Density and Surface Tension of Aqueous Solutions of (2-(Methylamino)-ethanol +2-Amino-2-methyl-1-propanol) and (2-(Methylamino)-ethanol + *N*-Methyl-diethanolamine) from (298.15 to 323.15) K

A. Venkat, G. Kumar, and M. Kundu*

Department of Chemical Engineering, National Institute of Technology, Rourkela, Orissa -769008, India

---

This paper presents experimental data on the density of aqueous blends of (2-(methylamino)-ethanol (MAE) + 2-amino-2-methyl-1-propanol (AMP)) and (2-(methylamino)-ethanol (MAE) + *N*-methyl-diethanolamine (MDEA)) at (298.15, 303.15, 308.15, 313.15, 318.15, and 323.15) K. This study also presents surface tension data of the aforesaid aqueous amine blends over the temperature range (298 to 323) 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. Density and surface tension data of the ternary mixtures are presented as a function of temperature and amine composition.

Introduction

Removal of hydrogen sulfide (H_2S) and carbon dioxide (CO_2) from natural gas and refinery off gases is a very important industrial operation, which necessitates the application as well as promotion of a whole range of alkanolamines starting from monoethanolamine (MEA), diethanolamine (DEA), di-2-propanolamine (DIPA), *N*-methyldiethanolamine (MDEA), 2-amino-2-methyl-1-propanol (AMP), and very recently piperazine (PZ), 2-piperidineethanol (2-PE), 2-(methylamino)-ethanol (MAE), and 2-(ethylamino)-ethanol (EAE). By varying the relative composition of amines in their aqueous blends to exploit the individual's merit, an optimum as well as energy efficient absorption system can be designed for a specific application. Specifically, the use of sterically hindered amines in the aqueous blends of amines enhances the capacity and rate of absorption of acid gases with good stripping characteristics and degradation resistance of the formulated solvent.[1,2] For the rational design of gas treating processes and its operation, knowledge of the physical properties of process solutions is necessary.

A few density data for the (MAE + AMP + H_2O) system and density as well as surface tension measurements for the (MAE + MDEA + H_2O) system have already been reported in the open literature.[3−5] No surface tension data on the (MAE + AMP + H_2O) ternary system have been reported to date. In this work, surface tension data of aqueous ternary mixtures of (MAE + AMP) and (MAE + MDEA) at (298, 303, 308, 313, 318, and 323) K have been measured for (MAE)/(MDEA or AMP) mass % ratios of 3/27, 6/24, 9/21, and 12/18. The density of aqueous (MAE + AMP) and (MAE + MDEA) ternary mixtures have been measured in the temperature range of (298.15 to 323.15) K. The total amine concentration was held constant at 30 mass %.

Experimental Section

Materials. All amines were supplied by Merck, with a purity of > 98 % for 2-(methylamino)-ethanol (MAE), > 98 % for *N*-methyl-diethanolamine (MDEA), and > 95 % for 2-amino-2-methyl-1-propanol (AMP). 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. The uncertainty in the composition of the amine solution was estimated as ± 0.007 %.

Table 1. Comparison of the Density Data (ρ/g·cm^{-3}) of the Pure MAE and the (MAE (1) + H_2O (2)) System from (298.15 to 323.15) K Measured in This Work with the Literature Values with $w_1 + w_2 = 1.0$

T	pure MAE		$w_1 = 17.8$				
K	ref 3	this work	ref 5	this work	$^a w_1 = 10$	$^a w_1 = 25$	$^a w_1 = 40$
298.15	0.937683	0.93618	0.99645	0.99631	0.99604	0.99763	0.99000
303.15	0.933789	0.93226	0.99449	0.99438	0.99506	0.99639	0.98970
308.15	-	-	-	0.99312	0.99282	0.99297	0.98610
313.15	0.925948	0.92442	0.99011	0.99009	0.99126	0.99029	0.98406
318.15	-	-	-	0.98861	0.98917	0.98761	0.97950
323.15	0.918024	0.91648	0.98507	0.98489	0.98677	0.98101	0.97670
^{b}% AAD		= 0.0015		= 0.0012			

[a] The density values are within a range of ± 0.003 to the interpolated values of Li et al.[5] [b] % Average absolute deviation in density data of the present work with respect to the literature. AAD % = $[\sum_n(\text{Density}_{\text{presentwork}} - \text{Density}_{\text{lit}})/\text{Density}_{\text{presentwork}}]/n \cdot 100$.

Density. The densities of the amine solutions were measured using a 25.3 mL Gay-Lussac pycnometer. The pycnometer containing the amine solution was immersed in a constant-temperature bath. The bath temperature was controlled within ± 0.05 K of the desired temperature using a circulator temperature controller (Polyscience, USA model No: 9712). The desired temperature of the bath containing amine solutions was also checked with a Pt 100 temperature sensor. Once the solution reached the desired temperature, it was weighed to within ± 0.001 g with an analytical balance. The uncertainty in the measurement of temperature was ± 0.04 K. Each reported density data was the average of three measurements. The average absolute deviations of the density measurements with respect to the results reported in the literature are shown in Table 1. The uncertainty in the measured density was estimated to be ± $7.7 \cdot 10^{-4}$ g·cm^{-3} (expanded uncertainty; for coverage factor $k = 2$).

---

* Corresponding author. E-mail: mkundu@nitrkl.ac.in, madhushreek@yahoo.com. Fax: 0661-2462999.

10.1021/je1002626

Table 2. Density, ρ ($g \cdot cm^{-3}$), for the (MAE (1) + AMP (2) + H_2O (3)) System from (298.15 to 323.15) K with $w_1 + w_2 = 0.3$

	T/K					
w_1/w_2	298.15	303.15	308.15	313.15	318.15	323.15
3/27	0.99498	0.99274	0.98990	0.98728	0.98438	0.98220
6/24	0.99656	0.99472	0.99221	0.98908	0.98584	0.98340
9/21	0.99741	0.99538	0.99229	0.98925	0.98640	0.98352
12/18	0.99834	0.99573	0.99288	0.98980	0.98688	0.98383

Table 3. Density, ρ ($g \cdot cm^{-3}$), for the (MAE (1) + MDEA (2) + H_2O (3)) System from (298.15 to 323.15) K with $w_1 + w_2 = 0.3$

	T/K					
w_1/w_2	298.15	303.15	308.15	313.15	318.15	323.15
3/27	1.02158	1.01897	1.01621	1.01336	1.01130	1.00901
6/24	1.02008	1.01791	1.01419	1.01182	1.00937	1.00743
9/21	1.01708	1.01455	1.01198	1.00949	1.00731	1.00509
12/18	1.01494	1.01253	1.00945	1.00680	1.00451	1.00205

Surface Tension. The surface tension measurement was carried out with a Data Physics tensiometer (model DCAT-11) using a plate-type measurement method. The temperature was controlled within ± 0.3 K of the desired level using a circulator temperature controller. 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 ± 0.35 $mN \cdot m^{-1}$ (expanded uncertainty; for coverage factor $k = 2$).

Results and Discussion

To validate the pycnometer and the experimental procedure of the measurement, the densities of pure and of mass fractions (10, 25, 17.8, and 40) % MAE aqueous solutions were measured at (298 to 323) K and compared with the values reported by Alvarez et al.[3] and Li et al.[5] The density values for aqueous MAE solutions are within a range of ± 0.003 at the interpolated values of Li et al.[5] and are presented in Table 1. The average absolute deviation in the density measurements of pure MAE and 17.8 % aqueous MAE solutions in comparison to the data reported by Alvarez et al.[3] and Li et al.[5] were found to be 0.15 % and 0.12 %, respectively. The measured densities of the solutions of (MAE (1) + AMP (2) + H_2O (3)) and (MAE (1) + MDEA (2) + H_2O (3)) in the temperature range of (298.15 to 323.15) K are presented in Tables 2 and 3, respectively, keeping the total amine mass percentage constant at 30 % with w as the mass fraction of each individual amine present in the solution.

The excess molar volumes were correlated by using the Redlich−Kister (R−K) equation

$$V_{jk}^{E}/\text{mL} \cdot \text{mol}^{-1} = x_j x_k \sum_{i=0}^{n} A_i (x_j - x_k)^i \tag{1}$$

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

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

The excess molar volume of liquid mixtures for a ternary system is given by

$$V^E = V_{12}^E + V_{13}^E + V_{23}^E \tag{3}$$

Table 4. Redlich−Kister Equation Fitting Coefficients of the Excess Volumes (V_m^E ($mL \cdot mol^{-1}$)) for the (MAE (1) + H_2O (2)) System

estimated MAE−H_2O (R−K) parameters		
	parameter	value
A_0	a	−16.653710
	b	0.071870
	c	−0.000105
A_1	a	21.749515
	b	−0.114928
	c	0.000164
A_2	a	41.021672
	b	−0.257555
	c	0.000414
[a](AAD) % correlation		0.104 %

[a]

$$\text{AAD } \% = [\sum_n (V_{m,cal}^E - V_{m,exp}^E)/V_{m,exp}^E]/n \cdot 100$$

The excess molar volume of the liquid mixtures (binary/ternary) can be determined from the experimentally measured molar volume (or density) of binary/ternary liquid mixtures along with the pure component molar volume of the constituent liquids in the mixture as per eq 4

$$V^E = V_m - \sum x_i V_i^o \tag{4}$$

where V_m is the molar volume of the liquid mixture (binary/ternary) and V_i^o is the molar volume of the pure component liquid in the mixture at the system temperature.

The molar volume of the liquid mixture from experimentally measured density is calculated by

$$V_m = \frac{\sum x_i M_i}{\rho_m} \tag{5}$$

where M_i is the molar mass of pure component i; ρ_m is the measured liquid density; and x_i is the mole fraction of the pure component i. By equating eq 3 and eq 4, one can obtain the requisite binary interaction parameters (A_i).

A Nissan type of equation, which is used to correlate the dynamic viscosity of ternary mixtures, has been used here to correlate the ternary density data of (MAE + AMP + H_2O) and (MAE + MDEA + H_2O) systems. The density of liquid mixtures can also be calculated by this alternative eq 6

$$\rho_m = \sum_{i=1}^{n} x_i \rho_i + \sum_{i \neq j} A_{ij} x_i x_j \tag{6}$$

where A_{ij} are the binary interaction parameters and ρ_m is the density of the ternary mixture.

A general set of temperature-dependent R−K parameters for the (MAE + H_2O) binary system have been developed considering 62 data points including experimental data generated in this work in the temperature range of (298.15 to 323.15) K and the data of Li et al.[5] over the entire composition range with a correlation deviation of 0.104 % and are presented in Table 4. A set of temperature-dependent parameters for the (AMP + H_2O) binary system have been developed with a correlation deviation of 0.033 % and are presented in Table 5 considering 66 data points from Henni et al.[6] over the entire composition

Table 5. Redlich−Kister Equation Fitting Coefficients of the Excess Volumes (V_m^E (mL·mol^{-1})) for the (AMP (1) + H_2O (2)) System

estimated AMP−H_2O (R−K) parameters		
parameter		value
A_0	a	−2.975265
	b	−0.014298
	c	0.000033
A_1	a	47.178166
	b	−0.266463
	c	0.000391
A_2	a	57.248373
	b	−0.361994
	c	0.000561
[a](AAD) % correlation		0.033 %

[a]

$$\text{AAD \%} = [\sum_n (V_{m,cal}^E - V_{m,exp}^E)/V_{m,exp}^E]/n \cdot 100$$

Table 6. Redlich−Kister Equation Fitting Coefficients of the Excess Volumes (V_m^E (mL·mol^{-1})) for the (MAE (1) + AMP (2) + H_2O (3)) System

estimated MAE−AMP (R−K) parameters		
parameter		value
A_0	a	−816.722289
	b	6.208049
	c	−0.011006
A_1	a	−67009.754554
	b	442.374353
	c	−0.674821
A_2	a	−834911.311191
	b	5650.216157
	c	−8.663625
[a](AAD) % correlation		0.0046 %

[a]

$$\text{AAD \%} = [\sum_n (V_{m,cal}^E - V_{m,exp}^E)/V_{m,exp}^E]/n \cdot 100$$

Table 7. Fitting Parameters for the Density ((ρ_m), g·cm^{-3}) of the (MAE (1) + AMP (2) + H_2O (3)) System by Equation 6

estimated Nissan (eq 6) parameters		
parameter		value
A_{13}	a	67.154895
	b	−0.5083999
	c	0.000821
A_{23}	a	3.615593
	b	−0.108645
	c	0.000181
A_{12}	a	−1497.071440
	b	9.679702
	c	−0.015598
[a](AAD) % correlation		0.023 %

[a]

$$\text{AAD \%} = [\sum_n (\rho_{m,cal} - \rho_{m,exp})/\rho_{m,exp}]/n \cdot 100$$

range and in the temperature range of (298.15 to 343.15) K. A general set of temperature-dependent (MAE + AMP) binary interaction parameters have been developed considering the (MAE + AMP + H_2O) ternary system data generated in this work in the temperature range of (298.15 to 323.15) K with a correlation deviation of 0.0046 % and are presented in Table 6. The correlated ternary densities for the (MAE + AMP + H_2O) system are in reasonable agreement with respect to the measured densities as reflected in the AAD % of 0.1 between the measured and correlated data by the R−K equation, where AAD % is the average absolute deviation percentage in

$$\text{density} = ([\sum_n (\rho_{m,cal} - \rho_{m,exp})/\rho_{m,exp}]/n \cdot 100),$$

$$n = \text{number of data}$$

A Nissan type of equation (eq 6) was used to correlate the ternary (MAE + AMP + H_2O) density data with a correlation deviation of 0.023 %. The resulting set of temperature-dependent fitting parameters is reported in Table 7. The comparisons between the measured and correlated densities by the R−K equation and eq 6 are shown in Figure 1. The figure reveals that the density of the ternary mixture (MAE + AMP + H_2O) decreases with increasing temperature and with decreasing mass fraction of MAE in the mixture. Equation 6 correlates the (MAE + AMP + H_2O) density data in a more precise way than the R−K equation.

A general set of temperature-dependent R−K parameters for the (MDEA + H_2O) binary system have been developed with a correlation deviation of 0.082 % considering 33 data points taken from Al-Ghawas et al.[7] in the temperature range (298.15 to 323.15) K and a MDEA mass fraction range of 0.10 to 0.50, and these are presented in Table 8. The (MAE + MDEA) binary parameters have been developed considering the (MAE + MDEA + H_2O) ternary system data generated in this work in the temperature range of (298.15 to 323.15) K keeping the total amine content as 30 % and with a correlation deviation of 0.019 %, which are presented in Table 9. The correlated density by the R−K equation shows an AAD % of 0.46 with respect to the measured ternary density data. Equation 6 correlated the (MAE + MDEA + H_2O) density data in a more precise way than the R−K equation, showing a deviation of 0.016 % between the measured density and correlated density. The resulting set of temperature-dependent fitting parameters (eq 6) is reported in Table 10. For the (MAE + MDEA + H_2O) system, the comparisons between the measured and correlated density by eq 6 are shown in Figure 2. As shown in Figure 2, the density of the ternary mixture (MAE + MDEA + H_2O) decreases with increasing temperature and increasing mass fraction of MAE in the mixture.

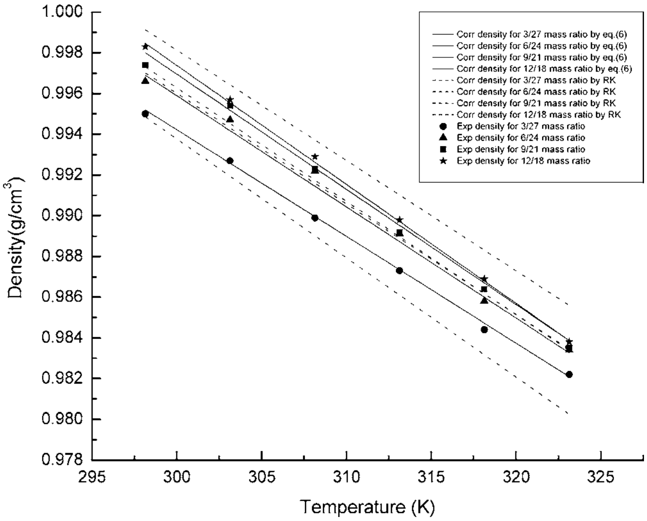

Figure 1. Density of the ternary (MAE (1) + AMP (2) + H_2O (3)) system at various amine compositions with varying temperature.

Table 8. Redlich−Kister Equation Fitting Coefficients of the Excess Volumes (V_m^E (mL·mol^{-1})) for the (MDEA (1) + H_2O (2)) System

estimated MDEA−H_2O (R−K) parameters		
parameter		value
A_0	a	1228.425354
	b	−4.973241
	c	0.002455
A_1	a	2456.537482
	b	−8.771605
	c	0.0003870
A_2	a	1150.258029
	b	−2.848991
	c	−0.0043031
[a](AAD) % correlation		0.082 %

[a]

$$\text{AAD}\,\% = [\sum_n (V^E_{m,cal} - V^E_{m,exp})/V^E_{m,exp}]/n \cdot 100$$

Table 9. Redlich−Kister Equation Fitting Coefficients of the Excess Volumes (V_m^E (mL·mol^{-1})) for the (MAE (1) + MDEA (2) + H_2O (3)) System

estimated MAE−MDEA (R−K) parameters		
parameter		value
A_0	a	−1410.708503
	b	8.067376
	c	−0.014646
A_1	a	22693.917453
	b	−161.563185
	c	0.419448
A_2	a	−1205535.830713
	b	5000.899371
	c	−3.955480
[a](AAD) % correlation		0.019 %

[a]

$$\text{AAD}\,\% = [\sum_n (V^E_{m,cal} - V^E_{m,exp})/V^E_{m,exp}]/n \cdot 100$$

Table 10. Fitting Parameters for the Density ((ρ_m), g·cm^{-3}) of the (MAE (1) + MDEA (2) + H_2O (3)) System by Equation 6

estimated Nissan (eq 6) parameters		
parameter		value
A_{13}	a	−16.561841
	b	0.035510
	c	−0.000061
A_{23}	a	1.212662
	b	−0.118602
	c	0.000197
A_{12}	a	315.129579
	b	−2.166264
	c	0.003751
[a](AAD) % correlation		0.016 %

[a]

$$\text{AAD}\,\% = [\sum_n (\rho_{m,cal} - \rho_{m,exp})/\rho_{m,exp}]/n \cdot 100$$

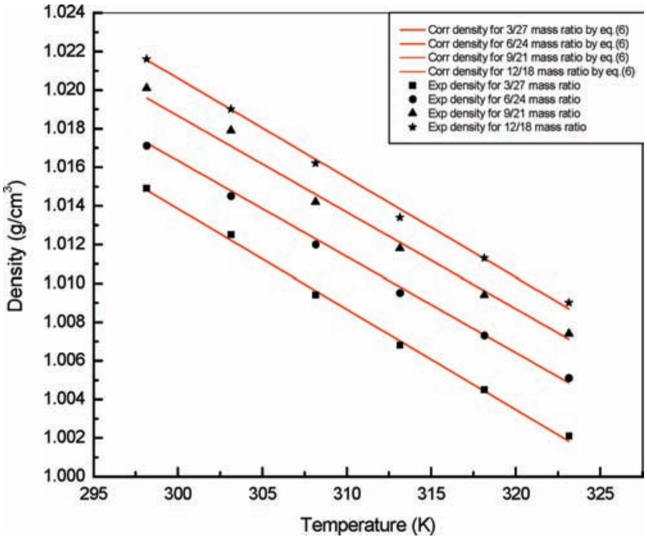

Figure 2. Density of the ternary (MAE (1) + MDEA (2) + H_2O (3)) system at various amine compositions with varying temperature.

Table 11. Surface Tension Data (σ/mN·m^{-1}) of the (MAE (1) + H_2O (2)) Binary System from (298.0 to 323.0) K Measured in This Work with $w_1 + w_2 = 1.0$

	T/K					
w_1/w_2	298.0	303.0	308.0	313.0	318.0	323.0
10/90	60.85	60.02	59.5	58.65	57.66	56.89
20/80	56.11	55.28	54.50	53.42	52.78	51.79
30/70	52.51	52.33	51.46	50.18	49.42	48.90
40/60	49.16	48.15	47.20	46.67	45.72	44.92

Table 12. Surface Tension Parameters (Temperature Based) K_1 and K_2 of Equation 7 for the (MAE (1) + H_2O (2)) Binary System

w_1/w_2	K_1 (mN·m^{-1})	K_2 (mN·m^{-1}·K^{-1})
10/90	108.1530	0.1585
20/80	107.5538	0.1725
30/70	100.6467	0.1605
40/60	98.4846	0.1658
[a](AAD) % correlation		0.23 %

[a]

$$\text{AAD}\,\% = [\sum_n (\sigma_{m,cal} - \sigma_{m,exp})/\sigma_{m,exp}]/n \cdot 100$$

Surface Tension. To validate the tensiometer and the experimental procedure of the measurement, the surface tension of mass fractions of (10, 20, 30, and 40) % MAE aqueous solutions were measured at (298.0 to 323.0) K and compared with the values reported by Alvarez et al.[4] These are presented in Table 11. It has been found that binary surface tension data generated in this work show a reasonable agreement with the interpolated measurements of Alvarez et al.[4] The (MAE (1) + H_2O (2)) binary system data have been correlated with respect to concentration as well as temperature with correlation deviations of 0.92 % and 0.23 %, respectively, and the regressed binary parameters are presented in Tables 12 and 13, respectively. The temperature and concentration based correlations are defined by eqs 7 and 8, respectively.

$$\sigma = K_1 - K_2 T \tag{7}$$

where σ is the surface tension; T is temperature; and K_1 (mN·m^{-1}) and K_2 (mN·m^{-1}·K^{-1}) are fitting parameters.

$$\left(\frac{\sigma - \sigma_2}{\sigma_2 - \sigma_1}\right) = -x_1\left(1 + \frac{a x_2}{1 - b x_2}\right) \tag{8}$$

where σ_1 and σ_2 are the MAE and water surface tension values; σ is the binary mixture surface tension; x_1 and x_2 are the amine and water mole fraction; a and b are fitting parameters.

Table 13. Surface Tension Parameters (Concentration Based) *a* and *b* of Equation 8 for the (MAE (1) + H_2O (2)) Binary System

	parameter	
T/K	*a*	*b*
298.0	0.6798	0.9595
303.0	0.6851	0.9594
308.0	0.7181	0.9553
313.0	0.7225	0.9571
318.0	0.7336	0.9577
323.0	0.7390	0.9578
[a](AAD) % correlation		0.92 %

[a]

$$\text{AAD}\ \% = [\sum_n (\sigma_{\text{m,cal}} - \sigma_{\text{m,exp}})/\sigma_{\text{m,exp}}]/n\cdot 100$$

The variation in surface tension data of aqueous MAE solution with respect to temperature and concentration is presented in Figures 3 and 4, respectively.

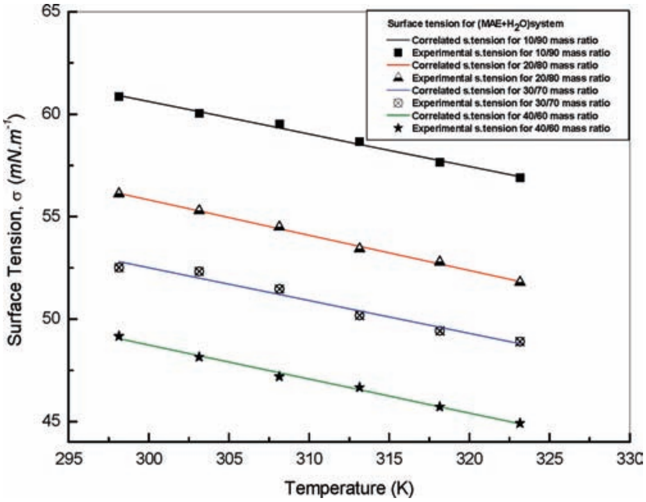

Figure 3. Surface tension of the binary (MAE (1) + H_2O (2)) system at various amine compositions with varying temperature (298 to 323) K. Correlated surface tensions are calculated using eq 7.

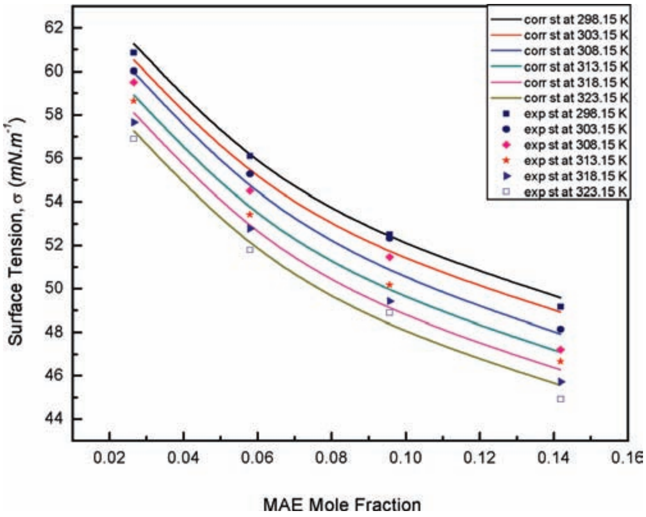

Figure 4. Surface tension of the binary (MAE (1) + H_2O (2)) system at various temperatures (298 to 323) K with varying MAE compositions. Correlated surface tensions are calculated using eq 8.

Table 14. Surface Tension Data (σ/mN·m^{-1}) for the (MAE (1) + AMP (2) + H_2O (3)) System from (298 to 323) K with $w_1 + w_2 = 0.3$

	T/K					
w_1/w_2	298.0	303.0	308.0	313.0	318.0	323.0
3/27	47.16	46.57	45.59	44.88	44.17	43.38
6/24	47.46	47.05	46.22	45.43	44.55	43.60
9/21	47.80	47.39	46.74	45.54	44.66	43.80
12/18	48.20	47.91	46.79	45.77	44.93	44.24

Table 15. Surface Tension Data (σ/mN·m^{-1}) for the (MAE (1) + MDEA (2) + H_2O (3)) System from (298 to 323) K with $w_1 + w_2 = 0.3$

	T/K					
w_1/w_2	298.0	303.0	308.0	313.0	318.0	323.0
3/27	54.92	54.36	53.58	52.61	51.72	50.99
6/24	54.72	54.03	53.38	52.32	51.44	50.69
9/21	54.56	53.97	53.14	52.24	51.21	50.51
12/18	54.38	53.81	53.03	52.02	51.10	50.40

Table 16. Surface Tension Parameters (Temperature Based) K_1 and K_2 for the (MAE (1) + AMP (2) + H_2O (3)) Ternary System

	K_1	K_2
w_1/w_2	(mN·m^{-1})	(mN·m^{-1}·K^{-1})
3/27	93.9105	0.1564
6/24	95.5606	0.1605
9/21	98.1688	0.1680
12/18	99.1204	0.1700
	[a](AAD) % correlation	0.29 %

[a]

$$\text{AAD}\ \% = [\sum_n (\sigma_{\text{m,cal}} - \sigma_{\text{m,exp}})/\sigma_{\text{m,exp}}]/n\cdot 100$$

Table 17. Surface Tension Parameters (Temperature Based) K_1 and K_2 for the (MAE (1) + MDEA (2) + H_2O (3)) Ternary System

	K_1	K_2
w_1/w_2	(mN·m^{-1})	(mN·m^{-1}·K^{-1})
3/27	103.6926	0.1631
6/24	104.2070	0.1656
9/21	104.8475	0.1682
12/18	104.0068	0.1659
	[a](AAD) % correlation	0.16 %

[a]

$$\text{AAD}\ \% = [\sum_n (\sigma_{\text{m,cal}} - \sigma_{\text{m,exp}})/\sigma_{\text{m,exp}}]/n\cdot 100$$

The measured surface tensions of solution of (MAE (1) + AMP (2) + H_2O (3)) and (MAE (1) + MDEA (2) + H_2O (3)) are presented in Tables 14 and 15 where *w* is the mass fraction of individual amine present in the solution. The surface tension of the ternary mixture (MAE (1) + AMP (2) + H_2O (3)) increases with decreasing temperature and increasing mass fraction of MAE in the mixture. The surface tension of the ternary mixture (MAE (1) + MDEA (2) + H_2O (3)) increases with decreasing temperature and decreasing mass fraction of MAE in the mixture. There is a small variation in surface tension with the changing relative amine composition for both systems.

The experimental surface tension data of ternary (MAE (1) + AMP (2) + H_2O (3)) and (MAE (1) + MDEA (2) + H_2O (3)) have been correlated with respect to temperature by eq 7 with correlation deviations of 0.29 % and 0.16 %, respectively. The fit parameters for the (MAE (1) + AMP (2) + H_2O (3)) and (MAE (1) + MDEA (2) + H_2O (3)) systems are presented in Tables 16 and 17, respectively. Figure 5 shows the experimental and correlated surface tension values of the (MAE (1) + AMP (2) + H_2O (3)) system with respect to temperature for

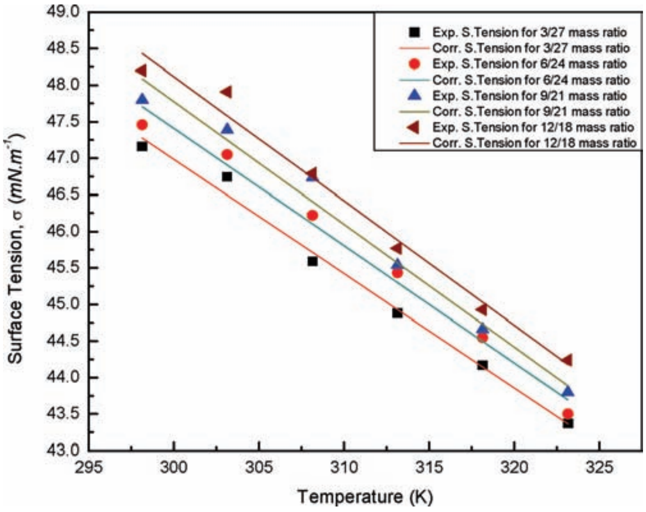

Figure 5. Surface tension of the ternary (MAE (1) + AMP (2) + H_2O (3)) system at various amine (MAE/AMP) ratios with varying temperature. Correlated surface tensions are calculated using eq 7.

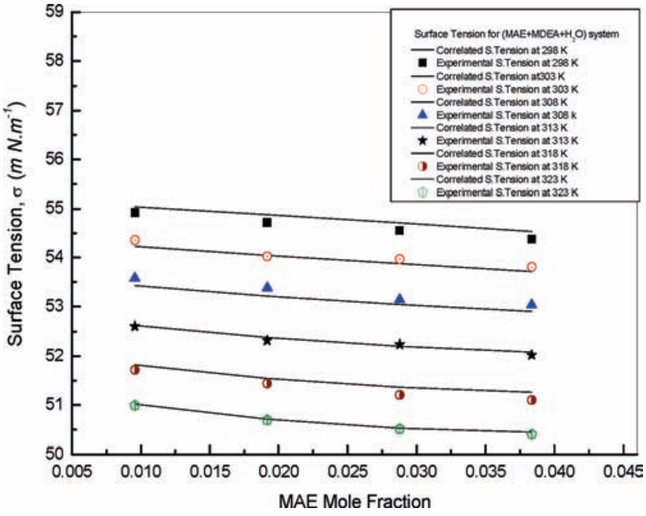

Figure 6. Surface tension of the ternary (MAE (1) + MDEA (2) + H_2O (3)) system at various temperatures with varying amine (MAE/MDEA) ratios. Correlated surface tensions are calculated using eq 8.

various blends of aqueous MAE/AMP. Figure 6 shows the experimental and correlated surface tension of the ternary (MAE (1) + MDEA (2) + H_2O (3)) system at various temperatures with varying amine (MAE/MDEA) composition. The relative deviation between experimental and estimated surface tensions was never greater than 0.3 % (using eq 7).

Conclusions

The densities and surface tensions of four mixtures for each of the ternary systems (MAE (1) + AMP (2) + H_2O (3)) and (MAE (1) + MDEA (2) + H_2O (3)) were measured over the temperature range of (298.15 to 323.15) K for (MAE)/(MDEA or AMP) ratios of 3/27, 6/24, 9/21, and 12/18. The correlated densities and surface tensions with respect to temperature and composition are in excellent agreement with the experimental data.

Supporting Information Available:

Three supplementary Tables (S1−S3) containing excess molar volumes of the (MAE (1) + H_2O (2)), (MDEA (1) + H_2O (2)), and (AMP (1) + H_2O (2)) binary systems. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Sartori, G.; Savage, D. W. Sterically hindered amines for CO_2 removal from gases. *Ind. Eng. Chem. Fundam.* **1983**, *22*, 239–249.

(2) Rebolledo-Libreros, M. E.; Trejo, A. Gas solubility of H_2S in aqueous solutions of *N*-methyldiethanolamine and diethanolamine with 2-amino-2-methyl-1-propanol at 313, 343 and 393 K in the range 2.5−1036 kPa. *Fluid Phase Equilib.* **2004**, *224*, 83–88.

(3) Alvarez, E.; Gomez-Diaz, D.; Rubina, M. D. L.; Navaza, J. M. Densities and viscosities of aqueous ternary mixtures of 2-(Methylamino)ethanol and 2-(Ethylamino)ethanol with Diethanolamine, Triethanolamine, N-Methyldiethanolamine, or 2-Amino-1-methyl-1-propanol from 298.15 to 323.15 K. *J. Chem. Eng. Data* **2006**, *51*, 955–962.

(4) Alvarez, E.; Gomez-Diaz, D.; Rubina, M. D. L.; Navaza, J. M. Surface Tension of aqueous binary mixtures of 2-(Methylamino)ethanol and 2-(Ethylamino)ethanol and Aqueous ternary mixtures of these amines with triethanolamine or *N*-Methyldiethanolamine from (298.15 to 323.15) K. *J. Chem. Eng. Data* **2008**, *53*, 318–321.

(5) Li, J.; Mundhwa, M.; Tontiwachuthikul, P.; Henni, A. Volumetric properties, viscosities, and refractive indices for aqueous 2-(Methylamino) ethanol solutions from (298.15 to 343.15) K. *J. Chem. Eng. Data* **2007**, *52*, 560–565.

(6) Henni, A.; Hromek, J. J.; Tontiwachuthikul, P.; Chakma, A. Volumetric properties and viscosities for aqueous AMP solutions from 25° C to 70° C. *J. Chem. Eng. Data* **2003**, *48*, 551–556.

(7) Al-Ghawas, H. A.; Hagewiesche, D. P.; Ruiz-Ibanez, G.; Sandall, O. C. Physicochemical properties important for carbon dioxide Absorption in aqueous Methyldiethanolamine. *J. Chem. Eng. Data* **1989**, *34*, 385–391.

Received for review September 16, 2009. Accepted August 8, 2010. The financial support by the Department of Science and Technology (DST), New Delhi, India, is gratefully acknowledged.

JE1002626