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Viscosities and Densities of Nine Binary 1-Alkanol Systems at 293.15 K and 298.15 K

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The viscosities and densities of nine binary *n*-alkan-1-ol systems, 1-propanol + 1-butanol, 1-propanol + 1-pentanol, 1-butanol + 1-pentanol, 1-butanol + 1-nonanol, 1-butanol + 1-decanol, 1-pentanol + 1-octanol, 1-heptanol + 1-octanol, 1-nonanol + 1-decanol, and 1-decanol + 1-undecanol, were experimentally determined over the entire composition range at temperatures of 293.15 K and 298.15 K and at atmospheric pressure. The experimental viscosity data were correlated by the McAllister three-body and four-body models and were used to test the predictive capability of the generalized corresponding state principle (GCSP) method.

Introduction

Viscosities and densities of liquid mixtures are needed for many engineering applications. Although there are several viscosity predictive models, their predictive capabilities should be subjected to critical testing by using reliable experimental data. Viscometric and volumetric data pertaining to *n*-alkan-1-ol liquid mixtures are relatively scarce in the literature.

In this work, which represents one part of a continuing program in our laboratory, we are reporting the viscosities and densities at atmospheric pressure, over the entire composition range, of nine binary liquid *n*-alkan-1-ol systems at 293.15 K and at 298.15 K. The binary systems investigated include 1-propanol + 1-butanol, 1-propanol + 1-pentanol, 1-butanol + 1-pentanol, 1-butanol + 1-nonanol, 1-butanol + 1-decanol, 1-pentanol + 1-octanol, 1-heptanol + 1-octanol, 1-nonanol + 1-decanol, and 1-decanol + 1-undecanol.

The viscosities of the binary systems were correlated by the three-body and four-body McAllister equations (1960). The three-body interaction model reported by McAllister (1960) is given by

$$\ln \nu = x_1^3 \ln \nu_1 + 3x_1^2x_2 \ln \nu_{12} + 3x_1x_2^2 \ln \nu_{21} + x_2^3 \ln \nu_2 - \ln[x_1 + x_2M_2/M_1] + 3x_1^2x_2 \ln[(2 + M_2/M_1)/3] + 3x_1x_2^2 \ln[(1 + 2M_2/M_1)/3] + x_2^3 \ln[M_2/M_1] \quad (1)$$

The kinematic viscosity of the liquid mixture is designated by ν, and ν_1, ν_2 are the kinematic viscosities, M_1, M_2 are the molecular weights, and x_1, x_2 are the mole fractions of the pure components 1 and 2 constituting the liquid mixture, respectively. The McAllister model adjustable parameters are given by ν_{12} and ν_{21}, whereas the four-body McAllister model is given by eq 2

$$\ln \nu = x_1^4 \ln \nu_1 + 4x_1^3x_2 \ln \nu_{1112} + 6x_1^2x_2^2 \ln \nu_{1122} + 4x_1x_2^3 \ln \nu_{2221} + x_2^4 \ln \nu_2 - \ln[x_1 + x_2M_2/M_1] + 4x_1^3x_2 \ln[(3 + M_2/M_1)/4] + 6x_1^2x_2^2 \ln[(1 + M_2/M_1)/2] + 4x_1x_2^3 \ln[(1 + 3M_2/M_1)/4] + x_2^4 \ln(M_2/M_1) \quad (2)$$

where ν_{1112}, ν_{2221}, and ν_{1122} are the McAllister model adjustable parameters.

The experimental viscosity data of binary systems were also used to test the predictive capability of the generalized corresponding states principle method (GCSP) (Teja and Rice, 1981). The pertinent GCSP equations are given by

$$\ln(\eta\epsilon) = \ln(\eta\epsilon)^{\mathrm{r1}} + \frac{\omega - \omega^{\mathrm{r1}}}{\omega^{\mathrm{r2}} - \omega^{\mathrm{r1}}}[\ln(\eta\epsilon)^{\mathrm{r2}} - \ln(\eta\epsilon)^{\mathrm{r1}}] \quad (3)$$

$$\epsilon = M^{-1/2}P_{\mathrm{c}}^{-2/3}T_{\mathrm{c}}^{1/6} \quad (4)$$

The following are the mixing rules proposed by Wong et al. (1984), which are useful for a large range of mixtures

$$T_{\mathrm{cm}}^2/P_{\mathrm{cm}} = \sum_i\sum_j x_ix_j(T_{\mathrm{c}ij}^2/P_{\mathrm{c}ij}) \quad (5)$$

$$\omega_{\mathrm{m}}(T_{\mathrm{cm}}^2/P_{\mathrm{cm}})^{2/3} = \sum_i\sum_j x_ix_j(T_{\mathrm{c}ij}^2/P_{\mathrm{c}ij})^{2/3}\omega_{ij} \quad (6)$$

$$T_{\mathrm{c}ij} = \zeta_{ij}(T_{\mathrm{c}ii}T_{\mathrm{c}jj})^{1/2} \quad (7)$$

$$(T_{\mathrm{c}ij}/P_{\mathrm{c}ij})^{1/3} = {}^1/_2[(T_{\mathrm{c}ii}/P_{ii})^{1/3} + (T_{\mathrm{c}ii}/P_{ii})^{1/3}] \quad (8)$$

$$\omega_{ij} + {}^1/_2(\omega_{ii} + \omega_{jj}) \quad (9)$$

and a simple mixing rule for molecular weights is

$$M_{\mathrm{m}} = \sum_i x_iM_i \quad (10)$$

where the subscript m denotes a property of the liquid

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Table 1. Density Data for Compounds Used for Density Meter Calibration

T = 293.15 K			T = 298.15 K		
compound	ρ/kg·L^{-1}	ref	compound	ρ/kg·L^{-1}	ref
octane	0.70267	TRC, 1988	octane	0.69862	TRC, 1988
decane	0.73012	TRC, 1988	undecane	0.7365	TRC, 1988
undecane	0.7402	TRC, 1988	tridecane	0.75271	TRC, 1988
tridecane	0.75610	TRC, 1988	N1.0[b]	0.7929	standard[b]
pentadecane	0.76838	TRC, 1988	S3[b]	0.8375	standard[b]
S3[b]	0.8409	standard	toluene	0.86220	Timmermans, 1950
toluene	0.8669	TRC, 1986	N10[b]	0.8699	standard[b]
N10[b]	0.8732	Standard[b]	benzene	0.87366	Timmermans, 1950
benzene	0.8790	TRC, 1986			

[a] Standard deviation of the fit = 0.000 17 kg/L at T = 293.15 K. Standard deviation of the fit = 0.0002 kg/L at T = 298.15 K. [b] Data of standards were obtained from Canon Instrument Co.

Table 2. Pure Component Properties and Their Comparison with the Literature Values at 293.15 K and 298.15 K

	T = 293.15 K					T = 298.15 K						
	ρ/kg· L^{-1}			ν/μm^2 s^{-1}	η/ mPa·s	ρ/kg· L^{-1}			η/mPa·s			ν/μm^2 s^{-1}
compound	this work	lit. value	source	this work	this work	this work	lit. value	source	this work	lit. value	source	this work
1-propanol	0.8036	0.80375	TRC Tables, 1991	2.741	2.203	0.7995	0.7994 0.79975	Rauf et al., 1983 TRC Tables, 1991	1.953	1.898 1.9430	Rauf et al., 1983 TRC Tables, 1995	2.443
1-butanol	0.8095	0.8097	TRC Tables, 1991	3.659	2.962	0.8057	0.8056	Rauf et al., 1983	2.593	2.524 2.5710	Rauf et al., 1983 TRC Tables, 1995	3.224
1-pentanol	0.8146	0.8151	TRC Tables, 1991	4.973	4.051	0.8109	0.8109 0.81090	Garcia et al., 1991 Riddick and Bunger, 1970	3.497	3.3952 3.5128	Garcia et al., 1991 TRC Tables, 1995	4.312
1-hexanol	0.8188	0.8196	TRC Tables, 1991	6.559	5.371	0.8152	0.81522	Dewan et al., 1991				5.610
1-heptanol	0.8223	0.8225	TRC Tables, 1991	8.581	7.056	0.8187	0.8190	Rauf et al., 1983	5.942	5.774 5.898	Rauf et al., 1983 TRC Tables, 1995	7.258
1-octanol	0.8253	0.8261	TRC Tables, 1991	11.176	9.223	0.8218	0.8211 0.82181	Rauf et al., 1983 Dewan et al., 1991	7.663	7.363	Rauf et al., 1983	9.325
1-nonanol	0.8279	0.8280	TRC Tables, 1991	14.166	11.728	0.8244	0.8244 0.8247	Rauf et al., 1983 TRC Tables, 1991	9.715	9.101	Rauf et al., 1983	11.785
1-decanol	0.8302	0.8300	TRC Tables, 1991	17.525	14.548	0.8268	0.8254 0.8265	Rauf et al., 1983 TRC Tables, 1991	11.829	10.974 11.800	Rauf et al., 1983 TRC Tables, 1995	14.308
1-undecanol	0.8325	0.8335	TRC Tables, 1991	20.362	16.952	0.8291	0.8297	TRC Tables, 1991	13.830	14.00	TRC Tables, 1995	16.681

mixture. The binary interaction coefficient, ζ_{ij}, is set to unity if eq 7 is employed as a viscosity predictive equation.

Experimental Section

Procedure. The viscosities and densities of nine pure n-alkan-1-ols were measured at 293.15 K and at 298.15 K under atmospheric pressure. The liquid mixtures were prepared in the same manner as described earlier by Asfour (1980). A Mettler HK 160 electronic balance with a reproducibility of ±2 × 10^{-7} kg was used to weigh the components involved. This resulted in an uncertainty of ±1.5 × 10^{-5} in the mole fraction of the components of a liquid binary system. Since n-alkan-1-ols are hygroscopic, they were kept over A-4 molecular sieve.

***Viscosity Measurement*.** The kinematic viscosities were measured by employing Canon-Ubbelohde viscometers purchased from Canon Instrument Company. The viscometers were held in a thermostat that is maintained at the desired temperature within ±0.01 K. As the kinematic viscosities of n-alkan-1-ols studied in this work vary from (2 to 20) × 10^{-6} m^2/s, four sets of viscometers were used with various sizes (size 50, size 75, size 100, and size 150 for kinematic viscosity range of (0.5 to 4, 1.6 to 8, 3 to 15, and 7 to 35) × 10^{-6} m^2/s, respectively.

The kinematic viscosity of a sample is a function of the efflux time of the sample flowing through a particular volume of the viscometer. The relationship is given by

$$\nu = Et - (F/t^2) \qquad (11)$$

where ν is kinematic viscosity and t is efflux time. Viscosity standards purchased from Canon Instruments Company were used for the determination of the constants E and F at each temperature level by using the least-squares

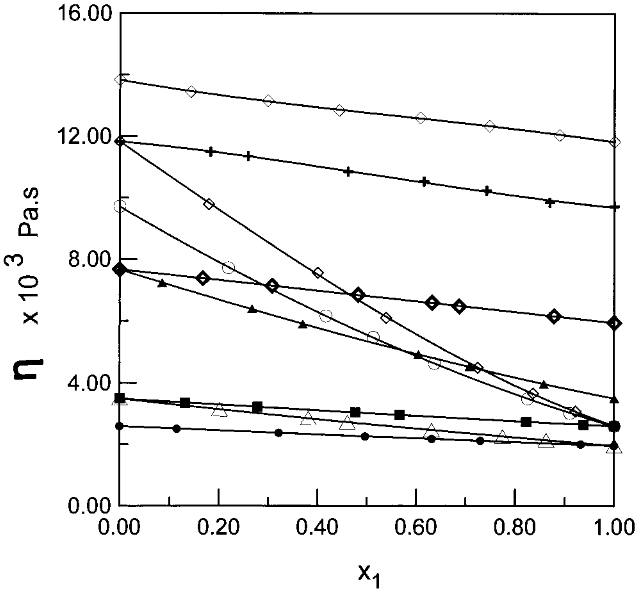

Figure 1. Change of Absolute Viscosity with Composition at 298.15 K: ●, 1-propanol (1) + 1-butanol (2); △, 1-propanol (1) + 1-pentanol (2); ■, 1-butanol (1) + 1-pentanol (2); ○, 1-butanol (1) + 1-nonanol (2); ◇ (middle curve), 1-butanol (1) + 1-decanol (2); ▲, 1-pentanol (1) + 1-octanol (2); boldface ◇, 1-heptanol (1) + 1-octanol (2); boldface +, 1-nonanol (1) + 1-decanol (2); ◇ (top curve), 1-decanol (1) + 1-undecanol (2).

Table 3. Experimental Viscosities and Densities for *n*-Alkanol Binary Liquid Systems at 293.15 K and 298.15 K

$T = 293.15$ K				$T = 298.15$ K			
x_1	ρ/kg L^{-1}	ν/μm^2·s^{-1}	η/mPa·s	x_1	ρ/kg L^{-1}	ν/μm^2·s^{-1}	η/mPa.s
1-Propanol (1) + 1-Butanol (2)							
0.0000	0.8095	3.659	2.962	0.0000	0.8057	3.224	2.597
0.1520	0.8089	3.510	2.840	0.1147	0.8053	3.113	2.507
0.3302	0.8080	3.360	2.715	0.3211	0.8040	2.958	2.378
0.5008	0.8070	3.180	2.566	0.4966	0.8030	2.816	2.261
0.6160	0.8063	3.068	2.474	0.6315	0.8021	2.708	2.172
0.7172	0.8057	2.991	2.410	0.7297	0.8015	2.643	2.118
0.8933	0.8046	2.836	2.282	0.9322	0.8001	2.501	2.001
1.0000	0.8036	2.741	2.203	1.0000	0.7995	2.443	1.953
1-Propanol (1) + 1-Pentanol (2)							
0.0000	0.8146	4.973	4.051	0.0000	0.8109	4.312	3.497
0.1659	0.8135	4.512	3.671	0.2007	0.8097	3.874	3.137
0.3648	0.8119	4.061	3.292	0.3810	0.8077	3.536	2.856
0.5097	0.8102	3.722	3.015	0.4603	0.8068	3.373	2.722
0.6041	0.8091	3.528	2.854	0.6314	0.8050	3.061	2.464
0.7449	0.8075	3.241	2.617	0.7745	0.8031	2.816	2.261
0.8506	0.8063	3.030	2.443	0.8626	0.8021	2.670	2.141
1.0000	0.8036	2.741	2.203	1.0000	0.7995	2.443	1.953
1-Butanol (1) + 1-Pentanol (2)							
0.0000	0.8146	4.973	4.051	0.0000	0.8109	4.312	3.497
0.1315	0.8143	4.749	3.867	0.1315	0.8105	4.136	3.353
0.2780	0.8134	4.549	3.700	0.2780	0.8096	3.992	3.232
0.4762	0.8126	4.294	3.489	0.4762	0.8088	3.757	3.038
0.5662	0.8121	4.176	3.392	0.5662	0.8083	3.661	2.959
0.8222	0.8109	3.857	3.127	0.8222	0.8070	3.393	2.738
0.9381	0.8100	3.720	3.013	0.9381	0.8062	3.278	2.642
1.0000	0.8095	3.659	2.962	1.0000	0.8057	3.224	2.597
1-Butanol (1) + 1-Nonanol (2)							
0.0000	0.8279	14.166	11.728	0.0000	0.8244	11.785	9.715
0.1608	0.8261	11.945	9.868	0.2186	0.8219	9.391	7.719
0.3832	0.8231	9.259	7.621	0.4166	0.8190	7.530	6.168
0.5372	0.8206	7.601	6.237	0.5129	0.8174	6.705	5.480
0.6674	0.8182	6.318	5.169	0.6368	0.8151	5.686	4.634
0.7995	0.8152	5.269	4.296	0.8253	0.8108	4.299	3.486
0.8991	0.8126	4.343	3.529	0.9103	0.8086	3.734	3.019
1.0000	0.8095	3.659	2.962	1.0000	0.8057	3.224	2.597
1-Butanol (1) + 1-Decanol (2)							
0.0000	0.8302	17.525	14.548	0.0000	0.8268	14.308	11.829
0.1748	0.8281	14.378	11.906	0.1793	0.8246	11.875	9.791
0.2939	0.8264	12.422	10.266	0.4002	0.8213	9.203	7.559
0.4910	0.8233	9.421	7.756	0.5389	0.8188	7.453	6.102
0.6325	0.8205	7.503	6.156	0.7242	0.8146	5.521	4.498
0.7787	0.8171	5.740	4.690	0.8360	0.8115	4.509	3.659
0.8851	0.8142	4.674	3.806	0.9219	0.8088	3.805	3.077
1.0000	0.8095	3.659	2.962	1.0000	0.8057	3.224	2.597
1-Pentanol (1) + 1- Octanol (2)							
0.0000	0.8253	11.176	9.223	0.0000	0.8218	9.325	7.663
0.1991	0.8239	9.646	7.947	0.0849	0.8212	8.804	7.229
0.3363	0.8226	8.702	7.158	0.2664	0.8195	7.791	6.385
0.4792	0.8213	7.788	6.397	0.3696	0.8186	7.212	5.903
0.6294	0.8195	6.786	5.561	0.6046	0.8161	6.029	4.921
0.7214	0.8187	6.329	5.182	0.7080	0.8149	5.552	4.524
0.9110	0.8165	5.316	4.341	0.8575	0.8130	4.884	3.970
1.0000	0.8146	4.973	4.051	1.0000	0.8109	4.312	3.497
1-Heptanol (1) + 1-Octanol (2)							
0.0000	0.8253	11.176	9.223	0.0000	0.8218	9.325	7.663
0.1671	0.8248	10.695	8.821	0.1671	0.8214	8.978	7.374
0.3071	0.8243	10.320	8.507	0.3071	0.8208	8.684	7.128
0.4819	0.8239	9.847	8.113	0.4819	0.8204	8.346	6.847
0.6319	0.8234	9.506	7.827	0.6319	0.8199	8.035	6.588
0.6868	0.8233	9.338	7.688	0.6868	0.8198	7.894	6.471
0.8784	0.8227	8.877	7.302	0.8784	0.8192	7.522	6.161
1.0000	0.8223	8.581	7.056	1.0000	0.8187	7.258	5.942
1-Nonanol (1) + 1-Decanol (2)							
0.0000	0.8302	17.525	14.548	0.0000	0.8268	14.308	11.829
0.1193	0.8300	17.104	14.195	0.1825	0.8264	13.900	11.487
0.3048	0.8295	16.588	13.760	0.2583	0.8262	13.728	11.342
0.4517	0.8292	15.941	13.219	0.4610	0.8258	13.135	10.846
0.5886	0.8289	15.471	12.823	0.6152	0.8254	12.759	10.532
0.7193	0.8286	15.031	12.455	0.7418	0.8252	12.399	10.231
0.8745	0.8282	14.518	12.023	0.8690	0.8248	11.945	9.852
1.0000	0.8279	14.166	11.728	1.0000	0.8244	11.785	9.715

Table 3 (Continued)

$T = 293.15$ K				$T = 298.15$ K			
x_1	ρ/kg L^{-1}	ν/μm^2·s^{-1}	η/mPa·s	x_1	ρ/kg L^{-1}	ν/μm^2·s^{-1}	η/mPa.s
1-Decanol (1) + 1-Undecanol (2)							
0.0000	0.8325	20.362	16.952	0.0000	0.8291	16.681	13.830
0.1426	0.8324	19.784	16.467	0.1426	0.8289	16.210	13.436
0.2980	0.8320	19.362	16.109	0.2980	0.8285	15.862	13.143
0.4429	0.8317	18.882	15.704	0.4429	0.8283	15.497	12.835
0.6078	0.8313	18.484	15.365	0.6078	0.8279	15.211	12.592
0.7475	0.8309	18.150	15.081	0.7475	0.8275	14.899	12.329
0.8890	0.8305	17.716	14.712	0.8890	0.8271	14.558	12.041
1.0000	0.8302	17.525	14.548	1.0000	0.8268	14.308	11.829

Table 4. Comparison of the %AAD for the GCSP and McAllister Model in Case of *n*-Alkan-1-ol Systems at 293.15 K and 298.15 K

			%AAD, McAllister model	
system	T/K	GCSP %AAD	three-body	four-body
1-propanol(1) + 1-butanol (2)	293.15	0.17	0.18	0.16
	298.15	0.23	0.14	0.14
1-propanol (1) + 1-pentanol (2)	293.15	0.20	0.10	0.11
	298.15	0.16	0.10	0.10
1-butanol (1) + 1-pentanol (2)	293.15	0.31	0.14	0.03
	298.15	0.19	0.12	0.10
1-butanol (1) + 1-nonanol (2)	293.15	2.52	0.46	0.43
	298.15	2.23	0.17	0.08
1-butanol (1) + 1-decanol (2)	293.15	3.51	0.12	0.09
	298.15	3.51	0.30	0.30
1-pentanol (1) + 1-octanol (2)	293.15	0.54	0.35	0.23
	298.15	0.48	0.08	0.08
1-heptanol (1) + 1-octanol (2)	293.15	0.23	0.07	0.07
	298.15	0.26	0.08	0.09
1-nonanol (1) + 1-decanol (2)	293.15	0.31	0.14	0.15
	298.15	0.34	0.24	0.23
1-decanol (1) + 1-undecanol (2)	293.15	0.49	0.15	0.12
	298.15	0.63	0.10	0.08
% absolute average deviation		0.91	0.17	0.14

technique to fit the viscosities of the standards with their corresponding efflux times to eq 11. The error in viscosity measurement was estimated to be $\pm 2 \times 10^{-9}$ m^2/s.

Density Measurements. The densities were measured by an Anton Paar DMA 60/602 density meter with a stated precision of 1.5×10^{-6} kg/L. The temperature of the measuring oscillating cell was maintained within ±0.01 K by a Haake N4-B circulator fitted with a calibrated platinum sensor (IPTS-68). The density meter was placed in a controlled temperature chamber. The temperature fluctuations within the chamber were kept within ±0.1 K through an elaborate temperature control system, which was described in detail by Asfour (1980) and by Wu (1992).

The following three-parameter equation, which was suggested by the manufacturer, was used to calculate the density from the knowledge of the oscillation period, τ

$$\rho = [A\tau^2/(1 - B\tau^2)] - C \qquad (12)$$

where ρ is density and τ is oscillation period. The values of the constants A, B, and C were determined by fitting the densities and corresponding oscillation periods of the calibrating liquids to eq 12 using least-squares.

Materials. 1-Propanol (99.5%+ HPLC grade) and 1-butanol (99.8%) were purchased from Sigma-Aldrich Co., whereas 1-pentanol, 1-octanol, 1-nonanol, 1-decanol, and 1-undecanol were obtained from Aldrich Chemical Co. all with a purity of 99.0+%. 1-Hexanol and 1-heptanol were purchased from Fluka Chemical Co. both with a purity of >99%.

A chromatographic test of reagent purity, using a 5 m × 0.53 mm methylsilicone capillary column and a flame ionization detector, confirmed the reagent purities stated by the manufacturers. The densities of all pure compounds measured at 293.15 K and at 298.15 K were compared with literature values as described later.

Results and Discussion

Table 1 lists the literature values of the densities of the compounds used for the calibration of the density meter at 293.15 K and 298.15 K. These density values and the corresponding density meter readings were used to evaluate the constants in eq 12 by the least-squares technique.

Table 2 reports a comparison between the pure component densities and viscosities at 293.15 K and at 298.15 K with the corresponding literature values. The measured densities of *n*-alkan-1-ols are in excellent agreement with the literature values.

There are differences between our measured viscosities of *n*-alkan-1-ols and those reported by Rauf et al. (1983). Our measured viscosities are consistently higher than the values reported by those authors. Careful examination of the Rauf et al. (1983) work reveals several factors that could have resulted in such differences. For example, those authors never referred to the fact that *n*-alkan-1-ols are hygroscopic and did not indicate whether they kept the *n*-alkan-1-ols (and their solutions) over molecular sieves; absorbed moisture results in lower *n*-alkan-1-ol viscosity values. Moreover, Rauf et al. (1983) employed water, which has relatively much lower viscosity than *n*-alkan-1-ols, for the calibration of their viscometers. This can introduce significant errors to their viscosity measurements. In addition, their temperature stability was reported as ±0.1 °C as opposed to ±0.01 K in our case.

No viscosity data of pure alkan-1-ols were found in the literature at 293.15 K, other than those reported by Rauf et al. (1983). Consequently, no meaningful comparison can

Table 5. McAllister Three- and Four-Body Parameters at 293.15 K and 298.15 K for the *n*-Alkan-1-ol Systems Investigated

		McAllister three-body model parameters × 10^6		McAllister four-body model parameters × 10^6		
system	T/K	ν_{12}	ν_{21}	ν_{1112}	ν_{1122}	ν_{2221}
1-propanol (1) + 1-butanol (2)	293.15	3.038	3.372	2.974	3.172	3.456
	298.15	2.714	2.934	2.647	2.812	3.008
1-propanol (1) + 1-pentanol (2)	293.15	3.497	4.124	3.271	3.818	4.297
	298.15	3.076	3.644	2.893	3.354	3.787
1-butanol (1) + 1-pentanol (2)	293.15	4.068	4.457	3.912	4.351	4.522
	298.15	3.557	3.928	3.445	3.784	3.991
1-butanol (1) + 1-nonanol (2)	293.15	7.129	10.097	6.032	8.331	11.042
	298.15	6.006	8.613	5.031	7.366	9.099
1-butanol (1) + 1-decanol (2)	293.15	8.062	12.533	6.515	10.102	13.484
	298.15	6.986	10.645	5.694	8.598	11.388
1-pentanol (1) + 1-octanol (2)	293.15	6.634	8.992	6.001	8.068	9.230
	298.15	5.888	7.553	5.422	6.688	7.931
1-heptanol (1) + 1-octanol (2)	293.15	9.445	10.231	9.221	9.826	10.460
	298.15	8.008	8.657	7.804	8.339	8.810
1-nonanol (1) + 1-decanol (2)	293.15	15.073	16.611	14.812	15.872	16.801
	298.15	12.393	13.770	12.034	13.466	13.677
1-decanol (1) + 1-undecanol (2)	293.15	18.327	19.094	17.977	18.984	19.238
	298.15	15.22	15.568	14.977	15.522	15.761

Table 6. Properties of the Pure 1-Alkanols Used for Viscosity Prediction by the GCSP Method

	critical temperature (K)		critical pressure (bar)		acentric factor	
compound	calcd by the Ambrose method (Reid et al., 1987)	lit. value (Reid et al., 1987)	calcd by the Ambrose method (Reid et al., 1987)	lit. value (Reid et al., 1987)	calcd by the Ambrose method (Reid et al., 1987)	lit. value (Reid et al., 1987)
1-propanol	536.4	536.8	51.6	51.7	0.631	0.623
1-butanol	563.0	563.1	44.5	44.2	0.599	0.593
1-pentanol	588.1	588.2	39.0	39.1	0.578	0.579
1-hexanol	611.5	611.	34.7	40.5	0.567	0.560
1-heptanol	633.2	633.	31.2	30.4	0.564	0.560
1-octanol	653.7	652.5	28.4	28.6	0.567	0.587
1-nonanol	673.1	671.	26.0		0.575	
1-decanol	691.0	687.	24.0	22.2	0.588	
1-undecanol	707.5		22.1		0.605	

be made between our viscosity data measured at 293.15 K and literature data. However, absolute viscosity data were found at 298.15 K in the TRC Tables (1995) (version 2.0) for 1-propanol, 1-butanol, 1-pentanol, 1-heptanol, 1-decanol, and 1-undecanol.

Table 2 reports the absolute viscosity, η, data obtained in this study, those found in the TRC Tables, and the data reported by Rauf et al. (1983) at 298.15 K.

The viscosity data reported in Table 2 clearly show that the viscosity data obtained in this study are in close agreement with those reported in the TRC Tables whereas relatively large differences occur between our viscosity data and those reported by Rauf et al. (1983). The reasons for such differences were discussed earlier in this article.

Table 3 reports the densities and viscosities of the nine binary *n*-alkan-1-ol systems over the entire composition range, at 293.15 K and at 298.15 K, under atmospheric pressure. Figure 1 depicts the change of the absolute viscosities of the liquid systems investigated with composition at 298.15 K.

Correlation of the Viscosities for Binary n-alkan-1-ol Systems by the McAllister Equation. The McAllister equations (1960), eqs 1 and 2, are considered one of the best for correlating viscosity with composition. Both the three-body and the four-body interaction models, given by eqs 1 and 2, respectively, were used to correlate the kinematic viscosity−composition data for the binary *n*-alkan-1-ol systems investigated in this study. The kinematic viscosities calculated by the McAllister equation are in excellent agreement with the experimental data. The values of the percent deviations are reported in Table 4 for each system. The absolute average deviation (AAD) is 0.17% when the three-body model is used and is 0.14% when the four-body model is employed.

The percent absolute average deviation (%ADD) is defined by the following equation

$$\mathrm{AAD} = \frac{1}{n}\sum_{i=1}^{n}\frac{|Y_i^{\mathrm{expl}} - Y_i^{\mathrm{calc}}|}{Y_i^{\mathrm{expl}}} \times 100 \qquad (13)$$

where Y is the value of the kinematic or absolute viscosity and n is the number of experimental points.

Table 5 lists the values of the McAllister parameters ν_{12}, ν_{21}, in case of the three-body interaction model, and ν_{1112}, ν_{1122}, ν_{2221} for the four-body interaction model.

Generalized Corresponding State Principle (GCSP). The experimental viscosity data were also used to test the predictive capability of the generalized corresponding states principle (GCSP) method (Teja and Rice, 1981) given by eqs 3 and 4.

The pure components of each system were selected as the two reference fluids. The Wong et al. (1984) model II mixing rules, eqs 5 through 10, were employed for calculating the pseudo-critical temperatures, pressures and the acentric factors for mixtures. The interaction terms in the mixing rules were set equal to unity in order to make the GCSP a completely predictive method.

The critical properties and acentric factors needed by the GCSP method are not available for all of the pure *n*-alkan-1-ols from C_3 to C_{11}. Consequently, the critical temperatures and pressures of the pure components that were not directly available from the literature were calculated with the help of the Ambrose method (Reid et al., 1987). The acentric factors for all pure components were calculated according to the definition of acentric factor and the Clapeyron vapor pressure expression as described by Reid et al. (1987). Table 6 lists the values of the critical properties and the acentric factors for all the 1-alkanols employed in this study.

Table 4 reports a comparison between the predicted absolute viscosities by the GCSP and the experimental data. The AAD is 0.91%, which indicates good agreement with the experimental data.

Conclusions

The viscosities and densities of nine pure *n*-alkan-1-ols were measured experimentally at (293.15 and 298.15) K over the entire composition range.

The binary system viscosities were correlated by the McAllister three- and four-body interaction models. The AAD's obtained are as low as 0.17% and 0.14%, respectively.

The GCSP method was found to predict the viscosity of the nine binary *n*-alkan-1-ol systems with an AAD of 0.91%.

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