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Densities, Viscosities and Excess Properties for Dimethyl Sulfoxide with Diethylene Glycol and Methyldiethanolamine at Different Temperatures

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Abstract: Densities and viscosities of the binary systems dimethylsulfoxide with diethylene glycol and methyldiethanolamine were measured at temperatures ranging from 293.15 to 313.15 K, at atmospheric pressure and over the entire composition range. The experimental density data was correlated as a function of composition using Belda's and Herraez's equations, and as a function of temperature and composition using the models of Emmerling et al. and Gonzalez-Olmos-Iglesias. The viscosity results were fitted to the Grunberg-Nissan, Heric-Brewer, Wilson, Noda, and Ishida and Eyring-NRTL equations. The values of viscosity deviation ($\Delta\eta$), excess molar volume (V^E), partial molar volumes ($\overline{V_1}$ and $\overline{V_2}$) and apparent molar volume ($V_{\varphi,1}$ and $V_{\varphi,2}$) were determined. The excess functions of the binary systems were fitted to the polynomial equations. The values of thermodynamic functions of activation of viscous flow were calculated and discussed.

Keywords: density; viscosity; excess molar volume; viscosity deviation; thermodynamic functions of activation

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1. Introduction

The removal of acidic gases or liquids such as carbon dioxide (CO_2), sulfur dioxide (SO_2), hydrogen sulfide (H_2S), carbonyl sulfide (COS) and carbon disulfide (CS_2) from natural settings, refineries, synthesis gas streams and petrochemicals are of increasing importance as environmental protection becomes more and more serious [1]. It is a significant operation in gas processing to eliminate acid compounds by means of various processes, among which is gas absorption by chemical solutions such as alkanolamines (monoethanolamine, diethanolamine, diisopropanolamine, or methyldiethanolamine) [2]. The importance of basic physicochemical properties for the density and viscosity data is an indispensable requirement over a broad range of temperatures for the absorption and desorption processes of SO_2 [3].

Dimethyl sulfoxide (DMSO) was used intensively in SO_2 absorption because of its low volatility and good affinity with SO_2 [4,5]. The physicochemical properties of solutions of glycols are useful, since such solutions are used in several processes in the pharmaceutical, petroleum, cosmetic, oil and food industries [6]. Binary solution of DMSO with glycols may attract attention due to the possible intermolecular interplay of S=O group in DMSO with –OH group in glycol [7].

In this work, the densities and viscosities of binary systems of dimethyl sulfoxide (DMSO) + diethylene glycol (DEG) or methyldiethanolamine (MDEA) were measured at temperatures between 293.15 and 313.15 K, over the entire composition range and at atmospheric pressure. Investigations into the literature have shown that these systems have been examined but not in the same conditions. Tsierkezos et al. [6] reported the values of densities for diethylene glycol with dimethylsulfoxide at 298.15 K and Naidu et al. [8] investigated the densities and viscosities of diethylene glycol with dimethyl sulfoxide at 308.15 K. Wang et al. [1] studied densities of binary mixtures of dimethyl

sulfoxide with methyldiethanolamine at atmospheric pressure with temperatures ranging from 293.15 to 363.15 K. Wang et al. [9] studied the densities and viscosities of diethylene glycol + dimethyl sulfoxide solutions in the temperature range 298.15–313.15 K.

The present work was mainly focused on investigating density and viscosity data of binary solutions of DEG + DMSO and MDEA + DMSO at T = 293.15, 298.15, 303.15, 308.15, and 313.15 K for the whole composition range. From our experimental data, excess molar volumes and viscosity deviations were calculated and correlated with the polynomial equations. The thermodynamic functions of activation of viscous flow have been estimated from the experimental values. Five equations were tested to correlate viscosity of the binary mixtures.

2. Materials and Methods

2.1. Materials

The chemical DMSO (mass ≥99.5%, CAS 67-68-5, water content ≤0.05%) was obtained from Merck, DEG (mass ≥99%, CAS 111-46-6, water content ≤1%) was supplied by Chemical Company and MDEA (mass ≥99%, CAS 105-59-9, water content ≤1%) was purchased from Chemical Company. In order to reduce the influence of water on the experiment, the chemicals DEG and MDEA were dried over molecular sieves (Fluka type 4 Å), and their effective component content was determined by means of gas chromatography. All specification of chemical samples is listed in Table 1. The measurements were made at atmospheric pressure, p = 0.1 MPa, which was measured in our laboratory by a mercury barometer with an uncertainty of ±0.002 MPa.

Table 1. Specification of chemical samples.

Chemical Name	Chemical Formula	Source	Mass Fraction Purity	Isolation Method
DMSO	C_2H_6OS	Merck	99.5%	None
DEG	$C_4H_{10}O_3$	Chemical Company	≥99.3%	Desiccation [a] and Degasification [b]
MDEA	$C_5H_{13}NO_2$	Chemical Company	≥99.3%	Desiccation [a] and Degasification [b]

[a] Molecular sieve type 4Å. [b] Ultrasound.

2.2. Measurements and Method Analysis

The binary solutions were prepared by weighing using an analytical balance (Adventurer Pro AV 264CM model) at atmospheric pressure and ambient temperature with a precision of $\pm 10^{-4}$ g. The uncertainty for the mixtures'mole fraction was less than 0.0006.

Densities of pure liquids and their mixtures were determined with an Anton Paar digital vibrating U-tube densimeter (model DMA 500). The temperature was determined with an integrated Pt100 platinum thermometer together with a Peltier element. The stated repeatability for density and temperature measurements by the manufacturer was 0.0002 g·cm^{-3} and 0.1 K respectively. The densimeter was calibrated with bidistilled and degassed water before and after each of the density measurements. The combined expanded uncertainty of the densities is estimated within 0.0015 g·cm^{-3} with a 0.95 level of confidence for the present work. Expanded uncertainty of the excess volume is estimated to be 0.04 cm^3·mol^{-1} (0.95 confidence level).

Viscosities of the pure compounds and of the binary solutions were determined with an Ubbelohde kinematic, viscosity measuring unit ViscoClock (Schott-Gerate GmbH) that was kept in a vertical position in a thermostatic bath (U-10 Freital). The temperature was controlled with a precision of ±0.05 K.

The kinematic viscosity was calculated using the equation:

$$\nu = At - (B/t) \quad (1)$$

where ν is the kinematic viscosity and t is the flow time, A and B are characteristic constants of the viscometer. The constants A and B were determined by taking doubly distilled water

and benzene (Merck, mole fraction purity ≥0.995) as the calibrating liquids. The accuracy of time measurement is ±0.01 s. The dynamic viscosity was determined using the equation:

$$\eta = \nu\rho \quad (2)$$

where ρ is the density of the liquid.

Each value of the viscosity was the average of five measurements (the measurements refer to the uncertainty values within ±0.02 s). The combined relative expanded uncertainty of the dynamic viscosity was estimated to be 5%. Expanded uncertainties in the deviation viscosity was estimated to be 0.06 mPa·s (0.95 of confidence).

3. Results

3.1. Density and Viscosity

The experimental densities and viscosities for pure DMSO, DEG and MDEA in the temperature range from 293.15 to 313.15 K are found to be in good agreement with reported values in the literature and comparison of these values is reported in Table 2.

DMSO density values reported in the literature [1,6,9–16] differ from our experimental data with a maximum of 0.2% and viscosity values reported in the literature [3,12,17–21] differ with a maximum of 2.5%. For DEG, density values found in the literature [1,9,22–28] differ with a maximum of 0.2% and for MDEA [1,29–34] they differ by less than 0.07%. Viscosity values reported in the literature differ from our results by a maximum of 2.3% for DEG [26,28] and a maximum of 2.1% for MDEA [29–31,35–37]. Viscosity values of DMSO and DEG reported by Wang et al. [9] differ by more than 30% compared with our results. These differences can be attributed to the different purity of the reagents used.

Table 2. Experimental and literature values of density (ρ) and viscosity (η) of the pure components in the temperature range from 293.15 to 313.15 K.

Component	T/(K)	ρ/(g·cm^{-3})		η/(mPa·s)	
		This Work	Lit. Value	This Work	Lit. Value
DMSO	293.15	1.1002	1.1002 [10] 1.10053 [11] 1.100865 [1] 1.0955 [12] 1.0954 [13] 1.09530 [6] 1.0946 [9] 1.0904 [12] 1.0900 [14] 1.0888 [9] 1.090812 [1] 1.0854 [12] 1.08573 [15] 1.0831 [9] 1.0807 [12] 1.08024 [16] 1.0785 [9] 1.080770 [1]	2.271	2.245 [17] 2.2255 [18] 2.00 [12] 2.025 [19] 1.40 [9] 1.84 [12] 1.843 [20] 1.21 [9]
	298.15	1.0952		2.021	1.69 [3] 1.6689 [21] 1.12 [9]
	303.15	1.0902		1.843	1.5351 [21] 1.52 [12] 1.00 [9]
	308.15	1.0853		1.710	
	313.15	1.0803		1.525	

Table 2. *Cont.*

Component	T/(K)	ρ/(g·cm^{-3})		η/(mPa·s)	
		This Work	Lit. Value	This Work	Lit. Value
DEG	293.15	1.1185	1.11705 [22] 1.116583 [23] 1.11303 [24]	33.270	-
	298.15	1.1148	1.11351 [25] 1.1128 [9]	26.865	27.15 [26] 27.5 [28]
	303.15	1.1108	1.11260 [1] 1.1098 [26] 1.10948 [27]	21.280	17.00 [9] 21.7 [28] 21.754 [26]
	308.15	1.1064	1.1093 [9] 1.1056 [26] 1.10629 [22]	17.291	12.4 [9] 17.26 [26] 16.9 [28]
	313.15	1.1024	1.1052 [9] 1.1023 [28] 1.102274 [23] 1.0998 [9]	14.117	10.4 [9] 14.2 [28] 8.19 [9]
MDEA	293.15	1.0409	1.0406 [29] 1.03966 [30] 1.0406 [1]	100.614	102.7 [31] 100.72 [29]
	298.15	1.0363	1.03556 [31] 1.037863 [32] 1.0331 [29]	74.927	74.81 [35] 57.57 [36]
	303.15	1.0326	1.03213 [30] 1.033017 [1]	57.582	57.615 [30]
	308.15	1.0288	1.02834 [31] 1.0303 [33] 1.0255 [29]	45.129	44.21 [37] 44.62 [29] 34.78 [36]
	313.15	1.0250	1.0250 [34] 1.025401 [1]	34.833	35.00 [37] 34.89 [29]

Standard uncertainties: $u(p)$ = 0.002 MPa, Expanded uncertainties: $Ur(\eta)$ = 5% and $U(\rho)$ = 0.0015 g·cm^{-3}(0.95 of confidence).

The experimental densities and viscosities for the binary systems DEG (1) + DMSO (2) and MDEA (1) + DMSO (2) are listed in Tables 3 and 4.

The density of binary system DEG (1) + DMSO (2) increases with the increase in DEG concentration, and for the system MDEA (1) + DMSO (2), density increases with the increase in DMSO concentration. Viscosity of binary system DEG (1) + DMSO (2) increases with the increase in DEG concentration, while for the system MDEA (1) + DMSO (2), it increases with the increase in MDEA concentration.

Table 3. Density values ρ/(g·cm^{-3}) as a functions of mole fraction in the temperature range from 293.15 to 313.15 K and at atmospheric pressure.

	T/(K)				
x_1	293.15	298.15	303.15	308.15	313.15
DEG (1) + DMSO (2)					
0.1062	1.1038	1.0988	1.0939	1.0889	1.0840
0.2007	1.1068	1.1019	1.0970	1.0921	1.0873
0.3034	1.1095	1.1049	1.1000	1.0951	1.0904
0.4110	1.1117	1.1072	1.1026	1.0978	1.0932
0.5108	1.1133	1.1090	1.1045	1.0998	1.0953
0.5972	1.1144	1.1102	1.1058	1.1012	1.0968
0.6955	1.1155	1.1114	1.1071	1.1025	1.0982
0.8096	1.1168	1.1128	1.1086	1.1041	1.0998
0.8819	1.1174	1.1135	1.1094	1.1049	1.1007

Table 3. *Cont.*

			T/(K)		
x_1	**293.15**	**298.15**	**303.15**	**308.15**	**313.15**
MDEA (1) + DMSO (2)					
0.1003	1.0899	1.0850	1.0803	1.0758	1.0712
0.1967	1.0808	1.0762	1.0718	1.0675	1.0631
0.2997	1.0725	1.0678	1.0635	1.0592	1.0550
0.4006	1.0654	1.0607	1.0565	1.0525	1.0483
0.5001	1.0595	1.0549	1.0509	1.0469	1.0428
0.6020	1.0544	1.0498	1.0459	1.0419	1.0379
0.6937	1.0504	1.0458	1.0419	1.0380	1.0341
0.7983	1.0465	1.0419	1.0381	1.0342	1.0303
0.8967	1.0436	1.0390	1.0353	1.0315	1.0277

Standard uncertainties: $u(x_1) = 6 \times 10^{-4}$, $u(p) = 0.002$ MPa, $u(T) = 0.1$ K; Expanded uncertainties: $U(\rho) = 0.0015$ g·cm^{-3} (0.95 of confidence).

Table 4. Viscosity values η/(mPa·s) as a functions of mole fraction in the temperature range from 293.15 to 313.15 K and at atmospheric pressure.

			T/(K)		
x_1	**293.15**	**298.15**	**303.15**	**308.15**	**313.15**
DEG (1) + DMSO (2)					
0.1062	3.110	2.877	2.520	2.281	2.049
0.2007	4.306	3.799	3.404	3.012	2.677
0.3034	5.792	5.115	4.334	3.883	3.383
0.4110	7.884	6.762	5.702	5.082	4.361
0.5108	10.198	8.630	7.072	6.337	5.394
0.5972	12.843	10.717	8.605	7.647	6.428
0.6955	16.372	13.356	10.796	9.502	7.951
0.8096	21.286	17.154	13.923	11.854	9.912
0.8819	24.874	20.097	16.220	13.703	11.431
MDEA (1) + DMSO (2)					
0.1003	5.745	4.859	4.170	3.680	3.173
0.1967	7.771	6.572	5.595	4.837	4.084
0.2997	10.987	9.100	7.542	6.364	5.508
0.4006	15.147	12.513	10.120	8.490	7.188
0.5001	21.152	16.806	13.775	11.189	9.673
0.6020	29.452	23.184	18.668	15.024	12.455
0.6937	40.462	30.372	24.585	19.888	15.955
0.7983	54.870	40.971	32.239	25.861	20.465
0.8967	71.350	53.015	40.925	32.869	25.494

Standard uncertainties: $u(x_1) = 6 \times 10^{-4}$, $u(p) = 0.002$ MPa, $u(T) = 0.05$ K; Expanded uncertainties: $Ur(\eta) = 5\%$.

The densities of binary solutions were represented as a function on composition by the following Belda [38] (Equation (3)) and Herraez [39] (Equation (4)) equations, and with composition and temperature using the Emmerling et al. [40] (Equation (5)) and Gonzalez-Olmos Iglesias [41] (Equation (6)) equations:

$$\rho = \rho_2 + (\rho_1 - \rho_2)x_1\left(\frac{1 + m_1(1 - x_1)}{1 + m_2(1 - x_1)}\right) \tag{3}$$

$$\rho = \rho_2 + (\rho_1 - \rho_2)x_1^{A + Bx_1 + Cx_1^2} \tag{4}$$

$$\rho = x_1\rho_1 + x_2\rho_2 + x_1x_2\left[\begin{array}{c} P_1 + P_2T + P_3T^2 + \left(P_4 + P_5T + P_6T^2\right)(x_1 - x_2) + \\ \left(P_7 + P_8T + P_9T^2\right)(x_1 - x_2)^2 \end{array}\right] \tag{5}$$

$$\rho = \sum_{i=0}^{2} A_i x^i \tag{6}$$

The temperature dependence of the densities (ρ_i) of each pure substance i involved in Equation (5) is expressed using the equation:

$$\rho_i = A_i + B_i T + C_i T^2 (i = 1,\ 2) \tag{7}$$

$$A_i = \sum_{j=0}^{2} A_{ij} T^i \tag{8}$$

The adjustable parameters of these equations (m_1, m_2, A, B, C, P_1–P_9, A_i, B_i, C_i and A_{ij}) were estimated using the experimental data and a nonlinear regression analysis employing the Levenberg-Marquardt algorithm [42]. Tables A1 and A2 in the Appendix A show the fitting parameters along with the standard deviation calculated with the equation:

$$\sigma = \left[\frac{\sum \left(X_{exp} - X_{calc} \right)^2}{m - n} \right]^{1/2} \tag{9}$$

where X is the value of the analyzed property, m is the number of data points, and n is the number of estimated parameters. Data presented in Tables A1 and A2 show that Herraez's equation offers the best results for correlating the density with composition, while Emmerling et al.'s equations the best for correlating the density of the binary solutions with composition and temperature.

In this paper, the one-parameter Grunberg–Nissan [43] and two-parameter Heric–Brewer [44], Wilson [45], Noda and Ishida [46] and Eyring-NRTL [47] models were used to represent the dependence of viscosity on the concentration of components in binary systems.

Grunberg and Nissan [43] proposed an equation based on a parameter:

$$ln\eta = x_1 ln\eta_1 + x_2 ln\eta_2 + x_1 x_2 d \tag{10}$$

The Heric–Brewer [44] equation with two parameters is:

$$ln\eta = x_1 ln\eta_1 + x_2 ln\eta_2 + x_1 lnM_1 + x_2 lnM_2 - ln(x_1 M_1 + x_2 M_2) + x_1 x_2 [\alpha_{12} + \alpha_{21}(x_1 - x_2)] \tag{11}$$

By the application of the Wilson [45] equation, viscosity of the binary mixtures can be expressed as:

$$\ln(\eta V) = x_1 \ln(\eta_1 V_1) + x_2 \ln(\eta_2 V_2) + x_1 \ln\left(x_1 + x_2 \frac{V_2}{V_1} \exp\left(-\frac{\lambda_{12}}{RT} \right) \right) + x_2 \ln\left(x_2 + x_1 \frac{V_1}{V_2} \exp\left(-\frac{\lambda_{21}}{RT} \right) \right) \tag{12}$$

Noda and Ishida [46] proposed the following semi-empirical equation:

$$\ln(\eta V) = x_1 \ln(\eta_1 V_1) + x_2 \ln(\eta_2 V_2) + x_1 x_2 \left[\frac{w_{12}}{x_2 + x_1 \exp\left(\frac{-w_{12}}{RT} \right)} + \frac{w_{21}}{x_1 + x_2 \exp\left(\frac{-w_{21}}{RT} \right)} \right] \tag{13}$$

The Eyring-NRTL [47] correlative model is given by the relation:

$$\ln(\eta V) = x_1 \ln(\eta_1 V_1) + x_2 \ln(\eta_2 V_2) + x_1 x_2 \left[\frac{\tau_{21} \exp(-\alpha \tau_{21})}{x_1 + x_2 \exp(-\alpha \tau_{21})} + \frac{\tau_{12} \exp(-\alpha \tau_{12})}{x_2 + x_3 \exp(-\alpha \tau_{12})} \right] \tag{14}$$

In these equations η, and η_1, η_2 are the dynamic viscosities of the liquid mixtures and of the pure components 1 and 2, x_1, x_2 are the mole fractions, M_1, M_2 are the molecular masses, V is the molar volume of the mixtures, V_1 and V_2 are the respective molar volumes of the pure components, T is the temperature, R is the gas constant; d, α_{12}, α_{21}, λ_{12}, λ_{21}, w_{12}, w_{21}, τ_{12} and τ_{12} are interaction parameters (viscosity coefficients) and reflect the non-ideality of the systems. The Eyring-NRTL equation has three parameters, including α, which is a measure of non-ideality of the systems, considered here to be fixed at 0.20 [48].

The parameters were estimated using the experimental viscosity data and a non-linear regression analysis employing the Levenberg-Marquardt algorithm [42].

The ability of these models to correlate viscosity data was tested by calculating the average absolute deviation (*ADD*%), between the experimental and calculated values, using the equation:

$$ADD\% = \frac{100}{m}\sum_{i=1}^{m}\left|\frac{\eta_{exp}-\eta_{cal}}{\eta_{exp}}\right|_i \quad (15)$$

where n is the number of experimental data points.

The presented data in Table A3 show that, for the DEG + DMSO system, ADD% values of maximum 2% are obtained for the Grunberg–Nissan and Noda–Ishida equations, and for the MDEA + DMSO system, the ADD% values for the two equations are very high (10%). For the Heric–Brewer equation, ADD% values of maximum 1.5% are obtained for the DEG + DMSO system and of maximum 6.0% in the case of the system formed by MDEA and DMSO. Approximately the same values are obtained for the Wilson equation. The Eyring–NRTL equation presents the best results, with ADD% values of maximum 0.8% for the DEG + DMSO system and maximum 3.3% for the MDEA + DMSO system. The higher ADD% in the MDEA + DMSO system than in the DEG + DMSO system can be attributed to higher deviation of the system from ideality. The obtained ADD% values lower than 5% are regarded to be acceptable for engineering calculations [49].

3.2. Excess Properties

3.2.1. Excess Molar Volume

The excess molar volumes have been calculated from the experimental densities data using the following equation:

$$V^E = \frac{[x_1M_1 + x_2M_2]}{\rho} - \left[\frac{x_1M_1}{\rho_1} + \frac{x_2M_2}{\rho_2}\right] \quad (16)$$

where x_1 and x_2 are the mole fractions of the components, M_1 and M_2 are the molar masses of components 1 and 2, ρ, ρ_1 and ρ_2 are the respective densities of the solution and of the pure components. The results of excess molar volumes are illustrated in Figures 1 and 2.

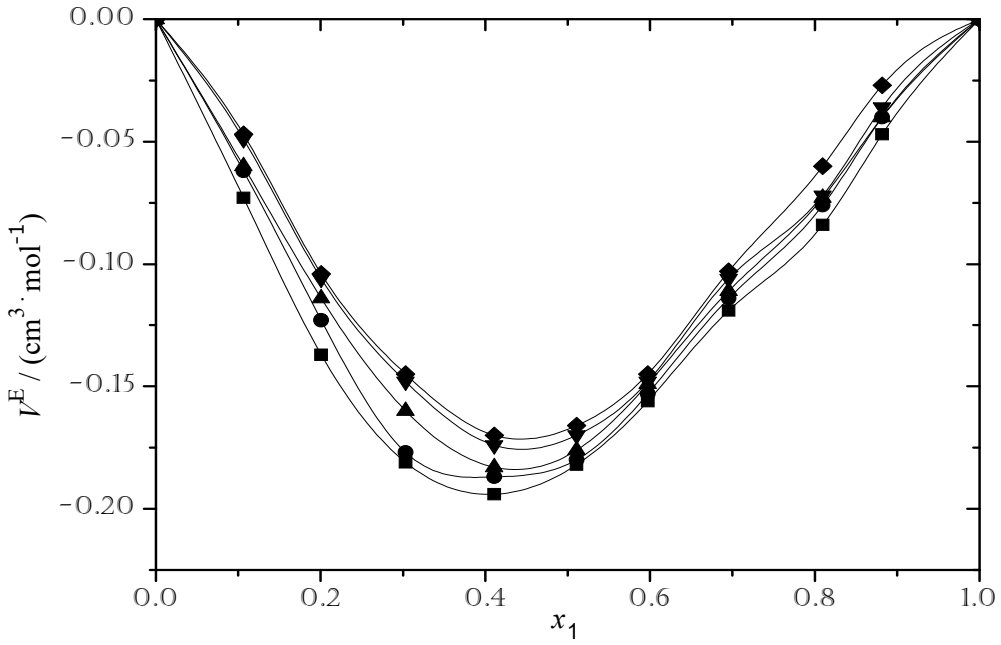


Figure 1. Excess molar volumes (V^E) with mole fraction for DEG (1) + DMSO (2) system at various temperatures: ■ 293.15 K; ● 298.15 K; ▲ 303.15 K; ▼ 308.15 K; ♦ 313.15 K.

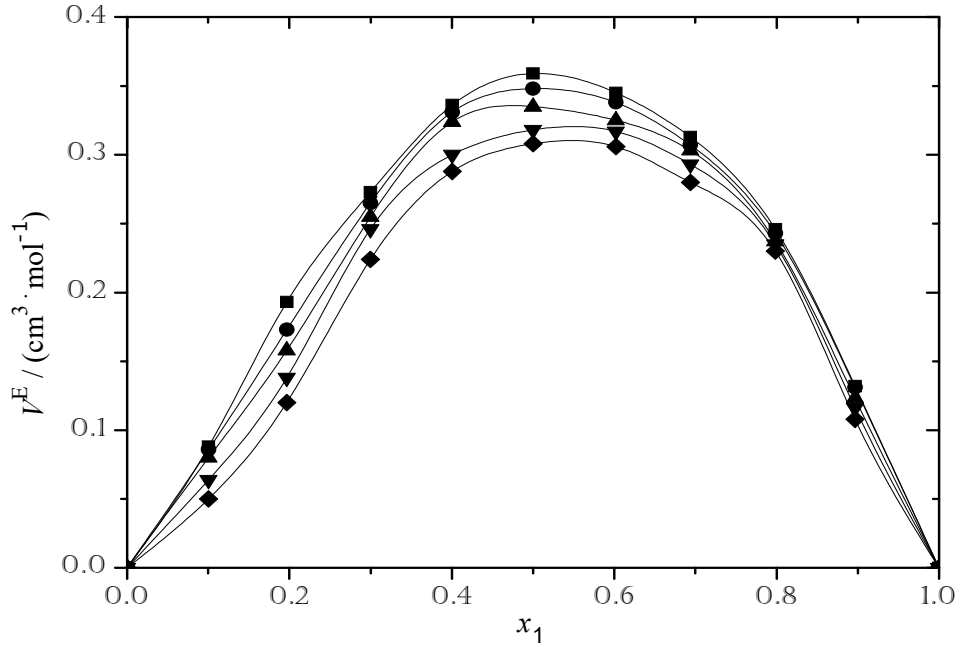


Figure 2. Excess molar volumes (V^E) with mole fraction for MDEA (1) + DMSO (2) system at various temperatures: ■ 293.15 K; ● 298.15 K; ▲ 303.15 K; ▼ 308.15 K; ♦ 313.15 K.

The experimental excess molar volumes are negative for the DEG + DMSO system and positive for the MDEA + DMSO binary system in the whole composition range at all temperatures.

The negative values are a consequence of the following effects: (1) strong intermolecular interactions due to the charge-transfer complex, dipole-dipole and dipole-induced dipole interactions, and H-bonding between unlike molecules finally leading to more efficient packing in the mixture than in the pure liquids; (2) structural effects which arise from suitable interstitial accommodation giving a more compact structure of solutions [50].

The negative excess volume values for the DEG + DMSO system indicated that the volume of the mixture was less than the sum of the volumes of the pure components, possibly due to contraction of the mixing volume caused by structural effects and strong intermolecular interactions between DEG and DMSO. Similar behavior was observed by Qiaoet al. [12] for the binary system tri-ethylene glycol + dimethyl sulfoxide.

The value became less negative with increasing temperature and arrived at the minimum around molar fraction 0.40 for DEG at all temperatures. These values indicate that there is a maximum volume contraction on mixing DEG with DMSO at a rate of 2:3.

Dimethyl sulfoxide is a highly polar solvent, not forming H-bond networks and tending toward self-association [1]. The molecular dynamics simulations demonstrated that in liquid DMSO, the H-bonds C–H . . . O=S are formed [51]. Amines are moderately polar but not as polar as alcohols of comparable molecular weights, and the polar nature of N–H results in the formation of hydrogen bonds with other amine molecules, or other H-bonding systems [52,53]. In addition, DMSO can provide an S=O group and the hydroxylamines can provide OH or C-H groups for interactions [54].

The positive values for the MDEA + DMSO system indicate that there were no strong intermolecular interactions. The positive values are due to expansion of the solution volume due to mixing caused by the hydrogen bond rupture and dispersive interactions between unlike molecules [55]. These positive values of excess volume for the MDEA + DMSO system can be explained by the fact that DMSO forms a strong associative structure and by the self-association of MDEA molecules. The effect of temperature on the excess volumes shows a systematic decrease with rising temperature.

3.2.2. Viscosity Deviation

The viscosity deviation ($\Delta\eta$) values were calculated from the experimental data of viscosity using the equation:

$$\Delta\eta = \eta - (x_1\eta_1 + x_2\eta_2) \quad (17)$$

where η is the dynamic viscosity of the mixture, x_1, x_2 and η_1, η_2 are the mole fractions and the dynamic viscosities of pure components 1 and 2, respectively.

The $\Delta\eta$ values are shown in Figures 3 and 4. The viscosity deviation values are negative at all investigated temperatures for both systems. The viscosity deviations may be generally explained by considering the following factors: (1) the difference in size and shape of the component molecules and the loss of dipolar association to a decrease in viscosity; (2) specific interactions between unlike molecules, such as H-bond formation, and charge transfer complexes may cause an increase in the viscosity of mixtures rather than in pure components. The former effect produces negative excess viscosity, and the latter effect produces positive excess viscosity [56]. For the DEG + DMSO system, the negative values of viscosity deviation indicate that the strength of specific interactions is not the only factor influencing the deviation in viscosity. The molecular size and shape of the components also play an important role [57]. For these systems the negative values of viscosity deviation indicate that the molecular size and shape of the components is a more important factor than the strength of specific interactions for determining the viscosity deviation.

The negative values of viscosity deviation for MDEA + DMSO corroborated with positive V^E values demonstrate that there were no strong molecular interactions.

The values of viscosity deviation decrease with an increase in temperature. An increase in temperature decreases self-association as well as the association between unlike components because of the increase in thermal energy [58].

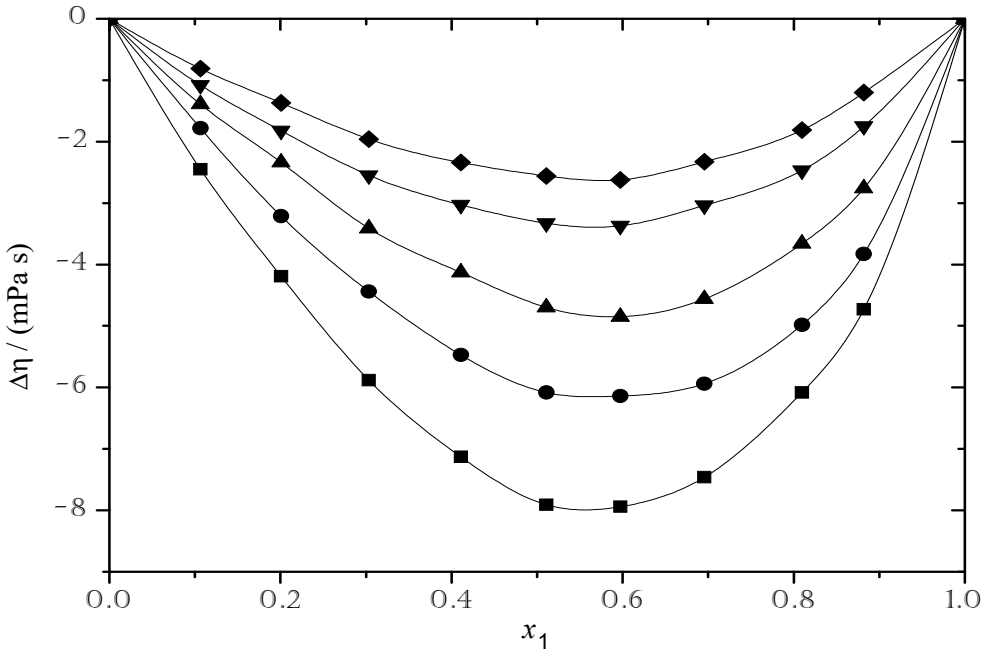


Figure 3. Viscosity deviation ($\Delta\eta$) with mole fraction for DEG (1) + DMSO (2) system at various temperatures: ■ 293.15 K; ● 298.15 K; ▲ 303.15 K; ▼ 308.15 K; ♦ 313.15 K.

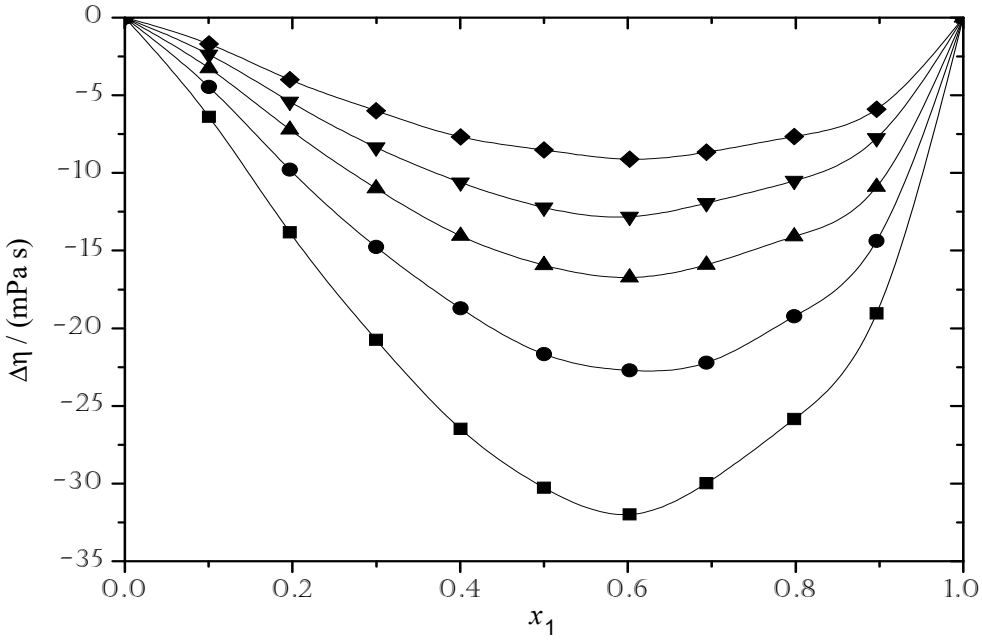


Figure 4. Viscosity deviation ($\Delta\eta$) with mole fraction for MDEA (1) + DMSO (2) system at various temperatures: ■ 293.15 K; ● 298.15 K; ▲ 303.15 K; ▼ 308.15 K; ♦ 313.15 K.

The excess molar volumes and viscosity deviationof the binary systems can be represented by the Redlich–Kister [59] (Equation (18)) and Hwang [60] (Equation (19)) equations:

$$X^E = x_1 x_2 \sum_{k=0}^{3} a_k (2x_1 - 1)^k \tag{18}$$

$$X^E = x_1 x_2 \left(A_0 + A_1 x_1^3 + A_2 x_2^3 \right) \tag{19}$$

where X^E represents either of the following properties: V^E, $\Delta\eta$; x_1, x_2 are the mole fractions of the components 1 and 2, respectively, and a_k, A_0, A_1, A_2 denote the polynomial coefficients.

In addition, the excess molar volumes were also correlated with the Myers and Scott [61] equation:

$$X^E = x_1 x_2 \frac{\sum_{k=0}^{p} B_k z_{12}^k}{1 + \sum_{l=1}^{m} C_l z_{12}^l} \tag{20}$$

where X^E is V^E and $z_{12} = x_1 - x_2$. B_k and C_l are polynomial coefficients.

The values of polynomial coefficients are given in Table A4 along with the standard deviation, σ, calculated with Equation (9). From the presented data it can be seen that, for both systems, the excess molar volume is best correlated using the Myers and Scott equation. The Redlich–Kister equation shows better results than the Hwang equation for correlating the viscosity deviation for both systems.

3.2.3. Apparent Molar Volume

The apparent molar volumes $V_{\phi,1}$ and $V_{\phi,2}$ of the binary systems were calculated with the equations [62]:

$$V_{\phi,1} = \frac{x_2 M_2}{x_1} \frac{\rho_2 - \rho_m}{\rho_2 \rho_m} + \frac{M_1}{\rho_m} \tag{21}$$

$$V_{\phi,2} = \frac{x_1 M_1}{x_2} \frac{\rho_1 - \rho_m}{\rho_1 \rho_m} + \frac{M_2}{\rho_m} \tag{22}$$

The values obtained in the temperature range from 293.15 to 313.15 K are listed in Tables A5 and A6.

3.2.4. Partial Molar Volumes

Partial molar volumes were calculated using the following equations:

$$\overline{V_1} = V^E + V_1^0 + (1 - x_1)\left(\partial V^E/\partial x_1\right)_{p,T} \quad (23)$$

$$\overline{V_2} = V^E + V_2^0 - x_1\left(\partial V^E/\partial x_1\right)_{p,T} \quad (24)$$

where V_1^0 and V_2^0 are the molar volumes of pure components. The derivative $\left(\partial V^E/\partial x_1\right)_{p,T}$ in Equations (23) and (24) was obtained by differentiation of Equation (18), which leads to the following equations:

$$\overline{V_1} = V_1^0 + x_2^2 \sum_{k=0}^{3} a_k (2x_1 - 1)^k - 2x_1 x_2^2 \sum_{k=1}^{3} a_k (2x_1 - 1)^{k-1} \quad (25)$$

$$\overline{V_2} = V_2^0 + x_1^2 \sum_{k=0}^{3} a_k (2x_1 - 1)^k + 2x_1^2 x_2 \sum_{k=1}^{3} a_k (2x_1 - 1)^{k-1} \quad (26)$$

The calculated values of partial molar volumes are listed in Tables A7 and A8.

Our results show that for the DEG + DMSO system, the decrease in the DMSO concentration leads to the increase in the values of the apparent molar volumes and partial molar volumes of DEG, and the decrease in the values of the apparent molar volumes and partial molar volumes of DMSO. For the MDEA + DMSO system the decrease in the DMSO concentration leads to the decrease in the values of the apparent molar volumes and partial molar volumes of MDEA and the increase in the values of the apparent molar volumes and partial molar volumes of DMSO.

3.3. Thermodynamic Functions of Activation

The activation energy of viscous flow was calculated with the equations [63]:

$$\eta = \frac{hN}{V} exp\left(\frac{\Delta G^{\neq}}{RT}\right) \quad (27)$$

$$\Delta G^{\neq} = \Delta H^{\neq} - T\Delta S^{\neq} \quad (28)$$

where η is the viscosity of a liquid solution, h is Planck's constant, N is Avogadro´s number, V is the molar volume of the solution, R is the universal gas constant, T is temperature,$\Delta G^{\neq}$, $\Delta H^{\neq}$ and $\Delta S^{\neq}$ are the molar Gibbs energy, enthalpy and entropy of activation of viscous flow. The plots of $ln(\eta V/hN)$ versus $1/T$ are linear in the temperature range 293.15 to 313.15 K and the values of enthalpy of activation of viscous flow ($\Delta H^{\neq}$) and entropy of activation viscous flow ($\Delta S^{\neq}$) were obtained from the corresponding slopes and intercept. The values of $\Delta G^{\neq}$ were also calculated. The values of thermodynamic functions of activation of viscous flow are listed in Table 5. The values of $\Delta G^{\neq}$ and $\Delta H^{\neq}$ are positive for both binary systems and increase with the decrease in DMSO concentration in the solution at a constant temperature. The values of $\Delta G^{\neq}$ at constant concentration decrease if the temperature increases, except for the pure DMSO.

The values of $\Delta S^{\neq}$ are positive for all compoundsand binary mixtures except DMSO.

The positive $\Delta H^{\neq}$. values decrease with increasing DMSO concentration, indicating that the viscous flow in DMSO is easier than in binary mixtures (DEG + DMSO, MDEA + DMSO) or in DEG. The $\Delta S^{\neq}$ values decrease with increasing DMSO concentration for both analyzed systems, which reveals that the viscous flow is more ordered processing DMSO than in binary mixtures or in DEG.

Table 5. Values of $\Delta G^{\neq}$, $\Delta H^{\neq}$, $\Delta S^{\neq}$ for the binary mixtures.

x_1	$\Delta H^{\neq}$ (kJ/mol)	$\Delta S^{\neq}$ (J/mol·K)	$\Delta G^{\neq}$ (kJ/mol) T/(K)				
			293.15	**298.15**	**303.15**	**308.15**	**313.15**
DEG (1) + DMSO (2)							
0.0000	14.02	−2.01	14.61	14.62	14.63	14.64	14.65
0.1062	15.59	0.26	15.51	15.51	15.51	15.50	15.50
0.2007	17.40	3.49	16.34	16.33	16.31	16.29	16.27
0.3034	19.96	9.58	17.15	17.10	17.05	17.01	16.96
0.4110	21.80	13.10	17.96	17.80	17.83	17.77	17.70
0.5108	23.55	16.72	18.65	18.57	18.48	18.40	18.32
0.5972	25.69	21.91	19.27	19.16	19.05	18.94	18.83
0.6955	26.68	23.06	19.91	19.80	19.68	19.57	19.45
0.8096	28.41	26.52	20.64	20.50	20.37	20.24	20.11
0.8819	29.02	27.12	21.07	20.93	20.80	20.66	20.53
1.0000	32.34	35.69	21.88	21.71	21.53	21.35	21.17
MDEA (1) + DMSO (2)							
0.0000	14.02	−2.01	14.61	14.62	14.63	14.64	14.65
0.1003	21.72	16.02	17.02	16.94	16.86	16.78	16.70
0.1967	23.69	19.72	17.91	17.81	17.71	17.61	17.52
0.2997	25.93	24.08	18.87	18.75	18.63	18.51	18.39
0.4006	28.08	28.27	19.79	19.65	19.51	19.37	19.23
0.5001	29.52	30.13	20.69	20.54	20.39	20.24	20.09
0.6020	32.32	36.46	21.63	21.45	21.26	21.08	20.90
0.6937	34.31	40.39	22.47	22.26	22.06	21.86	21.66
0.7983	36.57	45.18	23.32	23.10	22.87	22.64	22.42
0.8967	38.16	48.10	24.06	23.82	23.58	23.34	23.10
1.0000	39.56	49.62	25.01	24.76	24.51	24.27	24.02

4. Conclusions

Density and viscosity of the binary systems DEG (1) + DMSO (2) and MDEA (1) + DMSO (2) were determined at temperatures between 293.15 to 313.15 K and atmospheric pressure. The calculated V^E values are negative for the DEG (1) + DMSO (2) system and positive for the MDEA (1) + DMSO (2) system, while the calculated $\Delta\eta$ were negative for both systems. Models from Grunberg–Nissan, Heric–Brewer, Wilson, Noda–Ishida and Eyring–NRTL have been used to calculate viscosity coefficients and were compared with experimental data. The results showed that the Eyring–NRTL model is adequate to describe the viscosities of the binary mixtures. The activation energies of viscous flow were calculated. The values of $\Delta G^{\neq}$ and $\Delta H^{\neq}$ are positive for both binary systems and the values of $\Delta S^{\neq}$ are positive for all compounds and binary mixtures except DMSO.

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Appendix A

Table A1. Parameters for the Belda and Herraez equations and standard deviations at temperature range from (293.15 to 313.15) K.

Model	Parameters and σ/(g·cm^{-3})	*T*/(K)				
		293.15	**298.15**	**303.15**	**308.15**	**313.15**
DEG (1) + DMSO (2)						
Belda	m_1	0.0732	0.0781	0.0914	0.1248	0.0734
	m_2	−0.5208	−0.4861	−0.4518	−0.4087	−0.4267
	$10^4 \cdot \sigma$	1.49	1.94	1.81	1.97	2.12
Herraez	A	0.8147	0.8549	0.8652	0.8883	0.8994
	B	−1.0314	−1.1068	−1.0394	−1.0627	−1.0737
	C	0.7901	0.8852	0.8077	0.8238	0.8712
	$10^5 \cdot \sigma$	7.84	7.49	4.70	4.95	2.80
MDEA (1) + DMSO (2)						
Belda	m_1	0.3401	0.3454	0.3586	0.3935	0.4319
	m_2	−0.2987	−0.2827	−0.2690	−0.2366	−0.2016
	$10^4 \cdot \sigma$	1.13	1.24	1.53	1.77	2.09
Herraez	A	0.8238	0.8289	0.8346	0.8448	0.8576
	B	−0.7358	−0.7382	−0.7492	−0.7638	−0.7930
	C	0.3382	0.3382	0.3481	0.3557	0.3788
	$10^4 \cdot \sigma$	1.17	0.99	1.13	1.27	1.20

Table A2. Values of parameters in the range 293.15–313.15 K for the Emmerling et al. and Gonzales-Olmos-Iglesias models and standard deviations [1].

DEG (1) + DMSO (2)		
	Emmerling et al.	
$A_1 = 1.0860$	$B_1 = 9.7611 \times 10^{-4}$	$C_1 = -2.9500 \times 10^{-6}$
$A_2 = 1.4180$	$B_2 = -0.0012$	$C_2 = 2.9207 \times 10^{-7}$
$P_1 = -0.0368$	$P_2 = 3.6037 \times 10^{-4}$	$P_3 = -6.2313 \times 10^{-7}$
$P_4 = -0.3664$	$P_5 = 0.0023$	$P_6 = -3.6487 \times 10^{-6}$
$P_7 = 0.4773$	$P_8 = -0.0030$	$P_9 = 4.6316 \times 10^{-6}$
	$10^4 \cdot \sigma = 1.09$	
	Gonzalez-Olmos-Iglesias	
$A_{00} = 1.4584$	$A_{01} = -0.0014$	$A_{02} = 6.9155 \times 10^{-7}$
$A_{10} = -0.4239$	$A_{11} = 0.0028$	$A_{12} = -4.4132 \times 10^{-6}$
$A_{20} = 0.0383$	$A_{21} = -3.6947 \times 10^{-4}$	$A_{22} = 6.3730 \times 10^{-7}$
	$10^4 \cdot \sigma = 3.14$	
MDEA (1) + DMSO (2)		
	Emmerling et al.	
$A_1 = 1.6658$	$B_1 = -0.0034$	$C_1 = 4.2989 \times 10^{-6}$
$A_2 = 1.4324$	$B_2 = -0.0013$	$C_2 = 4.4600 \times 10^{-7}$
$P_1 = 0.1702$	$P_2 = -0.0016$	$P_3 = 3.0708 \times 10^{-6}$
$P_4 = -0.2610$	$P_5 = 0.0019$	$P_6 = -3.4634 \times 10^{-6}$
$P_7 = 0.3710$	$P_8 = -0.0026$	$P_9 = 4.5659 \times 10^{-6}$
	$10^4 \cdot \sigma = 1.52$	
	Gonzalez-Olmos-Iglesias	
$A_{00} = 1.4621$	$A_{01} = -0.0015$	$A_{02} = 8.2965 \times 10^{-7}$
$A_{10} = 0.3647$	$A_{11} = -0.0035$	$A_{12} = 6.4086 \times 10^{-6}$
$A_{20} = -0.1692$	$A_{21} = 0.0016$	$A_{22} = -3.0582 \times 10^{-6}$
	$10^4 \cdot \sigma = 3.87$	

[1] Units: A_i, P_1, P_4, P_7, A_{00}, A_{10}, A_{20}, σ:g·cm^{-3}; B_i, P_2, P_5, P_8, A_{01}, A_{11}, A_{21}: g·cm^{-3} K^{-1}; C_i, P_3,P_6, P_9, A_{02}, A_{12}, A_{22}: g·cm^{-3}·K^{-2}.

Table A3. Values of parameters for the relations of Grunberg–Nissan, Heric–Brewer, Wilson, Noda–Ishida and Eyring–NRTL and average absolute deviation in the temperature range from 293.15 to 313.15 K.

Model	Parameters and ADD%	T/(K)				
		293.15	**298.15**	**303.15**	**308.15**	**313.15**
DEG (1) + DMSO (2)						
Grunberg-Nissan	d	0.528	0.533	0.426	0.520	0.531
	ADD%	1.03	1.91	2.00	0.84	0.96
Heric-Brewer	α_{12}	0.575	0.582	0.475	0.568	0.579
	α_{21}	−0.122	−0.357	−0.350	−0.130	−0.164
	ADD%	0.75	0.41	0.69	1.45	0.51
Wilson	λ_{12}	−481.19	1985.47	1754.04	−287.47	724.45
	λ_{21}	−681.61	−1986.45	−1754.39	−868.51	−1501.24
	ADD%	0.82	0.86	1.23	0.56	0.50
Noda and Ishida	w_{12}	−30.23	−31.10	−28.29	−30.77	−31.31
	w_{21}	30.42	−31.28	28.43	30.96	31.50
	ADD%	1.02	1.90	1.97	0.85	0.93
Eyring-NRTL [a]	τ_{12}	−0.455	−1.227	−1.380	−0.544	−0.780
	τ_{12}	1.172	2.586	2.753	1.297	1.681
	ADD%	0.80	0.58	0.66	0.54	0.50
MDEA (1) + DMSO (2)						
Grunberg-Nissan	d	1.627	1.517	1.383	1.224	1.250
	ADD%	10.41	10.68	9.60	8.84	8.47
Heric-Brewer	α_{12}	1.719	1.610	1.474	1.316	1.342
	α_{21}	−1.889	−1.965	−1.762	−1.609	−1.574
	ADD%	5.82	5.02	4.82	4.90	3.68
Wilson	λ_{12}	3811.93	3720.99	3538.15	3393.73	3422.86
	λ_{21}	−3812.09	−3727.36	−3555.24	−3399.01	−3425.11
	ADD%	6.33	6.68	6.37	6.50	5.46
Noda and Ishida	w_{12}	−53.26	−52.00	−50.55	−48.21	−48.71
	w_{21}	53.84	52.55	51.04	48.65	49.17
	ADD%	10.43	10.68	9.62	8.88	8.49
Eyring-NRTL [a]	τ_{12}	0.014	−0.136	−0.049	−1.329	−1.362
	τ_{12}	14.593	14.381	15.552	8.453	7.5085
	ADD%	2.18	1.61	1.74	3.30	3.30

[a] Eyring-NRTL as two-parameter model (α = 0.20).

Table A4. Polynomial coefficients [1] and standard deviations (σ) for the binary systems in the temperature range from 293.15 to 313.15 K.

Model	Parameters and σ	T/(K)				
		293.15	**298.15**	**303.15**	**308.15**	**313.15**
V^E/(cm^3·mol^{-1})						
DEG (1) + DMSO (2)						
Redlich-Kister	a_0	−0.736	−0.726	−0.701	−0.679	−0.668
	a_1	0.420	0.411	0.339	0.287	0.280
	a_2	0.157	0.296	0.319	0.379	0.453
	a_3	−0.384	−0.422	−0.328	−0.307	−0.198
	$10^3 \cdot \sigma$	3.0	3.5	2.7	3.7	2.4
Hwang	A_0	−0.785	−0.821	−0.805	−0.803	−0.817
	A_1	0.545	0.703	0.689	0.717	0.853
	A_2	−0.139	0.071	0.150	0.285	0.348
	$10^3 \cdot \sigma$	7.4	8.0	6.3	6.3	4.4

Table A4. *Cont.*

Model	Parameters and σ	T/(K)				
		293.15	**298.15**	**303.15**	**308.15**	**313.15**
Myers and Scott	B_0	−0.730	−0.720	−0.708	−0.680	−0.666
	B_1	−0.391	−0.343	−0.003	−0.141	0.004
	B_2	−0.240	0.105	−0.394	0.137	0.518
	C_0	1.122	1.060	0.556	0.654	0.410
	C_1	1.001	0.693	1.488	0.680	0.018
	$10^3 \cdot \sigma$	2.9	3.3	2.0	3.9	2.6
MDEA (1) + DMSO (2)						
Redlich-Kister	a_0	1.436	1.403	1.364	1.307	1.259
	a_1	0.164	0.188	0.211	0.268	0.315
	a_2	−0.274	−0.307	−0.359	−0.411	−0.520
	a_3	0.208	0.250	0.240	0.264	0.281
	$10^3 \cdot \sigma$	5.1	5.3	8.4	10.0	10.4
Hwang	A_0	1.527	1.505	1.483	1.444	1.432
	A_1	−0.084	−0.083	−0.129	−0.120	−0.202
	A_2	−0.647	−0.737	−0.830	−0.977	−1.186
	$10^3 \cdot \sigma$	5.2	5.6	8.2	9.7	10.1
Myers and Scott	B_0	1.428	1.389	1.348	1.287	1.234
	B_1	−0.387	−0.586	−0.466	−0.425	−0.313
	B_2	−1.759	−1.874	−1.742	−1.836	−1.788
	C_0	−0.394	−0.573	−0.522	−0.545	−0.519
	C_1	−1.078	−1.152	−1.073	−1.162	−1.125
	$10^3 \cdot \sigma$	3.8	5.4	8.4	7.9	8.2
$\Delta\eta$/(mPa·s)						
DEG (1) + DMSO (2)						
Redlich-Kister	a_0	−30.94	−23.81	−18.47	−13.15	−10.22
	a_1	−8.67	−7.84	−7.25	−3.29	−2.78
	a_2	−6.08	−6.20	−2.65	−1.35	0.31
	a_3	−6.46	6.31	−0.60	−0.65	1.15
	σ	0.11	0.05	0.06	0.04	0.03
Hwang	A_0	−28.89	−21.73	−17.60	−12.70	−10.34
	A_1	−21.19	−20.30	−12.42	−6.00	−2.39
	A_2	4.89	3.67	5.41	2.40	3.29
	σ	0.11	0.07	0.06	0.03	0.04
MDEA (1) + DMSO (2)						
Redlich-Kister	a_0	−119.76	−85.34	−62.82	−48.12	−34.08
	a_1	−45.73	−35.93	−22.03	−17.44	−11.65
	a_2	−19.54	−20.99	−15.89	−7.35	−8.74
	a_3	−54.82	−43.35	−42.66	−27.20	−23.83
	σ	0.63	0.39	0.37	0.26	0.19
Hwang	A_0	−113.24	−78.34	−57.52	−45.67	−31.17
	A_1	−103.14	−88.66	−64.94	−41.77	−35.30
	A_2	51.24	32.85	22.75	22.27	12.10
	σ	0.80	0.56	0.59	0.38	0.32

[1] Units: $cm^3 \cdot mol^{-1}$ for V^E and mPa·s for $\Delta\eta$.

Table A5. Apparent molar volumes of DEG, $V_{\phi,1}$ ($cm^3 \cdot mol^{-1}$), for binary systems DEG + DMSO and apparent molar volumes of MDEA, $V_{\phi,1}$ ($cm^3 \cdot mol^{-1}$), for binary system MDEA + DMSO in the temperature range from 293.15 to 313.15 K.

	T/(K)				
x_1	**293.15**	**298.15**	**303.15**	**308.15**	**313.15**
DEG (1) + DMSO (2)					
0.0000	-	-	-	-	-
0.1062	94.499	94.922	95.293	95.770	96.147
0.2007	94.759	95.157	95.560	95.983	96.366
0.3034	95.077	95.445	95.861	96.287	96.679
0.4110	95.391	95.775	96.172	96.591	96.994
0.5108	95.645	96.035	96.440	96.858	97.270
0.5972	95.837	96.236	96.648	97.068	97.487
0.6955	96.023	96.433	96.853	97.280	97.707
0.8096	96.203	96.626	97.055	97.486	97.925
0.8819	96.306	96.736	97.171	97.605	98.049
1.0000	96.455	96.895	97.340	97.779	98.232
MDEA (1) + DMSO (2)					
0.0000	-	-	-	-	-
0.1003	114.274	114.764	115.141	115.450	115.770
0.1967	113.424	113.859	114.243	114.619	115.008
0.2997	112.488	112.975	113.405	113.843	114.263
0.4006	111.671	112.167	112.618	113.053	113.511
0.5001	110.936	111.429	111.886	112.343	112.815
0.6020	110.265	110.760	111.229	111.700	112.182
0.6937	109.730	110.226	110.706	111.183	111.671
0.7983	109.186	109.682	110.169	110.654	111.151
0.8967	108.731	109.226	109.719	110.208	110.711
1.0000	108.310	108.805	109.304	109.797	110.305

Table A6. Apparent molar volumes of DMSO, $V_{\phi,2}$ ($cm^3 \cdot mol^{-1}$), for binary systems DEG + DMSO and apparent molar volumes of DMSO, $V_{\phi,2}$ ($cm^3 \cdot mol^{-1}$), for binary system MDEA + DMSO in the temperature range from 293.15 to 313.15 K.

	T/(K)				
x_1	**293.15**	**298.15**	**303.15**	**308.15**	**313.15**
DEG (1) + DMSO (2)					
0.0000	71.014	71.339	71.656	71.989	72.322
0.1062	70.966	71.304	71.633	71.968	72.304
0.2007	70.899	71.244	71.585	71.917	72.254
0.3034	70.832	71.166	71.522	71.862	72.201
0.4110	70.780	71.124	71.462	71.801	72.145
0.5108	70.752	71.090	71.432	71.767	72.114
0.5972	70.752	71.095	71.438	71.764	72.111
0.6955	70.765	71.120	71.466	71.808	72.158
0.8096	70.725	71.111	71.467	71.799	72.211
0.8819	70.792	71.195	71.533	71.899	72.327
1.0000	-	-	-	-	-

Table A6. *Cont.*

	T/(K)				
x_1	**293.15**	**298.15**	**303.15**	**308.15**	**313.15**
MDEA (1) + DMSO (2)					
0.0000	71.014	71.339	71.666	71.989	72.322
0.1003	71.004	71.332	71.660	71.972	72.295
0.1967	71.080	71.389	71.709	72.018	72.340
0.2997	71.188	71.514	71.842	72.167	72.482
0.4006	71.337	71.670	72.004	72.302	72.632
0.5001	71.485	71.807	72.126	72.434	72.764
0.6020	71.634	71.959	72.273	72.597	72.923
0.6937	71.794	72.121	72.455	72.765	73.076
0.7983	72.003	72.333	72.655	72.986	73.320
0.8967	72.066	72.397	72.666	72.944	73.224
1.0000	-	-	-	-	-

Table A7. Partial molar volumes $\overline{V_1}$ ($cm^3 \cdot mol^{-1}$) for binary systems in the temperature range from 293.15 to 313.15 K.

	T/(K)				
x_1	**293.15**	**298.15**	**303.15**	**308.15**	**313.15**
DEG (1) + DMSO (2)					
0.0000	94.262	94.773	95.142	95.635	95.966
0.1062	94.243	94.679	95.067	95.533	95.888
0.2007	94.286	94.675	95.067	95.513	95.876
0.3034	94.375	94.728	95.115	95.541	95.904
0.4110	94.490	94.820	95.197	95.606	95.964
0.5108	94.600	94.918	95.284	95.681	96.033
0.5972	94.687	95.001	95.358	95.748	96.096
0.6955	94.770	95.082	95.431	95.816	96.161
0.8096	94.837	95.150	95.494	95.875	96.221
0.8819	94.862	95.176	95.519	95.900	96.246
1.0000	94.877	95.192	95.535	95.915	96.263
MDEA (1) + DMSO (2)					
0.0000	115.271	115.647	115.955	116.191	116.400
0.1003	115.225	115.644	115.978	116.266	116.539
0.1967	115.145	115.593	115.947	116.274	116.595
0.2997	115.034	115.505	115.877	116.235	116.595
0.4006	114.915	115.400	115.786	116.167	116.555
0.5001	114.799	115.292	115.689	116.087	116.492
0.6020	114.690	115.190	115.594	116.003	116.421
0.6937	114.607	115.110	115.519	115.936	116.360
0.7983	114.536	115.042	115.453	115.876	116.303
0.8967	114.495	115.003	115.415	115.840	116.269
1.0000	114.481	114.989	115.401	115.827	116.257

Table A8. Partial molar volumes $\overline{V_2}$ ($cm^3 \cdot mol^{-1}$) for binary systems in the temperature range from 293.15 to 313.15 K.

	T/(K)				
x_1	**293.15**	**298.15**	**303.15**	**308.15**	**313.15**
DEG (1) + DMSO (2)					
0.0000	71.014	71.338	71.666	71.989	72.322
0.1062	71.007	71.329	71.656	71.979	72.313
0.2007	70.992	71.313	71.639	71.960	72.293
0.3034	70.974	71.293	71.616	71.935	72.267
0.4110	70.954	71.274	71.593	71.910	72.242
0.5108	70.933	71.258	71.573	71.889	72.224
0.5972	70.907	71.241	71.554	71.871	72.213
0.6955	70.863	71.211	71.527	71.849	72.206
0.8096	70.774	71.146	71.475	71.809	72.202
0.8819	70.688	71.078	71.425	71.770	72.200
1.0000	70.471	70.897	71.295	71.669	72.189
MDEA (1) + DMSO (2)					
0.0000	71.014	71.338	71.666	71.989	72.322
0.1003	71.034	71.359	71.686	72.010	72.344
0.1967	71.086	71.411	71.738	72.064	72.400
0.2997	71.171	71.496	71.823	72.149	72.487
0.4006	71.281	71.605	71.931	72.257	72.593
0.5001	71.414	71.736	72.060	72.383	72.716
0.6020	71.577	71.896	72.214	72.534	72.859
0.6937	71.748	72.065	72.374	72.690	73.003
0.7983	71.977	72.292	72.587	72.897	73.192
0.8967	72.231	72.548	72.825	73.127	73.399
1.0000	72.548	72.872	73.122	73.417	73.657

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