·s	lit η/mPa·s
						1-Octanol							
13.493	13.49[a]	10.872	10.662[b]	8.944	9.183[a] 9.223[c] 9.2733[e]	7.498	7.363[b,f] 7.663[c] 7.5981[e] 7.368[k]	6.273	6.419[a] 6.24[g] 6.256[h,i] 6.120[k]	5.342	5.256[b] 5.4027[e] 5.250[f] 5.458[j] 5.352[k]	4.540	4.661[a] 4.53[f] 4.584[g] 4.646[j]
						1-Nonanol							
17.439		14.272	13.146[b]	11.635	11.728[c] 11.773[e]	9.519	9.101[b] 9.715[c] 9.6921[e]	7.806		6.604	6.522[b] 6.4938[e] 6.741[j]	5.668	5.707[j]
						1-Decanol							
22.064		17.988	16.465[b]	14.387	14.548[c] 14.4878[e]	11.735	10.974[b] 11.829[c] 11.7968[e] 11.790[f] 11.567[k]	9.561	9.652[k]	8.000	7.509[b] 8.3897[e] 8.124[f] 8.174[j] 7.918[k]	6.831	6.841[j]
						1-Undecanol							
				17.284	16.952[c]	13.721	13.830[c]	11.524		9.350	9.380[j]	7.841	7.837[j]

[a] Ref 10. [b] Ref 11. [c] Ref 4. [d] Ref 12. [e] Ref 13. [f] Ref 14. [g] Ref 15. [h] Ref 16. [i] Ref 17. [j] Ref 3. [k] Ref 18.

viscometer manual, Schott-Gerätte), and ρ is the density of the sample.

The densities of the pure solvents and respective solutions were measured with a digital oscillating u-tube density meter (Anton Paar, model DMA 4500) with an uncertainty of 5×10^{-5} g·cm^3. For all samples, and for each temperature, the density was measured at least twice. A third measurement was made only if the reproducibility between the two previous measurements was greater than 3×10^{-5} g·cm^3. The cell temperature of the density meter was controlled to within $\pm$ 0.01 K. Tridistilled water and dry air were used to calibrate the instrument. The uncertainty in the dynamic viscosity was less than 2×10^{-3} mPa·s.

Results and Discussion

The experimental densities and viscosities of the pure 1-alkanols, for each temperature investigated in this work, are presented in Table 1 and Table 2, along with literature values when available.[3,4,10−18]

As can be seen by the results presented in Table 1, the agreement between our density data and the literature values is excellent. For viscosities, the agreement between our data and those reported in the literature are also quite good, as shown in Table 2. However, a careful inspection of the results presented in Table 2 shows some differences between our measured viscosities and those reported by Rauf et al.[11] The values obtained in this study are always greater than the values reported by those authors.[11] Absolute relative deviations near 10 % were observed for 1-nonanol and 1-decanol at 288.15 K whereas deviations of the order of 5 % were observed between our data and those of the cited authors[11] at other temperatures.

A plot of ln η versus $1/T$ for the pure alcohols showed a linear profile for our data and also for the data of Rauf et

Table 3. Densities and Viscosities of Binary Mixtures at 101 kPa

x_1	ρ / g·cm^{-3}	η / mPa·s	$100\lvert(\eta - \eta_{calc})/\eta\rvert$	x_1	ρ / g·cm^{-3}	η / mPa·s	$100\lvert(\eta - \eta_{calc})/\eta\rvert$	x_1	ρ / g·cm^{-3}	η / mPa·s	$100\lvert(\eta - \eta_{calc})/\eta\rvert$
1-Octanol (1) + 1-Nonanol (2) at 283.15				1-Octanol (1) + 1-Nonanol (2) at 288.15				1-Octanol (1) + 1-Nonanol (2) at 293.15			
0	0.8350	17.439		0	0.8315	14.272		0	0.8281	11.635	
0.1001	0.8346	16.986	0.05	0.1001	0.8313	13.921	0.25	0.1001	0.8278	11.377	0.34
0.1998	0.8344	16.566	0.09	0.1998	0.8310	13.607	0.61	0.1998	0.8276	11.125	0.57
0.2999	0.8341	16.206	0.36	0.2999	0.8307	13.204	0.17	0.2999	0.8273	10.792	0.04
0.4003	0.8338	15.788	0.14	0.4003	0.8304	12.829	0.19	0.4003	0.8270	10.555	0.14
0.5001	0.8335	15.410	0.05	0.5001	0.8301	12.497	0.33	0.5001	0.8267	10.261	0.31
0.6001	0.8332	15.010	0.24	0.6001	0.8298	12.261	0.27	0.6001	0.8264	10.043	0.04
0.7000	0.8329	14.550	0.96	0.7000	0.8295	11.973	0.47	0.7000	0.8261	9.838	0.41
0.8001	0.8327	14.211	0.80	0.8001	0.8293	11.592	0.04	0.8001	0.8258	9.525	0.12
0.9001	0.8323	13.898	0.23	0.9001	0.8289	11.332	0.71	0.9001	0.8255	9.303	0.50
1	0.8321	13.493		1	0.8286	10.872		1	0.8252	8.944	
1-Octanol (1) + 1-Nonanol (2) at 298.15 K				1-Octanol (1) + 1-Nonanol (2) at 303.15 K				1-Octanol (1) + 1-Nonanol (2) at 308.15 K			
0	0.8247	9.519		0	0.8213	7.806		0	0.8178	6.604	
0.1001	0.8244	9.353	0.50	0.1001	0.8210	7.679	0.35	0.1001	0.8175	6.479	0.05
0.1998	0.8241	9.135	0.33	0.1998	0.8207	7.537	0.41	0.1998	0.8172	6.356	0.16
0.2997	0.8238	8.957	0.50	0.2997	0.8204	7.350	0.20	0.2999	0.8169	6.212	0.66
0.4003	0.8235	8.749	0.28	0.4003	0.8201	7.171	0.77	0.4003	0.8166	6.055	1.41
0.4996	0.8232	8.582	0.47	0.5001	0.8198	7.057	0.45	0.5001	0.8163	5.963	1.10
0.6001	0.8229	8.43	0.88	0.6001	0.8195	6.936	0.19	0.6001	0.8160	5.862	0.87
0.7000	0.8226	8.238	0.87	0.7000	0.8192	6.779	0.35	0.7000	0.8157	5.743	0.84
0.8001	0.8224	7.976	0.13	0.8001	0.8189	6.634	0.18	0.8001	0.8154	5.625	0.60
0.9001	0.8220	7.786	0.53	0.9001	0.8186	6.494	0.35	0.9001	0.8150	5.510	0.02
1	0.8219	7.498		1	0.8184	6.273		1	0.8150	5.342	
1-Octanol (1) + 1-Nonanol (2) at 313.15 K				1-Octanol (1) + 1-Decanol (2) at 283.15 K				1-Octanol (1) + 1-Decanol (2) at 288.15 K			
0	0.8143	5.668		0	0.8366	22.064		0	0.8333	17.988	
0.1001	0.8140	5.579	0.31	0.0995	0.8361	21.140	0.27	0.0995	0.8327	17.182	0.50
0.1998	0.8137	5.458	0.02	0.1998	0.8357	20.234	0.36	0.1998	0.8323	16.530	0.03
0.2999	0.8134	5.377	0.34	0.3007	0.8353	19.392	0.02	0.3007	0.8319	15.639	0.83
0.4003	0.8131	5.258	0.009	0.4001	0.8349	18.458	0.21	0.4001	0.8315	15.111	0.58
0.5001	0.8128	5.181	0.45	0.4996	0.8345	17.592	0.08	0.4996	0.8311	14.233	0.36
0.6001	0.8125	5.068	0.28	0.5988	0.8340	16.690	0.25	0.5988	0.8306	13.712	1.11
0.7000	0.8122	4.957	0.27	0.6998	0.8336	15.820	0.32	0.6998	0.8302	13.018	1.33
0.8001	0.8120	4.872	0.98	0.8001	0.8331	15.106	0.43	0.8001	0.8297	12.247	0.73
0.9001	0.8116	4.773	1.71	0.9000	0.8328	14.204	0.35	0.9000	0.8294	11.754	2.13
1	0.8114	4.540		1	0.8321	13.493		1	0.8286	10.872	
1-Octanol (1) + 1-Decanol (2) at 293.15 K				1-Octanol (1) + 1-Decanol (2) at 298.15 K				1-Octanol (1) + 1- Decanol (2) at 303.15K			
0	0.8299	14.387		0	0.8265	11.735		0	0.8230	9.561	
0.0995	0.8293	13.843	0.07	0.0995	0.8259	11.311	0.20	0.0995	0.8225	9.231	0.33
0.1998	0.8289	13.305	0.05	0.1998	0.8255	10.938	0.24	0.1998	0.8221	8.924	0.20
0.3007	0.8285	12.672	0.44	0.3007	0.8251	10.526	0.49	0.3007	0.8217	8.589	0.22
0.4001	0.8281	12.263	0.82	0.4001	0.8247	10.074	0.36	0.4001	0.8213	8.213	0.71
0.4996	0.8277	11.593	0.04	0.4996	0.8243	9.596	0.02	0.4996	0.8208	7.898	0.41
0.5988	0.8272	11.054	0.12	0.5988	0.8238	9.244	0.89	0.5988	0.8204	7.570	0.27
0.6998	0.8269	10.321	1.62	0.6998	0.8234	8.756	0.34	0.6998	0.8200	7.259	0.15
0.8001	0.8263	9.750	2.08	0.8001	0.8228	8.308	0.08	0.8001	0.8194	6.992	1.13
0.9000	0.8259	9.008	4.80	0.9000	0.8223	7.812	1.03	0.9000	0.8189	6.655	0.60
1	0.8252	8.944		1	0.8219	7.498		1	0.8184	6.273	
1-Octanol (1) + 1- Decanol (2) at 308.15K				1-Octanol (1) + 1-Decanol (2) at 313.15 K				1-Octanol (1) + 1-Undecanol (2) at 293.15 K			
0	0.8196	8.000		0	0.8163	6.831		0	0.8322	17.284	
0.0995	0.8191	7.768	0.05	0.0995	0.8156	6.649	0.34	0.1003	0.8315	16.401	0.49
0.1998	0.8187	7.492	0.26	0.1998	0.8152	6.408	0.02	0.2001	0.8310	15.207	2.69
0.3007	0.8183	7.211	0.48	0.3007	0.8148	6.189	0.14	0.2998	0.8305	14.400	2.19
0.4001	0.8178	6.961	0.19	0.4001	0.8144	5.979	0.52	0.4002	0.8297	13.803	0.07
0.4996	0.8174	6.672	0.41	0.4996	0.8139	5.711	0.01	0.4999	0.8290	12.780	0.85
0.5988	0.8169	6.389	0.53	0.5988	0.8135	5.513	0.72	0.5998	0.8283	12.191	1.49
0.6998	0.8165	6.143	0.02	0.6998	0.8130	5.287	1.03	0.6998	0.8277	10.954	1.97
0.8001	0.8159	5.851	0.31	0.8001	0.8124	5.057	1.22	0.8000	0.8269	10.237	1.33
0.9000	0.8155	5.653	0.89	0.9000	0.8120	4.784	0.39	0.8999	0.8262	9.416	2.31
1	0.8150	5.342		1	0.8114	4.540		1	0.8252	8.944	
1-Octanol (1) + 1-Undecanol (2) at 298.15 K				1-Octanol (1) + 1-Undecanol (2) at 303.15 K				1-Octanol (1) + 1-Undecanol (2) at 308.15 K			
0	0.8288	13.721		0	0.8254	11.524		0	0.8217	9.350	
0.1003	0.8281	13.348	1.39	0.1003	0.8248	10.947	1.01	0.1003	0.8213	9.118	1.06
0.2001	0.8276	12.542	0.04	0.2001	0.8242	10.355	1.79	0.2001	0.8207	8.645	0.009
0.2998	0.8270	11.972	0.67	0.2998	0.8236	9.808	1.89	0.2998	0.8202	8.207	0.38
0.4002	0.8263	11.227	0.13	0.4001	0.8229	9.281	1.49	0.4002	0.8195	7.773	0.44
0.4999	0.8256	10.643	1.00	0.4999	0.8222	8.745	1.20	0.4999	0.8188	7.392	0.28
0.5998	0.8249	9.948	0.77	0.5998	0.8215	8.252	0.44	0.5998	0.8181	6.989	0.74
0.6998	0.8243	9.276	0.50	0.6998	0.8208	7.691	0.69	0.6998	0.8174	6.490	0.34
0.8000	0.8235	8.693	0.90	0.8000	0.8201	7.271	0.24	0.8000	0.8166	6.137	0.59
0.8999	0.8228	8.002	0.35	0.8999	0.8193	6.723	0.15	0.8999	0.8158	5.728	0.30
1	0.8219	7.498		1	0.8184	6.273		1	0.8150	5.342	

Table 3. (Continued)

x_1	ρ / g·cm^{-3}	η / mPa·s	$100\lvert(\eta - \eta_{calc})/\eta\rvert$	x_1	ρ / g·cm^{-3}	η / mPa·s	$100\lvert(\eta - \eta_{calc})/\eta\rvert$	x_1	ρ / g·cm^{-3}	η / mPa·s	$100\lvert(\eta - \eta_{calc})/\eta\rvert$
1-Octanol (1) + 1-Undecanol (2) at 313.15 K				1-Nonanol (1) + 1-Decanol (2) at 283.15 K				1-Nonanol (1) + 1-Decanol (2) at 288.15			
0	0.8186	7.841		0	0.8366	22.064		0	0.8333	17.988	
0.1003	0.8178	7.665	1.16	0.1009	0.8365	21.495	0.13	0.1009	0.8332	17.444	0.66
0.2001	0.8173	7.350	1.04	0.2000	0.8364	21.125	0.53	0.2000	0.8330	17.060	0.55
0.2998	0.8168	6.995	0.74	0.3000	0.8362	20.651	0.65	0.3000	0.8328	16.694	0.39
0.4002	0.8160	6.652	0.93	0.4002	0.8360	20.154	0.57	0.3999	0.8327	16.196	1.16
0.4999	0.8153	6.336	1.64	0.5001	0.8359	19.708	0.64	0.5001	0.8325	15.818	1.21
0.5998	0.8146	5.991	1.96	0.6003	0.8357	19.169	0.18	0.6003	0.8323	15.439	1.37
0.6998	0.8139	5.615	1.68	0.6996	0.8356	18.591	0.61	0.6996	0.8322	15.201	0.68
0.8000	0.8131	5.295	2.22	0.7999	0.8354	18.140	0.76	0.7999	0.8320	14.851	0.72
0.8999	0.8123	4.957	2.15	0.9047	0.8352	17.776	0.35	0.9047	0.8318	14.478	0.84
1	0.8114	4.540		1	0.8350	17.439		1	0.8315	14.272	
1-Nonanol (1) + 1-Decanol (2) at 293.15 K				1-Nonanol (1) + 1-Decanol (2) at 298.15 K				1-Nonanol (1) + 1-Decanol (2) at 303.15 K			
0	0.8299	14.387		0	0.8265	11.735		0	0.8230	9.561	
0.1009	0.8298	14.099	0.16	0.1009	0.8264	11.524	0.31	0.1009	0.8229	9.398	0.31
0.2000	0.8296	13.729	0.37	0.2000	0.8262	11.357	0.92	0.2000	0.8228	9.242	0.61
0.3000	0.8295	13.498	0.04	0.3000	0.8261	11.127	0.93	0.3000	0.8226	9.083	0.87
0.3999	0.8293	13.224	0.08	0.4002	0.8259	10.873	0.68	0.4002	0.8224	8.886	0.66
0.5000	0.8291	12.998	0.44	0.5000	0.8257	10.621	0.39	0.5001	0.8222	8.703	0.56
0.6003	0.8290	12.478	1.58	0.6003	0.8255	10.385	0.20	0.6003	0.8220	8.504	0.24
0.6996	0.8288	12.365	0.40	0.6996	0.8254	10.171	0.15	0.6996	0.8219	8.332	0.19
0.7999	0.8286	12.092	0.52	0.7999	0.8251	9.933	0.10	0.7999	0.8217	8.160	0.15
0.9047	0.8284	11.829	0.47	0.9047	0.8249	9.725	0.03	0.9047	0.8215	7.929	0.52
1	0.8281	11.635		1	0.8247	9.519		1	0.8213	7.806	
1-Nonanol (1) + 1-Decanol (2) at 308.15 K				1-Nonanol (1) + 1-Decanol (2) at 313.15 K				1-Nonanol (1) + 1-Undecanol (2) at 293.15 K			
0	0.8196	8.000		0	0.8163	6.831		0	0.8322	17.284	
0.1009	0.8195	7.867	0.22	0.1009	0.8161	6.704	0.05	0.1002	0.8317	16.579	0.56
0.2000	0.8194	7.739	0.42	0.2000	0.8159	6.629	0.61	0.1996	0.8313	16.078	0.02
0.3000	0.8191	7.613	0.65	0.3000	0.8157	6.517	0.70	0.3004	0.8309	15.375	0.74
0.4002	0.8190	7.453	0.38	0.4002	0.8156	6.400	0.68	0.4001	0.8306	14.912	0.03
0.5000	0.8188	7.307	0.27	0.5001	0.8153	6.234	0.13	0.5000	0.8302	14.288	0.44
0.6003	0.8186	7.151	0.02	0.6003	0.8152	6.150	0.34	0.6002	0.8298	13.613	1.36
0.6996	0.8185	7.014	0.05	0.6996	0.8150	6.026	0.15	0.6994	0.8301	12.843	3.20
0.7999	0.8183	6.857	0.36	0.7999	0.8148	5.870	0.56	0.7995	0.8291	12.683	0.18
0.9047	0.8180	6.693	0.66	0.9047	0.8145	5.779	0.03	0.8997	0.8284	12.132	0.25
1	0.8178	6.604		1	0.8143	5.668		1	0.8281	11.635	
1-Nonanol (1) + 1-Undecanol (2) at 298.15 K				1-Nonanol (1) + 1-Undecanol (2) at 303.15 K				1-Nonanol (1) + 1-Undecanol (2) at 308.15 K			
0	0.8288	13.721		0	0.8254	11.524		0	0.8217	9.350	
0.1002	0.8283	13.428	1.13	0.1002	0.8249	11.155	0.28	0.1002	0.8215	9.247	1.95
0.1996	0.8279	12.834	0.06	0.1996	0.8245	10.732	0.03	0.1996	0.8211	8.926	1.57
0.3004	0.8275	12.555	1.16	0.3004	0.8241	10.366	0.17	0.3004	0.8207	8.681	2.03
0.4001	0.8272	11.977	0.09	0.4001	0.8238	9.973	0.005	0.4001	0.8203	8.333	1.25
0.5000	0.8268	11.524	0.39	0.5000	0.8234	9.577	0.25	0.5000	0.8199	8.014	0.73
0.6002	0.8264	11.320	1.48	0.6002	0.8230	9.200	0.36	0.6002	0.8195	7.710	0.35
0.6994	0.8266	10.549	1.92	0.6994	0.8232	8.746	1.54	0.6994	0.8197	7.333	1.18
0.7995	0.8256	10.354	0.19	0.7995	0.8222	8.272	2.95	0.7995	0.8188	7.133	0.17
0.8997	0.8250	9.929	0.04	0.8997	0.8215	8.195	0.46	0.8988	0.8181	6.897	0.31
1	0.8247	9.519		1	0.8213	7.806		1	0.8178	6.604	
1-Nonanol (1) + 1-Undecanol (2) at 313.15 K				1-Decanol (1) + 1-Undecanol (2) at 293.15 K				1-Decanol (1) + 1-Undecanol (2) at 298.15			
0	0.8186	7.841		0	0.8322	17.284		0	0.8288	13.721	
0.1002	0.8181	7.609	0.12	0.1007	0.8320	16.877	0.47	0.1007	0.8287	13.520	0.08
0.1996	0.8177	7.373	0.37	0.1997	0.8315	16.681	0.20	0.1997	0.8281	13.306	0.06
0.3004	0.8173	7.298	1.61	0.2999	0.8314	16.141	1.37	0.2999	0.8280	13.227	0.82
0.4001	0.8169	7.040	1.08	0.3998	0.8312	16.077	0.07	0.3998	0.8278	12.880	0.45
0.5000	0.8165	6.872	1.80	0.4997	0.8310	15.594	1.48	0.4997	0.8276	12.791	0.24
0.6002	0.8161	6.627	1.43	0.5978	0.8308	15.593	0.15	0.5978	0.8274	12.576	0.09
0.6994	0.8163	6.267	0.90	0.6999	0.8305	15.281	0.12	0.6999	0.8271	12.352	0.39
0.7995	0.8153	6.138	0.56	0.7989	0.8304	14.498	0.53	0.7989	0.8270	12.116	0.75
0.8997	0.8146	5.930	0.76	0.8995	0.8301	14.757	0.22	0.8995	0.8268	11.977	0.10
1	0.8143	5.668		1	0.8299	14.387		1	0.8265	11.735	
1-Decanol (1) + 1-Undecanol (2) at 303.15 K				1-Decanol (1) + 1-Undecanol (2) at 308.15 K				1-Decanol (1) + 1-Undecanol (2) at 313.15 K			
0	0.8254	11.524		0	0.8217	9.350		0	0.8186	7.841	
0.1007	0.8252	11.268	0.44	0.1007	0.8216	9.368	1.60	0.1007	0.8182	7.805	0.75
0.1997	0.8248	11.084	0.35	0.1997	0.8214	9.233	1.52	0.1997	0.8180	7.778	1.53
0.2999	0.8246	10.893	0.39	0.2999	0.8212	9.057	0.95	0.2999	0.8178	7.655	1.07
0.3998	0.8244	10.695	0.57	0.3998	0.8210	8.909	0.64	0.3998	0.8175	7.579	1.22
0.4997	0.8242	10.513	0.62	0.4997	0.8208	8.760	0.30	0.4997	0.8173	7.452	0.69
0.5978	0.8240	10.337	0.63	0.5978	0.8206	8.652	0.44	0.5978	0.8171	7.323	0.16
0.6999	0.8237	10.140	0.72	0.6999	0.8203	8.504	0.27	0.6999	0.8169	7.249	0.51
0.7989	0.8235	9.958	0.62	0.7989	0.8202	8.357	0.16	0.7989	0.8167	7.068	0.51
0.8995	0.8233	9.777	0.28	0.8995	0.8199	8.185	0.02	0.8995	0.8165	6.940	0.55
1	0.8230	9.561		1	0.8196	8.000		1	0.8163	6.831	

al.[11] Nevertheless, this is not the first time that a comparison between Rauf et al.[11] results with other viscosity data for pure 1-alkanols shows these discrepancies. Shan and Asfour[3,4] have also observed differences between their data and the viscosity values reported by Rauf et al.,[11] which they have attributed to the hygroscopic character of the alcohols, as the later authors[11] have not mention the use of molecular sieves. The use of water in the calibration of the viscometers employed by Rauf et al.[11] was also pointed out by Shan and Asfour[3,4] as another reasonable explanation for the deviations observed between their data and the viscosity values reported by Rauf et al.[11]

Table 4. Model Interaction Energy Parameters

system	α_{21} / K	α_{12} / K	MRSD / %	max dev / %
1-octanol + 1-nonanol	−112.426	142.223	0.18	1.7
1-octanol + 1- decanol	102.673	−83.2575	0.51	4.8
1-octanol + 1-undecanol	155.368	−116.318	0.69	2.7
1-nonanol + 1-decanol	−69.7400	79.4085	0.21	1.6
1-nonanol + 1-undecanol	−38.5229	44.0506	0.59	3.2
1-decanol + 1-undecanol	−102.133	124.957	0.22	1.6

Table 3 presents the experimental values of densities, dynamic viscosities measured from (283.15 to 313.15) K and at 101 kPa for the six binary mixtures studied in this work, and the relative deviations between experimental and calculated viscosity values. The experimental viscosity data have been correlated by a model previously developed by our group.[5,6] This model is based on Eyring's theory for viscous flow[7] and UNIQUAC's equation for the molar excess Gibbs free energy.[8,9] According to this model, the expression for calculation of the viscosity of nonelectrolyte liquid mixtures is[5,6]

$$\ln(\eta v) = \sum_{i=1}^{N_{SOL}} x_i \ln(\eta_i) + \ln\left(\sum_{i=1}^{N_{SOL}} x_i v_i^{o}\right) + \sum_{i=1}^{N_{SOL}} x_i \ln\left(\frac{\phi_i}{\theta_i}\right) + \frac{z}{2}\sum_{i=1}^{N_{SOL}} q_i x_i \ln\left(\frac{\theta_i}{\phi_i}\right) - \sum_{i=1}^{N_{SOL}} x_i q_i \ln\left[\sum_{k=1}^{N_{SOL}} \theta_i \exp\left(-\frac{\alpha_{ki}}{T}\right)\right] \quad (2)$$

where η is the dynamic viscosity of the mixture, v is the molar volume of the mixture, x_i is the mole fraction of component i, v_i^{o} is the molar volume of the pure liquid i at the same temperature and pressure of the mixture, ϕ_i is the volume fraction, θ_i is the surface area fraction, q_i is the surface area parameter of the UNIQUAC model, N_{SOL} is the number of solvents in the mixture, z is the coordination number, and α_{ki} is the UNIQUAC binary interaction parameter obtained by means of fitting experimental viscosity data of each binary liquid mixture.

For all the species the coordination number z is assigned the value of 10.[8,9] The values of volume and surface area parameters r_i and q_i for each solvent were obtained as recommended by Poling et al.[1] The objective function F used in the determination of the binary interaction parameters was

$$F = \sum_{1}^{N_D} (\eta_{calc} - \eta_{exp})^2 \quad (3)$$

where N_D is the total number of data points; the subscripts calc and exp refer to calculated and experimental data, respectively.

Table 4 shows the model interaction parameters for each binary system along with the overall mean relative standard deviation (MRSD) and the maximum relative deviation obtained. The MRSD is given by

$$\mathrm{MRSD} = \left(\frac{1}{ND}\sum_{1}^{ND}\left(\frac{\eta_{calc} - \eta_{exp}}{\eta_{exp}}\right)^2\right)^{1/2} \quad (4)$$

where ND is the number of data points.

The good agreement between the experimental and correlated values for the viscosity of the binary systems, at each temperature investigated, is evidenced by the low values of the relative deviations presented at the last column of Table 3.

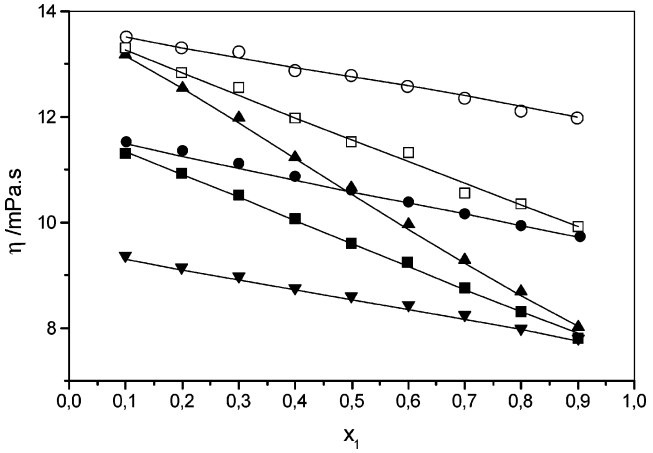

Figure 1. Dynamic viscosities at 298.15 K and 101 kPa: ▼, 1-octanol (1) + 1-nonanol (2); ■, 1-octanol (1) + 1-decanol (2); ▲, 1-octanol (1) + 1-undecanol (2); ●, 1-nonanol (1) + 1-decanol (2); □, 1-nonanol (1) + 1-undecanol (2); ○, 1-decanol (1) + 1-undecanol (2). The solid line represents the values obtained with eq 2.

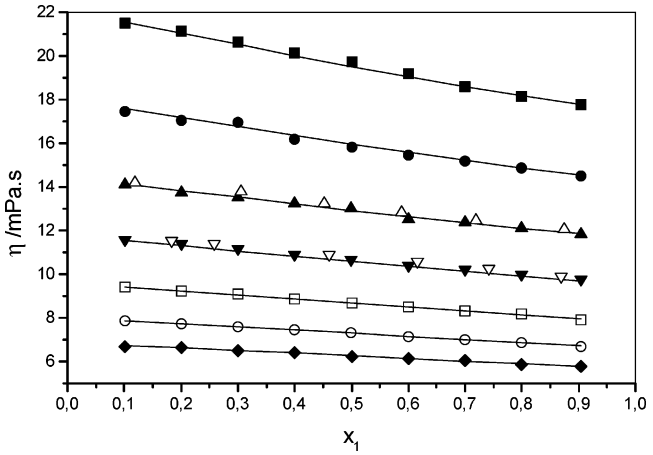

Figure 2. Dynamic viscosity of 1-nonanol (1) + 1-decanol (2) at 101 kPa and temperatures from (283.15 to 313.15) K: ■, 283.15 K; ●, 288.15 K; ▲, 293.15 K; △, data from ref 4 at 293.15 K; ▼, 298.15 K; ▽, data from ref 4 at 298.15 K; □, 303.15 K; ○, 308.15 K; ◆, 313.15 K. The solid line represents the values obtained with eq 2.

The dependence of viscosity with composition, for all the binary systems investigated in this work at 298.15 K, is plotted in Figure 1. For all the temperatures and binary systems investigated, a near-linear relationship between viscosity and mole fraction of the lower chain 1-alkanol was observed. Moreover, the calculated values, obtained by means of eq 2, are also represented in Figure 1.

Figure 2 shows the experimental values of the viscosity of the binary system 1-nonanol + 1-decanol at all the temperatures investigated. The calculated values, obtained by means of eq 2, are also represented in Figure 2.

Figure 3 shows the deviation between our experimental viscosity data as well as experimental literature data and the values calculated with eq 2 for the system 1-decanol + 1-undecanol at different temperatures.

As can be seen, the adopted model[5,6] described the experimental behavior quite well. Therefore, we expect that, with the parameters tabulated in Table 4, a good description of the viscosity dependence with composition will be obtained by means of eq 2 for the ternaries and quaternary systems constituted by 1-octanol, 1-nonanol, 1-decanol, and 1-undecanol.

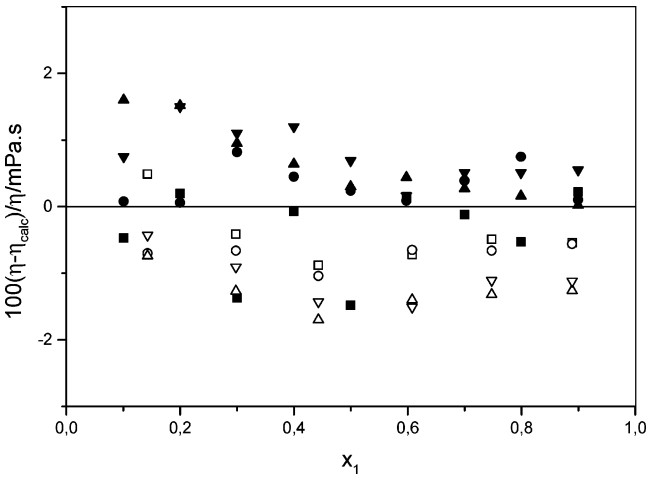

Figure 3. Relative deviation between experimental and calculated dynamic viscosities of 1-decanol (1) + 1-undecanol (2) at 101 kPa and temperatures from (293.15 to 313.15) K: ■, this work at 293.15 K; □, ref 4 at 293.15 K; ●, this work at 298.15 K; ○, ref 4 at 298.15 K; ▲, this work at 308.15 K; △, ref 3 at 308.15 K; ▼, this work at 313.15 K; ▽, ref 3 at 313.15 K.

Conclusions

The densities and dynamic viscosities of the binary systems 1-octanol + 1-nonanol, 1-octanol + 1-decanol, 1-octanol + 1-undecanol, 1-nonanol + 1-decanol, 1-nonanol + 1-undecanol, and 1-decanol + 1-undecanol have been measured. The temperature interval of investigation was (283.15 to 313.15) K, and the pressure condition was 101 kPa. Using those data, it was possible to obtain the binary interaction parameters of the model used.

The model adopted to correlate the experimental data showed a quite reasonable agreement for the whole temperature range investigated. The value of the overall average MRSD was 0.2 % for the system 1-octanol + 1-nonanol, 0.5 % for the system 1-octanol + 1-decanol, 0.7 % for the system 1-octanol + 1-undecanol, 0.2 % for the system 1-nonanol + 1-decanol, 0.6 % for the system 1-nonanol + 1-undecanol, and 0.2 % for the system 1-decanol + 1-undecanol.

In a subsequent work we will present the experimental and calculated results for the viscosity of the following ternary systems: 1-octanol + 1-nonanol + 1-decanol, 1-octanol + 1-nonanol + 1-undecanol, and 1-nonanol + 1-decanol + 1-undecanol.

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