Density and Viscosity of Aqueous Solutions of 2-Piperidineethanol, (2-Piperidineethanol + Monoethanolamine), and (2-Piperidineethanol + Diethanolamine) from (288 to 333) K

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The densities and viscosities of aqueous solutions of 2-piperidineethanol (2-PE) and aqueous blends of 2-piperidineethanol with monoethanolamine (MEA) and diethanolamine (DEA) have been measured at (288, 293, 298, 303, 308, 313, 318, 323, 328, and 333) K. The total amine mass fraction in all solutions was kept within 30 % in view of recent interest in using concentrated amine solutions in gas treating. Correlations for the density and viscosity of the binary and the ternary mixtures are presented.

Introduction

The removal of CO_2 from gaseous stream by absorption with chemical reaction in the liquid phase is usually employed in industry and as a method to retain atmospheric CO_2 to combat the greenhouse effect. For acid gas removal, sterically hindered amines, such as 2-amino-2-methyl-1-propanol (AMP) and 2-piperidineethanol (2-PE), have been shown to have higher absorption capacity, absorption rate, selectivity, and degradation resistance advantages over conventional amines such as monoethanolamine (MEA), diethanolamine (DEA), and *N*-methyldiethanolamine (MDEA).[1,2] 2-PE is a secondary amine in which a naphthenic ring group is attached to the amino group. The use of mixed amine systems, which combine the higher equilibrium capacity of the tertiary or sterically hindered amine with the higher reaction rate of the primary or secondary amine, can bring about the considerable improvement in gas absorption and great savings in regeneration energy requirements. Since the sterically hindered amine, 2-PE, does not form a stable carbamate,[3] bicarbonate, and carbonate ions may be present in the solution in larger amounts than the carbamate ions. Hence, the regeneration energy costs when aqueous solutions of 2-PE are used to absorb CO_2 may be lower, as in the case of using aqueous MDEA solutions. From these considerations (2-PE + MEA + H_2O) and (2-PE + DEA + H_2O) appear to be attractive new blended amine solvents. The physical properties, for example, density, and viscosity, of aqueous amine solutions are essential for the rational design of gas treating units and for optimum gas treating processes. Knowledge of the physical properties of process solutions is necessary for the operation of process equipments such as pumps and heat exchangers in a gas-treating unit. Solution density and viscosity are also important in the mass-transfer-rate modeling of absorbers and regenerators because these properties affect the liquid-film coefficient for mass transfer.

The density and viscosity data of aqueous solution of 2-PE and aqueous blend of (2-PE + MEA) have been studied in the literature, such as (2-PE + H_2O),[4] (2-PE + MEA + H_2O).[5,6] However, the density and viscosity of aqueous blend of (2-PE + DEA) has not yet been published in the open literature so far. Also the density and viscosity measurements for the (2-PE + H_2O) system have done earlier over the temperature range (298 to 356.5) K and (298 to 358) K, respectively, and the measurements for the (2-PE + MEA + H_2O) system have been done earlier over the temperature range (303 to 353) K. Hence, in this work the density and viscosity measurements have done in the temperature range (288 to 333) K to cover the gap.

In this work, the density and viscosity of aqueous solutions of 2-PE, 2-PE + MEA, and 2-PE + DEA were measured over the temperature range (288 to 333) K. The total amine mass fraction in the solution was kept within 30 %. The densities of the binary and ternary mixtures have been correlated in this work using Redlich−Kister equation. A Redlich−Kister equation for the viscosity deviation was applied to represent the viscosity of the binary mixture. The viscosities of the ternary mixtures have been correlated successfully using the equation of Grunberg and Nissan.

Experimental Section

Materials. Reagent grade 2-PE of 95 % purity was obtained from Acros Organic and MEA, and DEA of 98 % purity were obtained from E. Merck. Distilled water degassed by boiling was used for making the amine solutions. The total amine contents of the solutions were determined by titration with standard HCl using methyl orange indicator.

Density. The densities of the amine solutions were measured using a 26.76×10^{-3} m^3 Gay-Lussac pycnometer. The pycnometer containing the amine solution was immersed in a constant-temperature bath. The bath temperature was controlled within ± 0.3 K of the temperature range using a circulator temperature controller (HAAKE DC 50). Once the solution reached the desired temperature, it was weighed to within ± 0.0002 g with an analytical balance (AND GR-200). The uncertainty in the measurement of temperature was ± 0.2 K. Each reported density data was the average of three measurements. The experimental uncertainty in the measured density was estimated to be ± 0.06 %.

Viscosity. The viscosity was measured using an Ostwald viscometer. The viscometer was immersed in a thermostated bath. The bath temperature was controlled within ± 0.3 K of the desired level using a circulator temperature controller

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Table 1. Comparison of the Densities (ρ) of Pure MDEA and Aqueous MDEA Solutions Measured in This Work with Literature Values

	ρ/kg·m^{-3}							
	pure MDEA		10 % MDEA		20 % MDEA		30 % MDEA	
T/K	Al-Ghawas et al.[7]	this work	Al-Ghawas et al.[7]	this work	Al-Ghawas et al.[7]	this work	Al-Ghawas et al.[7]	this work
288	1044.5	1044.1	1007.8	1007.9	1018.0	1016.7	1029.0	1030.7
313	1026.7	1027.2	1000.7	1000.4	1009.1	1008.6	1018.0	1019.3
333	1012.3	1012.6	991.2	990.2	999.3	999.5	1006.9	1007.1
100AAD		0.04		0.05		0.07		0.10

Table 2. Comparison of the Viscosities (η) of Pure MDEA and Aqueous MDEA Solutions Measured in This Work with Literature Values

	η/mPa·s							
	pure MDEA		10 % MDEA		20 % MDEA		30 % MDEA	
T/K	Al-Ghawas et al.[7]	this work	Al-Ghawas et al.[7]	this work	Al-Ghawas et al.[7]	this work	Al-Ghawas et al.[7]	this work
288	141.90	142.02	1.707	1.703	2.650	2.624	4.402	4.399
313	34.78	34.73	0.907	0.899	1.301	1.305	1.937	1.929
333	14.50	14.66	0.627	0.630	0.858	0.860	1.207	1.218
100AAD		0.44		0.53		0.51		0.46

Table 3. Density (ρ) for 2-PE (1) + H_2O (2) from (288 to 333) K

	ρ/kg·m^{-3}									
100 w_1	T/K = 288	T/K = 293	T/K = 298	T/K = 303	T/K = 308	T/K = 313	T/K = 318	T/K = 323	T/K = 328	T/K = 333
5.00	1001.8	1000.1	998.90	997.60	996.00	994.30	992.40	990.30	987.70	983.50
10.00	1004.7	1002.3	1001.6	999.60	997.40	996.50	994.20	991.70	988.70	985.90
15.00	1005.0	1003.2	1002.4	1001.4	998.90	997.90	995.50	993.50	990.60	987.90
20.00	1011.1	1008.3	1005.9	1003.7	1001.7	999.30	996.70	994.70	991.90	988.70
25.00	1014.5	1012.5	1010.1	1007.5	1003.1	999.90	998.80	996.10	993.00	990.30
30.00	1017.3	1014.9	1012.7	1009.6	1006.4	1001.8	1000.2	997.30	994.30	991.30

Table 4. Density (ρ) for 2-PE (1) + MEA (2) + H_2O (3) and 2-PE (1) + DEA (2) + H_2O (3) from (288 to 333) K

	ρ/ kg·m^{-3s}									
w_1/w_2	T/K = 288	T/K = 293	T/K = 298	T/K = 303	T/K = 308	T/K = 313	T/K = 318	T/K = 323	TK = 328	T/K = 333
					2-PE/MEA					
3/27	1016.3	1013.9	1010.8	1008.7	1006.1	1003.5	1001.0	998.10	995.20	992.40
6/24	1015.9	1013.6	1010.3	1008.4	1005.9	1003.3	1000.7	997.80	994.90	992.00
9/21	1015.7	1013.3	1010.0	1008.0	1005.6	1003.1	1000.4	997.30	994.70	991.80
12/18	1015.5	1013.0	1009.8	1007.9	1005.1	1003.0	1000.2	997.00	994.50	991.60
15/15	1015.2	1012.8	1009.6	1007.8	1004.9	1002.8	1000.0	996.70	994.20	991.30
18/12	1015.1	1012.6	1009.2	1007.6	1004.7	1002.5	999.60	996.50	993.70	990.70
21/9	1014.9	1012.3	1008.9	1007.4	1004.5	1002.2	999.40	996.20	993.40	990.10
24/6	1014.7	1012.0	1008.5	1007.2	1004.3	1001.9	998.70	995.80	993.10	989.50
27/3	1014.4	1010.0	1008.1	1006.7	1004.1	1001.4	998.50	995.50	992.60	989.30
					2-PE/DEA					
3/27	1030.7	1028.7	1026.7	1024.5	1022.6	1020.5	1018.0	1015.3	1012.9	1009.0
6/24	1029.3	1027.2	1025.4	1023.4	1021.3	1018.8	1016.7	1013.8	1011.3	1008.1
9/21	1027.4	1025.1	1023.2	1021.0	1019.1	1016.7	1014.0	1011.5	1008.7	1005.6
12/18	1025.8	1023.8	1021.6	1019.3	1017.4	1015.0	1012.1	1009.5	1006.7	1003.2
15/15	1023.8	1021.6	1019.7	1017.3	1015.1	1012.7	1009.9	1007.2	1004.1	1001.3
18/12	1022.5	1019.7	1017.7	1015.5	1012.9	1010.2	1007.8	1005.1	1002.2	999.00
21/9	1020.1	1017.9	1015.3	1013.3	1010.9	1008.0	1005.2	1002.5	998.70	996.30
24/6	1018.0	1015.1	1013.4	1010.6	1008.4	1005.9	1002.7	999.90	996.80	993.80
27/3	1016.9	1014.2	1011.7	1009.0	1006.7	1003.6	1000.7	997.80	994.20	991.80

(HAAKE DC 50). The uncertainty in the measurement of temperature was ± 0.2 K. Each reported value was the average of three measurements. The experimental uncertainty was estimated to be ± 0.69 %.

Results and Discussion

Density. To validate the pycnometer and the experimental procedure of the measurement, the densities of pure MDEA and mass fractions of 10 %, 20 %, and 30 % MDEA aqueous solutions were measured at 288 K, 313 K, and 333 K and compared with the values reported by Al-Ghawas et al.[7] These are presented in Table 1. The average absolute deviations of the density measurements are 0.04 %, 0.05 %, 0.07 %, and 0.10 % for pure MDEA and mass fractions of 10 %, 20 %, and 30 % MDEA aqueous solutions, respectively. Thus, the density data obtained in this study are in good agreement with the data of Al-Ghawas et al.[7] The measured densities of solution of (2-PE (1) + H_2O (2)) are presented in Table 3 and solutions of (2-PE (1) + MEA (2) + H_2O (3)) and (2-PE (1) + DEA (2) + H_2O (3)) are presented in Table 4. w is the mass fraction of individual amine present in the solution. The density measurements of this study are in good agreement with the literature results. For the aqueous solution of mass fraction of 10.00 % 2-PE over the temperatures of (298 and 323) K, the experimental data of this study show 0.09 % deviation from the experimental data of Xu et al.[4] For the aqueous solution of mass fraction of 30.00 % 2-PE over the temperatures of (298 and 323) K, the experimental data of this study show 0.08 % deviations from

the experimental data of Xu et al.[4] For the amine blends of 2-PE and MEA like ($w_1 = 6$ % and $w_2 = 24$ %), ($w_1 = 12$ % and $w_2 = 18$ %), ($w_1 = 18$ % and $w_2 = 12$ %), and ($w_1 = 24$ % and $w_2 = 6$ %) over the temperatures of (303, 313, 323, and 333) K, the experimental data of this study show 0.03 %, 0.06 %, 0.10 %, and 0.17 % deviations, respectively, from the experimental data of Hsu and Li.[5] As shown in Table 3, densities of the binary mixture decrease with increasing temperature and decreasing mass fraction of 2-PE in the mixture. According to Table 4, densities of the ternary mixtures decrease with increasing temperature and increasing mass fraction of 2-PE in the mixture.

To correlate the densities of the liquid mixtures, a Redlich−Kister type equation for the excess molar volume is applied. For a binary system, the Redlich−Kister equation has the following expression:

$$V_{jk}^{E}/\mathrm{m^3 \cdot kmol^{-1}} = x_j x_k \sum_{i=0}^{n} A_i (x_j - x_k)^i \quad (1)$$

where A_i are pair parameters and are assumed to be temperature dependent:

$$A_i = a + b(T/\mathrm{K}) + c(T/\mathrm{K})^2 \quad (2)$$

The excess volume of liquid mixtures for the binary system is assumed to be

$$V^{E} = V_{12}^{E} \quad (3)$$

The excess volume of liquid mixtures for the ternary system is assumed to be

$$V^{E} = V_{12}^{E} + V_{23}^{E} + V_{13}^{E} \quad (4)$$

The excess volume of liquid mixtures can be calculated from the measured density of the fluids:

$$V^{E} = V_m - \sum x_i V_i^0 \quad (5)$$

where V_m is the molar volume of the liquid mixture and V_i^0 is the molar volume of the pure fluids at the system temperature. The molar volume of the liquid mixtures is calculated by

$$V_m = \frac{\sum x_i M_i}{\rho_m} \quad (6)$$

where M_i is the molar mass of pure component i, ρ_m is the measured liquid density, and x_i is the mol fraction of the pure component i.

A general set of temperature-dependent parameters has been developed using experimental data in the temperature range (288 to 333) K. For convenience, we have considered 2-PE as the first component and H_2O as second component in the binary mixture and 2-PE as the first component, MEA or DEA as the second component, and H_2O as third component in the ternary mixtures. The densities of the pure fluids have taken from the literature.[6] The determined parameters are presented in Tables 5 to 7.

Viscosity. To validate the viscometer and the experimental procedure of the measurement, the viscosities of pure MDEA and mass fractions of 10 %, 20 %, and 30 % MDEA aqueous solutions were measured at (288, 313, and 333) K and compared with the values reported by Al-Ghawas et al.[7] These are presented in Table 2. The average absolute deviations of the viscosity measurements are 0.44 %, 0.53 %, 0.51 %, and 0.46 % for pure MDEA and mass fractions of 10 %, 20 %, and 30 % MDEA aqueous solutions, respectively. Thus, the viscosity obtained in this study are in good agreement with the data of Al-Ghawas et al.[7] The measured viscosities of solution of (2-PE (1) + H_2O (2)) are presented in Table 8, and solutions of (2-PE (1) + MEA (2) + H_2O (3)) and (2-PE (1) + DEA (2) + H_2O (3)) are presented in Table 9. The viscosity measurements of this study are in good agreement with the literature data. For the aqueous solution of mass fraction of 10.00 % 2-PE over the temperatures of (298 and 313) K, the experimental data of this study show 0.60 % deviation from the experimental data of Xu et al.[4] For the aqueous solution of mass fraction of 30.00 % 2-PE over the temperatures of (298 and 313) K, the experimental data of this study show 3.27 % deviation from the experimental data of Xu et al.[4] For the amine blends of 2-PE and MEA like ($w_1 = 6$ % and $w_2 = 24$ %), ($w_1 = 12$ % and $w_2 = 18$ %), ($w_1 = 18$ % and $w_2 = 12$ %), and ($w_1 = 24$ % and $w_2 = 6$ %) over the temperatures of (303, 313, 323, and

Table 5. Binary Parameters (A_0, A_1, and A_2) of the Equation $V_{jk}^{E}/\mathrm{m^3 \cdot kmol^{-1}} = x_j x_k \sum_{i=0}^{n} A_i (x_j - x_k)^i$ for the Excess Volume for 2-PE (1) + H_2O (2)[a]

parameters		binary pair: 2-PE + H_2O
A_0	a	96.00856
	b	−0.610349
	c	0.968127×10^{-3}
A_1	a	211.9266
	b	−1.346351
	c	0.213430×10^{-2}
A_2	a	116.7735
	b	−0.741418
	c	0.117467×10^{-2}

[a] 100AAD = 0.05; no. of data points = 60.

Table 6. Binary Parameters (A_0, A_1, and A_2) of the Equation $V_{jk}^{E}/\mathrm{m^3 \cdot kmol^{-1}} = x_j x_k \sum_{i=0}^{n} A_i (x_j - x_k)^i$ for the Excess Volume for 2-PE (1) + MEA (2) + H_2O (3)[a]

parameters		binary pair: 2-PE + MEA	binary pair: MEA + H_2O	binary pair: 2-PE + H_2O
A_0	a	−0.663079	13.22194	0.065741
	b	0.006332	−0.094518	-0.486550×10^{-3}
	c	-0.132808×10^{-4}	0.166787×10^{-3}	0.861300×10^{-6}
A_1	a	−41.18122	32.18533	0.016103
	b	0.290627	−0.230759	-0.101581×10^{-3}
	c	-0.507922×10^{-3}	0.408151×10^{-3}	0.178500×10^{-6}
A_2	a	198.5861	19.46272	−0.080828
	b	−1.411208	−0.140071	0.566871×10^{-3}
	c	0.247939×10^{-2}	0.248452×10^{-3}	-0.100110×10^{-5}

[a] 100AAD = 0.05; no. of data points = 90.

Table 7. Binary Parameters (A_0, A_1, and A_2) of the Equation $V_{jk}^{E}/\mathrm{m^3 \cdot kmol^{-1}} = x_j x_k \sum_{i=0}^{n} A_i (x_j - x_k)^i$ for the Excess Volume for 2-PE (1) + DEA (2) + H_2O (3)[a]

parameters		binary pair: 2-PE + DEA	binary pair: DEA + H_2O	binary pair: 2-PE + H_2O
A_0	a	−4.051150	23.49430	0.092217
	b	0.025641	−0.141924	-0.577507×10^{-3}
	c	-0.410516×10^{-4}	0.214315×10^{-3}	0.884900×10^{-6}
A_1	a	−66.65661	58.67806	0.053045
	b	0.399770	−0.354834	-0.302950×10^{-3}
	c	-0.597874×10^{-3}	0.536547×10^{-3}	0.447500×10^{-6}
A_2	a	339.2432	36.61822	−0.167641
	b	−2.042377	−0.221714	0.997763×10^{-3}
	c	0.307011×10^{-2}	0.335771×10^{-3}	-0.149890×10^{-5}

[a] 100AAD = 0.03; no. of data points = 90.

Table 8. Viscosity (η) for 2-PE (1) + H_2O (2) from (288 to 333) K

	η/mPa·s									
100 w_1	T/K = 288	T/K = 293	T/K = 298	T/K = 303	T/K = 308	T/K = 313	T/K = 318	T/K = 323	T/K = 328	T/K = 333
5.00	1.364	1.298	1.116	1.064	0.959	0.828	0.776	0.684	0.651	0.585
10.00	1.775	1.655	1.423	1.316	1.216	1.015	0.965	0.828	0.778	0.695
15.00	2.313	2.097	1.762	1.599	1.489	1.253	1.156	0.995	0.975	0.837
20.00	2.935	2.696	2.289	2.037	1.869	1.511	1.429	1.193	1.173	1.013
25.00	3.921	3.506	2.968	2.603	2.382	1.938	1.795	1.523	1.390	1.229
30.00	5.218	4.697	3.858	3.429	3.069	2.468	2.229	1.891	1.769	1.536

Table 9. Viscosity (η) for 2-PE (1) + MEA (2) + H_2O (3), and 2-PE (1) + DEA (2) + H_2O (3) from (288 to 333) K

	η/mPa·s									
w_1/w_2	T/K = 288	T/K = 293	T/K = 298	T/K = 303	T/K = 308	T/K = 313	T/K = 318	T/K = 323	T/K = 328	T/K = 333
					2-PE/MEA					
3/27	3.566	3.074	2.608	2.184	1.893	1.631	1.514	1.304	1.169	1.052
6/24	3.686	3.102	2.610	2.252	1.926	1.676	1.537	1.315	1.174	1.067
9/21	3.749	3.185	2.716	2.326	1.940	1.739	1.559	1.329	1.186	1.089
12/18	4.045	3.319	2.744	2.404	1.982	1.791	1.570	1.359	1.204	1.104
15/15	4.129	3.385	2.853	2.479	2.108	1.836	1.605	1.409	1.239	1.110
18/12	4.165	3.574	2.967	2.557	2.215	1.895	1.642	1.436	1.282	1.152
21/9	4.182	3.583	3.031	2.645	2.288	1.958	1.710	1.493	1.335	1.188
24/6	4.539	3.851	3.193	2.750	2.395	2.017	1.819	1.544	1.395	1.246
27/3	4.671	3.876	3.201	2.851	2.477	2.170	1.945	1.645	1.473	1.317
					2-PE/DEA					
3/27	3.902	3.523	2.909	2.653	2.365	2.012	1.778	1.610	1.650	1.518
6/24	4.003	3.552	2.928	2.673	2.409	2.073	1.790	1.645	1.651	1.520
9/21	4.273	3.576	2.979	2.685	2.448	2.137	1.841	1.686	1.654	1.521
12/18	4.302	3.582	3.030	2.703	2.455	2.146	1.876	1.701	1.656	1.528
15/15	4.473	3.607	3.059	2.715	2.467	2.167	1.919	1.715	1.661	1.530
18/12	4.512	3.813	3.154	2.797	2.483	2.169	1.923	1.720	1.666	1.544
21/9	4.679	3.853	3.185	2.819	2.511	2.174	1.926	1.734	1.672	1.563
24/6	4.703	3.895	3.225	2.911	2.549	2.195	1.936	1.747	1.687	1.589
27/3	4.801	4.046	3.303	2.962	2.592	2.271	1.941	1.757	1.707	1.620

333) K, the experimental data of this study show 0.68 %, 0.67 %, 0.77 %, and 0.85 % deviations, respectively, from the experimental data of Hsu and Li.[6] As shown in Table 8, viscosities of the binary mixture decrease with increasing temperature and decreasing mass fraction of 2-PE in the mixture. According to Table 9, viscosities of the ternary mixtures decrease with increasing temperature and decreasing mass fraction of 2-PE in the mixture.

To correlate the viscosity of aqueous solution of 2-PE, a Redlich−Kister type equation for the viscosity deviation is applied. Using the kinematic viscosity instead of viscosity as a variable, the modified viscosity deviation expression[6] is as follows:

$$\delta\nu/10^{-3}\,\mathrm{m^2{\cdot}s^{-1}} = \ln \nu_\mathrm{m} - \sum_{i=1}^{n} x_i \ln \nu_i \qquad (7)$$

where ν is the kinematic viscosity; in η/ρ, η is the viscosity, and ρ is the density. The subscripts m and i represent the mixture and the ith pure fluid, respectively. The viscosities of the pure fluids have taken from the literature.[6] The following equation is utilized in this study to calculate the viscosity deviation of aqueous solution of 2-PE:

$$\delta\nu_{jk}/10^{-3}\,\mathrm{m^2{\cdot}s^{-1}} = x_j x_k \sum_{i=0}^{n} A_i (x_j - x_k)^i \qquad (8)$$

For a binary system, $\delta\nu_{12}$is a function of temperature and mole fraction and assumed to have the Redlich−Kister type expression:[8]

$$\delta\nu_{12}/10^{-3}\,\mathrm{m^2{\cdot}s^{-1}} = x_1 x_2 \sum_{i=0}^{m} A_i (x_1 - x_2)^i \qquad (9)$$

Table 10. Binary Parameters (A_0 and A_1) of the Equation $\delta\nu_{12}/10^{-3}$ $\mathrm{m^2{\cdot}s^{-1}} = x_1x_2\sum_{i=0}^{m}A_i(x_1 - x_2)^i$ for the Excess Volume for 2-PE (1) + H_2O (2)[a]

parameters		binary pair 2-PE + H_2O
A_0	a	−2.41787
	b	127.160
	c	−268.153
A_1	a	−11.1197
	b	−2139.96
	c	−93.0866

[a] 100AAD = 1.80; no. of data points = 60.

where A_i are pair parameters and are assumed to be temperature dependent:

$$A_i = a + \frac{b}{(T/\mathrm{K}) + c} \qquad (10)$$

For a binary system, the viscosity deviation of a liquid is assumed to be following expression:

$$\delta\nu = \delta\nu_{12} \qquad (11)$$

A general set of temperature-dependent parameters has been developed using experimental data in the temperature range (288 to 333) K. For convenience, we have considered 2-PE as the first component and H_2O as second component in the binary mixture. The determined parameters are presented in Table 10.

The model of Grunberg and Nissan[9,10] for the viscosity of liquid mixtures was used to correlate the viscosity data of the ternary mixtures. The equation of Grunberg and Nissan has the following form:

$$\ln(\eta_\mathrm{m}/\mathrm{mPa{\cdot}s}) = \sum x_i \ln \eta_i + \sum\sum x_i x_j G_{ij} \qquad (12)$$

where x_i is the mole fraction of the ith component in the mixture.

Table 11. Parameters (G_{12}, G_{23}, and G_{13}) of the Equation $\ln(\eta_m/\text{mPa·s}) = x_1 \ln(\eta_1/\text{mPa·s}) + x_2 \ln(\eta_2/\text{mPa·s}) + x_3 \ln(\eta_3/\text{mPa·s}) + x_1x_2G_{12} + x_2x_3G_{23} + x_1x_3G_{13}$ for 2-PE (1) + MEA (2) + H_2O (3) and 2-PE (1) + DEA (2) + H_2O (3)

		ternary pairs	
parameters		2-PE + MEA + H_2O	2-PE + DEA + H_2O
G_{12}	*a*	982.707	−2172.35
	b	−5.19976	14.1418
	c	0.00628	−0.02297
G_{23}	*a*	133.246	288.752
	b	−0.76555	−1.79354
	c	0.11430×10^{-2}	0.28915×10^{-2}
G_{13}	*a*	117.428	512.724
	b	−0.53563	−3.12356
	c	0.68805×10^{-3}	0.49185×10^{-2}

For a ternary system:

$$\ln(\eta_m/\text{mPa·s}) = x_1 \ln(\eta_1/\text{mPa·s}) + x_2 \ln(\eta_2/\text{mPa·s}) + x_3 \ln(\eta_3/\text{mPa·s}) + x_1x_2G_{12} + x_2x_3G_{23} + x_1x_3G_{13} \quad (13)$$

G_{ij} in eq 12 are temperature dependent and are assumed to have the form:

$$G_{ij} = a + b(T/\text{K}) + c(T/\text{K})^2 \quad (14)$$

The parameters of eq 12 are obtained by regression analysis of the experimental data of this work and are presented in Table 11. The calculated viscosities from the correlation (eq 12) are in excellent agreement with the experimental data, the average absolute deviation between the correlated and the experimental data for the (2-PE + MEA + H_2O) and (2-PE + DEA + H_2O) systems being about 2.33 %, and 1.89 %, respectively.

Conclusion

The densities and viscosities of six (2-PE + H_2O) mixtures as well as nine (2-PE + MEA + H_2O) and (2-PE + DEA + H_2O) mixtures were measured and correlated over the temperature range (288 to 333) K. The correlated densities and viscosities of the binary and ternary mixtures are in excellent agreement with the experimental data over the temperature and relative composition ranges studied.

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