Viscosities of Aqueous Blended Amines

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The viscosities of aqueous mixtures of diethanolamine (DEA) + *N*-methyldiethanolamine (MDEA), DEA + 2-amino-2-methyl-1-propanol (AMP), and monoethanolamine (MEA) + 2-piperidineethanol (2-PE) were measured from 30 °C to 80 °C. A Redlich−Kister equation for the viscosity deviation was applied to represent the viscosity. On the basis of the available viscosity data for five ternary systems, MEA + MDEA + H_2O, MEA + AMP + H_2O, DEA + MDEA + H_2O, DEA + AMP + H_2O, and MEA + 2-PE + H_2O, a generalized set of binary parameters were determined. For the viscosity calculation of the systems tested, the overall average absolute percent deviation is about 1.0% for a total of 499 data points.

Introduction

Solutions of alkanolamines are an industrially important class of compounds used in the natural gas, oil refineries, petroleum chemical plants, and synthetic ammonia industries for the removal of acidic components like CO_2 and H_2S from gas streams. A wide variety of alkanolamines such as monoethanolamine (MEA), diethanolamine (DEA), di-2-propanolamine (DIPA), and *N*-methyldiethanolamine (MDEA) have been used industrially for a number of years (Kohl and Riesenfeld, 1985). A recent advancement in gas-treating technology is the application of sterically hindered amines which offer absorption capacity, absorption rate, selectivity, and degradation resistance advantages over conventional amines for acid gases removal (Sartori and Savage, 1983). Two of sterically hindered amines are 2-amino-2-methyl-l-propanol (AMP) and 2-piperidineethanol (2-PE).

Recently, the use of blended amines has been shown to produce absorbents with improved absorption characteristics as well as superior stripping qualities for lesser energy requirement (Chakravarty et al., 1985). The physical properties of aqueous solution such as viscosity are required for the design of acid gas treatment equipments. The viscosity data of some aqueous solutions of blended amines have been studied in the literature: MEA + MDEA + H_2O (Li and Lie, 1994; Hagewiesche et al., 1995); MEA + AMP + H_2O (Li and Lie, 1994); DEA + MDEA + H_2O (Rinker et al., 1994). The viscosity of DEA + AMP + H_2O and MEA + 2-PE + H_2O systems has not yet appeared in the literature. The objective of this work was to measure the viscosity of ternary solutions of DEA + MDEA + H_2O, DEA + AMP + H_2O, and MEA + 2-PE + H_2O. Furthermore, a Redlich−Kister equation for the viscosity deviation will be applied to represent the viscosity of the aqueous solutions of blended alkanolamines. On the basis of the available viscosity data for five ternary systems, MEA + MDEA + H_2O, MEA + AMP + H_2O, DEA + MDEA + H_2O, DEA + AMP + H_2O, and MEA + 2-PE + H_2O, a generalized set of parameters will be determined.

Experimental Section

Alkanolamine aqueous solutions were prepared from distilled water. The distilled water was degassed by boiling. All alkanolamines are Riedel-de Haën reagent grade with the following purities: MEA, 99%; DEA, 99%; MDEA, 98.5%; AMP, 98%; 2-PE, 98%. The concentration of the alkanolamine aqueous solution was determined by titration of an liquid sample with HCl using methyl orange as the indicator. All alkanolamine aqueous solutions were found to be within ±0.2 mass % of the stated concentration. The kinematic viscosities of solutions were measured by means of Cannon−Fenske routine viscometers (sizes 25, 50, and 75) over the temperature range 30−80 °C. The measurements were performed in a constant-temperature water bath, in which the temperature could be held constant to ±0.05 °C. An electronic stopwatch with an accuracy of 0.01 s was used to measure the efflux times of the liquid samples. The kinematic viscosity of the solution was calculated from the multiplication of the efflux time with the viscometer constant. End effect corrections were neglected in the calculation of the kinematic viscosity, the same as the method of Rinker et al. (1994). Each reported measurement was the average of at least three runs with a maximum deviation in the kinematic viscosity of approximately ±0.1%. The absolute viscosity of fluid can be obtained by multiplying the kinematic viscosity by the density of the fluid. The experimental errors for the density measurements were estimated to be ±0.05% (Hsu and Li, 1997). The accuracy of the viscosities was estimated to be ±1.0% on the basis of comparisons with literature data for aqueous DEA solutions (Rinker et al., 1994).

Results and Discussion

For the viscosity measurement, we have obtained data for the systems at which viscosity data had been studied in the literature. Viscosities of 10 mass % DEA and 20 mass % DEA aqueous solutions have been reported by Rinker et al. (1994). The results of viscosity measurements for temperatures ranging from 40 °C to 80 °C are presented in Table 1. The difference between this study and the literature are 1.0% for both 10 mass % DEA and 20 mass % DEA aqueous solutions in average absolute percentage deviation. The viscosity data obtained in this study are in good agreement with the data of Rinker et al. (1994).

The viscosities of three blended amine aqueous solutions, DEA + MDEA + H_2O, DEA + AMP + H_2O, and MEA + 2-PE + H_2O, for the temperatures ranging from 30 °C to 80 °C were measured and presented in Tables 2−4. The concentrations were selected as a total of 20 and 30 mass % alkanolamine aqueous solutions. The viscosity of 10 mass % MEA + 10 mass % MDEA and 10 mass % MEA +

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Table 1. Comparison of the Viscosities of Aqueous DEA Solutions Measured in This Study with Literature Values

	η/(mPa·s)			
	10 mass % DEA		20 mass % DEA	
T/°C	Rinker et al. (1994)	this study	Rinker et al. (1994)	this study
40	0.898	0.883	1.304	1.280
60	0.624	0.625	0.848	0.854
80	0.465	0.470	0.606	0.604
av abs % dev		1.0		1.0

Table 2. Viscosities of DEA + MDEA + H_2O

	η/(mPa·s) (mass % DEA/mass % MDEA)				
T/°C	30/0	24/6	18/12	12/18	6/24
30	2.542	2.578	2.580	2.582	2.581
40	1.930	1.904	1.921	1.937	1.954
50	1.469	1.487	1.495	1.502	1.511
60	1.218	1.214	1.209	1.204	1.199
70	1.025	1.014	1.003	0.991	0.980
80	0.859	0.851	0.843	0.835	0.827

	η/(mPa·s) (mass % DEA/mass % MDEA)				
T/°C	20/0	15/5	10/10	5/15	MEA/MDEA 10/10
30	1.646	1.652	1.658	1.668	1.580
40	1.280	1.284	1.285	1.288	1.233
50	1.034	1.040	1.041	1.041	0.977
60	0.854	0.856	0.855	0.857	0.806
70	0.714	0.712	0.709	0.708	0.677
80	0.604	0.600	0.598	0.596	0.581

Table 3. Viscosities of DEA + AMP + H_2O

	η/(mPa·s) (mass % DEA/mass % AMP)			
T/°C	24/6	18/12	12/18	6/24
30	2.644	2.746	2.849	2.951
40	1.978	2.053	2.073	2.121
50	1.500	1.530	1.561	1.591
60	1.228	1.238	1.247	1.257
70	1.036	1.047	1.057	1.068
80	0.864	0.870	0.876	0.882

	η/(mPa·s) (mass % DEA/mass % AMP)			
T/°C	15/5	10/10	5/15	MEA/AMP 10/10
30	1.705	1.759	1.808	1.660
40	1.313	1.342	1.366	1.274
50	1.058	1.073	1.087	1.001
60	0.864	0.872	0.879	0.820
70	0.719	0.723	0.725	0.695
80	0.601	0.601	0.599	0.597

10 mass % AMP aqueous solutions are also reported in Tables 2 and 3.

To correlate the viscosity of liquid mixtures, a Redlich−Kister-type equation for the viscosity deviation is applied. Using the kinematic viscosity instead of viscosity as a variable, Pikkarainen (1983) modified the viscosity deviation expression proposed by Grunberg and Nissan (Prausnitz et al., 1986) as follows

$$\delta\nu = \ln \nu_{\mathrm{m}} - \sum_{i=1}^{n} x_i \ln \nu_i \tag{1}$$

where ν is the kinematic viscosity, 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 viscosity deviation expression proposed by Pikkarainen (1983), i.e., eq 1, is utilized in this study to calculate the viscosity deviation of the fluid.

For a binary system, the $\delta\nu_{12}$ is a function of temperature and mole fraction and assumed to have the Redlich−Kister type expression (Prausnitz et al., 1986)

Table 4. Viscosities of MEA + 2-PE + H_2O

	η/(mPa·s) (mass % MEA/mass % 2-PE)			
T/°C	24/6	18/12	12/18	6/24
30	2.239	2.406	2.567	2.750
40	1.699	1.803	1.901	2.016
50	1.318	1.385	1.459	1.564
60	1.061	1.104	1.161	1.221
70	0.881	0.906	0.943	0.998
80	0.739	0.759	0.784	0.826

	η/(mPa·s) (mass % MEA/mass % 2-PE)		
T/°C	15/5	10/10	5/15
30	1.560	1.692	1.780
40	1.214	1.299	1.366
50	0.971	1.041	1.076
60	0.809	0.847	0.882
70	0.676	0.712	0.725
80	0.581	0.606	0.619

$$\delta\nu_{12} = x_1 x_2 \sum_{i=0}^{m} A_i (x_1 - x_2)^{\mathrm{i}} \tag{2}$$

where A_{i} are pair parameters and assumed to have the following temperature dependence

$$A_i = a + \frac{b}{(T/\mathrm{K}) + c} \tag{3}$$

where a, b, and c are parameters.

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

$$\delta\nu = \delta\nu_{12}^{\mathrm{E}} + \delta\nu_{13}^{\mathrm{E}} + \delta\nu_{23}^{\mathrm{E}} \tag{4}$$

The viscosity of pure fluids, required to calculate the viscosity deviation as in eq 1, is assumed to be the following expression

$$\ln \nu = a_1 + \frac{a_2}{(T/\mathrm{K}) + a_3} \tag{5}$$

where a_{i} are parameters and are determined from the kinematic viscosities of pure fluids. Equation 5 is similar to that of DiGuilio et al. (1992) for viscosity of pure fluids except the kinematic viscosity is used in this study.

In eq 1, the density of fluids are required to calculate the viscosity deviation. In this study, the density of pure fluids, single-amine aqueous solutions, and blended amine aqueous solutions are calculated from a correlation based on the Redlich−Kister equation of the excess volume (Hsu and Li, 1997). The overall average absolute percent deviation (A.A.D.%) for the density calculations is 0.04% for 686 density data points including pure fluids, single-amine aqueous solutions, and ternary aqueous solutions of blended amines. The correlation can serve as a tool for density calculations for aqueous blended amines.

In eq 2, A_i are the pair-interaction parameters. A generalized set of parameters can, in principle, be developed on the basis of the available viscosity data in the literature. In this study we intend to develop a generalized set of parameters for the viscosity calculation of blended amine aqueous solutions. The ternary systems selected for viscosity calculation are MEA + MDEA + H_2O, MEA + AMP + H_2O, DEA + MDEA + H_2O, DEA + AMP + H_2O, and MEA + 2-PE + H_2O. The viscosity data utilized in this study include the following systems: pure fluids, water and alkanolamines; binary systems, single-amine aqueous

Table 5. Viscosity of Pure Fluids

system	*T*/°C	no. of data points	ref[a]	A.A.D.%[b]
H_2O	30−80	6	1	0.7
	15−60	10	2	0.5
MEA	30.45−150.55	8	3	0.1
	30−70	5	6	0.3
DEA	19.75−150.05	9	3	2.2
MDEA	15−60	8	2	0.9
	19.95−150.95	10	3	0.8
	30−80	6	5	0.7
AMP	30−80	6	5	0.3
2-PE	40−85.2	5	4	0.4
overall		73		0.7

[a] (1) Yaws et al., 1976. (2) Al-Ghawas et al., 1989. (3) DiGuilio et al., 1992. (4) Xu et al., 1992. (5) Li and Lie, 1994. (6) Song et al., 1996. [b] Calculated from eq 5.

Table 6. Parameters of the Viscosity Equation for Pure Fluids[a]

pure fluid	a_1	a_2	a_3
H_2O	−3.282 85	$4.560\,29 \times 10^{2}$	$-1.545\,76 \times 10^{2}$
MEA	−3.513 12	$8.931\,73 \times 10^{2}$	$-1.596\,12 \times 10^{2}$
DEA	−4.996 89	1.584×10^{3}	$-1.574\,49 \times 10^{2}$
MDEA	−4.063 99	$1.201\,96 \times 10^{3}$	$-1.544\,19 \times 10^{2}$
AMP	−4.367 85	$9.965\,98 \times 10^{2}$	$-1.929\,84 \times 10^{2}$
2-PE	−4.706 56	$1.172\,59 \times 10^{3}$	$-1.838\,67 \times 10^{2}$

[a] Parameters of eq 5.

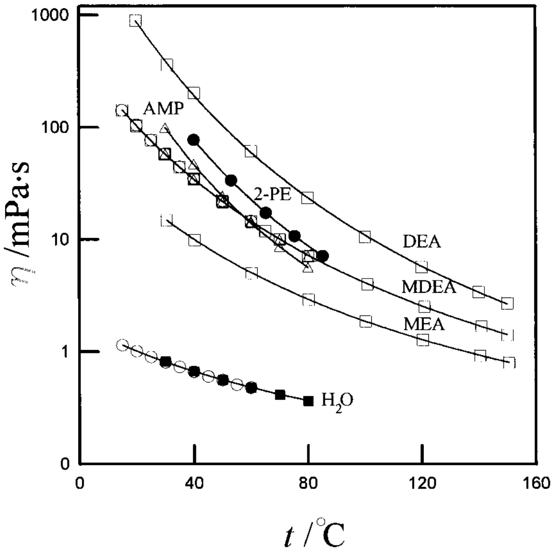

Figure 1. Viscosity of pure fluids: ■,Yaws et al., 1976; ○, Al-Ghawas et al., 1989; ●, Xu et al., 1992; □, DiGuilio et al., 1992; △, Li and Lie, 1994; solid lines, calculated using eq 5.

solutions; ternary mixtures, ternary aqueous solutions of blended amines.

The viscosity data of pure fluids applied are presented in Table 5. The temperature ranges from 15 °C up to 150 °C. The parameters determined upon applying eq 5 are presented in Table 6. The A.A.D.% is about 0.7% for 73 data points. The A.A.D.% of viscosity calculations for different investigators are also presented in Table 5. Except for the DEA (A.A.D.% = 2.2%), the A.A.D.% for fluids tested are all less than 1%. A similar result for DEA was obtained by DiGuilio et al. (1992) (A.A.D.% = 2.1%). The results of viscosity calculations of pure fluids are also shown in Figure 1. For MDEA, the agreement of viscosity measurements among different investigators (Al-Ghawas et al., 1989; DiGuilio et al., 1992; Li and Lie, 1994) are quite good. Among these pure fluids, DEA has the highest value of viscosity while water has the lowest viscosity. The viscosity of MDEA crosses both AMP and 2-PE near the temperature as of 50 °C and 100 °C, respectively. At 40 °C, the viscosity of pure fluids has the order as follows: DEA(200.9 mPa·s) > 2-PE(77.171 mPa·s) > AMP(46.926 mPa·s) > MDEA(34.309 mPa·s) > MEA(10.02 mPa·s) > H_2O (0.668 mPa·s).

Table 7. Viscosity of Binary Alkanolamine Aqueous Solutions

system	*T*/°C	conc. mass %	no. of data points	ref[a]	A.A.D.%[b]
MEA + H_2O	30−80	20	6	4	0.4
	30−80	30	6	4	0.3
	30−70	15.3	5	6	0.5
	30−70	30	5	6	0.5
DEA + H_2O	20−100	10	5	3	2.7
	20−100	20	5	3	0.6
	20−100	30	5	3	1.1
	30−80	10	3	7	1.8
	30−80	20	6	7	0.5
	30−80	30	6	7	2.5
MDEA + H_2O	15−60	10	8	1	0.3
	15−60	20	8	1	0.6
	15−60	30	8	1	0.6
	15−50	40	7	1	1.1
	15−60	50	8	1	0.8
	60−80	10	2	3	1.2
	60−100	20	3	3	1.7
	60−100	30	3	3	5.6
	60−100	40	3	3	1.6
	60−100	50	3	3	2.0
	30−80	20	6	4	1.4
	30−80	30	6	4	1.0
	30−50	40	3	4	0.9
	30−60	50	4	4	0.2
	29.85−49.85	30	3	5	1.2
	29.85−49.85	40	3	5	0.4
AMP + H_2O	30−80	20	6	4	0.9
	30−80	30	6	4	1.1
2-PE + H_2O	25−85.2	10	6	2	1.2
	25−85.2	30	6	2	1.8
	25−85.2	45	6	2	1.0
	25−85.2	60	6	2	1.2
	25−85.2	75	6	2	1.6
overall			178		1.1

[a] (1) Al-Ghawas et al., 1989. (2) Xu et al., 1992. (3) Rinker et al., 1994. (4) Li and Lie, 1994. (5) Hagewiesche et al., 1995. (6) Song et al., 1996. (7) This study. [b] Calculated from eq 2.

The viscosity data of five single-amine aqueous solutions; MEA + H_2O, DEA + H_2O, MDEA + H_2O, AMP + H_2O, and 2-PE + H_2O, are listed in Table 7. The temperature ranges from 15 °C to 100 °C, and the concentration ranges from 10 to 75 mass % amine. The binary parameters, A_i in eq 2, for five pairs, MEA + H_2O, DEA + H_2O, MDEA + H_2O, AMP + H_2O, and 2-PE + H_2O, are determined from the viscosity data of the single-amine aqueous solutions, and the values are listed in Table 9. For a total of 178 data points, the overall A.A.D.% for the viscosity calculations of binary systems is 1.1%. Except for the systems of 10 mass % DEA + H_2O (A.A.D.% = 2.7%), 30 mass % DEA + H_2O (A.A.D.% = 2.5%), and 30 mass % MDEA + H_2O (A.A.D.% = 5.6%), all the viscosity calculations are below 2% which is a quite satisfactory result. From the results of viscosity calculations in Table 7, it has been shown that the viscosity of single-amine aqueous solutions can be well-represented by the Redlich−Kister equation for the viscosity deviation, i.e., eq 2. In Figure 2 the differences between the calculated and experimental values of the viscosity deviations for MEA + H_2O are shown. The values of the differences ($\Delta = (\delta\nu)_{\text{calculated}} - (\delta\nu)_{\text{experimental}}$) are around ±0.02, and the A.A.D.% for the viscosity calculation is 0.5%. The results of viscosity calculations for DEA + H_2O, MDEA + H_2O, and 2-PE + H_2O are also shown graphically in

Table 8. Viscosity of Blended Amine Aqueous Solutions

system	T/°C	conc. mass1% + mass2%	no. of data points	ref[a]	A.A.D.%[b]
MEA + MDEA + H_2O	30−80	6 + 24	6	1	0.6
	30−80	12 + 18	6	1	0.3
	30−80	18 + 12	6	1	0.3
	30−80	24 + 6	6	1	0.5
	30−80	5 + 15	6	1	0.6
	30−80	15 + 5	6	1	0.6
	29.85−49.85	1.5 + 28.5	3	3	0.3
	29.85−49.85	3.0 + 27.0	3	3	0.5
	29.85−49.85	4.5 + 25.5	3	3	0.3
	29.85−49.85	2.0 + 38.0	3	3	0.5
	29.85−49.85	4.0 + 36.0	3	3	0.1
	29.85−49.85	6.0 + 34.0	3	3	0.6
	30−80	10 + 10	6	4	0.7
MEA + AMP + H_2O	30−80	6 + 24	6	1	1.2
	30−80	12 + 18	6	1	0.9
	30−80	18 + 12	6	1	1.0
	30−80	24 + 6	6	1	1.2
	30−80	5 + 15	6	1	0.4
	30−80	15 + 5	6	1	0.7
	30−80	10 + 10	6	4	0.5
DEA + MDEA + H_2O	20−100	2.11 + 47.89	5	2	0.9
	20−100	9.04 + 40.96	5	2	0.4
	20−100	15.31 + 34.69	5	2	1.1
	20−100	18.52 + 31.48	5	2	0.9
	30−80	5 + 15	6	4	0.6
	30−80	10 + 10	6	4	0.6
	30−80	15 + 5	6	4	0.7
	30−80	6 + 24	6	4	1.0
	30−80	12 + 18	6	4	1.3
	30−80	18 + 12	6	4	1.6
	30−80	24 + 6	6	4	1.9
DEA + AMP + H_2O	30−80	5 + 15	6	4	1.2
	30−80	10 + 10	6	4	1.0
	30−80	15 + 5	6	4	0.8
	30−80	6 + 24	6	4	1.3
	30−80	12 + 18	6	4	1.5
	30−80	18 + 12	6	4	1.7
	30−80	24 + 6	6	4	2.0
MEA + 2-PE + H_2O	30−80	5 + 15	6	4	1.2
	30−80	10 + 10	6	4	1.3
	30−80	15 + 5	6	4	0.4
	30−80	6 + 24	6	4	1.1
	30−80	12 + 18	6	4	1.1
	30−80	18 + 12	6	4	0.4
	30−80	24 + 6	6	4	1.1
overall			248		0.9

[a] (1) Li and Lie, 1994. (2) Rinker et al., 1994. (3) Hagewiesche et al., 1995. (4) This study. [b] Calculated from eq 4.

Table 9. Binary Parameters of the Redlich−Kister Equation for the Viscosity Deviation

		binary pairs				
params		MEA + H_2O	DEA + H_2O	MDEA + H_2O	AMP + H_2O	2-PE + H_2O
A_0	a	$2.583\,23 \times 10^{-1}$	$2.766\,55$	$-6.264\,93$	$4.012\,39$	$1.919\,44$
	b	$5.052\,07 \times 10^{2}$	$3.647\,95 \times 10^{3}$	$1.591\,58 \times 10^{3}$	$2.498\,56 \times 10^{2}$	$1.814\,07 \times 10^{3}$
	c	$-2.231\,55 \times 10^{2}$	$6.784\,30 \times 10^{1}$	$-1.796\,49 \times 10^{2}$	$-2.657\,12 \times 10^{2}$	$-1.800\,1 \times 10^{2}$
A_1	a	$-7.201\,06$	$1.715\,93 \times 10^{1}$	$2.879\,26$	$-2.684\,62$	$3.164\,62 \times 10^{1}$
	b	$2.308\,38 \times 10^{3}$	$-4.754\,87 \times 10^{3}$	$-4.030\,39 \times 10^{3}$	0.	$-3.882\,3 \times 10^{3}$
A_2	a	0.	0.	0.	0.	$2.621\,37 \times 10^{1}$

		binary pairs				
params		MEA + MDEA	MEA + AMP	DEA + MDEA	DEA + AMP	MEA + 2−PE
A_0	a	$2.454\,14 \times 10^{1}$	$-1.276\,91 \times 10^{2}$	$-3.711\,43 \times 10^{1}$	$-5.714\,03$	$-1.970\,78 \times 10^{2}$
	b	$-7.791\,67 \times 10^{3}$	$4.003\,92 \times 10^{4}$	$7.704\,51 \times 10^{3}$	0.	$4.518\,81 \times 10^{4}$
A_1	a	$-1.562\,56 \times 10^{1}$	$1.102\,32 \times 10^{2}$	$-1.334\,07 \times 10^{1}$	$-6.484\,08 \times 10^{1}$	$4.918\,21 \times 10^{2}$

Figures 3−5. As shown in Figure 3, for 20 mass % DEA + H_2O, there is a good agreement of the viscosity data between two investigators, and the A.A.D.% is 0.6%. However, only a fair calculation result is obtained for 30 mass % DEA + H_2O, and the A.A.D.% is 1.9%. For the MDEA + H_2O system, for the concentrations up to 50 mass % MDEA, except for the data of 30 mass % MDEA + H_2O (Rinker et al. (1994), A.A.D.% = 5.6) all the viscosity calculations are quite satisfactory (overall A.A.D.% = 1.1). At the same temperature, the viscosity of MDEA + H_2O increases as the mass % of MDEA increases. The viscosity calculations for the 2-PE + H_2O systems, with concentration range up to 50 mass % 2-PE, are quite good (A.A.D.% = 1.4) as shown in Figure 5.

The viscosity data of the aqueous blended amines considered in this study are MEA + MDEA + H_2O, MEA

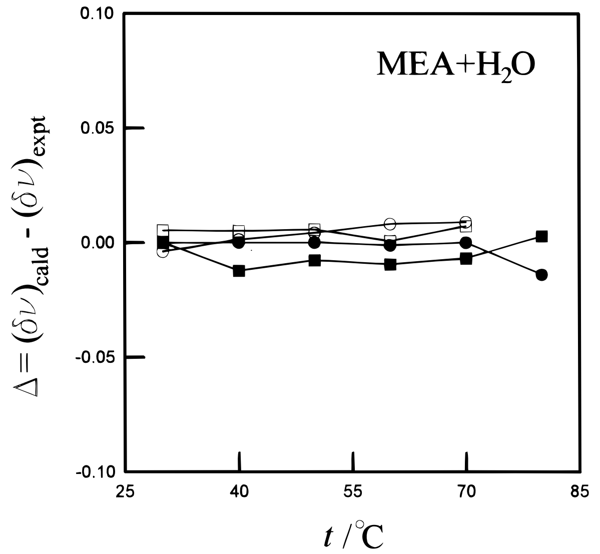

Figure 2. Difference of the viscosity deviations between calculated and experimental values for MEA + H_2O: ●, Li and Lie, 1994 (20 mass % MEA + H_2O); ■, Li and Lie, 1994 (30 mass % MEA + H_2O); ○, Song et al., 1996 (15.3 mass % MEA + H_2O); □, Song et al., 1996 (30 mass % MEA + H_2O); calculated values using eq 2.

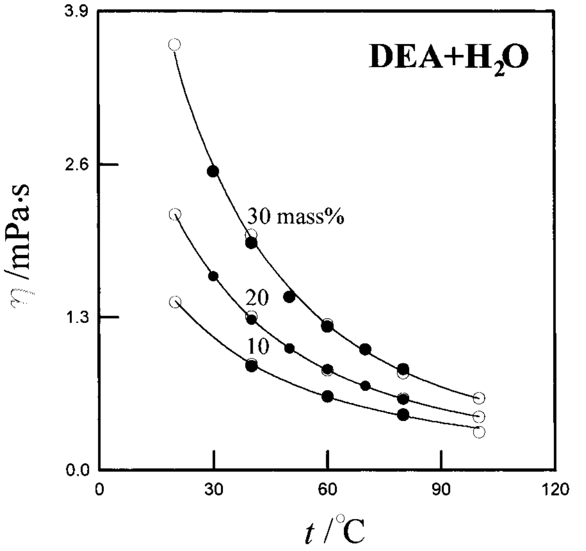

Figure 3. Viscosity of 10, 20, and 30 mass % DEA + H_2O: ○, Rinker et al., 1994; ●, this study; solid lines, calculated using eq 2.

+ AMP + H_2O, DEA + MDEA + H_2O, DEA + AMP + H_2O, and MEA + 2-PE + H_2O and are listed in Table 8. The parameters for eq 2 for MEA + MDEA, MEA+ AMP, DEA + MDEA, DEA + AMP, and MEA + 2-PE are determined from these ternary systems and are presented in Table 9. The calculated viscosities from the experimental values for all the ternary systems are less than 2%. The overall A.A.D.% is about 0.9% for a total of 248 data points. In Figure 6, the results of viscosity calculations for MEA + MDEA + H_2O are shown for seven concentrations (a total of 30 mass % amine) obtained from two data sources (Li and Lie, 1994; Hagewiesche et al., 1995). As shown in Figure 6, the viscosity calculations using the Redlich–Kister type equation, i.e., eq 4, for the ternary system MEA + MDEA + H_2O are quite satisfactory (A.A.D.% = 0.5% for 60 data points). Figure 7 shows the viscosity calculations for DEA + MDEA + H_2O for temperatures ranging from 20 to 100 °C. The A.A.D.% for the viscosity calculations for DEA + MDEA + H_2O is 1% for 62 data points.

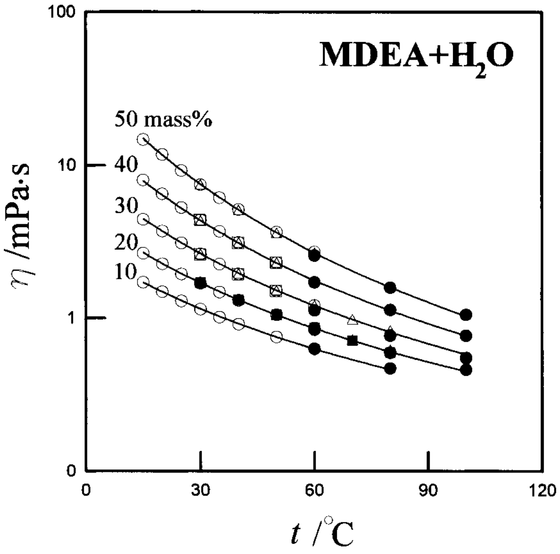

Figure 4. Viscosity of MDEA + H_2O for concentrations up to 50 mass % MDEA: ○, Al-Ghawas et al., 1989; △, Li and Lie, 1994; ●, Rinker et al., 1994; □, Hagewiesche et al., 1995; ■, this study; solid lines, calculated using eq 2.

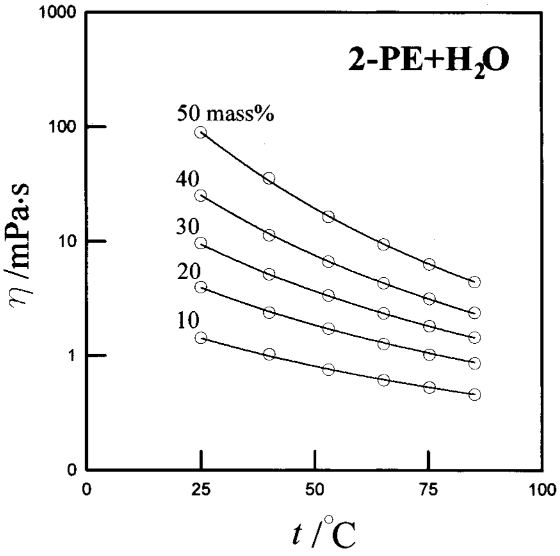

Figure 5. Viscosity of 2-PE + H_2O for various concentrations: ○, Xu et al., 1992; solid lines, calculated using eq 2.

Since viscosities of both DEA and MDEA are a lot higher than those of H_2O, the viscosities of the ternary solutions are strong function of the total mass % amines as shown in Figure 7. Also, for a total mass % amine for DEA + MDEA + H_2O, the viscosity of the solution is a weak funciton of the mass % of the individual amines, as shown in Figure 7. Thus, the viscosity of DEA + MDEA + H_2O is essentially a function of the temperature and the total mass % of blended amines. In Figure 8, the results of viscosity calculations for DEA + AMP + H_2O are shown for a total of 20 and 30 mass % blended amines. At 30 °C, the viscosity of DEA + AMP + H_2O increases as the AMP mass % increases, as shown in Figure 8. However, for the total 30 mass % DEA + AMP + H_2O at 80 °C, the differences among various mass % of individual amines becomes small, as shown in Figure 8. The results of viscosity calculations for seven MEA + 2-PE + H_2O systems are shown in Figure 9. The MEA + 2-PE + H_2O systems cover a concentration range from a total amine concentration 20 to 30 mass %. As shown in Figure 9, the viscosity calculations are quite satisfactory (A.A.D.% =

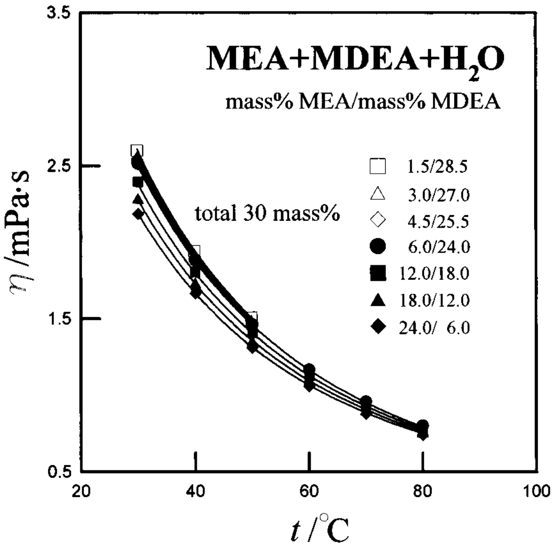

Figure 6. Viscosity of MEA + MDEA + H_2O for seven concentrations: □, △, ◇, Hagewiesche et al., 1995; ●, ■, ▲, ◆, Li and Lie, 1994; solid lines, calculated using eq 4.

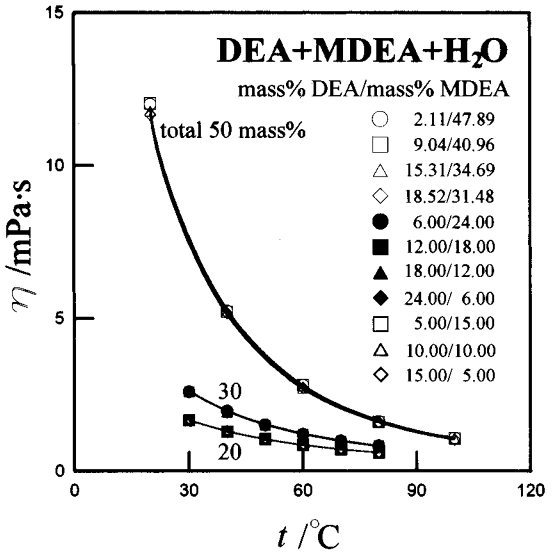

Figure 7. Viscosity of DEA + MDEA + H_2O for various concentrations: total 50 mass % amine; Rinker et al., 1994; total 30 and 20 mass % amine, this study; solid lines, calculated using eq 4.

0.9% for 42 data points). From the results presented in Table 8, it can be said that the viscosity of ternary aqueous solutions of blended amine tested in this study can be well-correlated by the equation of the viscosity deviation, i.e., eq 4. A summary of the results of viscosity calculations for pure fluids, single-amine aqueous solutions, and ternary aqueous solutions of blended amines is presented in Table 10. The overall A.A.D.% for 499 data points is 1.0%, which is satisfactory for the design calculations.

Conclusion

The viscosities of aqueous mixtures of diethanolamine + *N*-methyldiethanolamine + water, DEA + 2-amino-2-methyl-1-propanol + water, and monoethanolamine + 2-piperidineethanol + water were measured from 30 °C to 80 °C. A Redlich−Kister equation of the viscosity deviation was applied to represent the available viscosity data of five aqueous solutions of blended alkanolamines, MEA + MDEA + H_2O, MEA + AMP + H_2O, MEA + 2-PE + H_2O, DEA + MDEA + H_2O, and DEA + AMP + H_2O. On the basis of the available viscosity data in the literature, a generalized set of parameters in the Redlich−Kister viscosity equation was determined. The overall A.A.D.% for the viscosity calculations is 1.0% for 499 viscosity data points

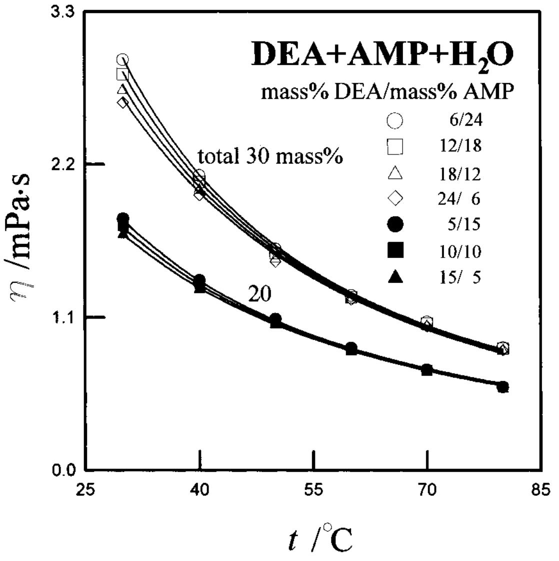

Figure 8. Viscosity of DEA + AMP + H_2O for seven concentrations: points, this study; solid lines, calculated using eq 4.

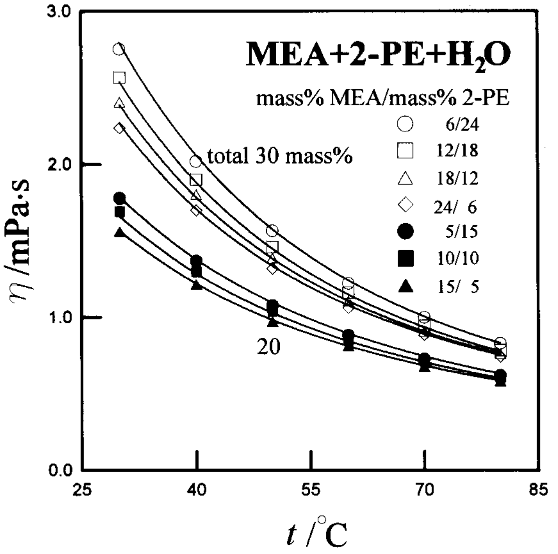

Figure 9. Viscosity of MEA + 2-PE + H_2O for seven concentrations: points, this study; solid lines, calculated using eq 4.

Table 10. Summary of the Result of Viscosity Calculations for Aqueous Alkanolamine Solutions Using the Redlich−Kister Equation

system	no. of data points	A.A.D.%
H_2O	16	0.6
MEA	13	0.2
DEA	9	2.2
MDEA	24	0.8
AMP	6	0.3
2-PE	5	0.4
MEA + H_2O	22	0.5
DEA + H_2O	30	1.5
MDEA + H_2O	84	1.1
AMP + H_2O	12	1.0
2-PE + H_2O	30	1.4
MEA + MDEA + H_2O	60	0.5
MEA + AMP + H_2O	42	0.8
DEA + MDEA + H_2O	62	1.0
DEA + AMP + H_2O	42	1.4
MEA + 2-PE + H_2O	42	0.9
overall	499	1.0

including pure fluids, single-amine aqueous solutions, and ternary aqueous solutions of blended amines. The results are satisfactory.

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