Viscosities of Single-Solute and Binary-Solute Aqueous Systems of Monoethanolamine, Diethanolamine, and 2-Amino-2-methyl-1-propanol

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The kinematic viscosities of binary solutions of monoethanolamine (MEA), diethanolamine (DEA), and 2-amino-2-methyl-1-propanol (AMP) with water and of ternary mixtures were measured at various concentrations (from 0 to up 2.0 mol·kg^{-1} at 0.5 mol·kg^{-1} intervals) and temperatures (from 293.1 K up to 323.1 K at 5.0 K intervals). Experimental viscosity data were correlated with concentration and temperature for single-solute and binary-solute solutions by means of empirical equations with deviations up to 1.2% and 1.9%, respectively.

Introduction

The removal of CO_2 from gaseous streams by absorption with chemical reaction in the liquid phase is usually employed both in the industry and as a method to retain atmospheric CO_2 to combat the greenhouse effect. Normally, aqueous solutions of amines are used to enhance the absorption rate of the process with respect to the physical absorption. These processes are carried out in aqueous single-solute or binary-solute solutions that produce an increase of the absorption enhancement factor.[1,2] The use of blended amines[3,4] or the sterically hindered amines[5,6] leads to a considerable improvement in absorption and a great savings in energy.The simultaneous presence of fine activated carbon particles and one or several amines in aqueous suspensions constitutes a system of considerable interest.[7−10]

The design of industrial absorption columns and the application of absorption models requires knowledge of the mass-transfer coefficients of the corresponding physical and chemical absorption processes. These data are commonly obtained from laboratory gas−liquid mass-transfer experiments. To calculate the required parameters from the experimental mass-transfer data, certain physical properties must be known, among them the viscosity of the liquid phase. In the literature few viscosity data have been reported as a systematic study with the concentration and temperature for these solutions of interest in the process of gas−liquid mass transfer. This paper reports measurements of kinematic viscosities of single-solute and binary-solute aqueous solutions of MEA, DEA, and AMP.

Experimental Section

Binary solutions of monoethanolamine (MEA), diethanolamine (DEA), and 2-amino-2-methyl-1-propanol (AMP) with water and of their ternary mixtures were made up at concentrations ranging from (0 to 2.0) mol·kg^{-1} (molality) at 0.5 mol·kg^{-1} intervals, both solutions of one or two solutes, and their viscosities were measured at temperatures ranging from 293.1 K to 323.1 K at 5.0 K intervals. MEA (>99% pure), DEA (>98.5% pure), and AMP (>95.5% pure) were Merck products. Water was distilled and desgassed. Solutions were made up by weighing of solutes and solvent on a Mettler AJ 150 balance precise to within ±0.0001 g, and in what follows their concentrations are expressed as molality (mol·kg^{-1} solvent); none deviated from the nominal value by as much as ±0.02%. All solutions were filtered before use.

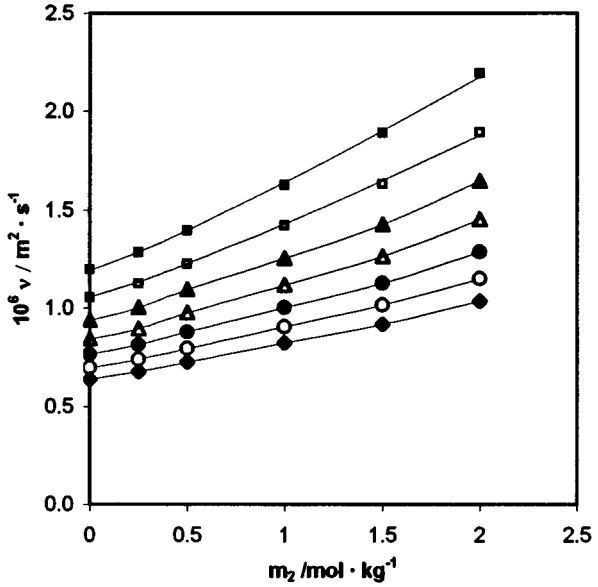

Figure 1. Kinematic viscosities of aqueous binary-solute systems with 1 mol·kg^{-3} MEA versus DEA concentration m_2 at various temperatures: 293.1 K (■); 298.1 K (□); 303.1 K (●); 308.1 K (○); 313.1 K (▲); 318.1 K (△); 323.1 K (♦).

The kinematic viscosities of the solutions at temperatures ranging from 293.1 K to 323.1 K in 5.0 K intervals were calculated from the transit time of the liquid meniscus through a capillary, measured to a precision of ±0.01 s in a Schott−Geräte AVS 350 automatic Ubbelohde viscosimeter. All measurements were quintuplicated; and values

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Table 1. Kinematic Viscosities of Monoethanolamine (1) + Diethanolamine (2) Aqueous Solutions at Various Molalities *m* and Temperatures *T*

	$10^6\nu$/m^2·s^{-1}					
T/K	m_2/mol·kg^{-1} = 0.0000	m_2/mol·kg^{-1} = 0.2500	m_2/mol·kg^{-1} = 0.5000	m_2/mol·kg^{-1} = 1.0000	m_2/mol·kg^{-1} = 1.5000	m_2/mol·kg^{-1} = 2.0000
			m_1/mol·kg^{-1} = 0.0000			
293.1	1.004	1.078	1.185	1.403	1.634	1.902
298.1	0.893	0.968	1.053	1.233	1.430	1.656
303.1	0.801	0.852	0.939	1.101	1.261	1.444
308.1	0.724	0.771	0.841	0.978	1.119	1.280
313.1	0.658	0.699	0.761	0.882	1.006	1.142
318.1	0.602	0.639	0.693	0.801	0.908	1.025
323.1	0.553	0.595	0.635	0.723	0.823	0.932
			m_1/mol·kg^{-1} = 0.2500			
293.1	1.044	1.138	1.226	1.442	1.705	1.971
298.1	0.926	1.006	1.081	1.264	1.487	1.717
303.1	0.827	0.900	0.963	1.118	1.309	1.499
308.1	0.747	0.810	0.867	0.999	1.162	1.324
313.1	0.680	0.736	0.783	0.900	1.038	1.181
318.1	0.622	0.671	0.712	0.816	0.934	1.060
323.1	0.572	0.616	0.652	0.744	0.846	0.956
			m_1/mol·kg^{-1} = 0.5000			
293.1	1.096	1.188	1.285	1.506	1.764	2.019
298.1	0.967	1.051	1.126	1.323	1.534	1.758
303.1	0.864	0.935	1.001	1.170	1.345	1.533
308.1	0.780	0.842	0.899	1.042	1.194	1.354
313.1	0.710	0.766	0.811	0.939	1.069	1.205
318.1	0.648	0.697	0.740	0.849	0.964	1.081
323.1	0.595	0.640	0.682	0.772	0.876	0.976
			m_1/mol·kg^{-1} = 1.0000			
293.1	1.195	1.283	1.394	1.626	1.889	2.194
298.1	1.052	1.124	1.227	1.421	1.632	1.893
303.1	0.939	1.003	1.094	1.255	1.427	1.650
308.1	0.844	0.897	0.977	1.117	1.264	1.453
313.1	0.766	0.815	0.879	1.004	1.129	1.287
318.1	0.698	0.739	0.797	0.905	1.017	1.151
323.1	0.639	0.677	0.726	0.824	0.920	1.036
			m_1/mol·kg^{-1} = 1.5000			
293.1	1.295	1.397	1.501	1.748	2.033	2.327
298.1	1.141	1.227	1.314	1.518	1.761	1.999
303.1	1.015	1.088	1.162	1.330	1.541	1.734
308.1	0.911	0.972	1.031	1.185	1.348	1.524
313.1	0.822	0.874	0.926	1.053	1.205	1.354
318.1	0.747	0.792	0.837	0.947	1.080	1.210
323.1	0.683	0.721	0.764	0.861	0.977	1.091
			m_1/mol·kg^{-1} = 2.0000			
293.1	1.405	1.508	1.632	1.879	2.181	2.521
298.1	1.234	1.320	1.424	1.631	1.880	2.161
303.1	1.094	1.167	1.255	1.447	1.640	1.869
308.1	0.984	1.042	1.117	1.266	1.444	1.637
313.1	0.882	0.939	1.005	1.129	1.287	1.445
318.1	0.798	0.849	0.907	1.017	1.147	1.292
323.1	0.731	0.773	0.824	0.920	1.034	1.159

deviating by more than 0.2% from the mean were discarded. Tridistilled water and 1-propanol were employed to calibrate the apparatus. The measured kinematic viscosities of both solvents from 293.1 K to 323.1 K all were within 0.2% of published values.[11,12] The temperature was controlled with a thermostated water bath with a precision of ±0.05 K.

Results

Tables 1−3 list the kinematic viscosities of the aqueous solutions of MEA + DEA, MEA + ADP, and DEA + AMP, respectively, from 293.1 K to 323.1 K and in the concentration range (0 to 2) mol·kg^{-1} for each solute. In all cases, at fixed concentration of solute *i*, the kinematic viscosity increases when the solute *j* concentration is increased. Moreover, the kinematic viscosity decreased with the temperature.

The experimental data presented of single-solute aqueous solutions were compared with the results reported by other authors in the range of concentration and temperatures employed. In this way, the maximum deviation between experimental data and the data obtained by correlations for kinematic viscosities of MEA solutions[13−15]

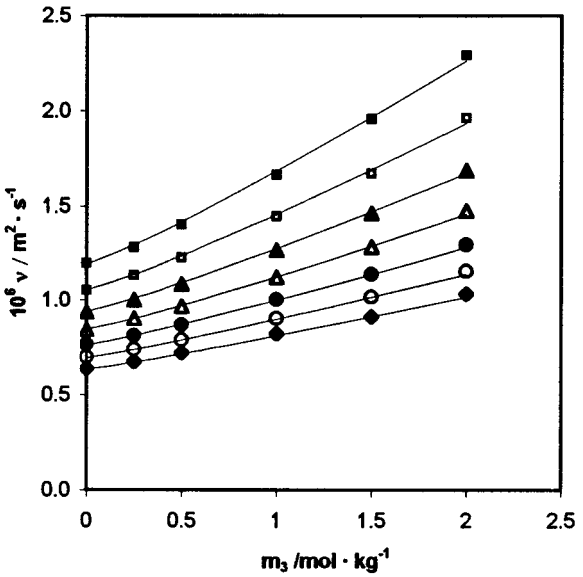

Figure 2. Kinematic viscosities of aqueous binary-solute systems with 1 mol·kg^{-3} MEA versus AMP concentration m_3 at various temperatures: 293.1 K (■); 298.1 K (□); 303.1 K (●); 308.1 K (○); 313.1 K (▲); 318.1 K (△); 323.1 K (♦).

Table 2. Kinematic Viscosities of Monoethanolamine (1) + 2-Amino-2-methyl-1-propanol (3) Aqueous Solutions at Various Molalities *m* and Temperatures *T*

	$10^6\nu$/m^2·s^{-1}					
T/K	m_3/mol·kg^{-1} = 0.0000	m_3/mol·kg^{-1} = 0.2500	m_3/mol·kg^{-1} = 0.5000	m_3/mol·kg^{-1} = 1.0000	m_3/mol·kg^{-1} = 1.5000	m_3/mol·kg^{-1} = 2.0000
			m_1/mol·kg^{-1} = 0.0000			
293.1	1.004	1.099	1.193	1.426	1.699	1.987
298.1	0.893	0.978	1.051	1.247	1.474	1.686
303.1	0.801	0.874	0.933	1.102	1.293	1.447
308.1	0.724	0.786	0.841	0.980	1.135	1.281
313.1	0.658	0.711	0.761	0.885	1.017	1.133
318.1	0.602	0.648	0.691	0.796	0.912	1.026
323.1	0.553	0.596	0.630	0.717	0.820	0.928
			m_1/mol·kg^{-1} = 0.2500			
293.1	1.044	1.135	1.242	1.478	1.761	2.062
298.1	0.926	1.003	1.094	1.283	1.523	1.765
303.1	0.827	0.893	0.968	1.128	1.329	1.522
308.1	0.747	0.806	0.869	1.002	1.171	1.335
313.1	0.680	0.729	0.789	0.899	1.040	1.180
318.1	0.622	0.667	0.713	0.822	0.930	1.053
323.1	0.572	0.611	0.654	0.749	0.838	0.947
			m_1/mol·kg^{-1} = 0.5000			
293.1	1.096	1.175	1.294	1.545	1.826	2.141
298.1	0.967	1.047	1.138	1.341	1.564	1.832
303.1	0.864	0.932	1.009	1.179	1.360	1.580
308.1	0.780	0.836	0.902	1.044	1.197	1.386
313.1	0.710	0.756	0.813	0.938	1.067	1.219
318.1	0.648	0.690	0.738	0.848	0.959	1.091
323.1	0.595	0.631	0.675	0.767	0.863	0.977
			m_1/mol·kg^{-1} = 1.0000			
293.1	1.195	1.280	1.401	1.665	1.956	2.293
298.1	1.052	1.132	1.228	1.445	1.670	1.962
303.1	0.939	1.003	1.085	1.266	1.463	1.687
308.1	0.844	0.903	0.966	1.123	1.283	1.474
313.1	0.766	0.813	0.871	1.005	1.138	1.296
318.1	0.698	0.739	0.790	0.904	1.018	1.155
323.1	0.639	0.677	0.722	0.823	0.916	1.035
			m_1/mol·kg^{-1} = 1.5000			
293.1	1.295	1.408	1.519	1.785	2.093	2.444
298.1	1.141	1.234	1.329	1.538	1.803	2.084
303.1	1.015	1.092	1.172	1.341	1.560	1.786
308.1	0.911	0.974	1.044	1.185	1.366	1.555
313.1	0.822	0.875	0.937	1.058	1.210	1.370
318.1	0.747	0.792	0.848	0.950	1.081	1.214
323.1	0.683	0.720	0.771	0.859	0.972	1.091
			m_1/mol·kg^{-1} = 2.0000			
293.1	1.405	1.497	1.638	1.919	2.252	2.593
298.1	1.234	1.311	1.434	1.658	1.926	2.196
303.1	1.094	1.159	1.258	1.445	1.662	1.881
308.1	0.984	1.032	1.118	1.271	1.453	1.631
313.1	0.882	0.926	1.000	1.133	1.284	1.432
318.1	0.798	0.838	0.904	1.016	1.146	1.270
323.1	0.731	0.764	0.820	0.920	1.029	1.137

was 2.5% and that with respect to other experimental data[16] was 2.2%. For DEA solutions deviations with respect to data of correlations[13−15,17] were less than 2.4% and 1.8% for other experimental data.[16,18] Finally, for AMP solutions was obtained 3.0% for data of correlation[13] and 2.3% with respect to other experimental data.[19]

The viscosity data for each single-solute solution were correlated with the molality m_i or m_j, and absolute temperature T was expressed by means of the empirical equation

$$\Delta\nu_i/(\mathrm{m^2\cdot s^{-1}}) = \nu_i - \nu_0 = Am^B \exp(C/T^D) \qquad (1)$$

and for binary-solute systems the equation is

$$\nu_{i+j}/(\mathrm{m^2\cdot s^{-1}}) = \nu_0 + \Delta\nu_i + \Delta\nu_j + Em_im_j \exp(F/T^D) \quad (2)$$

where ν_0 is the kinematic viscosity of water obtained from the literature[11] for each temperature, the parameter D = 2 (obtained by optimization for all systems), and A, B, C, E, and F are parameters to optimize.

Tables 4 and 5, respectively, show the values of optimized parameters A, B, and C for single-solute systems and the values of parameters E and F for binary-solute

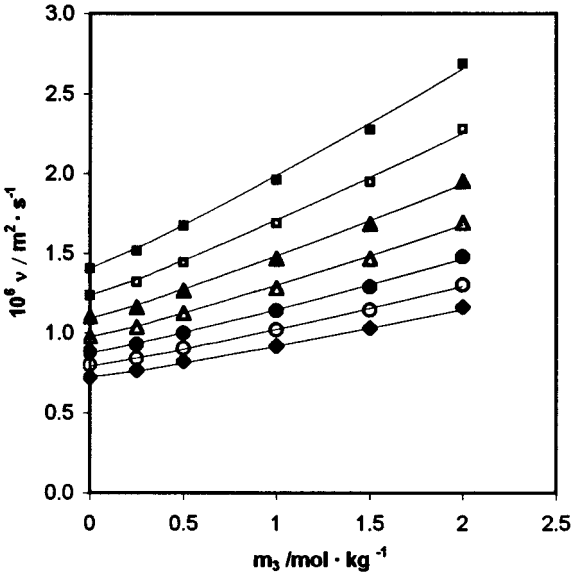

Figure 3. Kinematic viscosities of aqueous binary-solute systems with 1 mol·kg^{-3} DEA versus AMP concentration m_3 at various temperatures: 293.1 K (■); 298.1 K (□); 303.1 K (●); 308.1 K (○); 313.1 K (▲); 318.1 K (△); 323.1 K (♦).

Table 3. Kinematic Viscosities of Diethanolamine (2) + 2-Amino-2-methyl-1-propanol (3) Aqueous Solutions at Various Molalities *m* and Temperatures *T*

	$10^6\nu$/m^2·s^{-1}					
T/K	m_3/mol·kg^{-1} = 0.0000	m_3/mol·kg^{-1} = 0.2500	m_3/mol·kg^{-1} = 0.5000	m_3/mol·kg^{-1} = 1.0000	m_3/mol·kg^{-1} = 1.5000	m_3/mol·kg^{-1} = 2.0000
			m_2/mol·kg^{-1} = 0.0000			
293.1	1.004	1.099	1.193	1.426	1.699	1.987
298.1	0.893	0.978	1.051	1.247	1.474	1.686
303.1	0.801	0.874	0.933	1.102	1.293	1.447
308.1	0.724	0.786	0.841	0.980	1.135	1.281
313.1	0.658	0.711	0.761	0.885	1.017	1.133
318.1	0.602	0.648	0.691	0.796	0.912	1.026
323.1	0.553	0.596	0.630	0.717	0.820	0.928
			m_2/mol·kg^{-1} = 0.2500			
293.1	1.078	1.196	1.294	1.548	1.835	2.144
298.1	0.968	1.056	1.137	1.351	1.583	1.827
303.1	0.852	0.938	1.010	1.184	1.379	1.577
308.1	0.771	0.844	0.908	1.052	1.212	1.378
313.1	0.699	0.764	0.823	0.941	1.074	1.217
318.1	0.639	0.695	0.742	0.850	0.960	1.085
323.1	0.595	0.635	0.676	0.770	0.863	0.974
			m_2/mol·kg^{-1} = 0.5000			
293.1	1.185	1.293	1.403	1.697	1.978	2.321
298.1	1.053	1.135	1.231	1.468	1.696	1.986
303.1	0.939	1.016	1.087	1.283	1.471	1.708
308.1	0.841	0.905	0.970	1.131	1.292	1.487
313.1	0.761	0.814	0.873	1.005	1.150	1.309
318.1	0.693	0.744	0.792	0.901	1.025	1.163
323.1	0.635	0.674	0.722	0.812	0.927	1.042
			m_2/mol·kg^{-1} = 1.0000			
293.1	1.403	1.512	1.672	1.959	2.276	2.698
298.1	1.233	1.317	1.441	1.687	1.948	2.280
303.1	1.101	1.163	1.267	1.465	1.681	1.950
308.1	0.978	1.037	1.124	1.282	1.466	1.690
313.1	0.882	0.931	1.001	1.141	1.290	1.477
318.1	0.801	0.843	0.907	1.021	1.146	1.304
323.1	0.723	0.768	0.824	0.922	1.031	1.166
			m_2/mol·kg^{-1} = 1.5000			
293.1	1.634	1.790	1.931	2.261	2.651	3.098
298.1	1.430	1.555	1.667	1.934	2.245	2.608
303.1	1.261	1.363	1.451	1.673	1.918	2.219
308.1	1.119	1.205	1.278	1.463	1.667	1.907
313.1	1.006	1.074	1.141	1.285	1.469	1.658
318.1	0.908	0.963	1.021	1.148	1.297	1.460
323.1	0.823	0.870	0.922	1.031	1.160	1.303
			m_2/mol·kg^{-1} = 2.0000			
293.1	1.902	2.055	2.216	2.622	3.049	3.497
298.1	1.656	1.785	1.906	2.231	2.573	2.843
303.1	1.444	1.552	1.653	1.921	2.195	2.483
308.1	1.280	1.370	1.452	1.675	1.891	2.138
313.1	1.142	1.216	1.287	1.472	1.657	1.850
318.1	1.025	1.086	1.150	1.306	1.459	1.619
323.1	0.932	0.980	1.035	1.170	1.303	1.432

Table 4. Parameters (*A*, *B*, and *C*) of Eq 1 and Maximum ϵ_{max} and Average ϵ_{ave} Deviations for the Dependence of the Kinematic Viscosity of the Listed (MEA, DEA, and AMP Aqueous Solutions) Systems on the Solute Concentration at Various Temperatures

system	10^9A/m^2·s^{-1}·(mol·kg)$^{-B}$	*B*	$10^{-5}C$/K^{-2}	ϵ_{max}/%	ϵ_{ave}/%
MEA	1.8558	1.0857	3.9668	0.56	0.24
DEA	3.0510	1.1433	4.1938	1.13	0.49
AMP	1.8069	1.1356	4.7147	1.21	0.69

Table 5. Parameters (*E* and *F*) of Eq 2 and Maximum ϵ_{max} and Average ϵ_{ave} Deviations for the Dependence of the Kinematic Viscosity of the Listed (MEA + DEA, MEA + AMP, and DEA + AMP Aqueous Solutions) Systems on the Solute Concentration at Various Temperatures

system	$10^{12}E$/m^2·s^{-1}·(mol·kg)$^{-2}$	$10^{-5}F$/K^{-2}	ϵ_{max}/%	ϵ_{ave}/%
MEA + DEA	7.7623	7.4602	1.65	0.48
MEA + AMP	2.4284	8.6070	1.95	0.83
DEA + AMP	29.8853	7.2782	1.89	0.82

systems. Additionally, in each table the maximum and average deviations between the experimental and predicted values employing eq 1 and eq 2 are shown.

Figures 1−3 show experimental data and the fitted values of some systems, as examples, particularly, binary-solute systems with one solute with concentration 1 *m* and the other variable (MEA (1 *m*) + DEA; MEA (1 *m*) + AMP; and DEA (1 *m*) + AMP). In all cases, the cited behavior of kinematic viscosity with temperature and solute concentration is observed; furthermore, the proposed correlation is satisfactory in all ranges of concentration and temperature assayed.

Literature Cited

(1) Rinker, E.; Ashour, S.; Sandall, O. Kinetics and Modelling of Carbon Dioxide Absorption into Aqueous Solutions of *N*-Methyldiethanolamine. *Chem. Eng. Sci.* **1995**, *50*, 755−768.

(2) Pani, F.; Gaunand, A.; Cadours, R.; Bouallou, Ch.; Richon, D. Kinetics of Absorption of CO_2 in Concentrated Aqueous Methyldiethanolamine Solutions in the Range 296 K to 343 K. *J. Chem. Eng. Data* **1997**, *42*, 353−359.

(3) Hagewiesche, D.; Ashour, S.; Al-Ghawas, H.; Sandall, O. Absorption of Carbon Dioxide into Aqueous Blends of Monoethanolamine and *N*-Methyldiethanolamine. *Chem. Eng. Sci.* **1995**, *50*, 1071−1079.

(4) Dawodu, O.; Meisen, A. Degradation of Alkanolamine Blends by Carbon Dioxide. *Can. J. Chem. Eng.* **1996**, *74*, 960−966.

(5) Messaoudi, B.; Sada, E. Absorption of Carbon Dioxide into Loaded Aqueous Solutions of 2-Amino-2-Methyl-1-Propanol. *J. Chem. Eng. Jpn.* **1996**, *29*, 534−537.

(6) Xu, S.; Wang, Y.; Otto, F.; Mather, A. Kinetics of Reaction of Carbon Dioxide with 2-Aminio-2-Methyl-1-Propanol Solutions. *Chem. Eng. Sci.* **1996**, *51*, 841−850.
(7) Py, X.; Roizard, C.; Bergault, J.; Mideux, N. Physical and Chemical Mass Transfer Enhancement at Gas−Liquid Interface Due to Fine Catalyst Particles. *Trans. Chem. Eng.* **1995**, *73*, 253−259.
(8) Saha, A.; Bondyopadhyay, S.; Biswas, A. Absorption of Carbon Dioxide in Alkanolamines in the Presence of Fine Activated Carbon Particles. *Chem. Eng. Sci.* **1995**, *50*, 3587−3593.
(9) Vázquez, G.; Chenlo, F.; Vázquez, M. J.; Del Rio, A. Enhancement of CO_2 Absorption in a Stirred Tank in the Presence of Suspended Particles. *Proceeding of 12th International Congress of Chemical and Process Engineering*; Process Engineering Pub.: Prague (Czech Republic), 1996.
(10) Vázquez, G.; Chenlo, F.; Vázquez, M. J. Absorption of CO_2 by Aqueous Solutions of Amines Containing Activated Carbon Particles. *Proceeding 2nd European Congress of Chemical Engineering*, Paris (France), 1999; Société Française de Génie des Procédés: Nancy (France), 1999.
(11) Marsh, K. N. *Recommended Reference Materials for the Realization of Physicochemical Properties*; Blackwell Scientific Publications: Oxford, 1987.
(12) Vargaftik, N. B. *Tables of the Termophysical Properties of Liquids and Gases*, 2nd ed.; Hemisphere: Washington, DC, 1975.
(13) Littel, R. J.; Versteeg, G. F.; van Swaaij, W. P. M. Solubility and Diffusivity Data for the Absorption of COS, CO_2, and N_2O in Amine Solutions. *J. Chem. Eng. Data* **1992**, *37*, 39−45.
(14) Versteeg, G. F.; van Swaaij, W. P. M. Solubility and Diffusivity of Acid Gases (CO_2, N_2O) in Aqueous Alkanolamine Solutions. *J. Chem. Eng. Data* **1988**, *33*, 29−34.
(15) Weiland, R. H.; Dingman, J. C.; Cronin, D. B.; Browning, G. J. Density and Viscosity of Some Partially Carbonated Aqueous Alkanolamine Solutions and Their Blends. *J. Chem. Eng. Data* **1998**, *43*, 378−382.
(16) Snijder, E. D.; te Riele, M. J. M.; Versteeg, G. F.; van Swaaij, W. P. M. Diffusion Coefficients of Several Aqueous Solutions. *J. Chem. Eng. Data* **1993**, *38*, 475−480.
(17) Teng, T. T.; Maham, Y.; Hepler, L. G.; Mather, A. E. Viscosity of Aqueous Solutions of *N*-Methyldiethanolamine and of Diethanolamine. *J. Chem. Eng. Data.* **1994**, *39*, 290−293.
(18) Rinker, E. B.; Oelschlager, D. W.; Colussi, A. T.; Henry, K. R.; Sandall, O. C. Viscosity, Density, and Surface Tension of Binary Mixtures of Water and *N*-Methyldiethanolamine and Water and Diethanolamine and Tertiary Mixtures of These Amines with Water over the Temperature Range 20−100 °C. *J. Chem. Eng. Data* **1994**, *39*, 392−395.
(19) Saha, A. K.; Bondyopadhyay, S. S.; Biswas, A. K. Solubility and Diffusivity of N_2O and CO_2 in Aqueous Solutions of 2-Amino-2-methyl-1-propanol. *J. Chem. Eng. Data* **1993**, *38*, 78−82.

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