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SHORT ARTICLE

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# Volumetric and Surface Properties of Aqueous Mixtures of Polyethers at $T$ = (298.15, 308.15, and 318.15) K

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**ABSTRACT:** Density and surface tension for binary mixtures of diethylene glycol dimethyl ether, triethylene glycol dimethyl ether, and tetraethylene glycol dimethyl ether with water are measured over the whole concentration range at $T$ = (298.15, 308.15, and 318.15) K and atmospheric pressure. The experimental densities and surface tensions have been used to calculate excess molar volumes ($V^E$) and surface tension deviations ($\Delta\sigma$), respectively. While the excess molar volumes are compared with the existing literature data, surface tension measurements for these mixtures are reported for the first time. Molar surface energies and parachor have also been calculated from experimental surface tension data. Primary data on surface tension are fitted to a polynomial equation, whereas the $V^E$ and $\Delta\sigma$ derived from densities and surface tensions are fitted to the Redlich−Kister type polynomial equation.

## INTRODUCTION

The thermophysical properties of fluid mixtures depend markedly on the manner in which the pure constituents are associated with each other in the mixtures. The surface tension of mixtures is an important property for the design of contacting equipment, which is used to carry out chemical processes such as gas absorption.[1] The specific molecular interactions that occur on the surface and in the bulk region of liquid are characterized by surface tension.[2] Surface tension along with other thermodynamic properties is essential for practical and theoretical modeling of the liquid state of substances.[3,4]

In the present paper, we report the densities and surface tensions of binary liquid mixtures comprising of polyethers (diethylene glycol dimethyl ether, triethylene glycol dimethyl ether, and tetraethylene glycol dimethyl ether) and water at $T$ = (298.15, 308.15, and 318.15) K over the whole concentration range. The polyethers used are one of the main components forming Selexol, a widely used solvent in natural gas sweetening, and is made of a mixture of poly(ethylene glycol) dimethyl ethers. Also, these can be used as inert solvents for reduction in organometallic reactions involving alkali metals and used as cosolvent in brakes fluids, adhesives, and paints and electrodepositing. Further, these polyethers are of interest to understand interactions of water with amphiphilic molecules.[5,6] The surface tension for ethylene glycol dimethyl ether with water has been reported earlier.[7] The excess molar volumes for the present mixtures chosen for the study have also been reported in literature[8−12] at 298.15 K and different temperatures[5,6] and are compared with the present data at 298.15 K. Surface properties for these mixtures are reported and discussed for the first time.

## EXPERIMENTAL SECTION

**Materials.** Millipore grade water with conductivity < $0.66 \cdot 10^{-8}$ $S \cdot cm^{-1}$ was used throughout this study. Diethylene glycol dimethyl ether (mass fraction > 0.985), triethylene glycol dimethyl ether (mass fraction > 0.98), and tetraethylene glycol dimethyl ether (mass fraction > 0.97) were obtained from Merck-Schuchardt and were used without further purification. All of the liquids were kept in tightly sealed bottles to minimize the absorption of atmospheric moisture and $CO_2$. Prior to use all of the liquids were dried over 0.4 nm molecular sieves and were partially degassed under vacuum. The densities and surface tensions of the pure components along with their literature values[5,6,13−28] are reported in Table 1.

**Apparatus and Procedure.** The densities of the pure solvents and their binary mixtures were measured with an Anton Paar (model DMA 4500) vibrating-tube densimeter with a resolution of $5 \cdot 10^{-5}$ $g \cdot cm^{-3}$. A density check and an air/water adjustment were performed at 20 °C with doubly distilled, degassed water and with dry air at atmospheric pressure. The validation of the readings was done with double-distilled and degassed water, cyclopentane, propanol, benzene, bromobenzene, dimethyl sulfoxide, and *N*,*N*-dimethylformamide in the experimental temperature range. The temperature of the apparatus was controlled to within ± 0.01 K by a built-in Peltier device, and the uncertainty corresponding to change in temperature of ± 0.01 K is ± 0.0002 %. The accuracy in the density measurements was found to be ± 0.00002 $g \cdot cm^{-3}$. The overall uncertainty in comparison with literature data for the calibrating liquids and in the averaged density measurements of the binary mixtures is judged to be less than 0.002 %. The density values are repeatable to $3 \cdot 10^{-5}$ $g \cdot cm^{-3}$. The experimental uncertainty in the estimated excess molar volume is approximately ± $2 \cdot 10^{-3}$ $cm^3 \cdot mol^{-1}$. The uncertainty estimates do not include the effects of certain minor impurities that may be present in the solvents. The repeatability obtained with triplicate measurements on the same sample maintained inside the densimeter at

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Table 1. Experimental Densities ($\rho$) and Surface Tensions ($\sigma$) of the Pure Component Liquids Together with Literature Values

| component | $T$/K | $\rho\cdot10^3$/kg$\cdot$m$^{-3}$ | | $\sigma$/mN$\cdot$m$^{-1}$ | |
|---|---|---|---|---|---|
| | | exptl | lit. | exptl | lit. |
| diethylene glycol dimethyl ether | 298.15 | 0.94001 | 0.9399[13] | 24.56 | |
| | | | 0.9394[14] | | |
| | | | 0.9391[15] | | |
| | 308.15 | 0.93003 | 0.9285[16] | 27.65 | |
| | | | 0.92868[17] | | |
| | 318.15 | 0.91999 | 0.9186[16] | 23.44 | |
| triethylene glycol dimethyl ether | 298.15 | 0.98123 | 0.9811[15] | 27.56 | |
| | | | 0.98171[18] | | |
| | 308.15 | 0.97171 | 0.97115[17] | 28.48 | |
| | | | 0.97126[19] | | |
| | | | 0.9710[20] | | |
| | 318.15 | 0.96219 | | 27.83 | |
| tetraethylene glycol dimethyl ether | 298.15 | 1.00726 | 1.00665[5] | 33.74 | |
| | | | 1.0063[15] | | |
| | | | 1.00662[21] | | |
| | 308.15 | 0.99798 | 0.99634[17] | 32.45 | |
| | | | 0.99642[22] | | |
| | 318.15 | 0.98872 | | 31.71 | |
| water | 298.15 | 0.99705 | 0.99704[6] | 71.37 | 71.35[25] |
| | | | 0.9970480[23] | | 71.6[26] |
| | | | 0.99706[24] | | |
| | 308.15 | 0.99406 | 0.9940359[23] | 70.08 | 70.41[24] |
| | | | 0.99404[24] | | 70.1[26] |
| | 318.15 | 0.99025 | 0.99023[24] | 69.11 | 68.78[24] |
| | | | 0.99021[27] | | 68.84[28] |

constant temperature at different times during the course of present measurements is $1\cdot10^{-5}$ g$\cdot$cm$^{-3}$. The samples for density measurements were prepared by mass in the stoppered glass bottles. Surface tension measurements in both the pure liquids and their mixtures were carried out at different temperatures using a DataPhysics DCAT II automated tensiometer, which employs the Wilhelmy plate method. A wettable platinum blade with an area of 3.98 mm$^2$ (wetted length 40.20 mm) was immersed in solution and slowly withdrawn to measure the vertical force, which is related to the surface tension by ($\sigma = Fg/W$), where $\sigma$ is the surface tension, $F$ is the measured vertical force, $g$ is the acceleration of gravity, and $W$ is the perimeter of the blade. The measurements were performed by the titration method wherein the first component of the mixture was taken in the measurement cell (25 g) and the second component was added by mass in steps. Before each measurement, stirring was performed for about 5 min, and thereafter the mixture was kept for 5 min for equilibration. The resolution of the dynamic contact angle device used for surface tension measurements is 0.01 mN$\cdot$m$^{-1}$. The repeatability for the triplicate measurements done for the same sample was $\pm$ 0.03 mN$\cdot$m$^{-1}$. The uncertainty obtained in $\sigma$ values is < 0.3 mN$\cdot$m$^{-1}$. The uncertainty obtained in the $\Delta\sigma$ values is $\pm$ 0.4 mN$\cdot$m$^{-1}$. The uncertainty obtained for molar surface energy and parachor are found to be less than 0.3 N$\cdot$m$\cdot$mol$^{-1}$ and 0.4 (mN$\cdot$m$^{-1}$)$^{1/4}$ cm$^3\cdot$mol$^{-1}$, respectively. The concentrations for the density and surface tension measurements are different as both methods employed different methods and required different amount of solutions. The temperature of the measurement cell was controlled with a Julabo water thermostat within $\pm$ 0.1 K. Binary mixtures were prepared by mass, using an analytical balance with a precision of $\pm$ 0.0001 g (Denver Instrument APX-200). The mole fraction of each mixture was obtained with an accuracy of $1\cdot10^{-4}$ from the measured masses of the components. All molar quantities were based on the IUPAC relative atomic mass table.[29]

## RESULTS AND DISCUSSION

Experimental densities, $\rho$, along with the excess molar volumes $V^E$ for binary mixtures of polyethers (diethylene glycol dimethyl ether or triethylene glycol dimethyl ether or tetraethylene glycol dimethyl ether) and water at $T$ = (298.15, 308.15, and 318.15) K are listed in Table 2. Excess molar volumes were calculated from our measurements according to following equation

$$V^E = (x_1M_1 + x_2M_2)/\rho - x_1M_1/\rho_1 - x_2M_2/\rho_2 \qquad (1)$$

where $x_1$ and $x_2$ are mole fractions, $M_1$ and $M_2$ are molar masses, and $\rho_1$ and $\rho_2$ are the densities of pure components 1 and 2, respectively. $\rho$ is the density of the binary mixtures.

Experimental results on surface tension $\sigma$, and surface tension deviations $\Delta\sigma$, at different temperatures are reported in Table 3. Values of $\sigma$ were fitted to a polynomial type equation utilizing the

Table 2. Densities ($\rho$), and Excess Molar Volumes ($V^E$) for $x$ Polyether + $(1-x)$ Water Mixtures at $T$ = (298.15, 308.15, and 318.15) K

| $x$ | $\rho \cdot 10^3/\mathrm{kg \cdot m^{-3}}$ | | | $V^E \cdot 10^6/\mathrm{m^3 \cdot mol^{-1}}$ | | |
|---|---|---|---|---|---|---|
| | $T$/K = 298.15 | $T$/K = 308.15 | $T$/K = 318.15 | $T$/K = 298.15 | $T$/K = 308.15 | $T$/K = 318.15 |
| | | | $x$ Diethylene Glycol Dimethyl Ether + $(1-x)$ Water | | | |
| 0.0188 | 1.00255 | 0.99841 | 0.99430 | −0.265 | −0.264 | −0.278 |
| 0.0543 | 1.00680 | 1.00143 | 0.99625 | −0.679 | −0.685 | −0.710 |
| 0.1289 | 1.00243 | 0.99623 | 0.98910 | −1.230 | −1.27 | −1.295 |
| 0.1903 | 0.99476 | 0.98730 | 0.97979 | −1.461 | −1.492 | −1.537 |
| 0.3195 | 0.97875 | 0.97044 | 0.96172 | −1.575 | −1.619 | −1.655 |
| 0.4068 | 0.97055 | 0.96172 | 0.95275 | −1.535 | −1.573 | −1.615 |
| 0.4993 | 0.96315 | 0.95406 | 0.94464 | −1.394 | −1.434 | −1.461 |
| 0.6210 | 0.95566 | 0.94587 | 0.93650 | −1.155 | −1.150 | −1.201 |
| 0.7181 | 0.95074 | 0.94070 | 0.93128 | −0.908 | −0.886 | −0.945 |
| 0.8097 | 0.94627 | 0.93634 | 0.92676 | −0.580 | −0.575 | −0.625 |
| 0.9099 | 0.94233 | 0.93239 | 0.92258 | −0.225 | −0.225 | −0.253 |
| 0.9551 | 0.94097 | 0.93105 | 0.92112 | −0.090 | −0.096 | −0.109 |
| | | | $x$ Triethylene Glycol Dimethyl Ether + $(1-x)$ Water | | | |
| 0.0173 | 1.00622 | 1.00432 | 0.99853 | −0.240 | −0.285 | −0.265 |
| 0.0914 | 1.01965 | 1.01626 | 1.00741 | −0.989 | −1.036 | −1.077 |
| 0.1739 | 1.01724 | 1.01056 | 1.00145 | −1.406 | −1.452 | −1.431 |
| 0.2731 | 1.00997 | 1.00113 | 0.99210 | −1.538 | −1.565 | −1.601 |
| 0.3468 | 1.004700 | 0.99527 | 0.98606 | −1.560 | −1.561 | −1.589 |
| 0.4515 | 0.99825 | 0.98866 | 0.97925 | −1.312 | −1.365 | −1.404 |
| 0.5727 | 0.99240 | 0.98292 | 0.97334 | −1.135 | −1.110 | −1.080 |
| 0.6451 | 0.98970 | 0.98017 | 0.97059 | −0.955 | −0.930 | −0.903 |
| 0.7766 | 0.98598 | 0.97639 | 0.96682 | −0.635 | −0.610 | −0.590 |
| 0.8679 | 0.98402 | 0.97451 | 0.96492 | −0.415 | −0.410 | −0.391 |
| 0.8977 | 0.98345 | 0.97395 | 0.96434 | −0.343 | −0.340 | −0.321 |
| 0.9699 | 0.98195 | 0.97246 | 0.96291 | −0.120 | −0.125 | −0.118 |
| | | | $x$ Tetraethylene Glycol Dimethyl Ether + $(1-x)$ Water | | | |
| 0.0142 | 1.01113 | 1.00656 | 1.00129 | −0.260 | −0.249 | −0.238 |
| 0.0747 | 1.03525 | 1.02726 | 1.01904 | −1.063 | −1.016 | −0.975 |
| 0.1452 | 1.03672 | 1.02767 | 1.01851 | −1.502 | −1.441 | −1.386 |
| 0.2309 | 1.03130 | 1.02201 | 1.01258 | −1.649 | −1.590 | −1.531 |
| 0.2974 | 1.02641 | 1.01712 | 1.00772 | −1.587 | −1.535 | −1.482 |
| 0.4065 | 1.02020 | 1.01092 | 1.00156 | −1.381 | −1.338 | −1.294 |
| 0.5085 | 1.01634 | 1.00706 | 0.99773 | −1.172 | −1.136 | −1.100 |
| 0.5863 | 1.01423 | 1.00492 | 0.99558 | −1.016 | −0.983 | −0.949 |
| 0.6788 | 1.01216 | 1.00283 | 0.99348 | −0.812 | −0.783 | −0.750 |
| 0.8139 | 1.00947 | 1.00017 | 0.99083 | −0.434 | −0.417 | −0.391 |
| 0.8540 | 1.00876 | 0.99947 | 0.99015 | −0.311 | −0.298 | −0.277 |
| 0.9569 | 1.00743 | 0.99816 | 0.98889 | −0.044 | −0.042 | −0.035 |

method of least-squares with each point weighted equally.

$$\sigma = \sum_{i=0} A_i x_1^i \tag{2}$$

The coefficients $A_i$ for the correlation of $\sigma$−concentration data evaluated using least-squares method are given in Table 4 along with the resulting standard deviations.

The surface tension deviations $\Delta\sigma$ from mole fraction average were calculated from the relationship

$$\Delta\sigma = \sigma - (x_1\sigma_1 - x_2\sigma_2) \tag{3}$$

where $\sigma$ is the surface tension of the mixture, $x_1$ and $x_2$ are the mole fractions, and $\sigma_1$ and $\sigma_2$ are the surface tension of the pure components 1 and 2, respectively.

The calculated values of $V^E$ and $\Delta\sigma$ of the binary mixtures were fitted to a Redlich−Kister[30] type polynomial equation

$$Y(x) = x_1 x_2 \sum_{i=0}^{n} A_i (x_1 - x_2)^i \tag{4}$$

where $Y(x) = V^E/\mathrm{cm^3 \cdot mol^{-1}}$ and $\Delta\sigma/\mathrm{mN \cdot m^{-1}}$. The coefficients $A_i$ for the correlation of $Y(x)$−concentration data were

Table 3. Surface Tension ($\sigma$), Surface Tension Deviations ($\Delta\sigma$), Surface Energies ($E_a$), and Parachor ($P$) for $x$ Polyether + $(1 - x)$ Water Liquid Mixtures at $T$ = (298.15, 308.15, and 318.15) K

| | $\sigma$ | $\Delta\sigma$ | $E_a \cdot 10^2$ | $P$ |
|---|---|---|---|---|
| $x_1$ | $mN \cdot m^{-1}$ | $mN \cdot m^{-1}$ | $N \cdot m \cdot mol^{-1}$ | $(mN \cdot m^{-1})^{1/4}\ cm^3 \cdot mol^{-1}$ |
| | | $x$ Diethylene Glycol Dimethyl Ether + $(1 - x)$ Water | | |
| | | $T$/K = 298.15 | | |
| 0.0000 | 71.37 | 0.00 | 49.62 | 53 |
| 0.0047 | 49.27 | −21.88 | 34.91 | 49 |
| 0.0141 | 44.11 | −26.60 | 32.41 | 51 |
| 0.0279 | 42.26 | −27.80 | 32.66 | 54 |
| 0.0456 | 39.85 | −29.38 | 32.72 | 58 |
| 0.0874 | 35.99 | −31.29 | 33.55 | 69 |
| 0.1184 | 31.62 | −34.21 | 32.01 | 75 |
| 0.1582 | 30.69 | −33.27 | 34.13 | 86 |
| 0.2241 | 30.45 | −30.43 | 38.71 | 104 |
| 0.3191 | 29.90 | −26.54 | 44.50 | 132 |
| 0.4283 | 28.69 | −22.63 | 49.41 | 162 |
| 0.5164 | 28.08 | −19.12 | 53.38 | 187 |
| 0.6493 | 27.90 | −13.08 | 60.19 | 225 |
| 0.7841 | 26.77 | −7.89 | 64.37 | 262 |
| 0.8737 | 26.29 | −4.78 | 67.38 | 287 |
| 0.9228 | 25.69 | −1.88 | 68.01 | 299 |
| 0.9704 | 25.19 | −0.76 | 68.71 | 311 |
| 1.0000 | 24.56 | 0.00 | 68.20 | 318 |
| | | $T$/K = 308.15 | | |
| 0.0000 | 70.08 | 0.00 | 48.82 | 52 |
| 0.0014 | 53.47 | −16.55 | 37.46 | 49 |
| 0.0038 | 50.51 | −19.41 | 35.74 | 49 |
| 0.0085 | 47.12 | −22.60 | 33.97 | 50 |
| 0.0142 | 44.72 | −24.76 | 32.96 | 51 |
| 0.0279 | 41.30 | −27.59 | 32.02 | 54 |
| 0.0457 | 38.99 | −29.15 | 32.14 | 58 |
| 0.0875 | 33.65 | −32.72 | 31.51 | 68 |
| 0.1200 | 32.57 | −32.42 | 33.25 | 77 |
| 0.1602 | 31.09 | −32.19 | 34.90 | 87 |
| 0.2265 | 29.75 | −30.72 | 38.19 | 105 |
| 0.3217 | 29.19 | −27.24 | 43.86 | 133 |
| 0.4305 | 28.79 | −23.02 | 50.02 | 164 |
| 0.5179 | 28.41 | −19.69 | 54.44 | 189 |
| 0.6498 | 28.30 | −14.21 | 61.50 | 228 |
| 0.7831 | 27.70 | −9.15 | 67.03 | 267 |
| 0.8744 | 27.58 | −5.44 | 71.22 | 294 |
| 0.9165 | 27.54 | −3.61 | 73.13 | 306 |
| 0.9645 | 27.43 | −1.73 | 75.08 | 320 |
| 1.0000 | 27.65 | 0.00 | 77.33 | 331 |
| | | $T$/K = 318.15 | | |
| 0.0000 | 69.11 | 0.00 | 48.27 | 52 |
| 0.0015 | 55.76 | −13.28 | 39.19 | 50 |
| 0.0038 | 51.77 | −17.17 | 36.72 | 50 |
| 0.0081 | 48.33 | −20.41 | 44.55 | 73 |
| 0.0135 | 45.61 | −22.88 | 33.61 | 51 |
| 0.0269 | 41.95 | −25.93 | 32.50 | 54 |

Table 3. Continued

| | $\sigma$ | $\Delta\sigma$ | $E_a \cdot 10^2$ | $P$ |
|---|---|---|---|---|
| $x_1$ | $mN \cdot m^{-1}$ | $mN \cdot m^{-1}$ | $N \cdot m \cdot mol^{-1}$ | $(mN \cdot m^{-1})^{1/4}\ cm^3 \cdot mol^{-1}$ |
| 0.0444 | 39.33 | −27.75 | 32.39 | 58 |
| 0.0857 | 34.62 | −30.58 | 32.38 | 68 |
| 0.1091 | 28.86 | −35.27 | 28.77 | 72 |
| 0.1560 | 26.65 | −35.34 | 29.78 | 83 |
| 0.2194 | 25.34 | −33.75 | 32.27 | 100 |
| 0.3174 | 24.45 | −30.16 | 36.72 | 127 |
| 0.4248 | 24.26 | −25.45 | 42.13 | 157 |
| 0.5110 | 24.18 | −21.59 | 46.31 | 182 |
| 0.6513 | 23.87 | −15.50 | 52.29 | 221 |
| 0.7915 | 23.64 | −9.32 | 57.96 | 261 |
| 0.8844 | 23.50 | −5.24 | 61.53 | 288 |
| 0.9137 | 23.48 | −3.92 | 62.68 | 296 |
| 0.9547 | 23.46 | −2.01 | 64.29 | 308 |
| 1.0000 | 23.44 | 0.00 | 66.03 | 321 |
| | | $x$ Triethylene Glycol Dimethyl Ether + $(1 - x)$ Water | | |
| | | $T$/K = 298.15 | | |
| 0.0000 | 71.37 | 0.00 | 49.62 | 53 |
| 0.0012 | 53.35 | −17.97 | 37.34 | 49 |
| 0.0024 | 51.27 | −19.99 | 36.12 | 49 |
| 0.0029 | 49.07 | −22.17 | 34.66 | 49 |
| 0.0036 | 48.59 | −22.62 | 34.45 | 49 |
| 0.0043 | 47.60 | −23.58 | 33.88 | 49 |
| 0.0206 | 40.60 | −29.87 | 31.38 | 53 |
| 0.0375 | 38.88 | −30.85 | 32.44 | 59 |
| 0.0695 | 36.20 | −32.13 | 34.26 | 70 |
| 0.0905 | 33.99 | −33.42 | 34.58 | 77 |
| 0.1223 | 33.06 | −32.95 | 37.08 | 88 |
| 0.1630 | 32.87 | −32.00 | 41.08 | 104 |
| 0.2911 | 32.23 | −25.75 | 52.36 | 153 |
| 0.3517 | 31.66 | −24.30 | 56.65 | 176 |
| 0.4658 | 31.16 | −19.80 | 64.90 | 220 |
| 0.5830 | 30.50 | −15.33 | 72.14 | 264 |
| 0.6590 | 30.09 | −12.41 | 76.42 | 293 |
| 0.7279 | 29.54 | −9.94 | 79.55 | 318 |
| 0.8210 | 29.05 | −6.35 | 84.07 | 352 |
| 0.8823 | 28.52 | −4.19 | 86.21 | 374 |
| 0.9461 | 28.04 | −1.88 | 88.44 | 397 |
| 1.0000 | 27.56 | 0.00 | 89.94 | 416 |
| | | $T$/K = 308.15 | | |
| 0.0000 | 70.08 | 0.00 | 48.82 | 52 |
| 0.0009 | 53.01 | −17.03 | 37.11 | 49 |
| 0.0017 | 50.04 | −19.97 | 35.19 | 49 |
| 0.0026 | 47.96 | −22.01 | 33.89 | 49 |
| 0.0039 | 45.41 | −24.51 | 32.31 | 49 |
| 0.0109 | 41.72 | −27.91 | 30.79 | 50 |
| 0.0218 | 40.14 | −29.03 | 31.26 | 54 |
| 0.0353 | 38.28 | −30.33 | 31.70 | 58 |
| 0.0882 | 36.04 | −30.37 | 36.50 | 78 |
| 0.1214 | 34.06 | −30.97 | 38.25 | 89 |
| 0.1767 | 33.08 | −29.65 | 42.94 | 110 |
| 0.2497 | 32.48 | −27.21 | 49.23 | 138 |
| 0.2497 | 31.82 | −24.11 | 48.23 | 137 |

Table 3. Continued

| $x_1$ | $\sigma$ / $mN \cdot m^{-1}$ | $\Delta\sigma$ / $mN \cdot m^{-1}$ | $E_a \cdot 10^2$ / $N \cdot m \cdot mol^{-1}$ | $P$ / $(mN \cdot m^{-1})^{1/4}\ cm^3 \cdot mol^{-1}$ |
|---|---|---|---|---|
| 0.3400 | 31.44 | −21.41 | 55.59 | 172 |
| 0.4141 | 30.89 | −17.26 | 60.67 | 201 |
| 0.5272 | 30.74 | −15.06 | 69.06 | 245 |
| 0.5837 | 30.15 | −10.08 | 71.81 | 266 |
| 0.7176 | 29.76 | −6.07 | 80.00 | 318 |
| 0.8234 | 29.38 | −4.46 | 85.73 | 358 |
| 0.9458 | 28.74 | −1.99 | 91.22 | 403 |
| 1.0000 | 28.48 | 0.00 | 93.55 | 424 |
| | | $T$/K = 318.15 | | |
| 0.0000 | 69.11 | 0.00 | 48.27 | 52 |
| 0.0014 | 51.81 | −17.24 | 36.47 | 49 |
| 0.0021 | 47.47 | −21.55 | 33.54 | 49 |
| 0.0028 | 46.10 | −22.89 | 32.70 | 49 |
| 0.0039 | 44.63 | −24.32 | 31.84 | 49 |
| 0.0100 | 41.37 | −27.33 | 43.74 | 86 |
| 0.0212 | 39.06 | −29.17 | 30.43 | 54 |
| 0.034 | 37.85 | −29.86 | 31.28 | 58 |
| 0.0543 | 35.26 | −31.61 | 31.72 | 65 |
| 0.0791 | 32.67 | −33.58 | 32.22 | 73 |
| 0.0849 | 32.50 | −33.19 | 32.70 | 75 |
| 0.0917 | 32.42 | −32.83 | 33.37 | 77 |
| 0.1220 | 32.27 | −31.40 | 36.48 | 89 |
| 0.1848 | 32.14 | −29.34 | 42.74 | 113 |
| 0.2728 | 31.26 | −26.59 | 49.73 | 147 |
| 0.3289 | 31.05 | −24.49 | 54.28 | 169 |
| 0.3776 | 30.83 | −22.69 | 57.95 | 188 |
| 0.4688 | 30.30 | −19.46 | 64.11 | 223 |
| 0.6611 | 29.59 | −12.23 | 76.28 | 298 |
| 0.7234 | 29.40 | −9.85 | 79.94 | 322 |
| 0.8102 | 28.99 | −6.68 | 84.34 | 355 |
| 0.8562 | 28.68 | −5.09 | 86.26 | 372 |
| 0.8915 | 28.30 | −4.01 | 87.22 | 385 |
| 1.0000 | 27.83 | 0.00 | 92.02 | 425 |
| | | $x$ Tetraethylene Glycol Dimethyl Ether + $(1 - x)$ Water | | |
| | | $T$/K = 298.15 | | |
| 0.0000 | 71.37 | 0.00 | 49.62 | 53 |
| 0.0016 | 50.16 | −21.15 | 35.25 | 49 |
| 0.0020 | 48.89 | −22.40 | 34.45 | 49 |
| 0.0026 | 47.04 | −24.23 | 33.28 | 49 |
| 0.0031 | 46.37 | −24.88 | 32.91 | 49 |
| 0.0092 | 43.11 | −27.91 | 31.82 | 51 |
| 0.0174 | 41.23 | −29.49 | 31.98 | 54 |
| 0.0283 | 40.10 | −30.21 | 33.07 | 59 |
| 0.0570 | 39.54 | −29.69 | 37.52 | 72 |
| 0.0746 | 38.88 | −29.91 | 39.75 | 80 |
| 0.1026 | 38.65 | −28.63 | 43.88 | 94 |
| 0.1497 | 37.66 | −28.08 | 49.59 | 116 |
| 0.2264 | 36.29 | −26.56 | 57.82 | 153 |
| 0.2862 | 35.79 | −24.81 | 64.26 | 182 |
| 0.4268 | 35.09 | −20.22 | 78.41 | 251 |
| 0.5414 | 34.92 | −16.08 | 89.50 | 308 |
| 0.6144 | 34.46 | −13.79 | 95.17 | 343 |

Table 3. Continued

| $x_1$ | $\sigma$ / $mN \cdot m^{-1}$ | $\Delta\sigma$ / $mN \cdot m^{-1}$ | $E_a \cdot 10^2$ / $N \cdot m \cdot mol^{-1}$ | $P$ / $(mN \cdot m^{-1})^{1/4}\ cm^3 \cdot mol^{-1}$ |
|---|---|---|---|---|
| 0.7870 | 34.20 | −7.56 | 109.70 | 428 |
| 0.8286 | 34.19 | −5.99 | 113.20 | 449 |
| 0.9196 | 33.91 | −2.86 | 119.70 | 493 |
| 1.0000 | 33.74 | 0.00 | 125.40 | 532 |
| | | $T$/K = 308.15 | | |
| 0.0000 | 70.08 | 0.00 | 48.82 | 52 |
| 0.0014 | 51.00 | −27.17 | 35.90 | 49 |
| 0.0023 | 46.99 | −19.03 | 33.25 | 49 |
| 0.0032 | 45.45 | −23.00 | 32.36 | 49 |
| 0.0040 | 44.21 | −24.51 | 31.64 | 49 |
| 0.0090 | 42.87 | −25.72 | 30.05 | 47 |
| 0.0175 | 39.90 | −29.52 | 31.07 | 54 |
| 0.0275 | 39.08 | −29.96 | 32.21 | 58 |
| 0.0539 | 38.34 | −29.71 | 36.05 | 71 |
| 0.0715 | 37.36 | −30.03 | 37.91 | 79 |
| 0.0990 | 37.28 | −29.08 | 42.03 | 92 |
| 0.1478 | 35.51 | −29.01 | 46.78 | 115 |
| 0.2212 | 34.95 | −26.81 | 55.39 | 150 |
| 0.3074 | 34.22 | −24.29 | 64.20 | 192 |
| 0.4252 | 33.85 | −20.23 | 75.94 | 250 |
| 0.5523 | 33.58 | −15.72 | 87.62 | 313 |
| 0.6404 | 33.32 | −12.66 | 94.92 | 356 |
| 0.7835 | 33.05 | −7.55 | 106.40 | 427 |
| 0.8140 | 32.88 | −6.57 | 108.30 | 441 |
| 0.9479 | 32.64 | −1.77 | 118.10 | 507 |
| 1.0000 | 32.45 | 0.00 | 121.40 | 532 |
| | | $T$/K = 318.15 | | |
| 0.0000 | 69.11 | 0.00 | 48.27 | 52 |
| 0.0013 | 58.46 | −10.60 | 41.20 | 51 |
| 0.0019 | 54.20 | −14.84 | 38.35 | 50 |
| 0.0024 | 51.29 | −17.73 | 36.42 | 50 |
| 0.0033 | 47.59 | −21.40 | 34.00 | 49 |
| 0.0098 | 42.27 | −26.47 | 31.51 | 51 |
| 0.0187 | 40.41 | −28.02 | 31.81 | 55 |
| 0.0314 | 40.39 | −27.52 | 34.14 | 61 |
| 0.0584 | 38.25 | −28.68 | 36.89 | 73 |
| 0.0748 | 37.24 | −29.07 | 38.51 | 81 |
| 0.1022 | 36.50 | −28.79 | 41.85 | 94 |
| 0.1482 | 35.37 | −28.20 | 46.93 | 116 |
| 0.2219 | 33.81 | −27.00 | 54.00 | 151 |
| 0.3152 | 33.30 | −24.02 | 63.71 | 197 |
| 0.4328 | 32.94 | −19.98 | 75.11 | 255 |
| 0.5259 | 32.75 | −16.69 | 83.56 | 301 |
| 0.5974 | 32.47 | −14.30 | 89.30 | 336 |
| 0.7667 | 32.22 | −8.22 | 103.00 | 420 |
| 0.8249 | 32.05 | −6.21 | 107.10 | 448 |
| 0.9324 | 31.94 | −2.29 | 115.20 | 501 |
| 1.0000 | 31.71 | 0.00 | 119.40 | 533 |

obtained by fitting the equations to the experimental values with a least-squares method are given in Table 5 along with standard deviations $\delta$. The standard deviation was calculated by

$$\delta = [\sum_{1}^{n} (Y(x)_{\text{exptl}} - Y(x)_{\text{calcd}})^2/(n - m)]^{1/2} \quad (5)$$

where $n$ and $m$ are the number of experimental points and parameters, respectively.

Molar surface energies $E_a$ and parachor $P$, have also been calculated from experimental surface tensions and densities with following relationships

$$E_a = \sigma(M/\rho)^{2/3} \quad (6)$$

$$P = M\sigma^{1/4}/\rho \quad (7)$$

where other symbols have their usual meanings. These values are also reported in Table 3.

From Figures 1 to 3, it is observed that excess molar volumes for polyether (1) + water (2) binary liquid mixtures show negative deviations over whole concentration range at all temperatures. The magnitude of excess molar volume decreases with the increase in the polar headgroup of the polyether, that is, the

**Table 4. Standard Deviations ($\delta$) and Parameters $A_i$/mN·m$^{-1}$ in eq 2 for Surface Tension ($\sigma$/mN·m$^{-1}$)**

| $T$/K | $A_0$ | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $\delta$ mN·m$^{-1}$ |
|---|---|---|---|---|---|---|
| | | | $x$ Diethylene Glycol Dimethyl Ether + (1 − $x$) Water | | | |
| 298.15 | 47.36 | −171.63 | 537.74 | −672.74 | 289.09 | 1.55 |
| 308.15 | 49.30 | −208.86 | 687.18 | −89.78 | 396.78 | 2.25 |
| 318.15 | 51.83 | −239.31 | 704.13 | −847.68 | 356.96 | 4.44 |
| | | | $x$ Triethylene Glycol Dimethyl Ether + (1 − $x$) Water | | | |
| 298.15 | 49.06 | −209.78 | 758.04 | −1053.21 | 489.58 | 2.59 |
| 308.15 | 47.09 | −161.74 | 545.72 | −729.97 | 331.22 | 2.93 |
| 318.15 | 45.89 | −202.89 | 803.88 | −1197.42 | 592.27 | 2.54 |
| | | | $x$ Tetraethylene Glycol Dimethyl Ether + (1 − $x$) Water | | | |
| 298.15 | 46.62 | −113.77 | 394.41 | −548.04 | 259.46 | 2.22 |
| 308.15 | 45.28 | −122.78 | 426.13 | −578.91 | 265.59 | 2.47 |
| 318.15 | 49.64 | −193.37 | 691.99 | −958.13 | 448.02 | 4.29 |

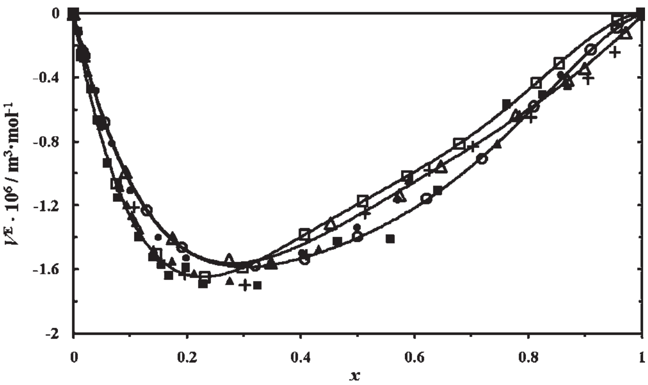


**Figure 1.** Excess molar volumes $V^E$ for ○, $x$ diethylene glycol dimethyl ether + (1 − $x$) water; ●, ref 8, $x$ diethylene glycol dimethyl ether + (1 − $x$) water; △, $x$ triethylene glycol dimethyl ether + (1 − $x$) water; ▲, ref 9, $x$ triethylene glycol dimethyl ether + (1 − $x$) water; □, $x$ tetraethylene glycol dimethyl ether + (1 − $x$) water; ■, ref 10, $x$ tetraethylene glycol dimethyl ether + (1 − $x$) water; +, ref 5, $x$ tetraethylene glycol dimethyl ether + (1 − $x$) water at 298.15 K. Smooth curves have been drawn from polynomial curve fitting.

**Table 5. Standard Deviations ($\delta$) and Parameters $A_i$/m$^3$·mol$^{-1}$ or $A_i$/mN·m$^{-1}$ in eq 4**

| $Y(x)$ | $T$/K | $A_0$ | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $\delta$ |
|---|---|---|---|---|---|---|---|
| | | | $x$ Diethylene Glycol Dimethyl Ether + (1 − $x$) Water | | | | |
| $V^E \cdot 10^6$/m$^3$·mol$^{-1}$ | 298.15 | −5.601 | 3.156 | −2.694 | 3.753 | | 0.009 |
| | 308.15 | −5.699 | 3.637 | −2.647 | 3.128 | | 0.013 |
| | 318.15 | −5.854 | 3.449 | −3.017 | 3.512 | | 0.010 |
| $\Delta\sigma$/mN·m$^{-1}$ | 298.15 | 47.39 | −172.67 | 541.48 | −686.28 | 297.18 | 1.55 |
| | 308.15 | 49.30 | −209.01 | 688.18 | −895.64 | 397.83 | 2.25 |
| | 318.15 | 51.26 | −269.15 | 871.56 | −1121.26 | 495.55 | 2.31 |
| | | | $x$ Triethylene Glycol Dimethyl Ether + (1 − $x$) Water | | | | |
| $V^E \cdot 10^6$/m$^3$·mol$^{-1}$ | 298.15 | −5.035 | 4.084 | −4.038 | 1.411 | | 0.030 |
| | 308.15 | −5.114 | 4.424 | −2.799 | 1.453 | −2.659 | 0.016 |
| | 318.15 | −5.153 | 4.866 | −2.397 | 0.975 | −3.127 | 0.024 |
| $\Delta\sigma$/mN·m$^{-1}$ | 298.15 | 49.09 | −212.56 | 777.11 | −1089.73 | 510.55 | 2.60 |
| | 308.15 | 47.10 | −161.74 | 545.73 | −729.97 | 331.22 | 2.93 |
| | 318.15 | 45.87 | −202.23 | 801.04 | −1193.21 | 590.22 | 2.58 |
| | | | $x$ Tetraethylene Glycol Dimethyl Ether + (1 − $x$) Water | | | | |
| $V^E \cdot 10^6$/m$^3$·mol$^{-1}$ | 298.15 | −4.759 | 4.011 | −5.092 | 5.590 | | 0.005 |
| | 308.15 | −4.615 | 3.926 | −4.797 | 5.217 | | 0.005 |
| | 318.15 | −4.465 | 3.828 | −4.475 | 5.020 | | 0.004 |
| $\Delta\sigma$/mN·m$^{-1}$ | 298.15 | 46.28 | −113.48 | 393.97 | −548.07 | 259.70 | 2.27 |
| | 308.15 | 45.28 | −122.78 | 426.13 | −578.91 | 265.59 | 2.47 |
| | 318.15 | 49.64 | −193.16 | 690.75 | −956.17 | 447.13 | 4.29 |


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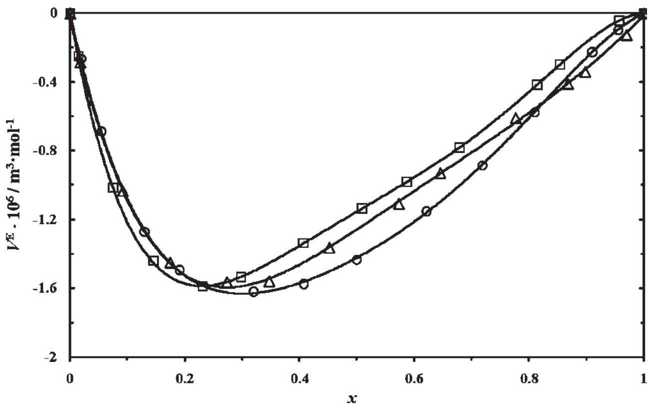


**Figure 2.** Excess molar volumes $V^E$ for ○, $x$ diethylene glycol dimethyl ether + $(1 - x)$ water; △, $x$ triethylene glycol dimethyl ether + $(1 - x)$ water; □, $x$ tetraethylene glycol dimethyl ether + $(1 - x)$ water at 308.15 K. Smooth curves have been drawn from polynomial curve fitting.

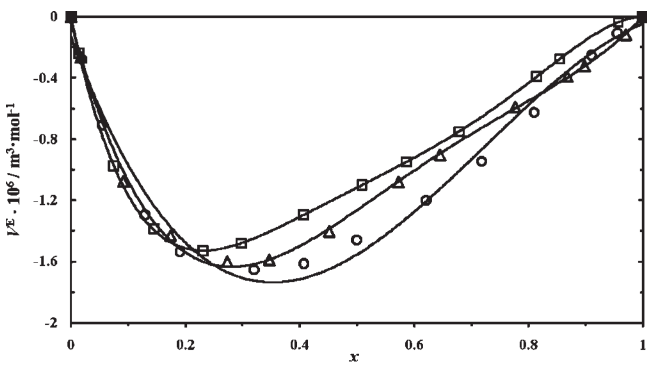


**Figure 3.** Excess molar volumes $V^E$ for ○, $x$ diethylene glycol dimethyl ether + $(1 - x)$ water; △, $x$ triethylene glycol dimethyl ether + $(1 - x)$ water; □, $x$ tetraethylene glycol dimethyl ether + $(1 - x)$ water at 318.15 K. Smooth curves have been drawn from polynomial curve fitting.

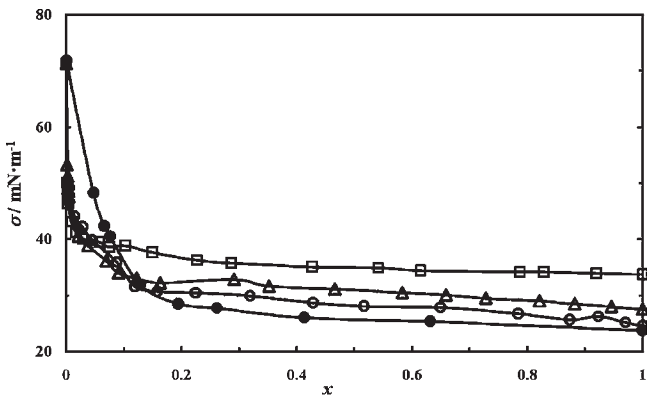


**Figure 4.** Experimental surface tension $\sigma$ for ●, ref 7, $x$ ethylene glycol dimethyl ether + $(1 - x)$ water; ○, $x$ diethylene glycol dimethyl ether + $(1 - x)$ water; △, $x$ triethylene glycol dimethyl ether + $(1 - x)$ water; □, $x$ tetraethylene glycol dimethyl ether + $(1 - x)$ water at 298.15 K. The solid lines are a guide for the eye.

presence of diethylene glycol units $[CH_2CH_2O]$ in the glyme chain lowers the excess molar volume. The negative values of $V^E$

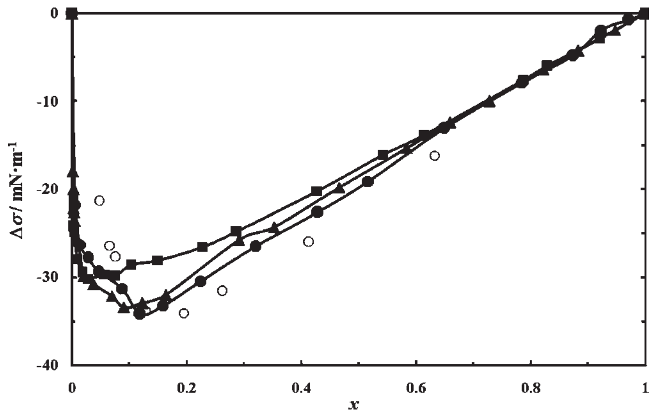


**Figure 5.** Surface tension deviations $\Delta\sigma$ for ○, ref 7, $x$ ethylene glycol dimethyl ether + $(1 - x)$ water; ●, $x$ diethylene glycol dimethyl ether + $(1 - x)$ water; ▲, $x$ triethylene glycol dimethyl ether + $(1 - x)$ water; ■, $x$ tetraethylene glycol dimethyl ether + $(1 - x)$ water at 298.15 K. The solid lines are a guide for the eye.

suggest a strong chemical or specific interaction between the unlike components which is maximum in diethylene glycol dimethyl ether—water mixture. For comparison we have shown the excess molar volumes calculated from densities reported earlier[5,8−10] for these binary mixtures. The difference in the values may be due to the method of measurements and purity of samples.

Figure 4 shows that the surface tension $\sigma$ for the binary liquid mixtures decreases with the increase in the concentration of polyether. Surface tension of the binary mixtures follows the order: ethylene glycol dimethyl ether[7] < diethylene glycol dimethyl ether < triethylene glycol dimethyl ether < tetraethylene glycol dimethyl ether. This sequence shows that the surface tension increases with the increase in the polar headgroup in the polyether. Surface tension deviations, $\Delta\sigma$, values at all of the studied temperatures are reported in Table 3. The values of $\Delta\sigma$ at 298.15 K are shown in Figure 5. The values are negative over the whole concentration range for all binary liquid mixtures and show a sharp minimum in the water- rich region. It shows maximum deviations for $x$ ethylene glycol dimethyl ether + $(1 - x)$ water mixture, and the magnitude decreases with increase in the number of polar head groups in polyether.

The surface energy $E_a$ and parachor $P$ are calculated using eqs 6 and 7 at studied temperatures for all binary liquid mixtures and are reported in Table 3. Both values increase with the increase in the concentration of polyether in liquid mixtures at all temperatures. Also the values for the mixtures increase at all temperatures as we shift from diethylene glycol dimethyl ether to triethylene glycol dimethyl ether to tetraethylene glycol dimethyl ether.

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## ■ REFERENCES

(1) Hawrylak, B.; Andrecyk, S.; Gabriel, C. E.; Gracie, K.; Palepu, R. Viscosity, surface tension and refractive index measurements of mixtures of isomeric butandiols with water. *J. Solution Chem.* **1998**, *27*, 827–841.

(2) Tsierkzos, N. G.; Melinou, I. E. Surface tension of 4-methyl-2-pemtanone/ethyl benzoate binary systems in the temperature range from 278.15 to 308.15 K. *J. Solution Chem.* **2006**, *35*, 279–296.

(3) Lyklema, J. The surface tension of pure liquids: thermodynamic components and corresponding states. *Colloids Surf. A* **1999**, *156*, 413–421.

(4) Ghafel, M. H.; Pakdel, L. Surface tension regularity of non-polar, polar and weak electrolyte liquid hydrocarbons. *Fluid Phase Equilib.* **2005**, *234*, 101–107.

(5) Henni, A.; Tontiwachwuthikul, P.; Chakma, A. Densities, Viscosities, and Derived Functions of Binary Mixtures: (Tetraethylene Glycol Dimethyl Ether + Water) from 298.15 to 343.15 K. *J. Chem. Eng. Data* **2004**, *49*, 1778–1781.

(6) Henni, A.; Naami, A.; Tontiwachwuthikul, P. Densities, Viscosities, and Derived Functions of Binary Mixtures: (Triethylene Glycol Dimethyl Ether + Water) and (*N*-Acetylmorpholine + Water) from 298.15 to 343.15 K. *J. Chem. Eng. Data* **2005**, *50*, 1038–1042.

(7) Kumar, A.; Mohandas, V. P.; Ghosh, P. K. Experimental surface tensions and derived properties of binary mixtures of water + alkoxyethanols ($C_1E_m$, m = 1, 2, 3) and water + ethylene glycol dimethyl ether ($C_1E_1C_1$) at (298.15, 308.15, and 318.15) K. *J. Chem. Eng. Data* **2003**, *48*, 1318–1322.

(8) Wallace, W. J.; Mathews, A. L. Density, refractive indices, molar refractions and viscosities of diethylene glycol dimethyl ether-water solutions at 25° C. *J. Chem. Eng. Data* **1964**, *9*, 267–268.

(9) Wallace, W. J.; Shephard, C. S.; Underwood, C. Density, refractive indices, molar refractions, viscosities, and dielectric constants of triethylene glycol dimethyl ether-water solutions at 25 °C. *J. Chem. Eng. Data* **1968**, *13*, 11–13.

(10) McGee, R. L.; Wallace, W. J.; Ratalczak, R. D. Densities, viscosities, refractive indices and molar refractions of the binary system tetraethylene glycol dimethyl ether-water at 25 °C. *J. Chem. Eng. Data* **1983**, *28*, 305–307.

(11) Pal, A.; Singh, Y. P. Excess Molar Volumes and Apparent Molar Volumes of $[xH(CH_2)_vO(CH_2)_2O(CH_2)_2OH + (1 - x)\ H_2O]$ (v = 1, 2, and 4) at the Temperature 298.15 K. *J. Chem. Thermodyn.* **1994**, *26*, 1063–1070.

(12) Pal, A.; Singh, Y. P. Excess Molar Volumes and Apparent Molar Volumes of $[xH(CH_2)_vO(CH_2)_2O(CH_2)_2O(CH_2)_2OH + (1 - x)H_2O]$ (v = 1, 2, and 4) at the Temperature 298.15 K. *J. Chem. Thermodyn.* **1995**, *27*, 1329–1336.

(13) Aminabhavi, T. M.; Gopalakrishna, B. Density, Viscosity, Refractive Index, and Speed of Sound in Aqueous Mixtures of N,N-Dimethylformamide, Dimethyl Sulfoxide, N,N-Dimethylacetamide, Acetonitrile, Ethylene Glycol, Diethylene Glycol, 1,4-Dioxane, Tetrahydrofuran, 2-Methoxyethanol, and 2-Ethoxyethanol at 298.15 K. *J. Chem. Eng. Data* **1995**, *40*, 865–861.

(14) de Ruiz Holgado, M. E.; de Schaefer, C. R.; Arancibia, E. L.; Katz, M. Excess molar volumes and viscosities of binary mixtures of bis(2-methoxyl)ether (diglyme) with chloroalkanes at 298.15 K. *Fluid Phase Equilib.* **1994**, *95*, 299–312.

(15) Pal, A.; Singh, Y. P. Viscosity in Water + Ethylene Glycol Dimethyl, + Diethylene Glycol Dimethyl, + Triethylene Glycol Dimethyl, and + Tetraethylene Glycol Dimethyl Ethers at 298.15 K. *J. Chem. Eng. Data* **1996**, *41*, 1008–1011.

(16) Ku, H. C.; Tu, C. H. Densities and Viscosities of Seven Glycol Ethers from 288.15 to 343.15 K. *J. Chem. Eng. Data* **2000**, *45*, 391–394.

(17) Tovar, C. A.; Carballo, E.; Cerdeiriña, C. A.; Legido, J. L.; Romani, L. Effect of temperature on W-shaped excess molar heat capacities and volumetric properties: Oxaalkane-nonane systems. *Int. J. Thermophys.* **1997**, *18*, 761–777.

(18) Dethlefsen, C.; Hvidt, A. Densities and derived volume functions of binary mixtures: (an ethylene glycol derivative + water) at 298.15 K. *J. Chem. Thermodyn.* **1985**, *17*, 193–199.

(19) Tovar, C. A.; Carballo, E.; Cerdeiriña, C. A.; Paz Andrade, M. I.; Romaní, L. Thermodynamic properties of polyoxyethyleneglycol dimethyl ether + n-alkane mixtures. *Fluid Phase Equilib.* **1997**, *136,*, 23–34.

(20) Pereira, S. M.; Rivas, M. A.; Real, J. N.; Legido, J. L.; Iglesias, T. P. Densities, Speeds of Sound, and Refractive Indices of the Mixture Nonane + Triethylene Glycol Dimethyl Ether at 288.15 K, 293.15 K, 298.15 K, and 308.15 K. *J. Chem. Eng. Data* **2002**, *47*, 919–922.

(21) Treszczanowicz, T.; Benson, G. C.; Lu, B. C. Y. Excess volumes for binary mixtures formed by 2,5,8,11-tetraoxadodecane or 2,5,8,11,14-pentaoxapentadecane with homologous n-alkanes. *Thermochim. Acta* **1990**, *168*, 95–102.

(22) Peleteiro, J.; Tovar, C. A.; Carballo, E.; Legido, J. L.; Romaní, L. Temperature dependence of the volumetric properties of binary mixtures containing oxoalkane + c-hexane. *Can. J. Chem.* **1994**, *72*, 454–462.

(23) Marsh, K. N. *Recommended Reference Materials for the Realization of Physicochemical Properties*; Blackwell Scientific Publications: Oxford, 1987.

(24) Enders, S.; Kahl, H.; Winkelmann, J. Surface Tension of the Ternary System Water + Acetone + Toluene. *J. Chem. Eng. Data* **2007**, *52*, 1072–1079.

(25) Rilo, E.; Pico, J.; García-Garabal, S.; Varela, L. M.; Cabeza, O. Density and surface tension in binary mixtures of CnMIM-$BF_4$ ionic liquids with water and ethanol. *Fluid Phase Equilib.* **2009**, *285*, 83–89.

(26) Markarian, S. A.; Terzyan, M. A. Surface Tension and Refractive Index of Dialkylsulfoxide + Water Mixtures at Several Temperatures. *J. Chem. Eng. Data* **2007**, *52*, 1704–1709.

(27) Lemmon, E. W.; McLinden, M. O.; Friend, D. G. Thermophysical Properties of Fluid Systems. In *NIST Chemistry Web Book*, NIST Standard Reference Database Number 69; Linstrom, P. J, Mallard, W. G., Eds.; National Institute of Standards and Technology: Gaithersburg, MD, 2005. http://webbook.nist.gov.

(28) Álvarez, E.; Vázquez, G.; Sánchez-Vilas, M.; Sanjurjo, B.; Navaza, J. M. Surface Tension of Organic Acids + Water Binary Mixtures from 20 to 50 °C. *J. Chem. Eng. Data* **1997**, *42*, 957–960.

(29) IUPAC Commission on atomic weights and isotopic abundances. 1985. *Pure Appl. Chem.* **1986**, *58*, 1677−1692.

(30) Redlich, O.; Kister, A. T. Algebric representation of thermodynamic properties and the classification of solutions. *Ind. Eng. Chem.* **1948**, *40*, 345–348.